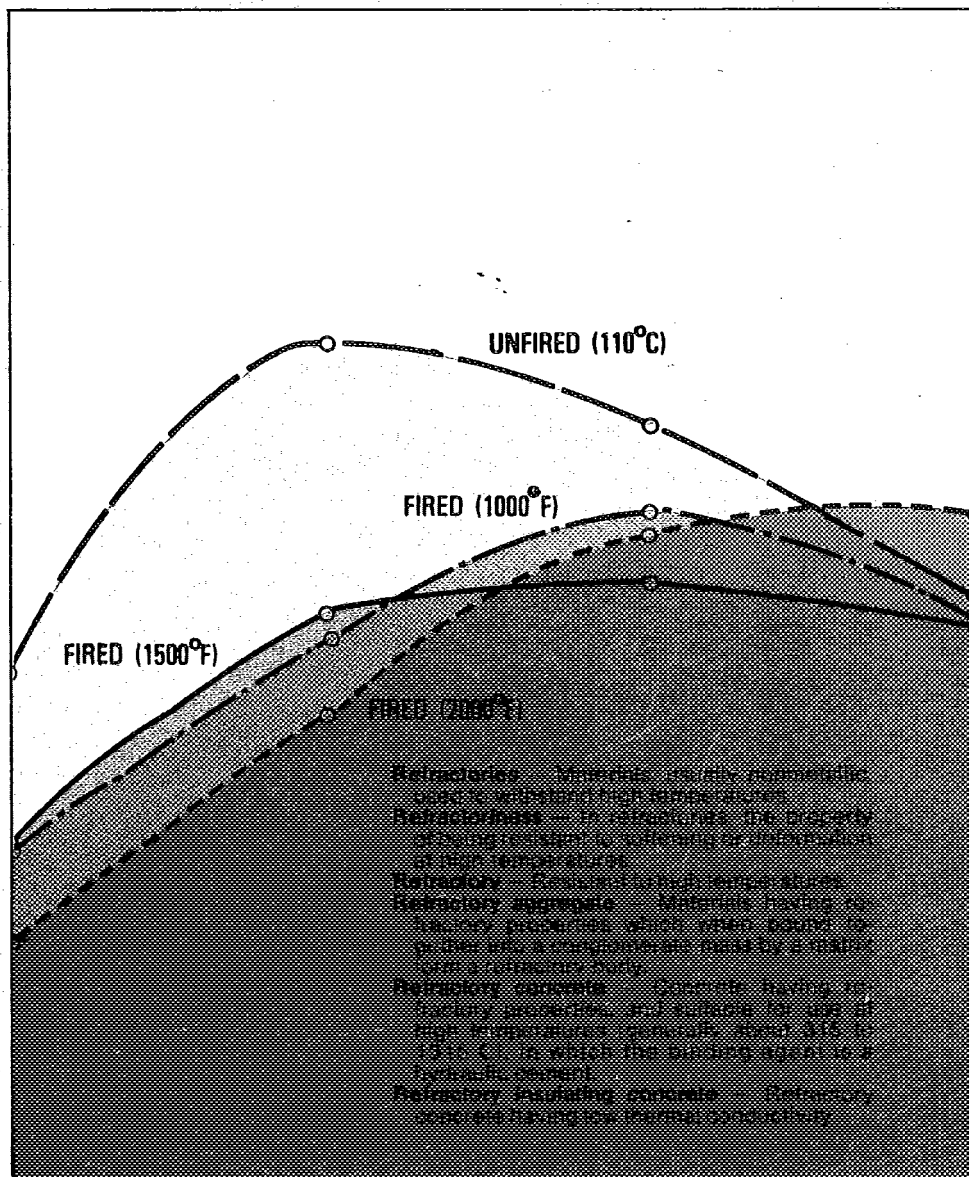


REFRACTORY CONCRETE



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PREFACE

Refractory concretes are versatile monolithic refractories that are widely used by steel producers, petrochemical processors, ceramic manufacturers, cement producers, foundries, and other industries. First introduced in the United States around 1926, they have grown significantly in tonnage and in the variety of their application since that time.

Despite the important role played by these unique materials, their coverage at scientific meetings and in the literature has been quite sporadic. In view of this situation, ACI Committee 547, Refractory Concrete, reasoned that a technical session devoted exclusively to the production, properties, and applications of refractory concretes would fill a long standing need. This initial interest led ultimately to the Symposium on Refractory Concrete sponsored by the committee at the annual Convention of the American Concrete Institute on Mar. 17, 1977.

Of the 14 papers presented at the symposium, 5 were invited, including, "Refractory Concretes - Past, Present, and Future," by T.D. Robson; "Properties of Refractory Concretes," by Wate T. Bakker; "Refractory Concrete - Use of Engineering Property Data for Design," by Robert Farris; "Refractory Concrete Applications in Refining and Petrochemical Operations," by Michael S. Crowley; and "Selection and Use of Refractory Concretes in the Steel Plant," by Richard L. Wessel. Other papers, reviewed by the committee and selected for presentation at the symposium, discussed the testing, characterization, and evaluation of refractory concretes in the fresh, hardened, and fired state; the gunite application of refractory concrete; the use of steel fibers as reinforcement in refractory concrete failures.

An international flavor was given to the symposium by Dr. Tom Robson (Isle of Man), who presented the keynote address and Dr. W. Kronert (Aachen, West Germany) who discussed the development of the ceramic bond in refractory concretes as revealed through scanning electron microscopy and x-ray diffraction analyses.

The excellent attendance at the symposium and favorable comments received subsequently confirmed the committee's belief that such a symposium was indeed overdue. The committee is pleased that ACI has chosen to publish the proceedings of the symposium and in doing so, make a wealth of practical information available to all those concerned with the production and use of this important refractory material.

Dr. David R. Lankard
Symposium Chairman

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SP 57-1**REFRACTORY CONCRETES:
PAST, PRESENT, AND FUTURE**

By T. D. ROBSON

Synopsis: Refractory concretes are defined and a brief discussion of the calcium aluminate cements which form their hydraulic bond is followed by a description of the early work which probably led to the first recorded use of a refractory concrete. A short historical account is given of the development (and some interesting uses) of refractory castable mixes before and after World War II. Attention is drawn to some of the basic differences in properties between refractory brickwork and refractory concrete, and to the value of refractory concrete for experimental or pilot-scale development work.

When refractory concrete is heated for the first time to its service temperature, the properties will depend mainly on the thermal reactions which can occur within the concrete, and ways of promoting these reactions at the lowest possible temperature are discussed. It is suggested that further improvements in refractory castables may result from extensive work in this field.

Keywords: aluminate cements and concretes; calcium aluminates; history; refractory concretes.

T.D. Robson graduated from the Universities of Glasgow and St. Andrews and, after periods of academic and industrial research, has been associated with the manufacture and use of calcium aluminate cements for the past 30 years. He retired from the Lafarge Organisation Ltd., England in 1975 but continues as a Director of Lafarge Fondu International s.a., Paris, France.

INTRODUCTION

By giving a historical background to the continuing story of refractory concrete, this paper may serve as a lead-in to the other papers which follow in this Symposium, where the Authors give more detailed attention to specific matters. Although reference will be made to several of the topics covered by subsequent papers, any discussion has therefore been limited to a few selected aspects.

REFRACTORY CONCRETE

In the widest sense the term refractory concrete could be applied to any graded refractory aggregate held together by a bond capable of giving a solid mass which has adequate properties both before and after firing to a relatively high temperature.

Mouldables, "plastics", and ramming mixes which essentially use a plastic clay bond, and other concretes which are bonded by various chemicals (including phosphates, oxychlorides etc.,) might therefore be included in this definition. Such concretes usually need some degree of heating before the working strength is obtained - and accordingly have been excluded from this survey. This leaves refractory concretes bonded by an hydraulic cement (either Portland or calcium aluminate) as these concretes can develop relatively high strengths after hardening at ambient temperatures, and they do not normally need any pre-heating before being put into service.

In practice the use of Portland cement in refractory concrete has usually been limited to the lower - temperature range - not because of any assumed lack of refractoriness, but rather because the free lime released on firing can cause crumbling when the concrete is submitted to thermal cycling with intervening periods in moist air. The addition of materials which combine with free lime (either pozzolamic or thermal action) reduces this potential weakness, and, particularly in the U.S.S.R. and some Eastern European countries, a useful field has therefore been found for a Portland cement bond in refractory concrete.

However this account will deal exclusively with refractory concretes bonded with a calcium aluminate cement. Such concretes may be subjected without damage to humid air, to wetting, or even to

quenching, after they have been fired to intermediate or high temperatures. They have of course the additional advantage of being very rapid-hardening and the term "refractory concrete" now generally implies that the bond is a calcium aluminate cement.

CALCIUM ALUMINATE CEMENT

This type of cement is manufactured in many countries and includes a very wide range of chemical compositions, but, almost without exception, one of the raw materials is either a natural bauxite (i.e. an impure form of alumina) or the nearly pure aluminium oxide extracted from bauxite.

Those cements made with alumina are white and contain only very small amounts of silica or iron oxide. In general they are much more refractory than those made from bauxites, since the latter cements contain substantially greater amounts of iron oxide and silica - which are contributed by the bauxite used in manufacture. The iron oxide content of bauxites varies widely in different localities and there is a corresponding difference in the cement compositions. However, even those made from a very low-iron bauxite (or those in which nearly all the iron oxide has been removed by reductive fusion) can be distinguished from the white cements, as all contain an appreciable amount of silica and a readily detectable quantity of titania.

Several calcium aluminates may be formed by reaction between lime and alumina, but the one common and essential factor in all the very varied calcium aluminate cements is the presence of a specific aluminate - namely monocalcium aluminate or CA. A calcium aluminate cement may be white, yellow, grey or black, it may contain 40% or 80% alumina, but its development of high-early strength, after a relatively slow set, is almost entirely due to this single aluminate.

