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NOVEL FORM FREE INSTALLATION METHOD FOR REFRACTORY CASTABLES

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ABSTRACT

After a brief history of different installation modifications, this paper introduces a novel installation technique, which enables form free placement of low cement and fully dispersed castable compositions. The method doesn't require the typical wet pumping equipment, as is needed for shotcreting, however delivers similar lining properties.

1. INTRODUCTION

The last decade could be considered the decade of monolithic installation methods. The advancements in castable compositions and applicability of shotcreting equipment brought a new dimension to the commercial success of form free monolithic installations. The improvements in rheology, better control of set behavior of low cement castables, slow flow decay and good response to flow modifiers made many refractory concretes ideal for pumping and shotcreting installations.

The evolution of the installation methods, from gunning, vibration casting through pump casting, shotcreting and dry shotcreting allows for good identification of possible advantages.

Direct comparison of properties after different modes of installations clearly demonstrates the evolutionary aspects of the refractory castable technologies and installation methods.

2. EVOLUTION OF FORM FREE INSTALLATIONS

The beginning of the nineties found the hydraulic refractory monolithic technology with well defined product categories such as high cement "conventional" systems and the advanced low cement or low moisture systems. The systems were readily available in both, cast or gunning versions. The refractory compositions were fine-tuned to serve the individual installation method. The low moisture systems were increasingly being installed not only by vibro-casting but also by pumping. Appropriate mix modifications allowed also for dry gunning. From the installation perspective the advantages of form free dry gunning were obvious, however because of the no flow requirement after wetting and rapid set, the properties of the gunned refractories were greatly compromised. Because of a short wetting period, stiffening and sticking additives were added to the dry mix. The final installed refractory had significantly diminished physical and thermo-mechanical properties when compared to a similar castable product. Highly compromised rheology of these systems with no flow and rapid set resulted in higher water demand and poor wettability. Not surprisingly, the installed refractory exhibited higher porosity, lower densities, lower strength, higher tendencies for slag infiltration and corrosion and shorter service life. Many attempts to improve these properties resulted in gunning compositions with very narrow water demand, high re-bound and poor gunning characteristics.

The form free installation remained intriguing, though the limited pumping technology did not allow the use of wet shotcreting methods to be applicable for very dense and thixotropic low moisture refractory castable systems. The improvements in swing-valve pumps, increased pressure and decreased cylinder diameter, however opened the door to new possibilities for form free installations of refractory castables. The new equipment allowed for less pressure line reductions and greater conveying distances [1].

The shotcreting technology includes wet mixing, wet transportation and wet spraying of a refractory castable via a nozzle at the end of the transfer lines. Because of the fully flowable state of the refractory castable, an activator is applied at the spraying nozzle to stiffen the mix and to initiate the setting mechanism. In contrast to gunning mixes the shotcrete castable compositions have optimum rheology with low water demand, excellent homogeneity, optimum physical and thermo-mechanical properties, lower porosity, higher densities, higher strength, improved corrosion resistance and longer service life.

Refractory manufacturers soon recognized that the combination of advanced castable technology with the new high-pressure swing-valve pumps delivered unique product opportunities. One of the first applications in the mid nineties [2] proved that shotcreted low cement castables have similar properties as comparable cast samples. The method received patent protection and specified the use of alkali chloride or alkali phosphates as the flocculating agent.

These early successes stimulated additional research activities. The equipment itself was not enough to get the optimum installed properties. The refractory composition and the proper application of very specific flocculating agents advanced the technology case by case. It was recorded [3] that, for example, the use of hydrated lime, or a combination of hydrated lime and calcium chloride as flocculating agents, is highly beneficial over the sodium silicate when shotcreting low cement trough or high alumina castables (Tables 1 and 2).

In a similar development a very specific use of set-modifying aluminum and magnesium salts has been identified as the optimum for shotcreting of cement free castables [4]. In this case it was very important that the accelerator does not contain silica, calcium oxide or alkalis, such as sodium oxide. Absence of calcium aluminate cements in the castable composition was the leading advantage, which allowed for improved performance of refractory linings in corrosive slag environments, such as steel ladles. Selection of an inappropriate accelerator would have a detrimental effect on slag corrosion resistance. The corrosion results confirmed that the shotcreted cement free castable, which was accelerated with the solution of aluminum sulfate had a slag affected depth very similar to cast-vibrated samples (Table 3). The test was done against a slag with C/S ratio around 4. The aggressivity of the slag was enhanced with the addition of 10% manganese oxide.

