

THE DESIGN FUNDAMENTALS OF HIGH TECHNOLOGY CASTABLES – AN UNDERSTANDING FOR STEELMAKERS

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1 Introduction

This paper will present a review, from a formulation and design perspective, of the key advances that have occurred in castable technology during recent years. Selected examples will show how formulations can be engineered to achieve target castable properties for eventual application in metal contact applications.

2 Formulation parameters

The refractory producer has numerous parameters and levers to optimise the performance of a refractory castable in a given application. Unfortunately these levers are sometimes at best only empirically understood and in many cases there are many opposing and conflicting parameters to optimise. Thus the refractory producer has to balance both quantitative and empirical knowledge with that acquired through experience in order to successfully design new castables for arduous application environments. These diverse parameters can be considered as design parameters relating to the final application as well as individual material design parameters relating to the actual material composition.

2.1 Refractory application design parameters

There are four main levers to consider when designing for a specific monolithic application. These can be considered to be raw materials, refractory product manufacture, product technology and application technology. Figure 1. shows some of the individual elements that would need to be considered within each of these broad areas. The refractory producer has therefore to acquire expertise in both the upstream (application) and downstream (raw material) arenas. This paper focuses upon the raw material and consequent formulation parameters but it is readily accepted that the other three areas are not necessarily independent nor less important.

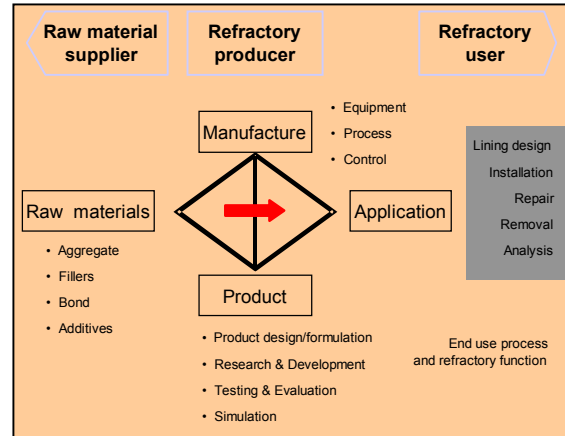


Figure 1. The monolithic refractory universe.

2.2 Material design parameters

The properties of monolithic refractories are only fully established once the products are installed and in service. Consequently the objectives of any formulation serve two purposes, firstly to assure the installation and commissioning technique chosen and secondly to develop the required properties in service. In many cases these are conflicting demands. Therefore the objectives of a monolithic formulation can often be considered to be the art of balancing material properties against the conflicting demands of an application. For example within steel ladle monolithics it is possible to reduce corrosion resistance but often at the expense of slag penetration and consequent loss of thermal spalling resistance.

The specific demands of an application are frequently known only qualitatively in terms of target refractory properties. Most refractory tests can only simulate a few of the possible dynamic factors which characterise the refractory environment. The choice of a given refractory can only be made after due consideration of the key factors which result in refractory wear. This then gives rise to numerous refractory solutions in terms of product types depending upon the key hypothesis adopted for refractory wear. Each refractory castable formulation will try to achieve

target properties which describe installation characteristics as well as final performance. The key levers are the raw material characteristics and the formulation chosen. This is illustrated in figure 2. It is evidenced that many of the target parameters relate to simulative properties and a large part of a refractory producer's skill still resides in the translation of end use environments into these parameters.

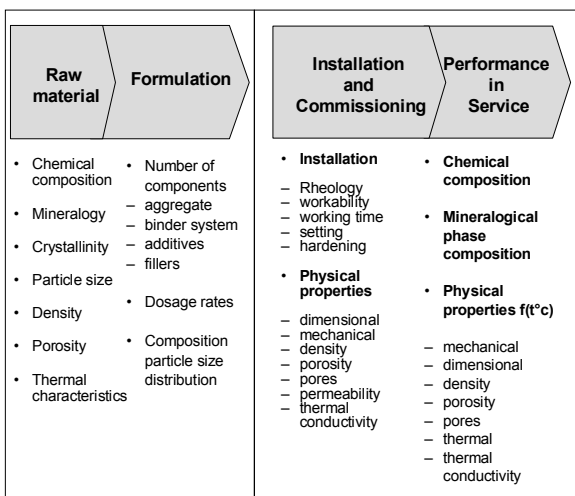
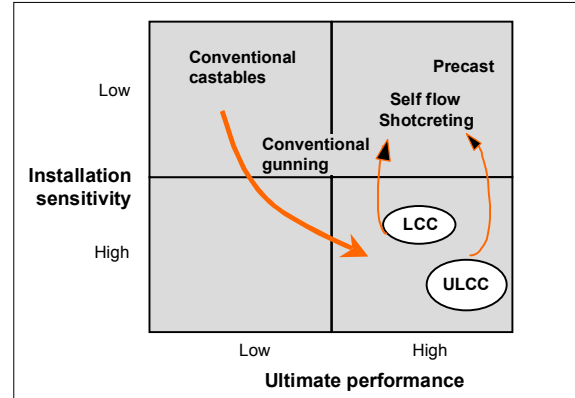