Calcium di-aluminate CA_2 has a much higher refractoriness than CA and, at the time when white cements of higher refractoriness and alumina content were first considered, some investigators thought that such cements should therefore consist largely of CA_2 . This of course was erroneous because CA_2 hydrates very slowly at ordinary temperatures, and in these conditions cannot produce the early strength normally expected from refractory concrete mixes. Nevertheless the hydration of CA_2 is accelerated by higher temperatures and it could have advantages in a refractory castable, provided that conditions were made suitable for its rapid hydration. About 12 years ago this led to the report that steam-curing a CA_2 refractory castable mix would result (other things being equal) in the highest fired strengths.

HISTORY

The hydraulic properties of compounds formed by reacting lime with alumina were known long before the individual calcium aluminates were isolated in a pure condition and positively identified, but it is rather startling to find that probably the first refractory concrete was made and put to practical use before 1856.

Several years before 1856 Henri Sainte-Claire Deville had been working in his laboratory at the Ecole Normale endeavouring to obtain the highest temperatures which his fuels (coal and "carburetted oils") could produce. He had concluded that there was a new scientific field to be investigated - that of 'high temperature chemistry'. He wished to study reactions at what he called "blue heat" - the temperature at which "platinum melts".

He had been using crucibles made from quicklime or carbon but, in fabricating alumina crucibles, he found that, although a paste made with water and calcined ammonium alum was plastic enough, it had too high a shrinkage to be used alone. He felt that some form of cement was required and therefore heated equal parts of alumina and pulverised marble to the highest temperature attainable in his air-blast furnace and he ground to a fine powder the resulting translucent mass. This cement (a very early form of white calcium aluminate cement) was then mixed with two parts of highly calcined alumina and gauged with water. After moulding into shape, the crucibles "set very hard and could withstand drying, handling and the action of heat". In fact he said that his crucibles softened slightly at the temperature of molten platinum but "showed a remarkable solidity after strong heating". He believed the cement to be a spinel i.e. monocalcium aluminate, but this was a supposition based solely on the proportions of lime and alumina he had used in its manufacture.

He also made some other observations which were well ahead of his time. For example he noted that complete fusion of the lime-alumina mixture was not essential for the development of hydraulic properties, and that a reduction in the cement content increased the refractoriness of his castable mixes. However, to retain adequate strength before firing he recommended that the castable should contain 5-10% CaO by analysis, the rest obviously being alumina.

Today a modern high-temperature castable mix based on white calcium aluminate and tabular or fused alumina will contain 2.5-5.0% or more of CaO. After more than 120 years we are still using the approximate formulation of Sainte-Claire Deville in this type of castable - although of course the modern castable mix has many sophistications of which he was unaware.

THE DEVELOPMENT OF COMMERCIAL CASTABLE MIXES

The commercial production, testing and marketing of a calcium aluminate cement was not completed until after the end of World War 1 and the cement was produced in France for purposes far removed from those of refractory concrete.

As early as 1909 the Aluminate Patent Co., was formed in the U.S.A. to exploit the patents of Spackman, but Spackman's aluminates were not intended to provide a cement on its own, but only as an addition to Portland cement, natural cement, slaked lime or plaster, in order to improve the properties of these binders. The resulting 'ALCA' cements, marketed in 1910-17, did not prove too successful but in 1924 the Atlas Aluminate Cement Co. started the manufacture of a true calcium aluminate cement at Northampton, Penn.

Calcium aluminate cements were soon being manufactured from bauxites in many locations and in many types of plant, including the blast-furnace method employed at the Rolandshutte works - which was then at Wiedenau. The various cements were almost entirely for rapid-hardening structural concrete or for chemical resistance (in particular for sulphate resistance).

It is perhaps doubtful whether the early work of Sainte-Claire Deville was responsible for the initial use of commercial cements in refractory concretes, and indeed the type of white cement made by him did not become commercially available in any quantity until many years after the production of cements made from bauxite. It is quite probable that the heat-resistant properties of the concrete made with the early cements and suitable aggregates were discovered anew - just as the rapid-hardening qualities of the cement came as a pleasant surprise.

Possibly the first mention of the use of refractory concrete in the U.S.A. was as early as 1924 and, at a time when it was being used mainly for refractory patching and small scale applications, it appears that some remarkably ambitious refractory concrete work was carried out in the U.S.A. - for furnace lining and even for blast-furnace lining.

During the 1930's however there was a great expansion everywhere in the use of refractory and refractory-insulating concretes, in the variety of applications, and in the literature reporting them. By the outbreak of World War 11 refractory concrete was well established in many industries for furnaces or ovens, as linings in boilers or stacks, and for heat-resistant foundations. At this period the Lafarge works on the Thames in England was very vulnerable to bombing attack and, at the request of the Government, many thousand tons of calcium aluminate cement were sealed in steel drums and distributed around the country (of course not all of this cement was intended for refractory use). During the War any user had to give reasons why he should obtain his quota of cement, and it was astonishing how many industries employing

refractories considered that this cement was essential for their continued operation at that time.

In the early days of refractory concrete very many users mixed their own concrete from a calcium aluminate cement and a refractory aggregate - either bought as such, or crushed by themselves. However dry castable mixes containing aggregate and cement in the correct proportions soon appeared on the market (one of the earliest may have been the so-called Kestner Cement) and ready-prepared proprietary mixes are now used by the great majority of refractory concrete clients. This trend developed more rapidly in the U.S.A. than in Europe but the European countries have been quickly following suit. The percentage of users who prepare their own mixes is now very small, but this type of use will probably always continue to some extent, particularly for certain low-duty applications where the user happens to have an adequate aggregate available. Examples of this are the utilisation of crushed bricks in the brick industry and the use of a local natural aggregate suitable for low-temperature applications.

The availability of carefully-compounded proprietary mixes, whose properties are kept within regular limits, has been an essential factor in the growing ability to design refractory concrete structures, since reliable data on the individual castables can be supplied by the manufacturer.

AFTER WORLD WAR II

In the years following the War the considerable number of catalytic cracking units built for the petroleum industry utilised large quantities of refractory and refractory-insulating concretes as linings in reactors and regenerators, as well as in heating furnaces etc. In a high proportion of applications in this industry the refractory concrete was placed by gun, and the same method was largely used by the iron and steel industry, which, in most countries is still the major user of refractory concretes.

The 1960's saw very many repairs to the throats and stacks of blast-furnaces without shutting down the furnace completely. This effected great savings, the concrete was placed very rapidly by gun, and the service life has usually been excellent.

Castable manufacturers had already played their part by producing castables specially designed for gunning (e.g. to minimise rebound) and mixes containing iron-free cement and aggregates to eliminate the attack of carbon monoxide on blast-furnace refractories.

A number of steam gas-reforming plants using naphtha as base stock were also erected in this period. White cement castables were mainly used for vessel linings and in this case it was found that even the tiny amount of silica in the cement had to be carefully controlled because, under plant conditions, it could be extracted, transported in a volatile form, and deposited elsewhere-leading to the possibility of

blockage.

Increasing knowledge of the basic factors governing the design of refractory concrete led to a further exploitation of the essentially monolithic character of the material. There was greater confidence in constructing very large furnaces, kilns etc., entirely in refractory concrete, and in using more massive pre-cast units.

The essential differences in properties and behaviour between refractory concrete and orthodox brickwork became of great importance although it is surprising how many excellent constructions were built by simple substitution of concrete for brickwork (dimension for dimension) and by employing a few empirical rules governing such things as the location of steel.

Unlike refractory bricks, whose final properties are largely fixed before reaching the user, a refractory concrete has properties which evolve and alter for a considerable time after it has been put into use. This is particularly so because practically all the refractory concrete in service is heated on one face only. In a construction of any substantial thickness it may take a very long time for the strength gradient, the thermal gradient and the moisture gradient to reach equilibrium between the "hot" and "cold" faces of the concrete. Accordingly the difficulties in designing and also in testing refractory concretes have been evident from the beginning.

However a constant feature since the earliest days has been the wide use of refractory castables in initial experimental and development work. This, of course, is due to the ease with which any desired shape can be cast and its form or dimensions can be altered, using fairly simple moulds. In many cases large scale applications for refractory concrete have followed but it is also quite normal to find that, once the product has been finalised, the commercial units may be made mainly with another material. It has been a common experience that any new industry, technology, or industrial development (which involves a refractory) has aroused interest in refractory concrete - usually at an early stage.

The advent of the jet-engine initially caused some concern to engineers responsible for the upkeep of the concrete runways. However the danger of high surface temperatures on the concrete was soon dispelled by the almost universal use of the nose-wheel type of under-carriages, although several parking bays for military aircraft were constructed in refractory concrete. Vertical take-off aircraft renewed this fear, and the original British V.T.O. prototype - the "Flying Bedstead" took off from a refractory concrete pad. Early silencing cells for jet-engine testing were also constructed in refractory concrete in both England and the U.S.A., as were gas-collecting chambers for industrial gas-turbine tests.

The initial trials for the abortive British rocket programme involved the construction of a refractory U-tube to allow escape of the hot gases from a missile contained in an underground silo. A one-sixth scale U-tube was first made from a mix of fused alumina and

white calcium aluminate cement, and this was tested by a rocket engine firing down one arm of the tube while the U-tube was placed horizontally on the ground instead of vertically in a silo.

Refractory concrete has also been used elsewhere for the blast and heat deflector bases on large rocket sites, especially where there was difficulty in obtaining the water supply required from the "wet" type of stand.

SOME REFLECTIONS ON THE NATURE OF REFRACTORY CONCRETE

Until the refractory castable has hardened and been put into service it is certainly an ordinary concrete with a hydraulic bond, and the usual principles governing the making of a good structural concrete ought to be applicable. But, after the concrete is heated up to the point of dehydration or decomposition of the cement hydrates, are we sure that these structural concreting principles have necessarily produced the optimum conditions (within the concrete) for the subsequent thermal reactions on which the refractory performance will depend? Once the mass is in a dehydrated state the conditions are foreign to the cement or concrete technologist but they are now within the field of the ceramist or refractories engineer.

In the case of refractory concrete it is the behaviour at the service temperature which is more important than the unfired strength. It is true that we must have a sufficiently high unfired strength, and we must remember that the "cold" face of the concrete may reach only very moderate temperatures, but, in most types of use, the loading on refractory concrete is very low in comparison with that to which structural concrete is submitted.

