Refractory Shotcrete—Current State-of-the-Art

by I. Leon Glassgold

The paper includes a brief history of refractory shotcrete making certain comparisons with portland cement shotcrete. Important characteristics and properties unique to refractory shotcrete are presented with special attention to corrosive and erosive environmental influences. Constituent ingredients such as binders, aggregates, and admixtures are discussed as are the relative merits of "field mixes" and "castables." The two shotcrete processes, dry-mix and wet-mix are explained in depth and their advantages and drawbacks assessed.
The equipment required for shotcrete applications, such as guns, compressors, mixers, elevators, and nozzles is introduced as are "hot gunning" and gun casting devices. The importance of an experienced crew, well maintained equipment, and appropriate installation techniques are explained. Emphasis is placed on the need for the proper curing, drying, and firing of refractory shotcrete to ensure a successful result. Various construction details, anchorage, steel fibers, and multicomponent linings are described together with current practices for the shotcrete repair and maintenance of refractory linings.

Keywords: curing; linings; mixing; mix proportioning; nozzles; **refractory concretes; shotcrete.**

Introduction

The term shotcrete was introduced by the American Railway Engineering Association in the early 1930's, and was adopted by the American Concrete Institute in February of 1951 to replace the term "pneumatically applied mortar" (PAM). Shotcrete is defined by the American Concrete Institute as "mortar or concrete projected at high velocity onto a surface." It is usually classified as fine or coarse aggregate shotcrete, depending on the aggregate gradation. If mixing water is added at the nozzle, it is known as the dry-mix process; if added at the mixer, the wet-mix process.

The dry-mix method was introduced almost 70 years ago under the proprietary name "Gunite", which was defined as the sand-cement product of the cement gun. Until the development of the "wet" gun and other dry process equipment after World War II, the original cement gun was the primary device for pneumatic placement of mortar and concrete. It was readily apparent that the equipment and techniques would not be limited to a combination of portland cement, sand, and water. Almost any type of aggregate, binder, and liquid, within certain physical limitations, could be handled with appropriate shotcrete equipment. Over the years, shotcrete procedures were applied to the installation of chemical-resistant preparations, quick sets, waterproofing products, refractory materials, and other proprietary mixes.

Of the specialties mentioned, the gunning of refractories, or in our terminology, refractory shotcrete, has probably had the widest application. Refractory shotcrete (which is refractory concrete) is defined as, "concrete which is suitable for use at high temperatures and contains hydraulic cement as the binding agent." Refractory shotcrete utilizes aggregates and binders which are suitable for use to 3400 F (1870 C) temperatures.

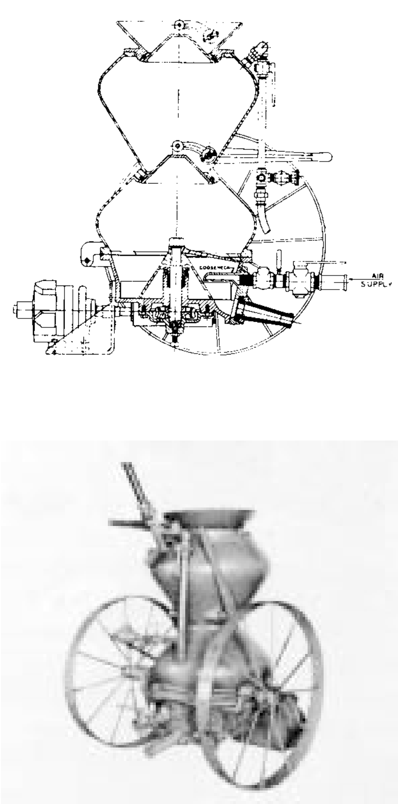

Figure 1: Double chamber gun (Allentown).

History

Refractory concrete technology parallels that of portland cement, but arrived on the scene about 100 years later. In each case, the discovery and production of a high strength hydraulic cement provided the impetus for the advance of the respective concrete technology. The discovery in 1824 of a calcium silicate binder, portland cement, initiated the start of the concrete industry. The commercial development of a calcium aluminate binder, Fondu in 1913 and Lumnite in 1924, precipitated the beginning of a refractory concrete technology. During the 1920's, mixtures of calcium aluminate cement and refractory aggregate were tested and used as patch materials for furnaces. Eventually, after many field trials and much experimentation, these materials were developed sufficiently for use as new or replacement refractory linings. As early as 1923, the literature refers to the use of shotcrete equipment (Allentown Cement Gun) for gunning refractory mixtures. From that time on, refractory shotcrete became an accepted process for installing all types of refractories in a variety of applications.