Fig 2. Monolithic material design parameters

2.3 Refractory castable development

Figure 3. shows the development paths of monolithic refractory castables during the last 25 years.



LCC = Low Cement Castable
ULCC = Ultra Low Cement Castable

Fig 3. Monolithic castables – development paths

The progression from conventional castables (CC) to Low cement castables (LCC) and to Ultra low cement castables (ULCC) relied upon the development of modified bond systems which utilised calcium aluminate cement in combination with reactive fine powders and additives. The objective of these initial developments was to enhance total performance which for the first time meant that castables could be considered for metal contact applications within Iron and Steel plants¹. However this was achieved at the expense of products with decreased installation tolerance and a higher risk of failure when subjected to less than ideal installations. More recent developments have focused upon the development of monolithic castables which offer the same level of performance but with more installation flexibility. Self flow, pumpable and shotcrete products are all part of this family of monolithic products.

The following sections discuss these developments in terms of formulation considerations using systems based upon Alumina, Alumina-Silica and Alumina-Magnesia as examples. It is these systems that are used within ladle applications in Iron and Steel plants. The examples are chosen to demonstrate the type of formulation constraints and choices for each system rather than marrying castable systems to specific ladle applications.

3 Deflocculated castables

The ability to use castables in metal contact applications was made possible with the development of low cement or deflocculated castables. These castables rely on the use of fine reactive fillers (silica, alumina, chrome etc.) to more effectively pack particles in the cast mass². At the same time a reduced calcium aluminate cement (CAC) content can be considered due to a higher inter-granular contact. Dispersing additives are then needed to fluidify the fine particles and allow castable placing at low water additions.

The benefits of incorporating these fillers, reducing cement content and using additives are;

- ↳ Lower CaO in the castable which limits low melting CAS_2 and C_2AS phases thus improving high temperature mechanical properties and corrosion resistance.
- ↳ Reduced water demand reduces porosity and increases density. Corrosion resistance and abrasion resistance are improved through a denser matrix structure.
- ↳ Improved particle packing improves thermo-mechanical properties as well as enhancing corrosion resistance.

This logic of deflocculated castables can be continued to castables with very low cement contents of less than 2%. The key formulation parameter is to ensure satisfactory placing characteristics at low water demand to maintain the dense low porosity cast structure, otherwise the benefits of these deflocculated castables would be lost. The active binder can be considered to be composed of three interdependent components:- the calcium aluminate cement, the additives and the fine reactive fillers³. The choice of each of these components becomes a critical factor in controlling castable rheology. The choices must be made whilst at the same time ensuring target installed properties are met. The most commonly used fine fillers are fume silica and

fine alumina in conjunction with a high purity calcium aluminate cement, typically a 70% Alumina content. The fine alumina and silica will react at high temperature to form mullite (providing CaO% is kept low) which enhances high temperature thermo mechanical behaviour. The additives used will depend upon the specific choice of fillers. Previous studies have shown the impact and the role of additives and fillers in a variety of castable systems⁴. The impact of fume silica and alumina type is extremely important. Table 1. shows the result of changing fume silica type in a typical high purity alumina low cement castable which has a 5% addition of a 70% Alumina cement together with 10% of a fine reactive alumina and 5% fume silica.

Table 1 The effect of fume silica type upon castable placing properties.