Is it therefore possible that in the past we have given undue importance to the cement technologist and not enough to the ceramist or refractory engineer? Should we continue to use the term "refractory concrete" or should we not standardise on "castable refractory"?

As an example consider a defect which has long been attributed to refractory concrete - the drop in strength shown by most castables in the intermediate temperature zone i.e. in temperatures sufficient to dehydrate the bond but insufficient to create much of the so-called ceramic bond. Early attempts to accelerate the formation of this ceramic bond generally consisted in making additions of various fluxes most of which did little good and usually reduced the maximum temperature of use.

Attention was therefore turned to the possibility of speeding-up the solid-state reactions within the refractory - reactions which can take place long before there is any appreciable liquid formation. Obviously the more finely divided a material the lower the temperature at which these reactions will proceed with some velocity.

As far as the cement is concerned the process of hydration, followed by dehydration, converts the anhydrous material into an extremely fine and active form.

Accordingly, the first conclusion we draw is that we have to encourage as much of the cement to hydrate as possible. It does not matter much which hydrate we produce and therefore a higher temperature of hydration (caused either by ambient temperature or by self-generated heat during hardening) will give the desired result.

The second conclusion is that we should provide (either in the cement or in the castable) sufficient very finely divided material with which the already active cement constituents can combine in the solid state and at comparatively low temperatures.

At this point a concrete technologist concerned only with structural calcium aluminate cement concrete might start to worry about conversion caused by high temperatures during hardening. But the validity of the above conclusions is shown by the fact (known for a very long time) that the fired strength of a fully converted refractory concrete is never lower (and is almost invariably higher) than the fired strength of a similar concrete in which no conversion has taken place.

It is sometimes difficult for a concrete technologist (who has a natural tendency to concentrate on the structural or as-cast strength of a concrete) to remember that a refractory concrete will be judged primarily by its behaviour when the hydraulic bond (his main concern) has just disappeared.

It is still true of course that some of the ordinary concreting principles continue to apply to the making of refractory concrete. No more water than is necessary should be used in the mix, and some form of curing may be necessary to avoid premature drying, but one would never think of adding to a structural calcium aluminate cement concrete, the variety and quantity of various materials which may justifiably be added to a refractory castable - provided that they fulfil three conditions.

1. They must not affect the setting-time of the cement to an undesirable extent.
2. They must allow the castable to develop an acceptable (though not necessarily very high) strength in the cold.
3. They must have a favourable effect on the properties of the fired concrete, particularly in the intermediate temperature zone.

THE FUTURE

In the next years there may be further progress in modifying the cements and castables so that they will provide even more favourable conditions for low-temperature reactions to take place as the concrete is heated in service for the first time. Castables will probably become even more complex mixtures.

We have never been able to reinforce refractory concrete by the methods of the civil engineer and steel has been used mainly to hang or support the concrete unit. Steel which can safely be embedded in the concrete in the form of fibres has a marked effect on the mechanical properties and the addition of steel fibres to refractory castables will have an increasing influence on design possibilities, and on the control of cracking - particularly in large refractory concrete units.

One of the disappointing features of refractory castables has been the inability to utilise fully the refractory properties of magnesia aggregates, because the lime-magnesia-alumina system contains many low-melting eutectics. Perhaps the answer here will be a barium aluminate cement, or a barium-calcium aluminate cement, and the considerable work which has previously been done in this field will then come to fruition.

The less expensive cements made from bauxite seems to have an assured future in providing the base-load for the refractory castable market. White calcium aluminate cements however have shown the most rapid development since they became available and it is likely that this progress will continue. Castables made from them can be safely used at temperatures which would have delighted the pioneer Henri Sainte-Claire Deville.

SP 57-2**PROPERTIES OF
REFRACTORY CONCRETES**

BY WATE T. BAKKER

Synopsis: A wide variety of aggregates, both dense and lightweight is used in refractory concretes. There are also several types of cement. Thus a wide variety of refractory concrete products with markedly different properties is available. Installation, curing, drying and heating practices also affect the properties of refractory concretes markedly. During service, temperature and environmental conditions may further modify the properties of refractory concrete. Properties of refractory concretes are therefore transitory. This paper concentrates on the unique properties common to all refractory concretes, the effect of installation, curing, drying and heating practices, commonly used raw materials and the effects of service conditions.

Keywords: aggregates; aluminate cements and concretes; binders (materials); chemical analysis; compressive strength; curing; drying; flexural strength; heating; installing; permeability; physical properties; placing; porosity; raw materials; refractory concretes; rheological properties; thermal properties; thermal shock; volume change.

Mr. Wate T. Bakker is Branch Chief, Materials in the Fossil Energy Research Division of ERDA-FE, where he is responsible for the direction, coordination, and management of all materials research in support of coal conversion and utilization processes. Prior to joining ERDA in 1975, he was associated with General Refractories Company. Here he was in charge of research and development of Alumina-Silica refractories.

Introduction

Refractory concrete*is a relatively new class of refractories. Calcium aluminate cement, the key ingredient in most refractory concretes was first produced in France in 1918 and somewhat later in the USA. In the 1930's hydraulically setting castables were in general, though limited, use in the USA.(1) At this time the first published papers on refractory concretes began to appear also.

Initially most refractory concretes were mixed on the job site similar to regular concrete. In the late forties and early fifties specially formulated premixed refractory concretes became more generally available and with it came an increased interest in their properties. (2-8)

Until the early fifties the only commercially available calcium aluminate cements were of rather low purity. They contained high amounts of iron oxide and silica. Hence the application of concretes was limited to relatively low temperatures. Calcium aluminate cements of higher purity were introduced during the fifties and found rapid acceptance in the refractories industry. The availability of high purity cements expanded the use of refractory concretes considerably and made high temperature applications possible. As a result renewed interest in the properties of calcium aluminate bonded refractory concretes was shown both in the USA(9-15) and in Europe.(16-18) All along the quality of refractory concretes was enhanced through the use of more controlled installation techniques such as pneumatic gunning and vibratory casting.

All developments described above have led to a very diversified usage of refractory concretes and a large number of products, quite often tailor made for various applications. The growth of refractory concrete sales is shown in figure 1. Because of the wide variety of aggregates and cements used, the range of properties of available refractory concretes is large. In this paper we will concentrate on those properties which make refractory concrete unique.

Refractory concretes have the following advantages over conventional refractories:

*Refractory concretes are usually called "Castables." However the more correct name "Refractory Concrete" is gaining in popularity.

1. quick installation and low construction cost.
2. fully anchored constructions are possible
3. reduced and simplified furnace maintenance
4. thermal conductivity is one-half to one-third that of fired brick, thus thinner linings can be used or thermal efficiency improved.
5. good thermal-shock resistance
6. no joints
7. prefired shapes need not be stocked
8. ready availability
9. greater flexibility in design possible

II. Raw Materials

A. Binders

A refractory concrete can be defined as a granular refractory material which, when mixed with water, will harden at room temperature to a degree sufficient to support its own weight. Ordinary portland cement cannot be used in refractory concrete except for very low temperature applications, as portland cement bonded concretes rapidly lose their strength at temperatures over about 600°C(8). Thus in most cases calcium aluminate cements are used as binders. A few other chemicals such as sodium silicates and certain phosphates have also airsetting properties and are used in specialized applications. However, we will limit ourselves in this paper to the discussion of calcium aluminate bonded refractory concretes. Thus, more narrowly, a refractory concrete is a graded refractory aggregate containing a hydraulic binder consisting mainly of calcium aluminate cement.

The main active ingredient in all calcium aluminate cements is mono-calcium aluminate $\text{CaO} \cdot \text{Al}_2\text{O}_3$, or CA in the customary cement technology shorthand.* Other cementitious constituents such as C_{12}A_7 , CA_2 may occur in some commercial cements while silica and iron containing compounds such as C_2AS_5 , C_2S , $\text{C}_6\text{A}_2\text{F}$, CF_2 etc. are present in less pure cements. In addition to the cementitious phases inert materials such as Al_2O_3 and CaTiO_3 may occur, in some cases in major amounts. The properties of the binder are further influenced by such physical factors as particle size, crystallite size and the amount of glassy phase present. Thus most commercially available binders have distinctly different properties, which will affect the characteristics of the final product. Generally one can divide the calcium aluminate cements in three classes:

1. Low purity cements These products are manufactured from relatively high iron bauxites and limestones by fusion or sintering. They contain 510% Fe_2O_3 or FeO and SiO_2 as the main impurities and can only be used in refractory concretes with service limits up to about 2500 F.
2. Intermediate purity cements These products are manufactured from low iron bauxite, mostly by sintering with limestone. They contain

*C = CaO A = Al_2O_3 S = SiO_2 F = FeO H = H_2O

5% SiO_2 , but only 1-2% Fe_2O_3 as the main impurities. Usage of this type of cement is generally limited to concretes with a service limit of 2900 F or less.

3. High purity cements These products are made from "Bayer" alumina or aluminum hydroxide and high purity limestone or hydrated lime. They contain more alumina and generally less than 2% total impurities. Cements of this type are significantly more expensive than bauxite based cements and are used mostly in products with service limits of 2900 F or above or in applications where a very low iron content is required, such as blast furnace gunning mixes.

Table I gives the chemical composition of typical commercial cements.

B. Aggregates

In principle all refractory grains can be used as aggregates in refractory concretes. In practice most aggregates contain mainly alumina and silica in various forms. They range from crushed fire brick containing 30-45% Al_2O_3 to high purity sintered or fused alumina. The most widely used aggregate is probably calcined flint or kaolin, containing 42-45% Al_2O_3 . Other widely used dense aggregates are calcined bauxite, chrome ore and to a lesser extent calcined magnesite. Examples of typical dense aggregates are given in table II.

For insulating concretes lightweight materials are used as a complete or partial substitute for dense grain. Most commonly used lightweight materials are expanded shale, perlite, expanded fireclay aggregate and alumina bubbles. Table III gives some examples.