The retention of hot mechanical properties in high purity alumina systems was the reason why silica and alkali free flocculating agents have been successfully utilized with these systems [5]. Interestingly, though the shotcreted lining did not fully reach the properties of cast-vibrated installations (Table 4), the properties were significantly better when compared to similar gunning materials. The major compositional difference was the presence of ball clays in the gunning mixes (Table 5); an ingredient necessary to protect the non-slumping attributes of the gunning mixes. On the other hand the castable composition was fully dispersed, as is typical for low cement systems.

The data in Table 4 indicate that the fully dispersed shotcreted castable has lower density than the cast sample, but greater than the gun mixes. The biggest advantage, however, is being seen in improved hot properties. The hot modulus of rupture is comparable between the cast and shotcrete samples and significantly higher than the strength of the gunning mixes. Interestingly, both gunning mixes had non-measurable hot strength at 1593°C indicating that the systems had exceeded the use limit. The data is clear evidence for a technical advantage of shotcrete over gunning and well illustrates the limitations of either the conventional or low moisture gunning mixes.

Additional improvement in shotcreted properties of low cement castables was realized when the high-pressure process for shotcreting was developed [6]. This method introduced air into the spraying nozzle under pressure up to 0.6 MPa and at a velocity of about 150 meters per second. As a result, the velocity of the wet castable mix striking the target surface is very high giving higher compaction and improved physical properties.

Table 6 lists two examples of shotcrete mixes that were installed via wet shotcreting. Table 7 shows the difference in physical properties of these two formulations between the standard shotcreting and the high velocity installation method.

Table 7 shows a slight decrease in porosity of the cured refractory mixes as deposited with the high pressure and high velocity shotcreting method. Similarly there is improvement in densities. However, the most notable advantage is the increase in cold crushing

Table 1 Compositions of Trough and High Alumina Low Cement Castables [3]

Trough Castable		80% Alumina Castable	
Brown Fused Alumina	62.5%	Calcined Bauxite	55%
Calcined Alumina	7.5	Raw Kyanite	13.25
Silicon Carbide Fines	16	Fine Alumina	21.75
Microsilica	4	Microsilica	6
Carbon Black	2	Calcium Aluminate Cement	4
Calcium Aluminate Cement	4	Rheology and Dewatering Additives	0.35
Raw Kyanite	1.25		
Silicon Metal	2.5		
Rheology and Dewatering Additives	0.25		

Table 2 Effect of Flocculating Additives [3]

Refractory/Property	Flocculating Additive		
Trough Castable	**Sodium Silicate**	**Hydrated Lime**	**Hydrated Lime/ Calcium Chloride**
Density after 110°C [g/cm^3]	2.79	2.82	2.82
Porosity after 110°C [%]	17.5	16.3	16.6
Modulus of Rupture after 110°C [MPa]	2.8	9.7	8.7
Hot Modulus of Rup. @ 1370°C [MPa]	1.8	3.0	3.00
Slag Corrosion Index (6 hours/1565°C)	1.00	0.76	0.73
80% Alumina Castable	**None**	**Sodium Silicate**	**Hydrated Lime**
Density after 110°C [g/cm^3]	2.74	2.65	2.71
Porosity after 110°C [%]	17.9	21	18.8
Modulus of Rupture after 110°C [MPa]	11.8	7.0	16.4
Crushing Strength after 110°C [MPa]	42.0	27.0	54.0
Hot Modulus of Rup. @ 1370°C [MPa]	7.4	4.7	6.3

Table 3 Corrosion Resistance of Cement Free Castable System [4]

	Installation Method	
Corrosion/Penetration	Cast-Vibrated	Shotcreted
Corroded Area [cm^2]	0.9	1.5
Penetrated Area [cm^2]	3.8	3.5
Total Affected Area (6 hours/1595°C) [cm^2]	4.7	5.0

Table 4 Properties of High Purity Alumina Castables and Gunning Mixes [5]

Property	Installation Method/Composition			
	Castable	Shotcrete	Conventional Gun Mix	Low Moisture Gun Mix
Density after 110°C [g/cm3]	3.12	2.89	2.59	2.69
Porosity after 110°C [%]	14	18	28	25
Modulus of Rupture after 110°C [MPa]	13.4	7.0	10.9	8.5
Hot Modulus of Rupture @1370°C [MPa]	14.1	8.5	0.7	2.1
Hot Modulus of Rupture @ 1480°C [MPa]	7.0	11.3	-	-
Permanent Lin. Change after 1593°C [%]	+0.2	+0.3	-3.1	-1.5

Table 5 Compositions of High Purity Alumina Castables and Gunning Mixes [5].