	LCC 1	LCC 2	LCC 3
Fume silica type			
SiO ₂ %	97,5	85,5	91,2
Carbon %	<0,5	4,1	2,0
B.E.T. m ² /g	20	17	21
pH	6,9	9,4	8,7
Castable flow %			
T=0 mins	158	80	112
T=30 mins	144	0	115
T= 60 mins	140	0	105
Working time mins	95	30	135
5% water added in each case			

The effect upon castable workability, as measured by flow under vibration, is extremely marked. The castable working time is also clearly dependant upon the quality of fume silica used. High pH values and high carbon contents in the fume silica result in castables with poor placing properties. It has been shown that the observed behaviour is due to differing interactions between the additives, the fume silica and the cement. A further example in figure 4⁵. shows the effect of fume silica type on the additive dosage needed for a given final setting time in a simplified mortar system of CAC and fume silica. The effect of additive dosage, in this case sodium tri-poly phosphate, upon setting time with two different fume silica types can be seen. The differences seen are believed to be due to the fact that the

hydration of the calcium aluminate cement is modified in the presence of fume silica. Therefore the choice of fume silica must be made carefully to ensure target placing characteristics are met as well as ensuring that minimum variation occurs in the castable due to variation of quality of the fume silica. Given that a lot of fume silica is derived as a by product of Ferro-Silicon/Silicon metal production, this is no easy task. It is also true that the calcium aluminate cement must show repeatable behaviour to ensure stable castable properties.

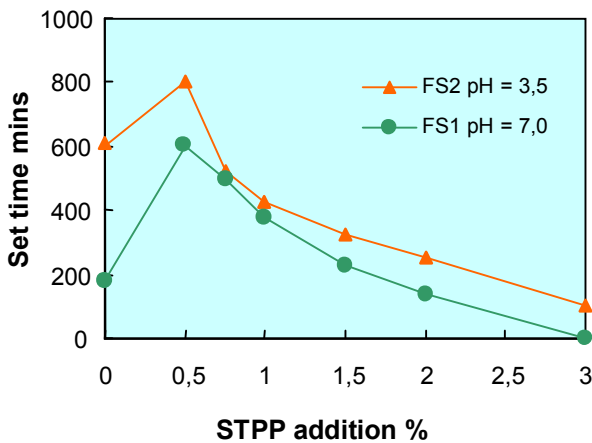


Fig 4. The effect of fume silica type on setting time

The choice of fine alumina is also important in determining castable placing properties as well as the degree of mullitisation at high temperature. The mullitisation will govern the hot strength development. Using the same base castable system as that used in table 1, different fine reactive alumina powders were assessed for their effect upon castable placing properties. Two key parameters were found to play a major role in determining castable fluidity, the B.E.T. surface area and the soluble soda (Na_2O) level in the alumina⁶. In both cases higher B.E.T and soda levels led to reduced flow and shorter working times as well as an acceleration of the CAC hydration. Figure 5. shows the relationship between the soluble soda level in various reactive aluminas

and the castable working time. It should be noted that the other properties of fine alumina's such as particle size and crystal size can also have a significant impact upon castable properties.

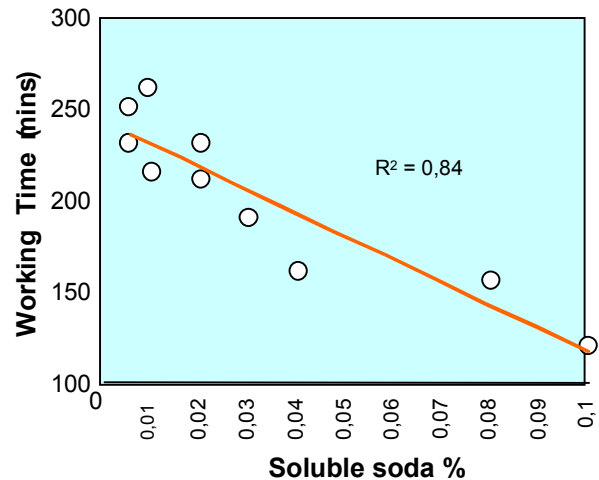


Fig 5. The effect of soluble soda on castable working time

The control of placing characteristics through formulation modification is also possible by optimising the dispersing additives. It is possible to add several additives simultaneously, each with a different function, to modify castable rheology. For example, the use of a multiple additive system allows an optimisation of the initial castable flow as well as the flow decay. The example in table II shows the effect of a multiple additive system upon castable properties. In this example the use of four additives (LCC 5) allows the water demand to be reduced by 20% whilst maintaining placing properties and mechanical properties. Two dispersing additives are used to disperse the fine fillers i.e. the phosphate is used for the fume silica whilst the polyacrylate is used to disperse the reactive alumina. Two types of retarders/stabilisers are added to ensure a working time of 60 minutes even at the lower water demand of 4%.