Major advances have occurred in the past 20 years with the introduction of new and improved refractory materials. Shotcrete equipment and placement techniques have also become more sophisticated and, as a result, have spawned alternate methods of installation such as "gun casting." The great upsurge in the use of refractory shotcrete for pyroprocessing and heat containment applications is sufficient evidence of its utility and effectiveness and its acceptance by all segments of the industry as an important method for the placement of refractory concrete.

Characteristics

Refractory shotcrete differs from ordinary shotcrete in many ways. The primary difference is that some refractory shotcretes have a service termperature that can range to 3400 F (1870 C).

The physical properties, such as crushing strength, modulus of rupture, thermal conductivity, linear change, and density vary with temperature. In addition, refractory shotcrete, like all refractory concretes exhibits variable properties throughout its thickness after firing due to a temperature gradient from the hot to cold surface. This characteristic must be considered in the design of a refractory shotcrete lining, and requires that its installation be exacting and meticulous.

The design must also take into consideration such factors as thermal cycling, thermal shock, chemical attack, abrasion, and erosion. Refractory shotcrete, therefore, uses a wide range of materials to counteract the variety of influences that can affect the ultimate service life of a particular installation. Another characteristic of refractory shotcrete is that its 24 hr strengths are similar to the 28-day strengths of portland cement shotcrete.

The rapid setting of most refractory shotcrete dictates the need for special gunning and finishing procedures; however, this is more than compensated by the fact that the installation can be utilized more quickly.

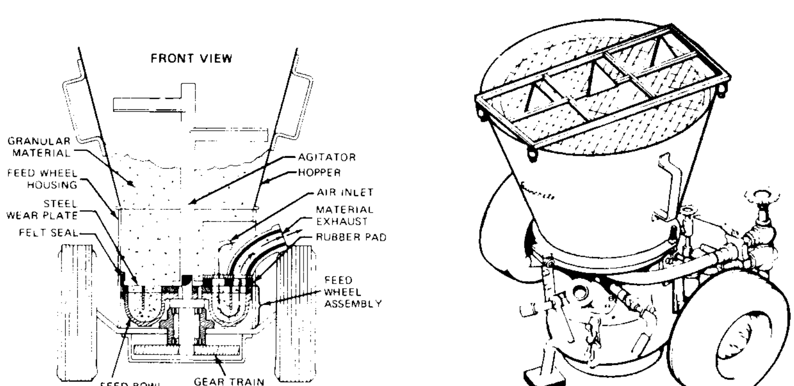

Figure 2: Rotary gun (feedbowl design—Reed & Cyclone).

Sources

Refractory shotcrete is applied at the job site from field-mixed materials or commercially packaged "refractory castables."

Field mixes are what the name implies. The separate ingredients as binder and aggregate are delivered to the job site in bulk. They are proportioned, mixed, and installed as needed. Field mixes are usually of lower unit cost than the packaged castables, but it is important to insure uniformity of aggregate size, shape, and gradation, and to properly proportion the binder and aggregate. In addition, some of the more sophisticated aggregates and binders are not available either commercially or conveniently in small quantities. Undetected contaminants can also be present to affect product quality.

The commercially-packaged castables are factory blended, and bagged in convenient sizes for shipping and handling. They only require the addition of water to produce a refractory concrete or mortar. Admixtures may also be present to obtain enhanced properties. The factory-manufactured castables provide a wider range of products, and are usually subjected to exhaustive quality control.

It is important to understand that field mixes, properly formulated and applied, can produce an economical refractory shotcrete; however, commercial castables are usually superior because of the wider variety available and better control over the final product. The cost of materials usually increases with service temperature; therefore, it is uneconomical to use a 3400 F product for a 2000 F maximum application, everything else being equal.

