Novel Form-Free Installation Method for Refractory Castables

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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 does not require the typical wet pumping equipment, as is needed for shotcreting, but delivers similar lining properties.

Introduction

The last decade could be considered the decade of enhancement 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.

Evolution of Form-Free Installations

The beginning of the '90s 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 vibrocasting 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 thermomechanical 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 the properties resulted in gunning compositions with very narrow water demand, high rebound, 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 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 thermomechanical 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 '90s[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 able to produce 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 compared to 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 not contain any sources of silica, calcium oxide, or alkalis such as sodium oxide. The absence of calcium aluminate cements in the composition of the castable 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 had 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-effected depth very similar to cast-vibrated samples (Table 3). The test was done against a slag with a calcium silicate (*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, although the shotcreted lining did not fully reach the properties of cast-vibrated installations (Table 5), 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 4), an ingredient necessary to protect the nonslumping attributes of the gunning mixes. On the other hand,

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 Fine	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**
Specific Gravity @ 110 °C	2.79	2.82	2.82
Porosity @ 110°C [%]	17.5	16.3	16.6
Modulus of Rupture @ 110°C [MPa]	2.8	9.7	8.7
Hot Modulus of Rup. @ 1370°C [MPa]	1.8	3.0	3.0
Slag Corrosion Index (6 hours/1565°C)	1.00	0.76	0.73
80% Alumina Castable	**None**	**Sodium Silicate**	**Hydrated Lime**
Specific Gravity @ 110 °C	2.74	2.65	2.71
Porosity @ 110°C [%]	17.9	21	18.8
Modulus of Rupture @ 110°C [MPa]	11.8	7.0	16.4
Cold Crushing Strength @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

Measurement Conversion Table

1 MPa	=	145 psi
1 cm^2	=	0.16 in^2
1 cm^3	=	0.06 in^3
°F	=	1.8 x °C + 32

the castable composition was fully dispersed, as is typical for low cement systems.

The data in Table 5 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 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 the 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 shows the difference in physical properties of two formulations between the standard shotcreting and the high velocity installation method.

Table 6 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 strength and the decrease in abrasion

Table 4: 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			Calcined Alumina	22.5
Tabular Alumina – Fine	13.5			Amorphous Alumina	2
Calcium Aluminate Cement	5	Calcium Aluminate Cement	21.7	Calcium Aluminate Cement	8
Raw Dolomite	4	Ball Clay	3.3	Ball Clay	3
Rheology Additives	0.3			Microsilica	4.5
				Rheology Additives	0.15

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

Property	Installation Method/Composition			
	Castable	Shotcrete	Conventional Gun Mix	Low Moisture Gun Mix
Specific Gravity @ 110 °C	3.12	2.89	2.59	2.69
Porosity @ 110°C [%]	14	18	28	25
Modulus of Rupture @ 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 6: Properties of Wet-Process Sprayed Materials[6]

Properties	70% Shotcrete Material			Super Duty Shotcrete		
Shotcrete Method	Standard	New	Difference	Standard	New	Difference
Specific Gravity @ 110 °C	2.41	2.42	0.01	2.33	2.35	0.02
Specific Gravity @ 815 °C	2.36	2.40	0.04	2.30	2.33	0.03
Porosity @ 815°C [%]	21.5	20.6	-0.9	20.9	20.7	-0.2
Porosity @ 110°C [%]	18.9	18.4	-0.5	17.6	16.5	-1.1
Cold Crushing Strength @110°C [MPa]	23.9	33.1	9.2	40.1	41.5	1.4
Cold Crushing Strength @815°C [MPa]	29.2	31.7	2.5	31.7	51.1	19.4
Abrasion Volume Loss @110°C [cm^3]	19.8	9.3	-10.5	8.5	4.3	-4.2
Abrasion Volume Loss @815°C [cm^3]	22.8	12.2	-10.6	13.5	11.1	-2.4

volume loss. The improvements in abrasion resistance are around 100% and clearly indicate more intimate contact 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.

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, nonferrous 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 setup and cleanup time when compared to a conventional dry gunning process. The need for a large-capacity wet mixer, an expensive swing-valve pump, and a 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 setup time, cleanup time, and overall labor requirements 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 diminish the physical and thermomechanical properties of dry gunned installations and make this method technologically inferior to shotcreting of wet mixes.

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 to in North America as 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."