These examples have shown that the “binder” system in deflocculated castables is comprised of an interdependent combination of CAC, reactive fillers and additives and that the optimisation of a castable can only be done by considering all three

components simultaneously. A change in one of the components implies a change to the overall system. Therefore one of the most important formulation parameters is the assurance of reliable and repeatable behaviour through appropriate selection of stable raw materials.

Table II The effect of additive type upon a LCC

	LCC 4	LCC 5
	Single additive	Multiple additive
Composition		
Alumina aggregate	80	80
Reactive Alumina 1	10	10
Fume Silica	5	5
70% CAC	5	5
Additives		
Sod. Tri-polyphosphate	0,12	0,03
Sod. Polyacrylate		0,03
Sod. Bicarbonate		0,015
Citric acid		0,015
Water addition %	5	4
Vibration flow %		
T=0	123	109
T=30	80	80
Working time mins	50	60
Cold crushing strength Mpa		
110°C	154	165
800°C	166	165
1100°C	210	245

4

Castables in the system alumina silica

The previous section considered the formulation fundamentals of typical deflocculated castable systems. These standard low cement castables are somewhat handicapped in terms of high temperature performance. This is due to the formation of CAS_2 and C_2AS (where $C=CaO$, $A=Al_2O_3$, $S=SiO_2$) phases which are liquid at relatively low temperatures. Thus once these phases form in any quantity the hot mechanical properties deteriorate rapidly. Improvements to these low cement castables can only be made through a change in the basic mineral system. In the case of

deflocculated castables two options exist. Both options involve moving the mineral system from a ternary C-A-S system to binary systems based upon A-S or A-C. The objective is to reduce the formation of liquids at low temperature within the castable matrix. The first option relies on reducing the CaO level (i.e. the cement content) down to trace levels of <1%. When CaO levels are reduced to ultra low levels then mullite is readily formed at high temperature through the reaction of silica and fine alumina. This controls the high temperature mechanical properties. These ULCC castables exhibit greater mechanical strengths at temperature. The second option is to reduce the (S) silica level and formulate deflocculated castables in the system of alumina – lime. This binary system relies on the formation of CA_6 as the high temperature bonding phase. This is formed through solid phase sintering of the fine alumina and calcium aluminate cement during castable use. The superior mechanical properties can be seen in figure 6. Here the refractoriness under load of two castable systems is demonstrated.

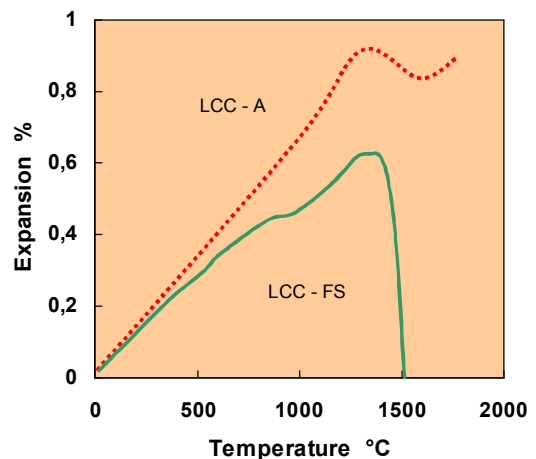


Fig 6. Refractoriness under load for two castable systems

The first is a standard LCC (LCC-FS) based upon high purity alumina with fume silica whilst the second is a low cement castable (LCC-A) with only fine alumina and without fume silica in the matrix. Removing fume silica from the deflocculated castable poses several problems in

terms of maintaining castable placing characteristics. Generally more rapid flow decay profiles and shorter working times are seen with alumina only LC castables. This has been shown to be due to differing interactions within the different castable bond systems⁷. In effect, when fine silica is present as fume silica there is a natural retarding effect which prolongs castable working time.

When the silica is removed and replaced with alumina this effect is lost and must be compensated by a change of additive system. This once again reinforces the notion of an interdependent system based upon CAC, reactive fillers and additives.