Ingredients

As indicated previously, the hydraulic binders in refractory shotcrete are calcium aluminate cements, which are manufactured throughout the industrial world. They are available in three types: low purity, intermediate purity, and high purity. The higher the purity, the higher the aluminum oxide content and the lower the iron oxide content; the higher the maximum service temperature, the higher the aluminum oxide content.

Among the aggregates used in increasing order of service temperatures are: slag, limestone, trap rock, expanded shale, vermiculite, perlite, calcined fireclay, clacined bauxite, kaolin, and tabular or fused alumina. Admixtures should not be used with refractory castables unless the manufacturer is consulted prior to use. Water for use in refractory shotcrete should be potable, and free of acids, alkalies, or other contaminants. Portland cement and calcium aluminate cement combined in a mix will accelerate the hardening process in the shotcrete.

Installation

Shotcreting is one of several methods for placing refractory materials. It is one of the most effective methods and is particularly effective where forms are impractical, access is difficult, thin layers and/or variable thicknesses are required, normal casting techniques cannot be employed, or economy dictates.

As indicated earlier, there are two shotcrete processes; dry-mix and wet-mix. In the dry-mix method, the castable (aggregate plus binder) is predampened and premixed prior to being placed in the cement gun. This will reduce rebound, minimize loss of binder and other fines, and eliminate any segregation that might have occured in the bagged material. To avoid prehydration and caking before use, mix only enough material for immediate use. A screw-type elevator-mixer is ideal for this purpose. The essentially dry mix is transported to the nozzle, where sufficient water is added for proper placement and hydration.

The wet-mix process mixes the castable and water, and conveys it to the nozzle in a wet state, where compressed air is added to increase the exit velocity.

Generally, the dry method has become the primary procedure for applying refractory shotcrete. Even though it gives greater rebound, it provides greater flexibility, fewer application restrictions, less nozzleman fatigue, lower water requirements, and usually higher strengths than the wet-mix method. However, where patching at high temperatures is required, the wet-mix method is recommended for this hot shotcrete application. Material for hot gunning is usually a special mix which contains only a relatively small amount of calcium aluminate cement. Technically, it is not considered a refractory concrete.

Equipment

The equipment used in refractory shotcrete is essentially the same as used in ordinary shotcrete with some changes required for specified applications. A standard complement of shotcrete equipment consists of a compressor, mixer, cement gun, nozzles, miscellaneous hoses, and on occasion, a pressure pump. The gun is the delivery equipment which introduces the material into the shotcrete hose at high velocity. The size and type of equipment required for a particular project is dictated by the process used and the job at hand.

The key to the shotcrete process, whether dry-mix or wet-mix, is the gun, which consists of two basic types: the continuous feed, and the batch or single-charge gun.

In the dry process, there are two basic types of continuous flow guns, the double chamber and the rotary (Fig. 1,2,3,). The batch or single-charge gun is a single-chamber gun which is loaded with castable and kept on standby for quick emergency patching of small hot spots in a kiln, hearth, or furnace (Fig. 4). The double-chamber gun uses the upper chamber for intermittent loading with the lower chamber providing continuous flow. The rotary gun has a single chamber which is loaded continuously and, by means of a special metering device, maintains continuous flow. The choice of gun usually depends on job conditions, but more often than not, depends on the installer's preference and experience.

The wet-mix process utilizes either a positive displacement, peristaltic, or dual chamber pneumatic feed-type gun for continuous flow. All are essentially concrete pumps with the first two having continuous loading characteristics, and the last, intermittent loading. A single-chamber pneumatic-feed gun may be used for single batching, but does not have the utility of the dry single-batcher.

Mixers of almost any type can be used, depending on job size and type, site layout, and production required. The most convenient is the elevator mixer of which there are two types: (1) proportioning, mixing, and predampening used for both field mixes and castables (Fig. 5); and (2) mixing and predampening used primarily for castables (Fig. 6,7). These are high-production units which can handle large volumes of material. For low-volume jobs, a paddle-type mortar mixer can do a satisfactory job (Fig. 8). As previously mentioned, adequate predampening of dry-mix ingredients is required not only for the reasons stated, but also because many lightweight castables have highly absorptive aggregates. Additional predampening water may be needed to assure adequate wa-