Shotgunning Equipment

The requirements for the equipment are quite simple. The method can utilize any standard Reed, Allentown, or other pneumatic gunning machine. If predampening is required, an additional predampening mixer could be used. As with the dry gunning, the method requires an air compressor with a minimum of 500-cfm 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. In addition, the nozzle is 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 or a swing valve pump. The schematic of the method is in Fig. 1 and the sketch of the nozzle is in Fig. 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 a 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 7).

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, 80, and 50% alumina low cement compositions. Although the compositions were similar in chemistries, they were optimized for the particular installation method. The gunning mixes had low cement bond but contained no

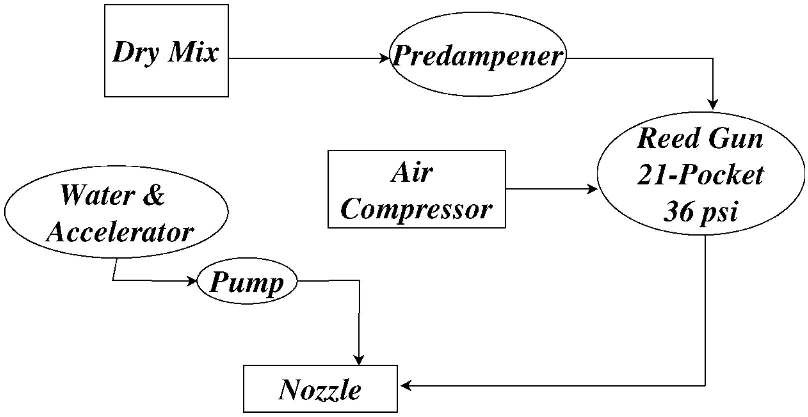

Figure 1: Schematic of Shotgunning Process.

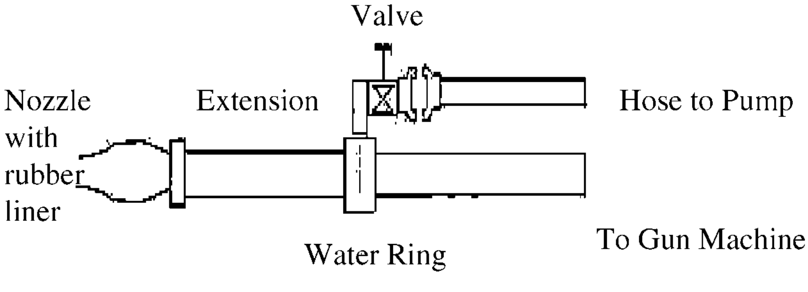

Figure 2: Nozzle Details for Shotgunning.

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.

As expected, in all instances the dry gunning delivered the worst properties and the vibrocasting 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 vibrocast samples (with the exception of density). As seen from the data, the method appears to have especially significant beneficial effects 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 8). 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 vibrocast installations.

Advantages and Disadvantages of Shotgunning

The biggest advantage of shotgunning is the simplicity of the equipment. Because of the easy startup and cleanup, the 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 composition, the final properties of installed linings surpass the properties of gunning mixes.

On the other hand, the shotgunning process poses some disadvantages over cast installations and, in some specific instances, also over shotcrete installations. The rebound rate is at a level between 5 to 15% and is higher than in 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

Table 7: Properties of Refractory Low Cement Systems from Different Installation Methods

Installation Method	Dry Gunning	Wet Shotcrete	Shotgunning	Cast
95 % Alumina Low Cement Refractory Systems				
Specific Gravity @ 110 °C	2.69	3.01	2.90	3.12
Porosity @ 110°C [%]	27	19	20.4	13
MOR @ 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				
Specific Gravity @ 110 °C	2.55	2.60	2.60	2.71
Porosity @ 110°C [%]	23	22.2	22.4	19
MOR @ 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				
Specific Gravity @ 110 °C	2.27	2.33	2.33	2.36
Specific Gravity @ 815 °C	2.22	2.29	2.25	2.29
MOR @ 110°C [MPa]	10.5	13.4	19.0	10.6
MOR @815°C [MPa]	12.6	8.5	18.3	9.9
Abrasion Loss [cm^3]	10	12	5.6	7

Table 8: Comparative Results from Different Installation Methods

Installation Method	Vibro-Cast		Shotgunning	Shotcrete
	High Cement	Concrete with Metakaolin		
Specific Gravity @ 815 °C	2.11	2.17	2.13	2.16
CCS @ 815°C [MPa]	23	43	44	39
Abrasion Loss [cm^3]	22	9	9	10

than during shotcreting, which makes the method less economical on large installation jobs.

The advantages of this simple installation method are, however, helping to gain its field acceptance. Shotgunning is becoming a common installation method in cement and lime plants. The maintenance and 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.

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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