These effects can clearly be seen in the following example. Evidence is shown in table III of the difference in behaviour between three castable types, a 'standard' LCC (LCC-FS) model system an ULCC system and a LCC system based only upon Alumina as the reactive fine filler.

Table III Comparison of three castable types

CaO%	LCC-FS 1,45	ULCC 0,58	LCC - A 1,7
Alumina Aggregate	80	80	83
Fume silica	5	5	0
Reactive alumina 1	10	10	0
Reactive alumina 2	0	3	11
70% CAC	5	2	6
Additives	0,054	0,054	0,078
Water addition % For vib. flow of 100%	3,8	3,7	5,2
Working time mins	65	90	20
Cold crushing strength Mpa After 24 hours	60	38	25

As table III shows the system without fume silica has somewhat higher water demand, (for an equivalent flow) shorter working time and lower green strengths. The benefits of this system can be more clearly seen when high temperature strength development is considered. Figure 7 shows the hot modulus of rupture data for the three castable systems at

1200°C and 1500°C. The standard LCC system shows a sharp drop in strength due to liquid phase formation. The ULCC system shows increasing strength development at higher temperatures due to more sintering and presumably more mullitisation. The LCC Alumina system shows the highest mechanical strength at 1500°C due to the formation of CA₆.

Therefore the often held belief that any CaO level is detrimental in castable systems is not true for all mineral systems. In fact within the A-C system the formation of CA₆ can be exploited to yield castables with higher hot strength. However it must be noted that these systems pose the greatest challenges in terms of rheological control. This is developed further in the following section.

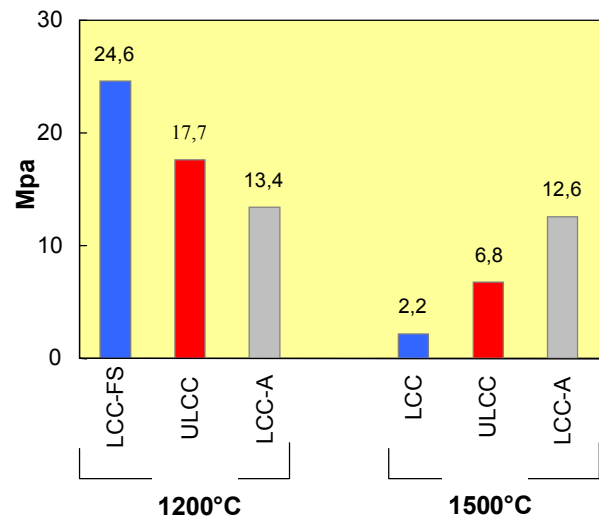


Fig. 7. Hot Modulus of Rupture for three castable systems.

5 Magnesia containing castables

Magnesia containing castables can be conceived either by adding a pre-formed alumina-magnesia spinel aggregate or by the reaction of MgO with Al₂O₃ to form in situ spinels within the castable matrix. These two systems present unique challenges in terms of formulation control particularly with reference to placing properties and thermo mechanical behaviour. The fundamental differences between the two systems

are shown in figure 8. It is seen that the two types of magnesia containing castables follow two different formulation logics. The alumina spinel castables are similar in conception to the LCC-A type castables discussed in the previous section whilst the spinel forming castables tend to follow an ULCC formulation logic. A deflocculated 'bond' system is however at the heart of both castable types.

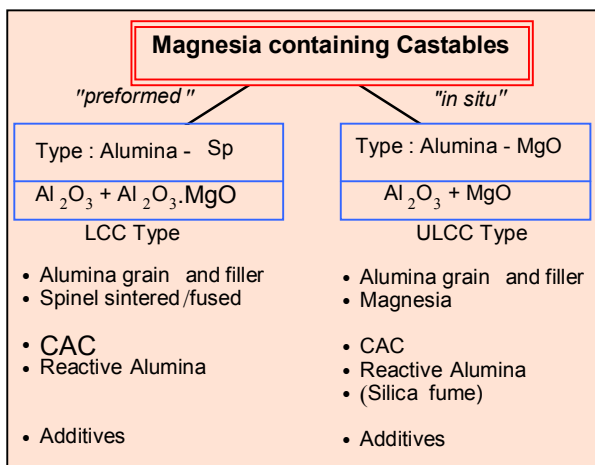


Fig. 8. Formulation logics of magnesia containing castables.