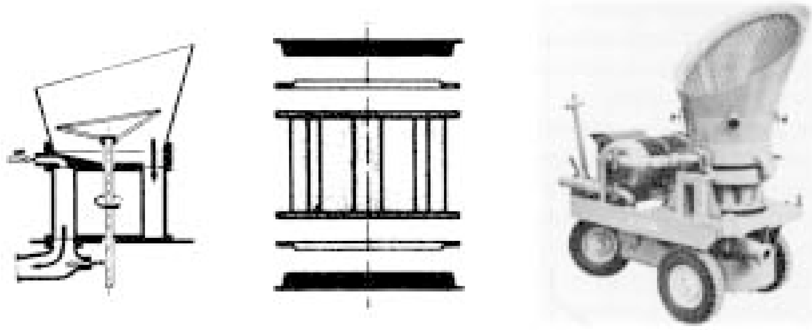

Figure 3: Rotary gun (rotor design—Allentown & Jetcretor).

ter availability for proper hydration of the shotcrete.

Compressors should be sized to provide sufficient volume of air at the pressure required to ensure quality in-place shotcrete. Inadequate air results in lowered exit velocities and can reduce the physical properties of the shotcrete. In the dry method, it is also important that sufficient water at high pressure is available at the nozzle to handle fluctuations in flow to improve gunning characteristics, and to maintain the design properties of the shotcrete.

Many of the nozzles used in ordinary shotcreting are also applicable to refractory work. They include the straight taper, hamm (Fig. 9), double bubble (Fig. 10), venturi, spirolet, and 90 deg nozzle. There is some difference of opinion as to which nozzle type is best for refractory shotcrete. Since there is little data available to prove that one is better than another, it must be concluded that they all do an adequate job in most cases, and the nozzleman should use that nozzle with which he is most comfortable.

A relatively new innovation is the hydro-nozzle of which there are many varieties. One type used in dry-mix shotcrete consists of two nozzle bodies spaced a variable distance apart. Initial dampening of the shotcrete occurs at the first nozzle body with final wetting near the exit. This allows for premixing the materials before final wetting, which purportedly reduces dusting and rebound and provides a more plastic and better hydrated shotcrete. Another type, which provides a similar effect, has a short piece of hose inserted between the nozzle body and nozzle tip (Fig. 11). Success in applying dry-mix re-

Figure 4: Single chamber guns (Allentown).

fractory shotcrete is dependent on proper predampening and in-hose prewetting procedures.

Water pumps are an important requirement for refractory shotcreting where adequate pressures are not available. Emphasis must be placed on the fact that refractory shotcrete be properly hydrated. Job planning should include a thorough check of

Figure 5: Proportioning, mixing, predampening mixer.

Figure 6: Mixing, predampening mixer with double chamber gun.

available water volumes and pressures to determine if a pump is necessary.

Special techniques

Hot gunning or shotcreting hot spots at high temperature requires special nozzles or "lances," which are manipulated from outside the furnace (Fig. 12,12a). The design of the lance depends on furnace configuration, temperature, and application requirements. Some nozzles merely consist of a steel pipe with nozzle and standard nozzle body. Others use the dual nozzle-body concept, some the hydro-nozzle, and still others a concentric pipe mechanism with the outer shell containing cooling water. As indicated earlier, the wet-mix process has certain advantages in hot gunning procedures.

The gun-casting technique is an outgrowth of the shotcrete process. It uses the same equipment, except that the nozzle is replaced by a casting head (Fig. 13). Casting heads exist in several shapes and forms, and are essentially energy or velocity-reducing devices (Fig. 14). They permit small or large aggregate castables to be placed at low velocity in a manner similar to pumped or extruded refractory concrete (Fig. 15). Their use practically eliminates rebound, and allows for efficient and economical placement of large or small volumes of material to distant and inaccessible locations. It is a technique which should develop into an important placement procedure.

Quality control

The actual installation of refractory shotcrete is similar, in most respects, to conventional shotcrete. Good quality requires well-maintained equipment, a more than sufficient volume of air, water at required pressure and volume, and an experienced foreman, nozzleman, and crew. The foreman and nozzleman, individually, must be experienced in surface preparation, anchor placement, equipment setup, gun operation, placement technique, finishing, and curing. He must know the proper angle nozzle technique for thin layers to 6 in. (152 mm) (Fig. 16), and the bench "gunning" or 45 deg angle method for thick layers above 6 in. (Fig. 17). It is imperative that the refractory materials, gun, hoses, compressor, and mixer be properly balanced and coordinated in order to achieve the best result. It should be noted, however, that not all conventional shotcrete installation techniques apply to refractory shotcrete, and a careful evaluation of the gunning procedures must be made prior to placement.