Castable		Conventional Gunning Mix		Low Moisture Gunning Mix	
High Purity Alumina Grain	70%	High Purity Alumina Grain	75%	High Purity Alumina Grain	60%
Reactive Calcined Alumina	7.5	Calcium Aluminate Cement	21.7	Calcined Alumina	22.5
Tabular Alumina - Fine	13.5	Ball Clay	3.3	Amorphous Alumina	2
Calcium Aluminate Cement	5			Calcium Aluminate Cement	8
Raw Dolomite	4			Ball Clay	3
Rheology Additives	0.3			Microsilica	4.5
				Rheology Additives	0.15

Table 6 Compositions of 70% Alumina and Super Duty Low Moisture Shotcrete Materials [6]

70% Shotcrete Material		Super Duty Shotcrete Material	
60% Alumina Grain	63.75 %	Calcined Clay Aggregate	65%
Raw Kyanite	15.25	Raw Kyanite	15
Fine Alumina	11	Fine Alumina	6
Microsilica	6	Microsilica	6
Calcium Aluminate Cement	4	Calcium Aluminate Cement	8
Rheology and Dewatering Additives	0.33	Rheology and Dewatering Additives	0.43

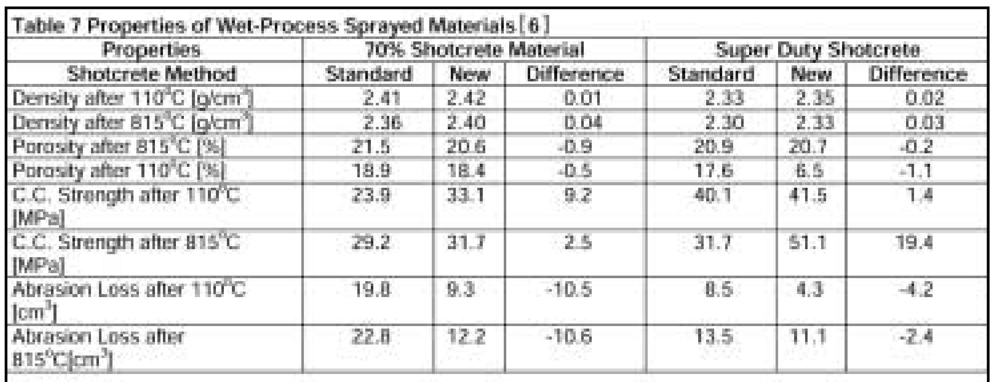

Table 7 Properties of Wet-Process Sprayed Materials [6]

Properties	70% Shotcrete Material			Super Duty Shotcrete		
Shotcrete Method	Standard	New	Difference	Standard	New	Difference
Density after 110°C [g/cm³]	2.41	2.42	0.01	2.33	2.35	0.02
Density after 815°C [g/cm³]	2.36	2.40	0.04	2.30	2.33	0.03
Porosity after 815°C [%]	21.5	20.6	-0.9	20.9	20.7	-0.2
Porosity after 110°C [%]	18.9	18.4	-0.5	17.6	6.5	-1.1
C.C. Strength after 110°C [MPa]	23.9	33.1	9.2	40.1	41.5	1.4
C.C. Strength after 815°C [MPa]	29.2	31.7	2.5	31.7	51.1	19.4
Abrasion Loss after 110°C [cm³]	19.8	9.3	-10.5	8.5	4.3	-4.2
Abrasion Loss after 815°C[cm³]	22.8	12.2	-10.6	13.5	11.1	-2.4