In addition to the raw materials mentioned above, minor additives are used in many commercial products to improve their overall performance. Many of these additives are of a proprietary nature. An example is the addition of raw kyanite to reduce high temperature shrinkage.

III. Classification of Refractory Concretes

Refractory concretes are classified according to ASTM classification C-401.(19) (Table IV). For regular (dense) concretes the classification criteria are strength and service limit. The service limits is arbitrarily defined as the temperature below which the linear reheat change of samples heated for five hours is less than 1.5%. There are seven classes (A-G) having service limits ranging from 2000-3200 F.

Insulating concretes are classified by bulk density and service limit. The allowable bulk density increases with service limit. At present five classes are recognized (N-V) having service limits ranging from 1700 F, for a 55 lb/ft^2 concrete to 3200 F for a 105 lb/ft^2 concrete.

The ASTM classification system described above is relatively broad and is generally not sufficient for specification purposes for critical applications. Especially the classification system for

insulating concretes appears inadequate as several insulating concretes have been developed which combine a high service limit with a relatively low bulk density. These do not fit into the system.

In addition to the general purpose refractory concretes classified by ASTM, there are many special purpose products, generally covered by user's specifications. Unfortunately those specification are not uniform. They are based on specific service conditions. For instance concretes designed for use in blast furnaces must have a good resistance to carbon monoxide desintegration, for other applications abrasion resistance is a prime requirement. Refractory concretes mainly intended for application by pneumatic gun must exhibit good adherence to the wall during application and have a minimum amount of rebound loss. It is a tribute to the versability of refractory concrete and the ingenuity of the producers, that most of these special requirements have been met. This achievement has contribute significantly to the growth of refractory concrete as a substitute for preformed refractory products.

IV. Installation of Refractory Concretes

Proper installation of refractory concretes is the key to achieving acceptable performance. The responsibility rest not only with the installer or user, but also with the manufacturer of the product. In almost all cases refractory concretes will be installed by relatively unskilled labor under less than ideal conditions. The manufacturer must therefore design its products in such a manner that acceptable performance can be expected even if installation practices are less than ideal.

Basically, there are three major ways of installing refractory concretes, by troweling, casting and gunning. For optimum performance, products specially designed for the intended method of application should be used.

We can be brief about application by troweling, since this is a minor application, mainly intended for patching worn linings. Products intended for troweling must exhibit excellent plasticity and adherence properties. To achieve this clay, bentonite and other plasticizers are usually added to the concrete. This normally increases the water needed to provide a workable mix and is detrimental to the physical properties of the concrete, especially its strength. Therefore, products intended for troweling cannot normally be recommended for casting purposes. Troweling mixes have occasionally found successful application as maintenace gun mixes, where good adherence properties are more important than the achievement of high strength.

Casting of refractory concretes is the most common method of installation. Good installation practices must achieve a homogeneous casting, while using the highest possible cement/water ratio. Here the rheological properties of the concrete, as a function of time and water content are important. This ideal castable should have a good flowability at a low water content. A slight tendency to be thixotropic is generally not harmful, especially when the concretes installed by vibratory casting. Dilatent mixes should be avoided. Furthermore, the

rheological properties of the wet concrete should not change significantly with time, even on hot summer days. Generally a working time of about 30 minutes is sufficient, when the refractory concrete is mixed in relatively small batches, using a paddle mixer or similar equipment. However, when large scale equipment such as a "Ready mix" truck is being used, a longer working time is preferable. The working time of any given concrete is dependent on the setting characteristics of the binder and the ambient temperature.

Setting times are indicated by changes in temperature with time and changes in viscosity with time. Figures 2 and 3 show time-temperature and time viscosity curves for cements/water slurries (11,20). It is noted that some high purity cements have relatively short setting times, and may need special precautions in hot weather.

The water content used during application determines to a large extent the quality of the resulting concrete after setting. Unfortunately there is no generally applicable method to determine the optimum water content, because of significant differences in rheological behavior of various cements. For field application the empirical "ball in hand" method is the only practical way to estimate the desirable water content. The effect of cement/water ratio on the strength of dense concretes is shown in Figure 4. (28) Figure 5 shows that excess water can seriously degrade both strength and high temperature volume stability of insulating concretes.

Gunning refractory concrete has become an increasingly popular method of installation (20). The reasons are 1) cost of installation is significantly lower, especially for large installations, 2) the quality of the installed concrete is superior to that of cast concrete, because of a lower water/cement ratio. However, these advantages can only be fully realized when the concrete is especially designed for installation by gunning and experienced gun operators and nozzle men are used, otherwise high rebound losses, will increase costs and entrapped rebound can seriously degrade the quality of the resulting refractory lining.

As in casting the rheological properties of the concrete are controlling factors, especially the behavior of the concrete in the first 20 minutes. In order to provide good adherence, and minimize rebound losses, the concrete paste should have a relatively high viscosity and be non thixotropic. Since all of the water, except 2-4% predampening water, is added manually at the nozzle, small variations in water content must not unduly affect the adherence of the product. For most cements small additions of clay minerals suffice to achieve this. Care should be taken to use only the minimum effective amount, as large additions will seriously affect the physical properties after setting. For some cements clay additions alone are not effective. Proprietary admixtures have been developed by various producers to provide the necessary balance between acceptable gunning characteristics and physical properties after setting. Thus a good refractory gun mix can be installed with a rebound loss of 10-15% or less and 10-20% high strength than a similar cast products.

There are generally only minor differences in density between gunned and cast regular refractory concrete. However, insulating concretes can suffer significant increases in density even when gunned at 1/3 of the air pressure used for dense concretes, as is usually recommended. This increase in density can seriously affect their insulating value. Insulating concretes based on expanded refractory clays appear to be superior to insulating concrete based on perlite. (Table 5)

V Effect of Curing and Heating on Properties of Refractory Concretes

Figure 6 (14,21) shows the minerals present during the hydration and dehydration of CA, the main cementitious constituent of refractory cements, at various temperatures. Until recently the conventional wisdom was to keep the concrete cool during curing to improve the formation of the hexagonal hydrates CAH_{10} and C_2AH_8 . Thus the standard method of curing was to spray the concrete with water to keep it both cool and wet. However, field experiments with membrane curing (22) indicated that it was only necessary to maintain a high humidity to ensure good physical strength after curing. It was further found that low curing temperatures enhance explosive spalling when the first heat up is too fast. (23) (24)

Work done by Kopanda (25) for concretes containing low and intermediate purity cements (figure 7) and by Givan et al. (21) for high purity cement, (figure 8) show that the cured strength of concretes containing less pure cements indeed decreases with increases curing temperature. However, the strength after drying and firing is maximized at temperatures over 90 F for all cements.

During the initial heat up the hydraulic bond is destroyed at 400-600°F. For most cements this resulted in a significant decrease in strength, at least when measured at room temperature after heating. However, the strength of concretes containing high purity cements generally decreases less markedly. When properly cured and heated their strength after heating can be as high or higher than after drying only. Because significant amounts of water must be removed during heat up and the permeability of concretes is generally low, care must be taken to heat the concrete slow enough to prevent cracking. Figure 18 illustrates the effect of heating rate on the strength of 9 x 4-1/2' x 3' shapes cut from a gunned 50% Al_2O_3 concrete. (26).

VI. Chemical Properties of Refractory Concretes

In this chapter we will briefly discuss the chemical stability of refractory concretes in the presence of corrosive substances which may be present during service.

Generally refractory concretes are considered less suitable for use in contact with corrosive liquids such as slags. The reasons is that the calcium aluminate bond in the concrete reacts at higher temperatures with aluminum silicates in the refractory grain to form low melting calcium aluminum silicates, similar to the silicates common

to most slags. This leads in many cases to rapid wear. Figure 10 compares the slag resistance of a BF gun mix with that of various alumina-silica brick. (20)

Extra high alumina concretes consisting mainly of sintered (tabular) alumina and high purity cement have a good resistance to "basic" slags as the binder reacts with the grain to form CA_6 , which is very refractory and is stable in the presence of high lime slags. On the other hand the same concretes are less stable in the presence of "acid", high silica slags as is illustrated in figure 11. In this application a 95% alumina concrete wore away rapidly, but a phosphate bonded product with approximately the same Al_2O_3 content was satisfactory.

Refractory concretes are corroded by acid condensates which may occur on the cold phase of the lining in various applications in the chemical industry. The cold face temperature is therefore generally designed to fall above the dew point of the gases.

The refractoriness of refractory concretes as measured by the PCE test is generally a meaningless property because of the larger difference in composition of the matrix and the aggregate. Thus generally, liquids are formed and deformation occurs at temperatures far below the softening point indicated by PCE test.

Disintegration of refractory concretes in CO rich atmospheres can occur, when the concrete contains free iron or iron oxides. (13) Free iron is usually present in refractory concretes when the fine fractions are produced by ball milling using steel balls. Low purity cements often contain significant amounts of free iron oxides also. Generally the total iron content of the concrete is less indicative of its carbon disintegration potential than amount of iron compounds soluble in HCL. The HCL leachable iron must be low preferably less than 0.1% and certainly less than 0.2%. The actual resistance of the concrete depends on the distribution of the active iron compounds. Only a few coarse iron rich grains are needed to cause significant cracking in the standard ASTM test (19). When the active iron compounds are well dispersed in the matrix, a somewhat greater amount can be tolerated.

It has recently been shown that CO can also affect the bond phase itself at least in the presence of steam (figure 12).^{*} Under these conditions calcium formate is formed instead of the usual calcium aluminate. During relatively short term tests (18 days) the strength of the products if not affected significantly but there is a downward trend.

Volatile alkali compounds in the gas atmosphere are particularly harmful to refractory concretes. Desintegration of the refractory is caused here by the formation of low density alkali-alumina silicates. (figure 13) (20) However, there are some indications that refractory concretes can perform well in alkali laden surroundings such as the

^{*}Personal communication, D. E. Day, University of Missouri at Rolla.

blast furnace, if cracking is minimized and a glassy layer is formed at the surface to seal off the pore system.(27)

Hydrogen attack on refractory concretes is the same as that on other refractories and occurs mainly through the reduction of silica and silicates to the volatile SiO (29). The cement binder itself should be resistant to hydrogen attack.