Whatever the technique, the ultimate goal is to apply full-thickness linings in one pass, at a measured, steady, nonpulsating rate of flow. This will limit laminations, and minimize rebound, sand pockets, and rolling or curling. If the shotcrete is placed uniformly, there is little need for finishing. The refractory should be left in its in-place state. Should finishing be required, an absolute minimum should be done, and only in a manner that avoids surface pulls, hair cracks, and breaking of the bond (Fig. 18). A trowel finish can also prevent excess water from escaping. This can cause internal cracking and surface spalling during heat-up. Shotcreting refractory castables, especially the lightweight variety, usually increases the in-place density and *k*-factor of the lining. This must be taken into account when determining the thickness required for an insulating shotcrete installation. It is also important that surfaces be thoroughly wetted prior to shotcreting to avoid the loss of hydration water from the mix.

Curing, drying, firing

Refractory shotcrete achieves its ultimate strength in 24 hr. Therefore, it is important that proper curing procedures be instituted immediately after installation and be continued for 24 hr in order to achieve complete hydration and to control drying shrinkage. The usual methods are effective: wet burlap cover, fine spraying, or a resin-type curing membrane.

After curing and before placing the refractory shotcrete in service, it is essential that the lining be dried to eliminate both free and combined water. Thorough drying minimizes the chance for explosive spalling resulting from the internal formation of steam. Effective drying can be achieved by establishing a controlled progressive heat-up schedule during initial firing. A well executed

Figure 7: Mixing, predampening mixer with rotary gun.

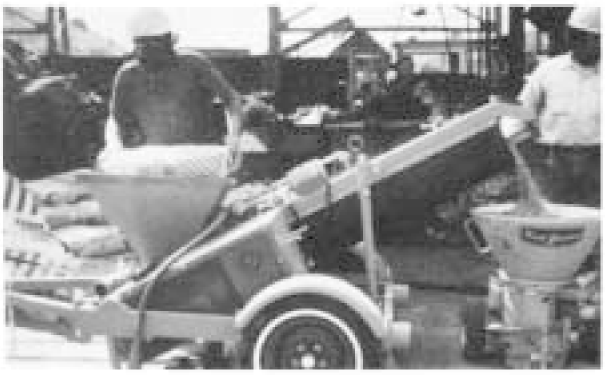

Figure 8: Mortar mixer with predampening assembly.

Figure 9: Hamm nozzle with nozzle and water ring.

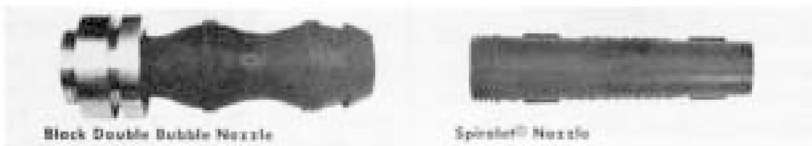

Figure 10: Nozzles used in refractory shotcrete.

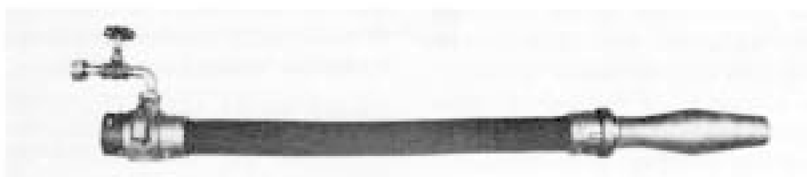

Figure 11: Hydro-mix nozzle assembly.

Figure 12: Hot gunning with special nozzle (lance).

heat-up procedure will assure the integrity of a lining, thereby providing a longer service life.

Construction details

There are many miscellaneous construction details which are unique to refractory construction. Shotcrete installations vary from a few inches to several feet in thickness, and forming procedures are similar to those of conventional concrete technology. However, when the form is the backup or support structure, usually steel plate, it is essential that the joints be sound and tight. Warpage of the shell can result in a localized reduction in the design thickness. This increases the possibility of hotspots and future failure of the refractory, particularly in these sections.