5.1 Alumina – Spinel castables

The base model compositions for Alumina-Spinel castables are found in Table IV. The function of the Alumina-Magnesia spinel aggregates, in limiting slag ingress due to trapping of Fe and Mn in the spinel lattice, has been well documented⁸. The quantity and type of spinel chosen in this example is typical of those values found in the literature⁹. These compositions are silica free to ensure that no liquid phase products are formed at high temperature.

The 'bond' system follows the same principle as that explained in the previous section with LCC-A castables i.e. they are deflocculated castables using only fine reactive alumina together with CAC as the reactive binder phase. The type of fine spinel was chosen to be inactive as far as castable placing was

concerned but thermally reactive at high temperature. In fact the presence of spinel was not found to have any marked effect upon castable rheology. Due to the nature of the ladle applications with these materials, a high initial flow with a stable flow decay and working time minimum of at least 45 to 60 minutes was considered to be absolutely necessary.

Table IV base compositions for magnesia containing castables

Raw materials	Alumina Spinel	Alumina Magnesia
Sintered Alumina -7mm	58	82
Alumina-Spinel		
- 1mm	25	-
Silica Fume	-	2
Reactive Alumina (RA2)	11	8
Magnesia - 0,4mm	-	5
70% CAC	6	3

An optimisation of the 'binder phase' (CAC, additives and reactive alumina) system was required to achieve these values. Table V shows three basic additive systems which meet the basic placing property criteria. Previous work had shown the need to add retarders to the system to compensate for the natural tendency of these Alumina-Spinel castables to lose workability rapidly¹⁰. The three systems use fundamentally different dispersants with correspondingly different active mechanisms.

Table V Additive systems

	Add1 %	Add2 %	Add3 %
Sod. Hexametaphosphate Boric acid	0,06 0,01		
Sod. Polyacrylate Boric acid		0,05 0,022	

Sod. carbonate		0,001	
Polyglycol			0,3
Lithium carbonate			0,002

Add 1 is a pure electrostatic dispersing system with boric acid as a retarder, add 2 uses a polyacrylate dispersant with two retarders whilst add 3 uses a polymer system with an electrosteric type of dispersing mechanism. In the latter case the dispersing and retarding effect of the polyglycol is so strong that a small addition of an (Lithium Carbonate) accelerator is necessary.

The resulting castable flow for each of these additive types is shown in figure 9. It was considered that 160mm flow would be the minimum possible consistent with good placing properties. It can be seen that with add 2 and 3 very low water additions are possible (less than 4%) whilst still maintaining sufficient flow properties. Furthermore the working times were in line with the target values. The impact of additives within these formulation logics is evident.

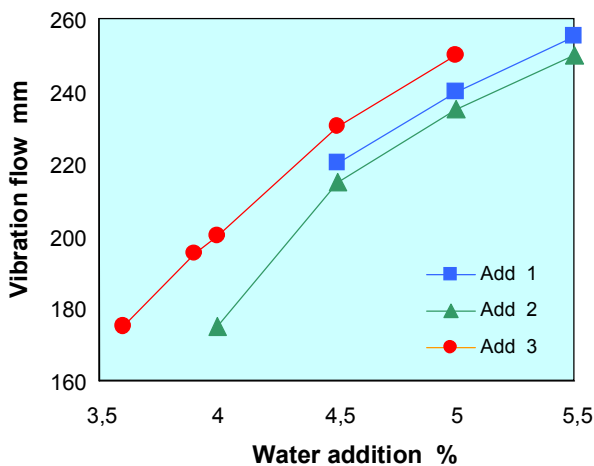


Fig 9. The flow properties of different additive systems

Reactive alumina is also a key formulation parameter. The alumina plays a role in determining castable rheology due to the interdependent binder system of these deflocculated castables. Furthermore the reactive alumina will also strongly influence the degree of sintering and strength development

at high temperatures. The following example shows the effect of 4 commercially available reactive aluminas which were selected on the basis of B.E.T surface area values, particle size distributions and soda contents. A summary of the key properties of these aluminas is shown in table VI.