Steam affects the strength of very high alumina concretes adversely (figure 14) (30). The strength degradation occurs during the dehydration of the AH (Boehmite) bond phase and the formation of the high pressure $\text{C}_4\text{A}_3\text{H}_3$ phase. It is not clear that these changes are the root causes of the strength loss or that the alumina grain itself is affected by the high pressure steam. High density pure alumina ceramics are also degraded by high pressure steam. Calcined flint-high purity alumina cement concretes show no strength degradation. In the latter case the formation of a CAS_2 (anorthite) bond phase was demonstrated.

In silica containing concretes the dissolution of silicate by steam must also be considered. A small amount of weight loss is reported by Crowley, (31) but the effect on the strength of the concrete is not discussed.

The combined effect of complex gas mixtures on refractory concretes has not been explored. Studies are presently underway to explore this for coal gasification service conditions.

VII Physical Properties of Refractory Concretes

Assuming that the refractory concrete has been cast, cured and dried properly, we can now discuss its physical properties at various temperatures. It must be stressed again that all properties of refractory concretes are likely to be time and temperature dependent.

A. Porosity & Permeability

Since the density of refractory concretes is mainly dependent on the refractory aggregate it varies widely. (30 lbs/ctf - 170 lbs/cft) Porosity and permeability fall in a closer range. Generally the porosity of refractory concrete is high as compared to most brick, but its permeability is very low because of a very small average poresize. Figure 17 shows this to be true up to the temperature at which the cement reacts which the aggregate to form a ceramic or glassy bond phase. Beyond this point the concrete acts very much like a fired refractory brick.

Insulating concretes have a much higher porosity than regular refractory concretes, because of highly porous filler materials used. Porosities of 50% are common. Little is known about the permeability of these products.

B. Thermal Properties

The thermal conductivity of refractory concrete is generally lower than that of equivalent brick because of its lower density. Figure 16 shows some typical thermal conductivity curves as function of mean temperature (32). It is noted that there is a significant drop in thermal conductivity after the first heat up due to the dehydration of the binder. However, in actual installations the concrete at the cold face of the lining usually never get completely dehydrated. For design purposes the thermal conductivity curve prior dehydration is therefore generally used. The thermal conductivity of refractory concrete consisting of alumina silica aggregates and a calcium aluminate binder is mainly depended on its density. Wallace and Geriss(33) experimentally determined the relationship shown in figure 16. Thermal conductivity data thus derived are generally sufficiently accurate to be used for design purposes. The presence of high thermal conductivity gases will significantly increase the overall thermal conductivity of a refractory liner, especially with high porosity insulating concretes (38).

The specific heat of a refractory concrete depends on its chemical composition. However since the contributions of Al_2O_3 and SiO_2 to the specific heat are numerically close there is only a small increase in specific heat with increasing Al_2O_3 content. For most design purposes one may assume that the specific heat increases from about 0.2 Btu/lb/°F to about 0.3 Btu/lb/°F at 2500 F. The specific heat is a function of the material not of its physical form. Heat capacity on the other hand increases with the density of the material and is low for insulating concretes.

C. Volume Stability

Volume stability is one of the critical but probably least understood properties of refractory concrete. Volume stability is composed of two independent effects: reversible thermal expansion and permanent changes, expansion or contraction, caused by chemical reactions during heat up.

The reversible linear expansion coefficient for most alumina-silica refractories is about 3×10^{-6} in/in/F. It increases with increasing alumina content to about 4×10^{-6} in/in/F for 95% alumina concretes. Castables containing chrome ore as an aggregate have an even higher linear coefficient of expansion 5×10^{-6} in/in/F.

Permanent volume changes can occur during setting and dehydration of the concrete and again when a glassy bond is formed at elevated temperatures(34). Shrinkage during dehydration is generally low about 0.1 - 0.3%. Final shrinkage or expansion at temperatures over 2000 F, when the glassy (ceramic) bond is formed is very much composition dependent. Normally one may expect shrinkage at this point. However, some calcined clays of low purity tend to expand in this region. In other cases additives designed to combat shrinkage, such as raw kyanite are added to the mix. (Figure 17)

Excessive shrinkage may cause cracking either during heatup or cooldown. ASTM therefore specifies a maximum linear shrinkage of 1.5% at all temperature below the service limit. However for applications where cracking is extremely detrimental, such as petrochemical processes using a hydrogen atmosphere, specifications are considerably more restrictive and a shrinkage of less than 0.5% or even 0.1% is the maximum allowed.

D. Strength

The strength properties generally measured are crushing strength and modulus of rupture, usually employing a three point bending rig. Most measurements are done at room temperature after heating to various temperatures. The more meaningful testing of strength at the actual service temperature is rapidly increasing in popularity.

Figures 18 and 19 give typical hot and cold MOR curves for 40-50% Al_2O_3 castables using a high purity (20) and an intermediate purity cement respectively. The cold MOR generally decreases significantly during the dehydration of the cement, although less when using a high purity cement than when using a medium purity cement. This drop in strength is not present to the same extent in the hot modulus of rupture. The greatest difference in MOR occurs at high temperatures where a glassy phase is formed. The cold MOR becomes very large here, while the hot MOR decreases rapidly with increasing viscosity of the glassy phase. In general the modulus of rupture of dense refractory concrete varies from about 700-1500 psi after drying at 220 F.

The hot and cold modulus of rupture of light weight concretes follows the same general trend (table 6). In general the modulus of rupture of lightweight refractory concretes varies between 50 psi and 400 psi, depending on its weight and cement content.

The cold crushing strength of castables is usually 3 to 5 times that of modulus of rupture. For dense concretes it varies between 2000 and 8000 psi, for lightweight concretes with densities up to 50 lbs/ft³ it varies between 200 and 500 psi. For materials having a density of 75-100 lb/ft³ it varies from 1000-2500 psi. The hot compressive strength is usually not determined.

The modulus of elasticity as a function of temperature has been studied by McCullough and Rigby (35) as a function of temperature. Figure 20 gives typical curves for concretes containing medium and high purity cements, respectively. The shape of the curve is very similar to that of the hot modulus of rupture curve of similar products.

E. Thermal Shock

Little has been published about the thermal shock resistance of refractory concretes as compared to other types of refractory. Practical experience has shown that the thermal shock resistance of refractory concretes is excellent as long as no excessive amounts of glassy phase is formed. This is in agreement with the fact that refractory concretes generally have a very fine pore size distribution as compared to brick.

This structure is destroyed when a glassy bond is formed at high temperatures.

F. Erosion Resistance

The erosion resistance of refractory concretes is roughly dependent on their strength. The bond phase is generally worn away preferentially(30). Concretes made with high purity high alumina cements are generally more resistant to erosion than those made with lower purity cement. Erosion is a power function of particle velocity (figure 21).

G. Creep (Refractoriness Under Load)

Because of glass formation at relatively low temperature, refractory concretes generally deform plastically under relatively low loads at temperatures over about 2000 F, even when high purity alumina cement is used. For instance a 50% alumina gunning concrete containing a high purity cement, deforms 1-3% under 25 psi load at 2460°F (1350°C). When very high loads are used (500-2000 psi) rapid creep is already observed at temperatures as low as 600-1000°F.(37). Total creep does not vary much with temperature. It is inferred by the authors that the cement deforms until contacts between the aggregates are established (Figure 22).

Table 1
Chemical Composition of Calcium
Aluminate Cements

CLASS BRAND	LOW PURITY		INTERMEDIATE PURITY		HIGH PURITY	
	A	B	A	B	A	B
Al_2O_3	41.0	40.0	55.0	51.0	79.0	73.0
CaO	37.0	37.0	37.0	40.0	18.0	25.0
SiO ₂	9.0	3.0	5.0	6.0	0.1	0.7
Fe ₂ O ₃	11.0	18.1	1.5	0.6	0.3	0.3

Table II

Aggregates Used in Dense Refractory Concretes

TYPICAL CHEMICAL COMPOSITION %	CALCINED FIRECLAY 40-50% Al_2O_3	CALCINED ALABAMA BAUXITE 60% Al_2O_3	CALC. S. A. BAUXITE 80-90% Al_2O_3	HIGH PURITY ALUMINA SINTERED OR FUSED 99 + % Al_2O_3	CHROME ORE (PHILLIPINE)
SiO_2	45-55	34.9	25.9	0.06	5.5
Al_2O_3	40-50	60.6	70.1	99.5	31.0
Fe_2O_3	0.5-1.5	1.3	1.1	0.06	15.5
TiO_2	1.0-2.0	2.5	2.9	Tr.	—
CaO	0.1-0.2	0.07	0.05	Tr.	0.5
MgO	0.05-0.1	0.12	0.03	Tr.	16.0
Cr_2O_3	—	—	—	—	31.5
ALKALIES	0.5-1.5	0.11	0.13	0.07	—
P.C.E.	30-34	37-38	38-39	N.D.	N.D.
BSG	2.4-2.6	2.7-2.8	2.85-3.0	3.4-3.6 (SINTERED) 3.7-3.9 (FUSED)	3.9
OPEN- POROSITY %	3-10	3-7	4-10	5.0 (SINTERED) 0-3 (FUSED)	

Table III

Light Weight Aggregates Used In
Refractory Insulating Concretes

GENERIC NAME	PERLITE	EXPANDED SHALE (HAYDITE)	EXPANDED FIRECLAY	ALUMINA BUBBLES
TYPICAL CHEMICAL COMPOSITION. %				
Al ₂ O ₃	19.5	24.0	27.1	99.0
SiO ₂	70.0	63.0	64.3	0.8
Fe ₂ O ₃	0.8	5.5	2.1	0.15
TiO ₂	0.1	1.5	2.0	Tr.
ALKALINE EARTHS	0.3	4.0	0.8	Tr.
ALKALIES	8.2	2.0	3.3	0.5
BULK DENSITY, lb/ft ³	9-11	55-60	28-32	34-38
PYROMETRIC CONE EQUIVALENT	8-11	N.D.	27	>38
OF	2300-2450		2980	>3400