Special anchorage is used in refractory shotcrete to minimize and counter the effects of thermal and mechanical stress, vibratory forces, dead loads, and operational malfunctions. Anchors are not used as reinforcement but as a method for maintaining the integrity and continuity of the monolithic refractory lining.

For temperatures to 800 F (427 C) 2 to 4 in. (51 to 102 mm) thin layer shotcrete may utilize welded-wire fabric or chain-link fencing of carbon steel. Hex steel has also found wide application, particularly in the petroleum industry where it is utilized in the wear surfaces of a lining. These materials may be available in alloy form. However, when a choice is made, attention must be paid to all operational and corrosive influences.

For higher temperatures, the most commonly used anchors are stainless alloy V-clips or "bull horns," as they are known in the industry (Fig. 19). Cast metal alloy castings may be substituted for V-clips when they cannot properly support the lining weight. V-clips in design are either bolted or welded to the support shell. Current practice uses an anchor having unequal legs and a length about ⅔ the thickness of the refractory shotcrete. Generally, anchor spacing, arrangement, size, material, and type are dependent on lining thickness, maximum temperature, service conditions, and the attrition rate of the lining.

Alloy anchors usually have a design limit of 2000 F (1093 C), possibly somewhat higher where conditions are suitable. Where higher service temperatures prevail, prefired ceramic refractory anchors are utilized to about 3200 F (1760 C) (Fig. 20). Where shotcrete thicknesses are greater than 9 in. (229 mm), they may be used in place of metallic anchors, and extend to the hot face of the shotcrete. Ceramic anchors are usually attached to a hook bolt which is bolted or welded to the shell.

Multicomponent linings, usually consisting of an insulating back up of lightweight refractory and a wear surface of normal weight refractory, are employed for many applications. Single anchors extending through both components must be protected from splatter and rebound, or cleaned after the back up material is installed. An alternate procedure is to use two-component anchors of various types, which are installed prior to the application of each component. There are also single split anchors available which can be opened to provide a V-clip in the second component. In some multi-component linings with relatively low service temperature, hex steel or chain-link fencing can be used as the anchor in the wear surface of lining (Fig. 21). This type of anchorage requires a special support or spacer which extends through the back up lining. Under certain service conditions, problems can arise that can cause a failure in this type of lining. The use of fibers and the development of special castables having improved insulating and erosion-resistant qualities have reduced dependency on this type of anchoring system.

As noted earlier, anchors are not used as a substitute for reinforcement. Deformed steel reinforcing bars should also be avoided in refractory application. Metal in the form of pipes, overflow boxes, and steel bolts should not be imbedded in refractory shotcrete because they can be a source of lining failure. However, the use of dispersed steel fibers, either carbon or stainless, to improve the properties of refractory shotcrete is rapidly gaining favor. It is claimed that fibers improve flexural strength, reduce the effect of thermal and mechanical stress, and increase thermal shock and spall resistance. Fibers can be introduced into the castable in the mixer at the field site. However, more consistent quality control could be achieved when they are plant-mixed in the prepackaged castable. Before using a particular fiber in refractory shotcrete, it is important to check its compatibility with the application and its environment. Steel fiber use in refractory shotcrete should not be considered a replacement for standard anchorage.

Since most refractory castables expand only at high temperatures, the use of expansion joints in refractory shotcrete is problematical, and is probably dependent on the application, service temperature, and need to contain liquids and gases. Where experience or design criteria indicate, provision should be made for the installation of expansion materials such as wood, cardboard, or expanded polystyrene. They may be installed before or during shotcreting, and left in place to burn out when firing the unit.

If the joint must be tight, expansion-compensating materials such as special ceramic fibers are packed into the joint after shotcreting. Construction joints occur when shotcrete is not applied monolithically or continually. They should be squared off perpendicular to the shell surface, leaving a clean and sharp surface to bond with the next application. Expansion materials are not placed in a construction joint. Construction joints in multi-component linings should be staggered to avoid occurence at the same location. As a rule, any type of joint in refractory shotcrete may be a future source of trouble, and should be avoided if at all possible.