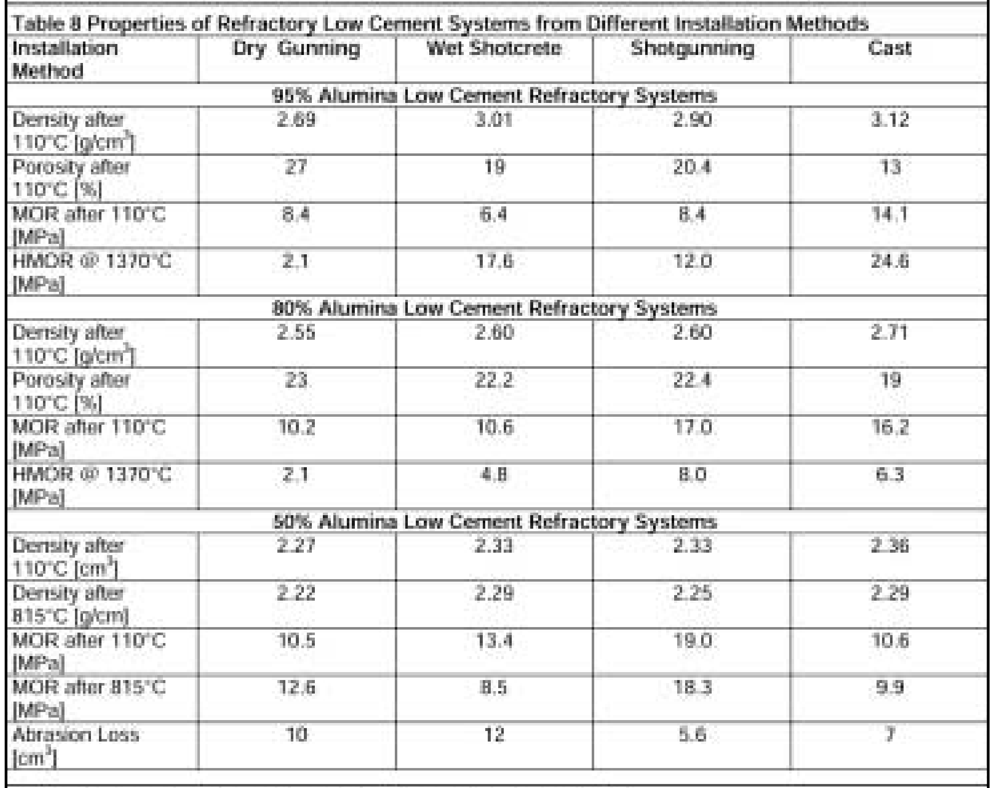

Table 8 Properties of Refractory Low Cement Systems from Different Installation Methods

Installation Method	Dry Gunning	Wet Shotcrete	Shotgunning	Cast
95% Alumina Low Cement Refractory Systems				
Density after 110°C [g/cm³]	2.69	3.01	2.90	3.12
Porosity after 110°C [%]	27	19	20.4	13
MOR after 110°C [MPa]	8.4	6.4	8.4	14.1
HMOR @ 1370°C [MPa]	2.1	17.6	12.0	24.6
80% Alumina Low Cement Refractory Systems				
Density after 110°C [g/cm³]	2.55	2.60	2.60	2.71
Porosity after 110°C [%]	23	22.2	22.4	19
MOR after 110°C [MPa]	10.2	10.6	17.0	16.2
HMOR @ 1370°C [MPa]	2.1	4.8	8.0	6.3
50% Alumina Low Cement Refractory Systems				
Density after 110°C [cm³]	2.27	2.33	2.33	2.36
Density after 815°C [g/cm]	2.22	2.29	2.25	2.29
MOR after 110°C [MPa]	10.5	13.4	19.0	10.6
MOR after 815°C [MPa]	12.6	8.5	18.3	9.9
Abrasion Loss [cm³]	10	12	5.6	7