The impact of alumina type on castable flow profiles is shown in figure 10. Here, the add 2 system was used and the initial flow was targeted to be 200mm on an ASTM shock table. Water demand for each of the castable types was 5% with the exception of RA4 which needed 6,6% water before satisfactory flow performance could be reached.

Table VI Properties of reactive aluminas

	B.E.T m ² /g	Na ₂ O %
Alumina RA1	7,0	0,08
Alumina RA2	3,3	0,02
Alumina RA3	3,0	0,26
Alumina RA4	0,8	0,27

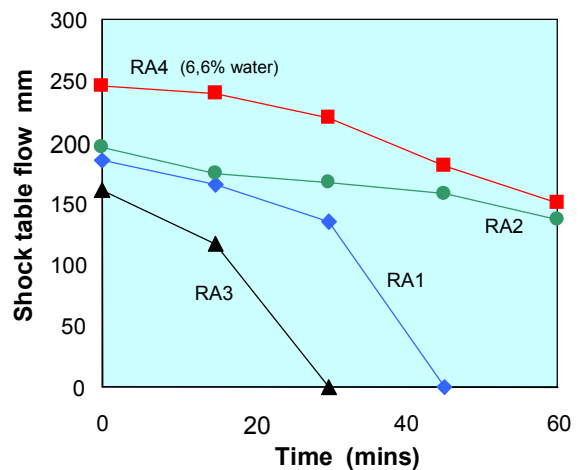


Fig 10. The effect of Alumina type upon flow properties.

Each type of alumina shows a unique flow profile with the each additive system. Changing this to a different additive type(s) would certainly yield differing results.

The optimisation of placing properties is done to ensure suitable fluidity at low water demand but at

the same time steps must be taken to ensure that strength development, de-moulding times and final thermo mechanical properties are not compromised by an optimisation of placing properties. This can be seen in table VII where the short term mechanical strengths 24 hours after casting are quoted. It is evidenced in this table that the add 3 system with the optimum flow properties did not yield the best results in terms of mechanical strength development. This would probably have implications for de-moulding times.

Table VII Mechanical strength development

CCS Mpa	RA1	RA2	RA3	RA4
Add 2				
24 hours	44	44	33	10
110°C	112	116	109	52
Add 3				
24 hours	25	23	23	24
110°C	98	90	113	92

An analysis of the underlying mechanisms has shown⁷ that there exists two types of interactions, which explain a specific working time/flow and the acquisition of mechanical strength. The first interaction is related to the dissolution of the calcium aluminate cement into solution and thus controls working time. The other is the massive precipitation of the cement hydrates which governs the mechanical strength development of the cast structure. Due to the interactive nature of the binder phase the type of additive system and alumina can and does impact upon these reactions, thus controlling flow/working time and mechanical strength development.

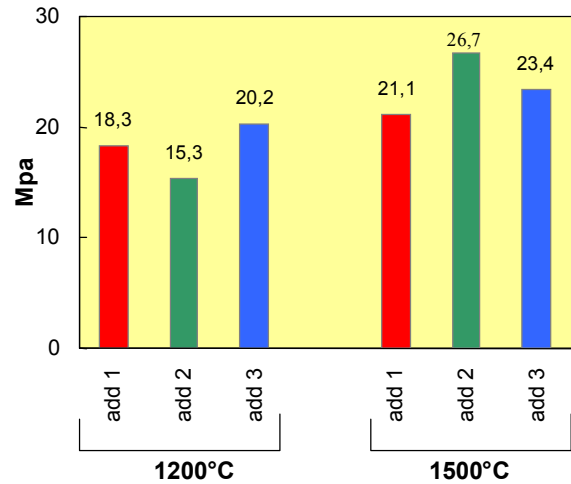


Fig. 11. The effect of additive systems upon hot modulus of rupture

As discussed previously it is important not to compromise high temperature properties through the optimisation of the casting process. Figure 11 shows the effect of additive type upon hot modulus of rupture at 1200°C and 1500°C. In all cases the castables contained the RA2 alumina which had given good flow and working times along with suitable strength development. As can be seen the additive type has a noticeable effect upon hot strength development. Add 1 has little impact upon sintering activity between 1200°C and 1500°C. In contrast add 2 appears to have a marked effect upon strength development at 1500°C. Add 3 shows similar behaviour to add 1. It is considered that there are two factors which could explain these differences. Firstly, the additive systems strongly influence placing characteristics and consequently installed porosity of the castable. Secondly, the residual elements from the additives could act as mineralisers for promoting solid state sintering at high temperature. These two factors together would alter the microstructure and therefore the mechanical strengths at temperature.