Figure 13: Casting head used in gun-casting.

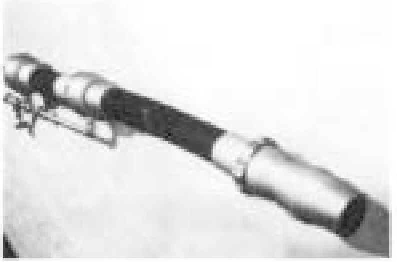

Figure 14: Casting head (A. P. Green).

Repair

Premature failure in refractory shotcrete and concrete occur because of thermal stress and shock, excessive temperature, mechanical loading, erosion, corrosion, anchorage failure, and operational upsets. When there is a loss of lining section due to one or more of these influences or effects, repairs must be made at some point in the deterioration process. If repairs are required during a cam-

Figure 15: Gun casting (note completed section at upper right).

Figure 16: Right angle nozzle technique.

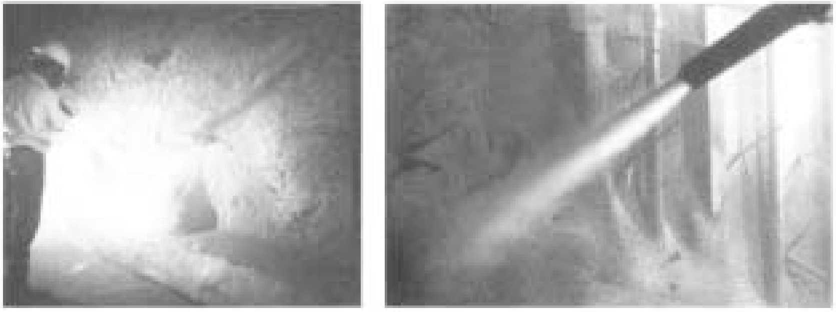

Fig. 17: Bench gunning or 45 deg angle nozzle technique.

Fig. 18: Removing high spots after gunning.

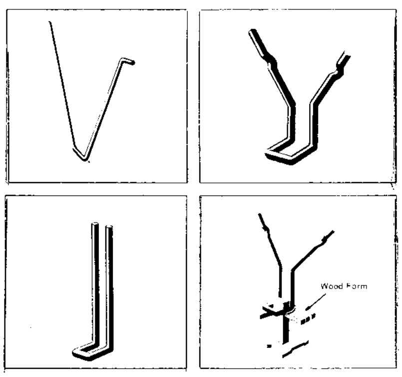

Fig. 19: V-Clip anchors (bull-horns).

Fig. 20: Ceramic anchors interspersed with corrugated V-Clips.

paign or operating run, the only method available without shutting down is the hot-gunning shotcrete process (Fig. 12,22,23). This procedure is only possible if ready access to the repair area can be made through openings or ports utilizing the special "lances" described previously. In addition, to ensure satisfactory impact, surface retention, and compaction, material delivery should be uniform with minimal pulsations. Water volume and pressure should be sufficient to thoroughly wet the mix to avoid drying prior to impact. The end of the lance should be held as close as possible to the repair area, with thin layers being applied successively to minimize entrapment of steam and subsequent spalling. Above all, competent and knowledgeable personnel are required to assure an efficient and successful repair. Since different plants have dissimilar designs, needs, and requirements, each organization must experimentally develop its own hot-gunning techniques so as to guarantee continuity of operation in an expeditious manner. Generally, hot-gunned repairs do not have the service life or properties of the original lining.

The majority of refractory repairs are "cold repairs" made during normal shutdown, under somewhat controlled conditions. In some quarters, repair is equated with replacement of entire linings, but this should only be done when the size of repair and degree of deterioration make it impractical to do otherwise. Localized repair is usually a viable, practical, and economical procedure for prolonging the service life of a lining. However, it is imperative to follow well established repair methods to insure a satisfactory result.

Normally, refractory linings should be repaired with a material similar or compatible with the original installation. Refractory shotcrete would, therefore, only be used for linings constructed with refractory concrete or shotcrete. However, under certain conditions, it can be used to repair brick and plastic firebrick. These conditions have as much to do with the logistics and economics based on availability of materials, skilled labor, and equipment, as with the technical aspects of the repair. On the other hand, it is sometimes convenient and expeditious to repair refractory concrete and shotcrete linings with a hand-placed castable or rammed plastic firebrick. This is usually feasible when the areas to be repaired are small and do not justify the expense of mobilizing the shotcrete equipment.