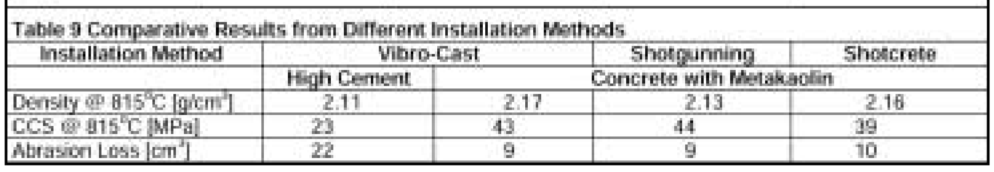

Table 9 Comparative Results from Different Installation Methods

Installation Method	Vibro-Cast		Shotgunning	Shotcrete
	High Cement	Concrete with Metakaolin		
Density @ 815°C [g/cm³]	2.11	2.17	2.13	2.16
CCS @ 815°C [MPa]	23	43	44	39
Abrasion Loss [cm³]	22	9	9	10

strength and the decrease in abrasion volume loss. The improvements in abrasion resistance are around 100% and clearly indicate more intimate contacts between the coarse fractions of the compositions and the fine dispersed matrix. The beneficial influence of the high velocity impact during spraying is clearly demonstrated.

3. DRY SHOTCRETING OR SHOTGUNNING

The technology of shotcreting has significantly advanced during the last several years and today this technique has become the major installation method of refractory linings in steel, non-ferrous metal, chemical, mineral and ceramic processing plants. The only remaining disadvantage of the method is that the installation equipment is relatively expensive and requires significantly more set-up and clean-up time when compared to a conventional dry gunning process. The need for large capacity wet mixer, expensive swing-valve pump and very specific pump for the set activators makes shotcreting quite complex and sophisticated.

On the other hand, a simple pneumatic dry gun is the only piece of machinery required for conventional dry gunning. The simplicity of the dry-gunning equipment reduces the set-up time, clean-up time and overall labor requirement at the job site. The problem with such a process, however, is that very specific gunning refractory mixes, formulated for no flow after wetting, for rapid set and with very stiff consistency can only be used. Because of a short wetting period, stiffening and sticking additives are typically added to the dry mix to prevent slumping of the refractory, to reduce rebound during spraying and to expand the water range. All of the above significantly diminishes the physical and thermo-mechanical properties of dry gunned installations and makes this method technologically inferior to shotcreting. The next phase of evolution in refractory installation techniques is a specific installation method, which overcomes the complexity of the equipment required for shotcreting, and allows dry gunning of more advanced fully dispersed castable compositions [7]. This patented dry shotcreting method is commonly referred in North America as Shotgunning.

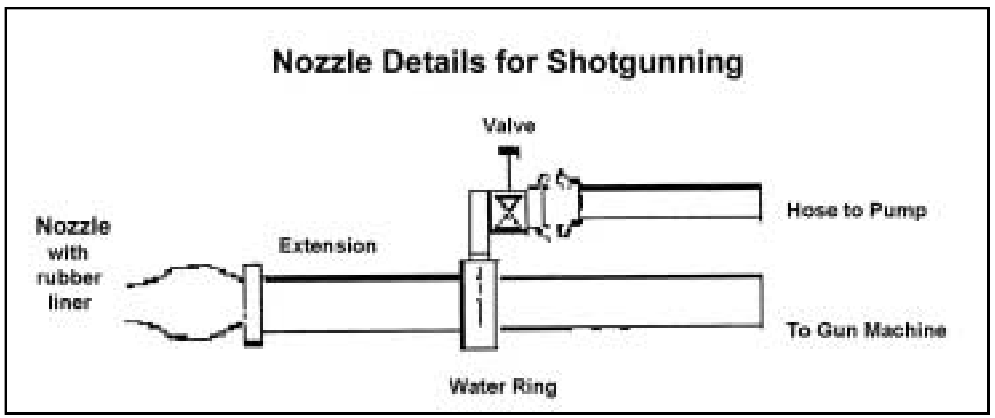

Figure 2. Nozzle for Shotgunning

The method is defined as "the pneumatic installation of castable refractories using standard pneumatic gunning machines in conjunction with the introduction of accelerating additives at the spraying nozzle".

3.1. SHOTGUNNING EQUIPMENT

The requirements for the equipment are quite simple. The method can utilize any standard Reed, Allentown or other pneumatic gunning machine. If pre-dampening is required an additional pre-dampening mixer could be used. As with the dry gunning, the method requires an air compressor with a minimum of 790 m³/hr output. The set activator is added directly to the main water supply, which requires an admixture barrel and an admixture pump. The fact that the activator is part of the main water supply makes the spraying nozzle very similar to a dry gunning nozzle. The nozzle is in addition equipped with a mixing extension, or whip to extend the wetting time of the sprayed castable. The method in contrast to wet shotcreting does not require a large capacity mixer and swing valve pump. The schematic of the method is in Figure 1 and the sketch of the nozzle is in Figure 2.