Table IV

Classification Of Refractory Concretes*

A REGULAR DENSE CONCRETES

TEST REQUIREMENTS	CLASSES OF ALUMINA-SILICA-BASE CASTABLE REFRACTORIES						
	CLASS A	CLASS B	CLASS C	CLASS D	CLASS E	CLASS F	CLASS G
PERMANENT LINEAR SHRINK- AGE NOT MORE THAN 1.5 PERCENT WHEN FIRED FOR 5 h AT	2000 F (1095 C)	2300 F (1260 C)	2500 F (1370 C)	2700 F (1480 C)	2900 F (1595 C)	3100 F (1705 C)	3200 F (1760 C)

B INSULATING CONCRETES

TEST REQUIREMENTS	CLASSES OF INSULATING CASTABLE REFRACTORIES						
	CLASS N	CLASS O	CLASS P	CLASS Q	CLASS R	CLASS S	CLASS V
PERMANENT LINEAR SHRINKAGE NOT MORE THAN 1.5 PERCENT WHEN FIRED FOR 5 h AT MAXIMUM BULK DENSITY, lb/ft ³ (kg/m ³) AFTER DRYING AT 220 TO 230 F (104 TO 110 C)	1700 F (925 C) 55 (881)	1900 F (1040 C) 65 (1041)	2100 F (1150 C) 75 (1201)	2300 F (1260 C) 95 (1522)	2500 F (1370 C) 105 (1682)	2700 F (1480 C) 115 (1782)	2900 F (1595 C) 125 (1882)

*ASTM C401

Table V

Effect of Air Pressure on Rebound Loss and Density of
Gunned Insulating Concrete Based on
Expanded Fireclay Aggregate

AIR PRESSURE, psi	15	25	35
REBOUND, %	14	23	26
DENSITY, lb/ft ³ :			
AFTER 230°F	86	100	108
AFTER 1500°F	81	95	104
THERMAL CONDUCTIVITY			
BTU in/ft ² hr °F			
500°F MEAN TEMP.	2.65	3.6	4.2

Effect of Aggregate on Gunned Density of
Insulating Concrete Air Pressure 15 psi

Table VI

	PERLITE BASED CONCRETE		EXPANDED CLAY BASED CONCRETE	
	CAST	GUNNED 15 psi AIR PRESSURE	CAST	GUNNED 15 psi AIR PRESSURE
<u>230°F:</u>				
DENSITY, lb/ft ³	60	84	58	67
COLD CRUSHING STRENGTH, psi	350	550	580	650
<u>2000°F:</u>				
DENSITY, lb/ft ³	51	79	55	60
COLD CRUSHING STRENGTH, psi	150	500	300	600
THERMAL CONDUCTIVITY BTU in/ft ² hr °F				
500°F MEAN TEMP.	1.7	2.6	1.7	1.9

Table VII
Hot And Cold Modulus Of Rupture Of Insulating Refractory
Concrete Based On Expanded Fireclay Aggregate

MODULUS OF RUPTURE, psi		
	AT TEMPERATURE	AT ROOM TEMPERATURE AFTER FIRING
230°F	350	350
1000°F	300	N.D.
1500°F	250	250
2000°F	210	225
2500°F	240	470
2700°F	90	800

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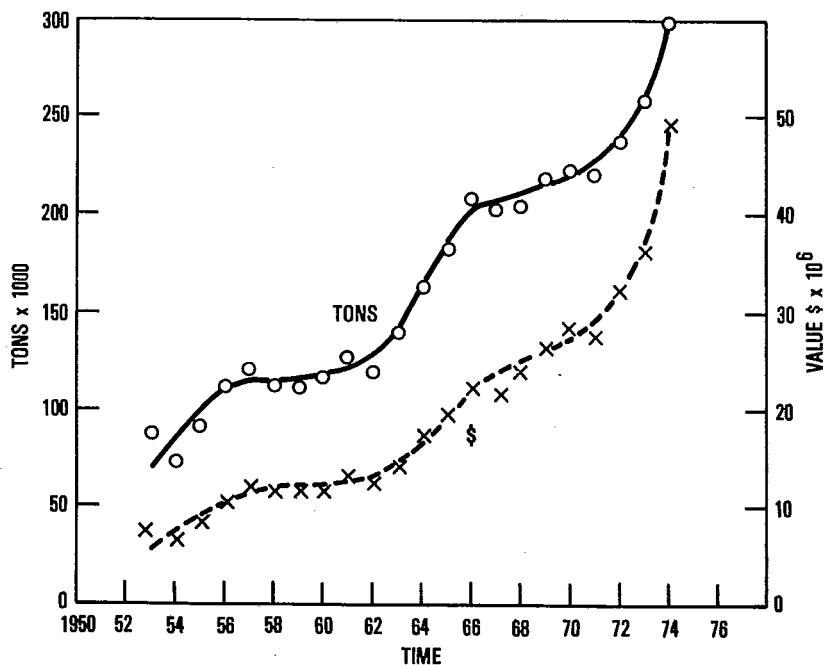


Fig. 1--Production of refractory concrete in the USA

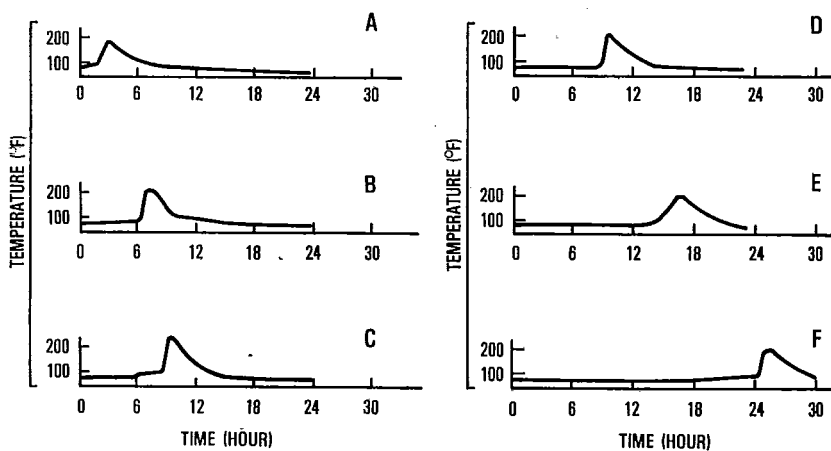


Fig. 2--Heat evolution curves of commercial calcium aluminate cements

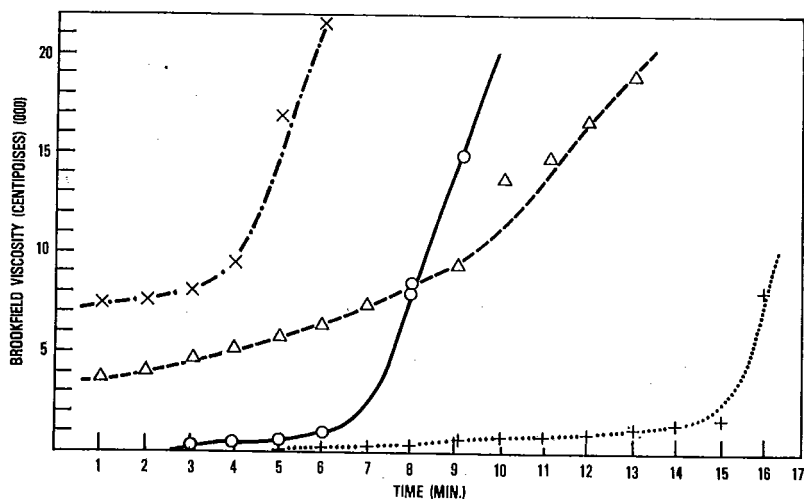


Fig. 3--Viscosity of cement-water slurries

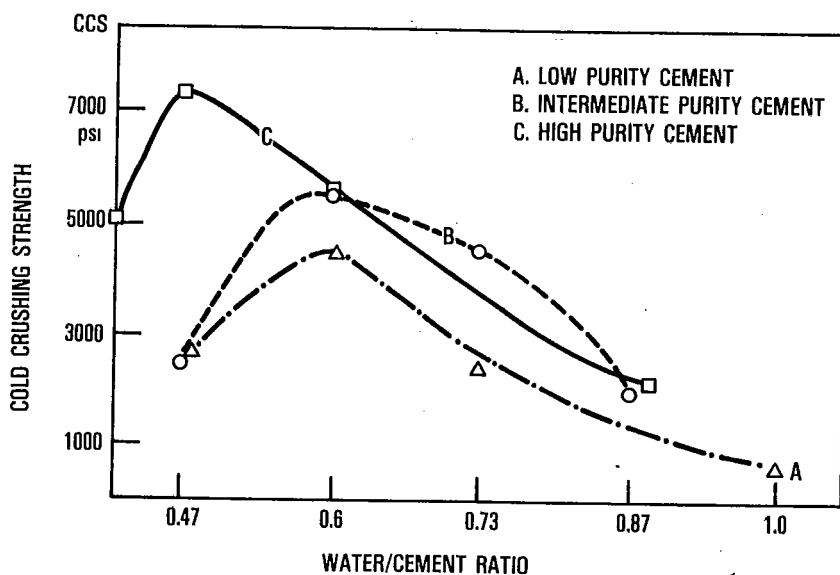


Fig. 4--Effect of water-cement ratio on dried strength of dense refractory concrete