Quality surface preparation is very important to the success of a repair, and should not be bypassed except for emergency situations. It is important to maximize mechanical bond, since chemical bond at the repair interface is very weak and almost nonexistent. This requires that all loose, spalled, and deteriorated materials be removed, and the newly exposed surface be roughened to promote bond. Areas not requiring chipping, including those immediately adjacent to the repair area, should be sandblasted to remove all deleterious substances that could interfere with proper bond. The area to be shotcreted must be sound, clean, and textured for best results.

Exposed anchors should be tight, and cleaned of all extraneous material. If sufficient anchors are not exposed, it may be necessary to install additional anchors which penetrate the lining and are attached to the shell. If the thickness of remaining lining or other conditions makes this procedure impractical, special concrete anchors should be installed in the older refractory.

When installing anchors is not feasible, cutting keyways and scarifying the surface may be an effective substitute. The use of fibers in shotcrete is becoming more common, and may help retain the integrity of the repair and slow its eventual breakdown.

Prior to shotcreting, the repair area should be wetted down sufficiently to prevent the absorption of moisture from the shotcrete. This is particularly important when repairing or shotcreting lightweight castables, which normally have high porosity. This is accomplished with an air-water blast from the nozzle normally used to clean the surface prior to gunning. Installation, curing, drying, and firing procedures are similar to those used for installing the full or new linings described earlier. It is important in this type of repair not to finish the shotcrete, but to leave it with a natural or gun finish. Trimming and finishing can break the bond and open hair cracks, especially in thin layer repairs.

Figure 23: Hot gunning a ladle, lower area about 1500 to 1700° F (816 to 927° C).

Conclusion

The purpose of this paper was to briefly outline, delineate, and summarize the state of the art of refractory shotcrete. Much of the material is consensus oriented, but some does represent the practice and prejudice of the author. The multiplicity of factors and parameters in the equation that is refractory shotcrete does not easily lend itself to a solution acceptable to all segments of the industry. Whether manufacturer, installer, or ultimate user, each must alter the variables involved and find a solution that most nearly fits his individual needs. This evaluation process has been going on from the very beginning and has increased our knowledge of refractory behavior resulting in improved refractory quality and the development of new and versatile materials which permit higher service temperatures and more sophisticated application techniques.

With continued effort in this direction, we can look forward to the expansion of the shotcrete process into areas now dominated by other materials and techniques.

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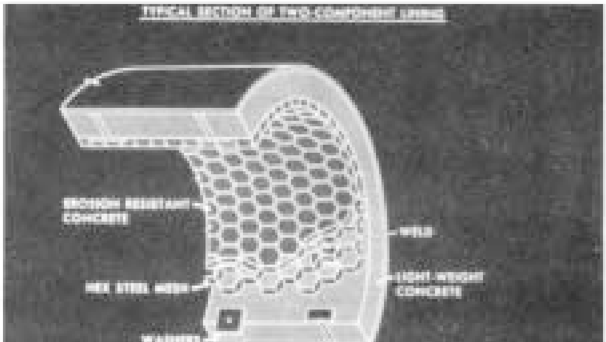

Figure 21: Hex steel detail in two-component lining.

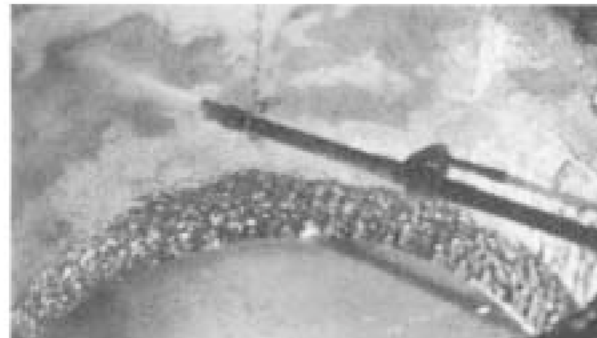

Figure 22: Hot gunning refractory shotcrete lower area is red-orange heat.