3.2. SHOTGUNNING PROPERTIES

The acceleration step at the nozzle allows shotgunning to be applied to many low cement refractory systems. Some helpful modifications over cast compositions are however recommended. The shotgunning low cement systems are formulated with smaller top particle size and have an adjusted rheology package for fast wetting. These modifications improve the shotgunning characteristics of the mix, but have some negative effects on physical properties (Table 8).

The properties of low cement systems formulated for specific installation methods are compared against each other in Table 8. The comparison is done for 95% alumina, 80% alumina and 50% alumina low cement compositions. Although the compositions were similar in chemistries, they were optimized for a particular installation method. The gunning mixes had low cement bonds, but contained no slumping additives, such as clays. The cast compositions had optimum coarse particle packing, which enhanced the densities. The compositions for shotcreting and shotgunning were identical, formulated with finer particle size distribution and fast wetting rheology.

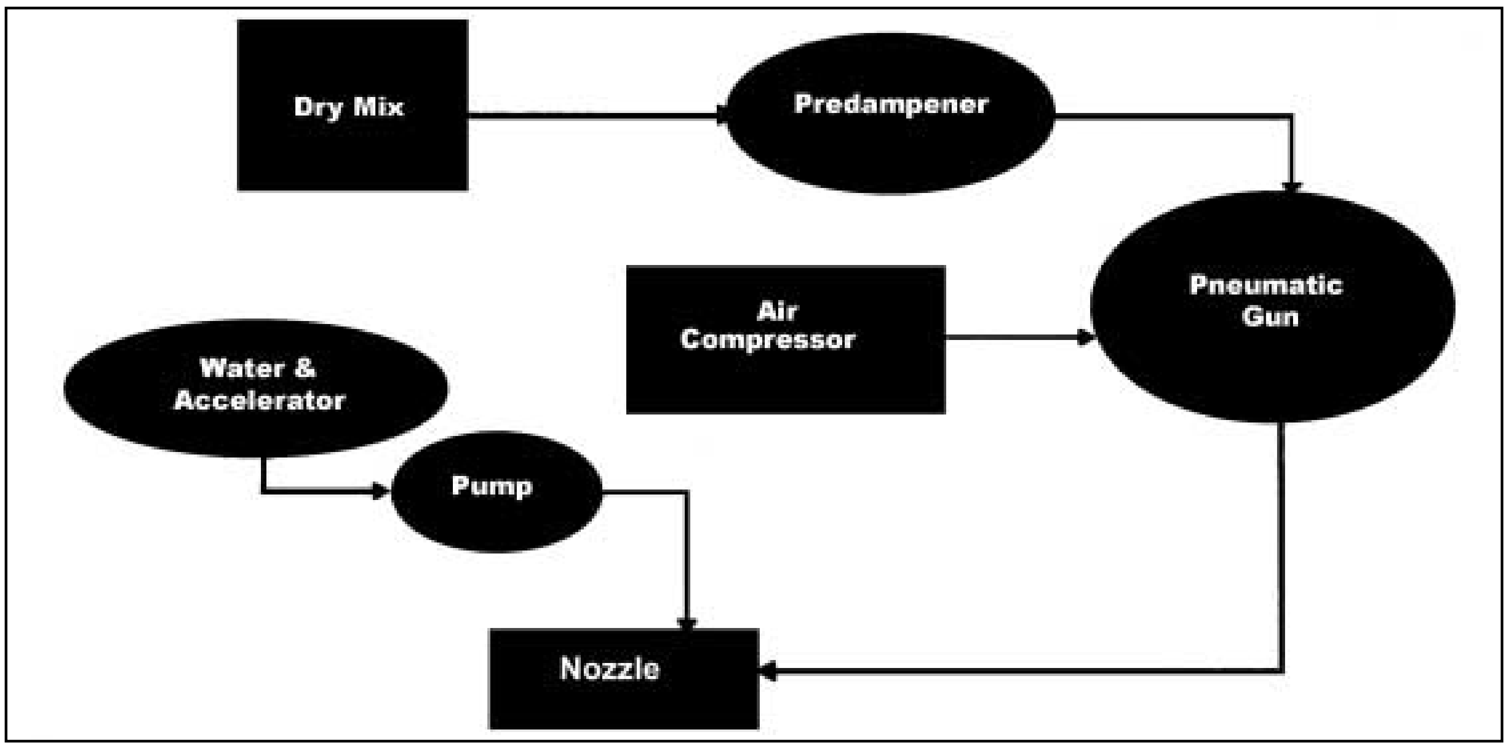

Figure 1. Schematic of Shotgunning Process

As expected, in all instances the dry gunning delivered the worst properties and the vibro- casting the best. Major differences could be seen in all properties. The properties of shotcrete and shotgunning samples were somewhere in between. Surprisingly, the better properties of shotcreted 95% alumina systems versus shotgunned, were reversed in 80% and 50% alumina systems. The 50% alumina shotgunned properties surpassed even the properties of vibro-cast samples (with the exception of density). As seen from the data, this method appears to have an especially significant beneficial effect on abrasion resistance.

Good results with the 50% alumina low cement system, which is formulated with a super duty aggregate, encouraged us to seek an improvement also in the conventional high cement compositions in this chemistry range. These are typically formulated with poor rheology and rapid flow decay, which prohibits their use in pumping applications. The results of the work in detail were reported during UNITECR'99 [8]. The final composition, formulated with pozzolanic metakaolin, delivered enhanced rheology, very flowable composition and overall improved properties over conventional high cement technology (Table 9). The system proved to be very friendly during shotgunning installation and because of slow flow decay it could be universally used also for shotcrete or vibro-cast installations.

3.3. ADVANTAGES AND DISADVANTAGES OF SHOTGUNNING

The biggest advantage of shotgunning is the simplicity of the equipment. Because of the easy start-up and clean up, this method is more economical for small size installations than shotcreting. The ability to dry gun low cement castables makes this method technologically more advanced over gunning of conventional gunning mixes. The addition of set activators or accelerators eliminates the narrowness of the water range at the nozzle and makes the gunning process more user friendly. Because of the use of more advanced fully dispersed low moisture castable compositions, the final properties of installed linings surpass the properties of gunning mixes.