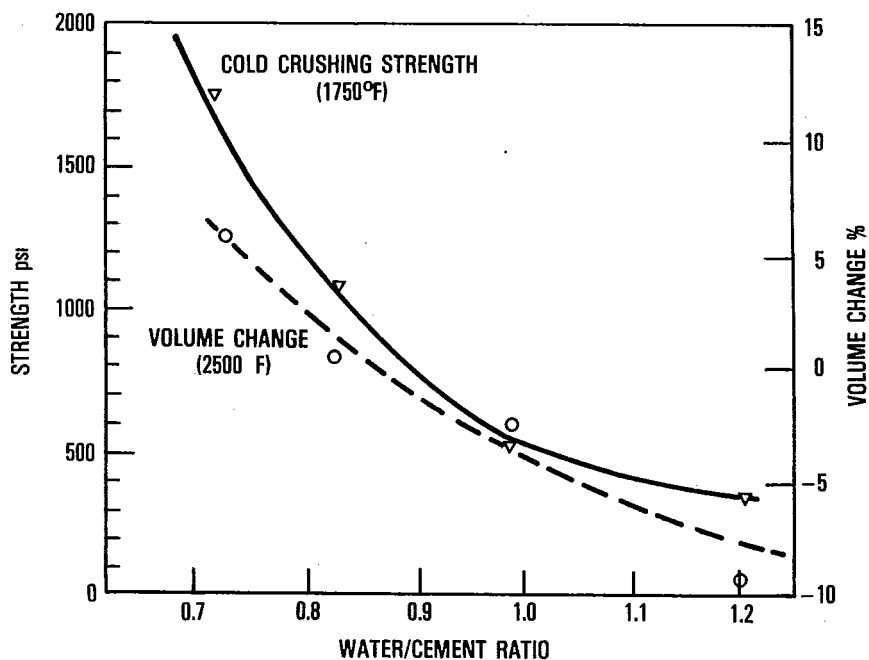


Fig. 5--Strength and volume stability of 75 lb/ft³ insulating concrete

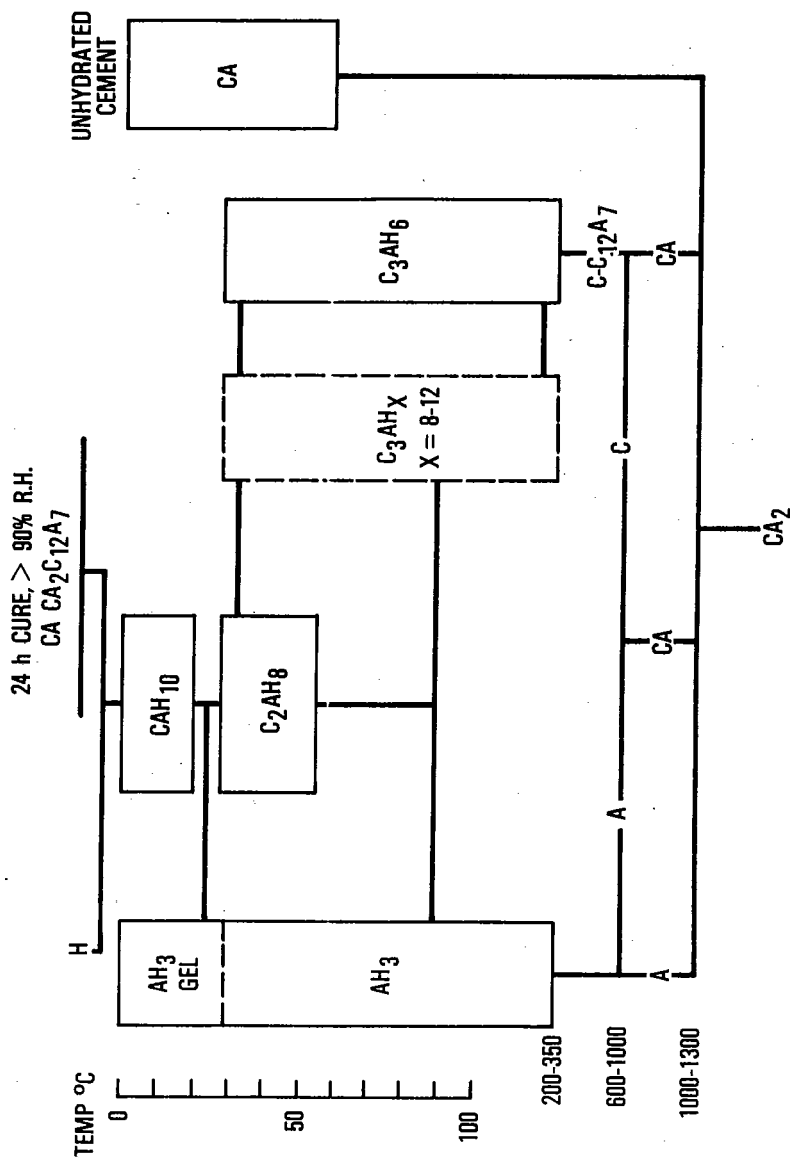


Fig. 6--Hydration and dehydration of calcium aluminate cement

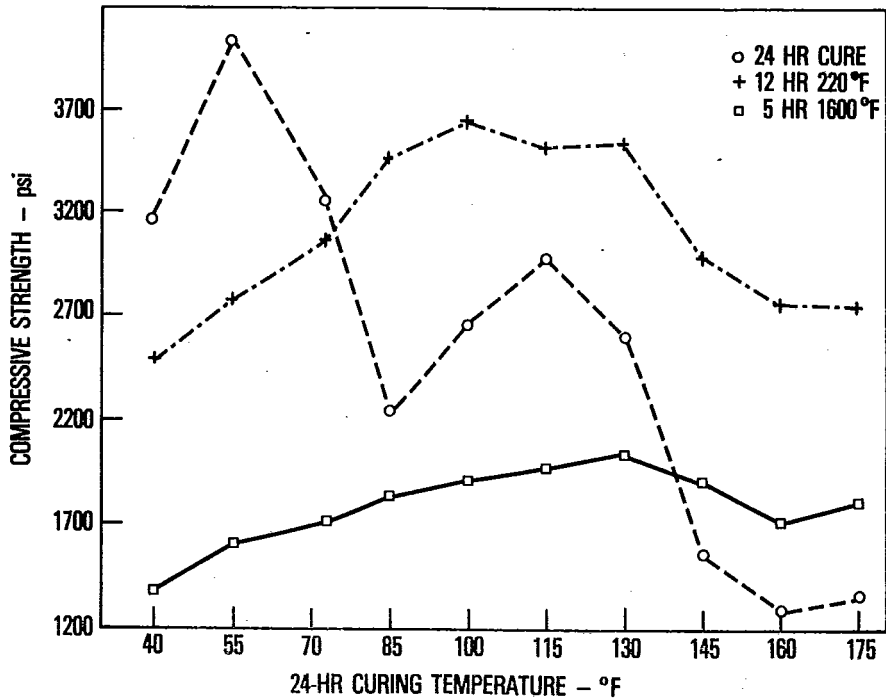


Fig. 7--Strength as a function of curing temperature, low purity cement, calcined fireclay aggregate

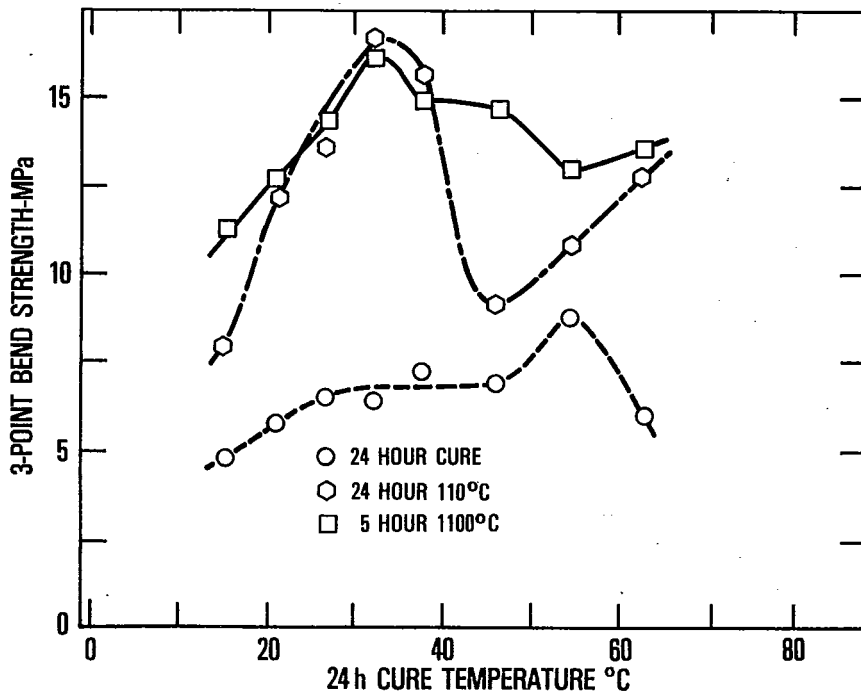


Fig. 8--Strength as a function of curing temperature high purity cement, tabular alumina aggregate

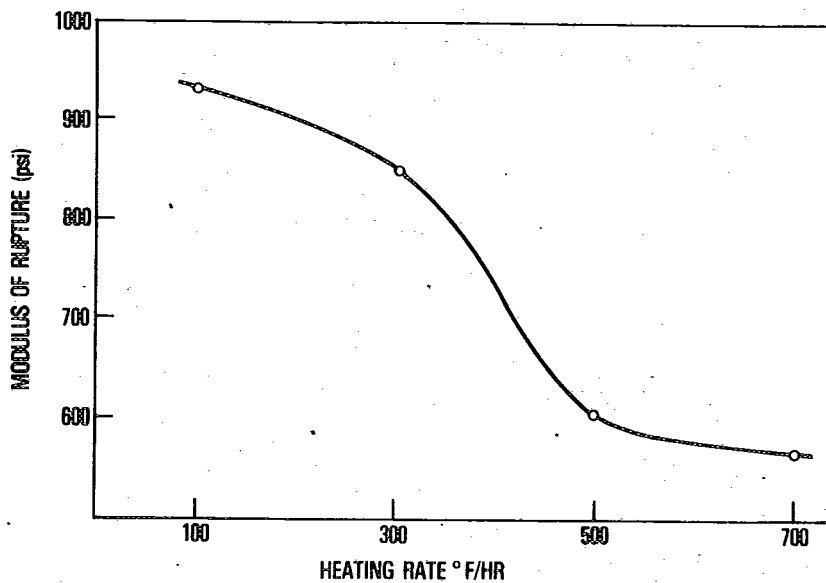
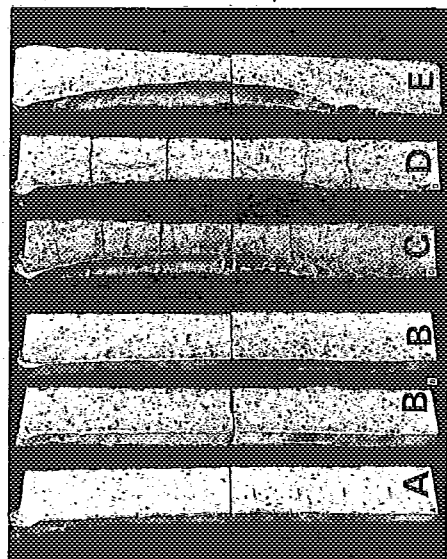