On the other hand, the shotgunning possesses disadvantages over cast installations and in some specific instances also over shotcrete installations. The rebound rate is at the level between 5-15% and is higher than with a typical shotcrete installation. In addition, the dry process generates more dust than is the typical experience during shotcreting. Lastly, the installation rates are slower than during shotcreting, which makes the method less economical on large installation jobs.

The advantages of this simple installation method are helping to gain its field acceptance.

Shotgunning is becoming a common installation method in cement and lime plants. The maintenance or installation of cyclones, risers, nose rings, cooler walls, cooler rings and lifters are becoming standard practice. Aluminum plants utilize shotgunning for maintenance of lower and upper sidewalls. Several field trials also have been run in steel applications, where the shotgunning method was tested for hot maintenance of steel ladle bed joints, slag lines and lip rings.

4. CONCLUSIONS

The last decade could be considered the decade of installation methods. The improvements in pump casting allowed for successful application of shotcreting for form free installation of low cement refractory castables. The evolution culminated with the development of a dry shotcreting method, commonly called shotgunning.

The properties of shotgunning materials exhibit advantages over conventional gunning and in some instances also over shotcreting. Simple equipment makes the method increasingly attractive for field installations, especially for smaller size installation jobs.

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SAMPLE PREPARATION, THERMAL EXPANSION, AND HASSELMAN'S THERMAL SHOCK PARAMETERS OF SELF-FLOW REFRACTORY CASTABLES[1, 2]

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[2] Based in part on the dissertation submitted by W. L. Headrick, Jr. for the Ph.D. degree in ceramic engineering, University of Missouri-Rolla, Rolla, MO, 65409.

ABSTRACT

Thermal shock resistance is among the most important properties of refractory castables. High cement based castables were found to have the lowest coefficient of thermal expansion and high elastic modulus, critical energy release rate for crack initiation and work of fracture. This led to high resistance to damage initiation by thermal shock and a high minimum ΔT for resisting long cracks decreasing as the amount of bonding phase decreased. However, minimum elastic energy available for crack propagation and minimum crack propagation on initiation of fracture were low for the high cement based castables and increased as the amount of bonding phase decreased.

I. INTRODUCTION

Thermal shock resistance is among the most important properties of refractory castables. Hasselman's thermal shock parameters are given by the following equations:

$$R = \frac{\sigma}{\alpha E} \qquad (1)$$

$$R' = \frac{\sigma k}{\alpha E} \qquad (2)$$

$$R'' = \frac{\sigma D}{\alpha E} \qquad (3)$$

$$R''' = \frac{E}{\sigma^2} \qquad (4)$$

$$R'''' = \frac{WOF \times E}{\sigma^2} \qquad (5)$$

agation; minimum ΔT for propagating long cracks, σ is fracture strength, α is coefficient of thermal expansion, E is elastic modulus, k is thermal conductivity, D is thermal diffusivity and WOF is work of fracture [1-3].

These equations can be converted to fracture energy based equations by Irwin's relationship [4]:

$$G_C = \frac{\pi \sigma^2 a_0}{E} \qquad (7)$$

where: G_C is the critical fracture initiation energy, and a_0 is the initial flaw size.

The term a_0 is related to largest grain size (d_l) for refractory castables [5-11]. So, rearranging the thermal shock equations for the non-thermal transport based equations and substituting in d_l results in:

$$R = \sqrt{\frac{G_C}{\pi d_l \alpha^2 E}} \qquad (8)$$

$$R''' = \frac{\pi d_l}{G_C} \qquad (9)$$

$$R'''' = \frac{WOF \pi d_l}{G_C} \qquad (10)$$

$$R_{st} = \left(\frac{WOF}{\alpha^2 E}\right)^{1/2} \qquad (11)$$

These parameters will be calculated based on thermal expansion, G_C and WOF values at room temperature as reported in the studies, "Energy Release Rates as a function of Thermal Gradient of Self-Flow Refractory Castables by the Wedge Splitting Test

Table I. Alcoa 605S Composition

Component	Wt. %
Alcoa Tabular Alumina 6x10	16
Alcoa Tabular Alumina 8x14	12
Alcoa Tabular Alumina 14x28	12
Alcoa Tabular Alumina 28x48	15
Alcoa Tabular Alumina 48x200	10
Alcoa Tabular Alumina –100	10
Alcoa Tabular Alumina –325	10
Alcoa A3000FL	5
CA 14, CA 270 or Alphabond 100	5
Elkem Micorsilica 971	5
Sodium Hexametaphosphate	0.063; % of total batch
Total	**100.063**

Table II. Tabular Alumina Composition for Testing

Component	Wt. kg
Alcoa Tabular Alumina 6x10	16
Alcoa Tabular Alumina 8x14	12
Alcoa Tabular Alumina 14x28	12
Alcoa Tabular Alumina 28x48	15
Alcoa Tabular Alumina 48x200	10
Alcoa Tabular Alumina –100	10
Alcoa Tabular Alumina –325	10
Elkem Micorsilica 971	5
Darvan 7S	0.075
Total	**90.075**

experiment. All of the compositions were based on Alcoa's 605S mix. The aggregate was mixed to make a total weight of 90.075 Kg. See Table I for the composition of 605S and Table II for the tabular alumina based recipe. Table II lists the composition selected for testing as it has been shown by ALCOA to flow very well (self-flow) and can be prepared as either a low cement based recipe or no cement based recipe by using either CA14, CA270, or Alphabond 100 (Alcoa Aluminum Company of America, Pittsburgh, PA).

The white fused alumina recipe was reverse engineered to have approxi-

resulting particle size distributions for tabular and white fused alumina with a Furnas distribution of r=1.25 and a maximum sieve size of 3200, where the equation for the Furnas distribution is:

$$\text{Cumulative Weight \% Retained} = 1 - 100 \times \frac{r^{\ln d} - r^{\ln d_s}}{r^{\ln d_l} - r^{\ln d_s}} \qquad (12)$$

where: r = ratio between consecutive sizes, d = diameter of particle, d_s = diameter of smallest particle and d_l = diameter of largest particle.

The mixes were prepared so that only one set of aggregate components was mixed for the white fused alumina and