Fig. 9--Effect of heating rate on the strength of a gunned 50 percent Al_2O_3 concrete



BRAND NAME	AREA EROSION, %
A. HIGH PURITY 90% Al_2O_3 BRICK	4.5
B. PHOSPHATE BONDED 85% Al_2O_3 BRICK	3.0
C. HIGH FIRED S.D. FIRECLAY BRICK (42% Al_2O_3)	33.0
D. DENSE 60% Al_2O_3 BRICK	13.1
E. 50% Al_2O_3 REFRACTORY CONCRETE	30.0

Fig. 10--Results of slag test, using b.f. slag with a basicity of 1.1 at 2750 F (1510 C)

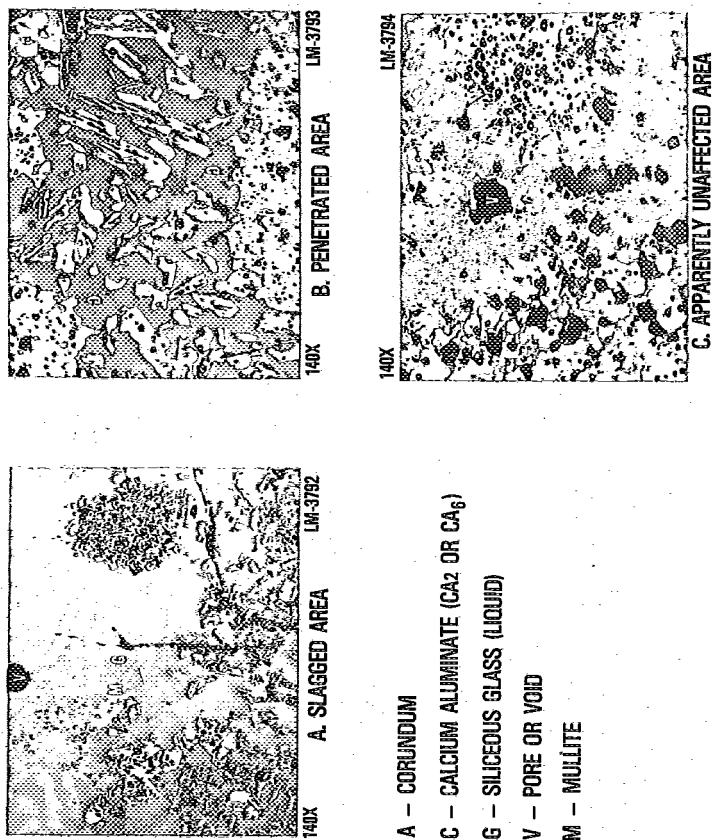


Fig. 11--Reaction of high alumina concrete with acid slag

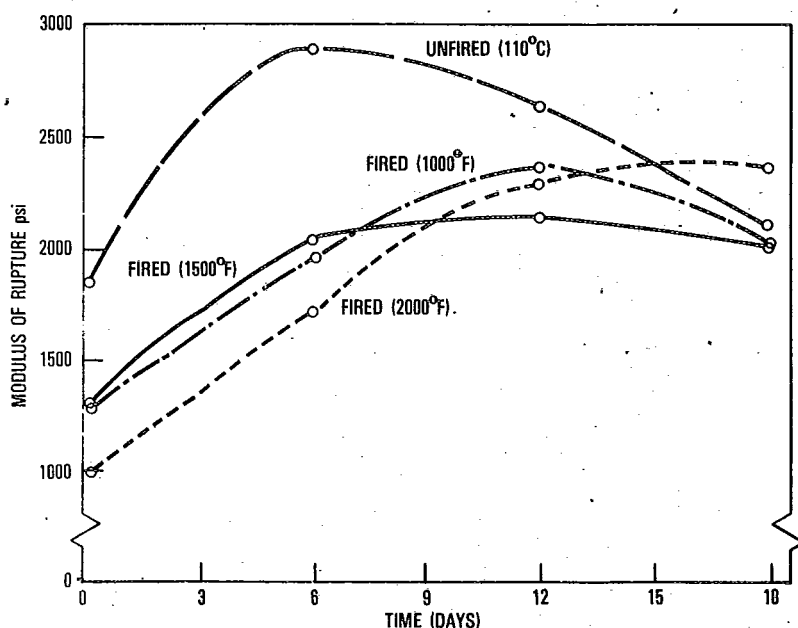


Fig. 12--Effect of steam-CO atmosphere on strength of 95 percent Al_2O_3 concrete

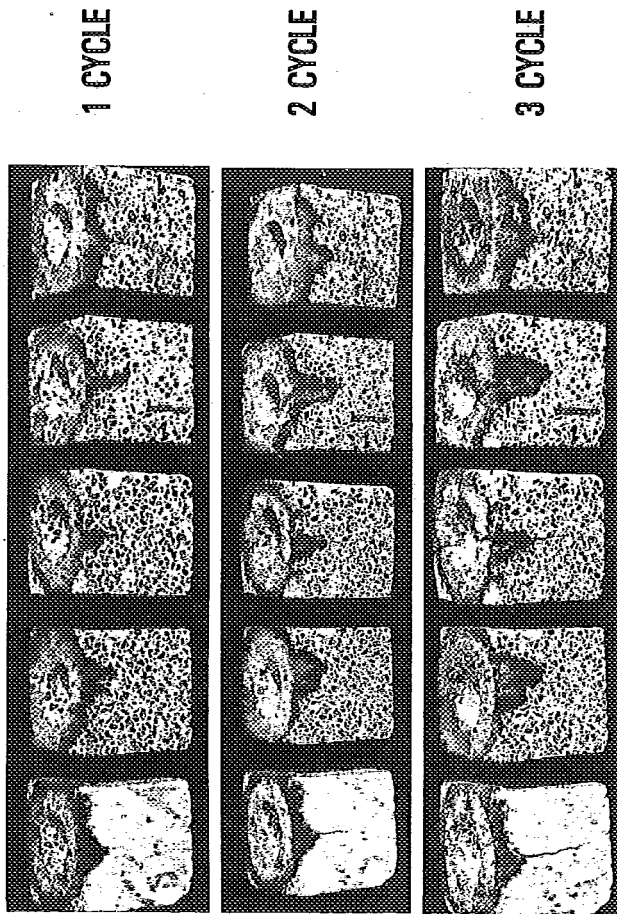


Fig. 13--50 percent Al_2O_3 refractory concrete after ASTM alkali test

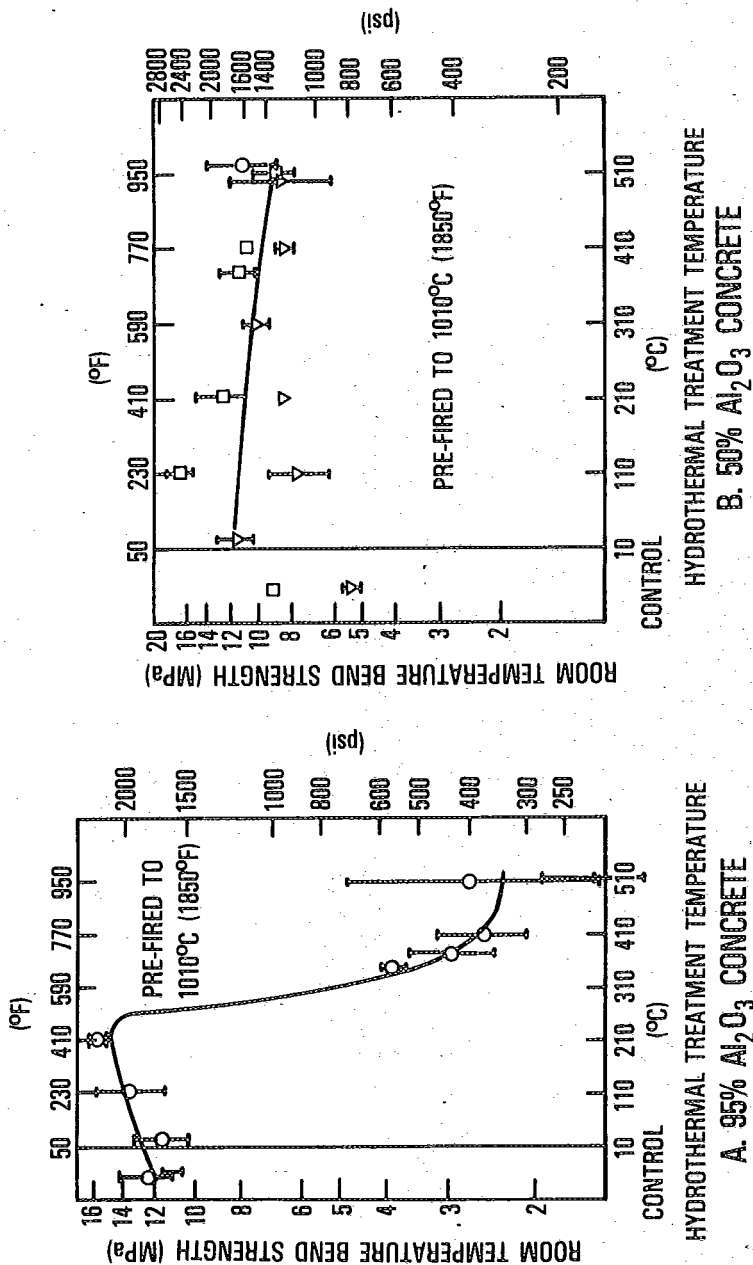


Fig. 14--Effect of high pressure steam on refractory concretes