One of the inherent advantages of these castable systems is related to the porosity and more specifically the distribution of porosity in terms of the pore size distribution.

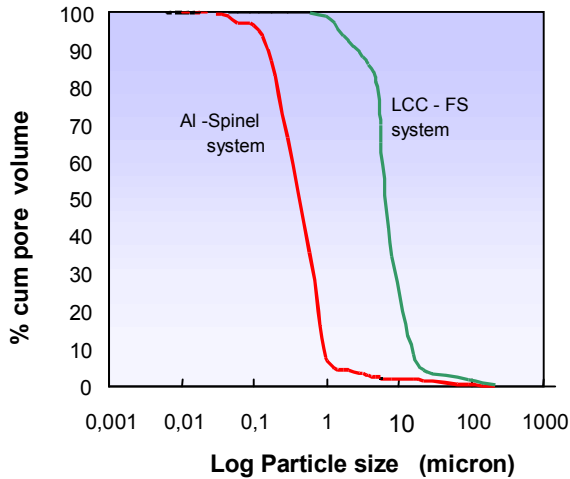


Fig. 12. Pore size distribution for two castable systems

Figure 12. shows a comparison of pore size distributions for two castables after firing at 1500°C. The average pore size with the Alumina-Spinel castable (with RA2 and add 2) is significantly smaller ($d_{50} = 0,8\text{micron}$) than a corresponding standard LCC system ($d_{50} = 10\text{micron}$). This would be favourable in limiting metal and slag ingress due to capillary actions.

5.2 Alumina – Magnesia castables

The base model composition for Alumina-Magnesia castables is illustrated in Table IV. The formulation basis is a ULCC system with smaller or trace amounts of fume silica. The spinel phase is formed in situ and since it is produced by reaction in the matrix it has been found to offer a high degree of corrosion resistance in certain ladle applications. This type of formulation approach presents three inter linked challenges which need to be addressed for reliable application.

- ↪ Impact of magnesia upon castable rheology which leads to short working times and rapid flow decay¹¹.
- ↪ Risk of magnesia hydration and subsequent destruction of the castable¹².
- ↪ +8% volume expansion when spinel forms in the castable matrix¹³.

These three issues are somewhat related. For example fine reactive silica (fume or precipitated) is sometimes incorporated into these castables to fulfil several functions. It is primarily added to control thermal expansion¹⁴, through the idea of auto stress relaxation with liquid phase formation to compensate for the expansile reaction during spinel formation. Secondly, fume silica facilitates rheological control and thirdly it has been suggested as a means to control magnesia hydration.

Due to these three factors the choice of magnesia becomes the key formulation parameter for these types of castables. Two of the important considerations are illustrated below. Figure 13 shows the impact of magnesia fineness upon castable flow and working time. Three synthetic magnesia's, coarse (<0,4mm), fine (<0,1mm) and medium (mix coarse and fine) types were evaluated in a castable based on the base proposition in table IV. The effect of the fine magnesia can be seen as a lower flow, more rapid flow decay and shorter working time. A change in either additives and/or silica type would be needed to correct this type of behaviour.

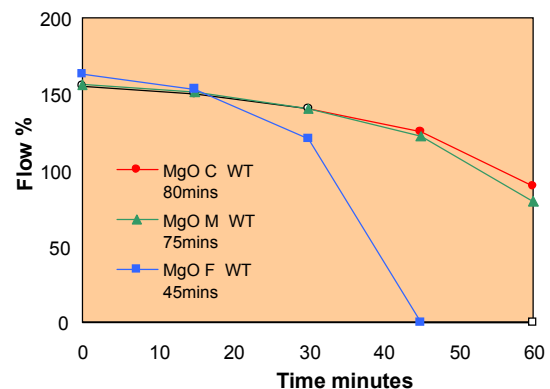


Fig 13. The effect of magnesia fineness upon castable flow

A second example of the impact of magnesia type is shown in figure 14. Here the hydration resistance of different magnesia types is assessed in an autoclave test (1 hour at 7 bar and 150°C). The degree of hydration is measured by XRD using the Alumina peaks as the stable reference.

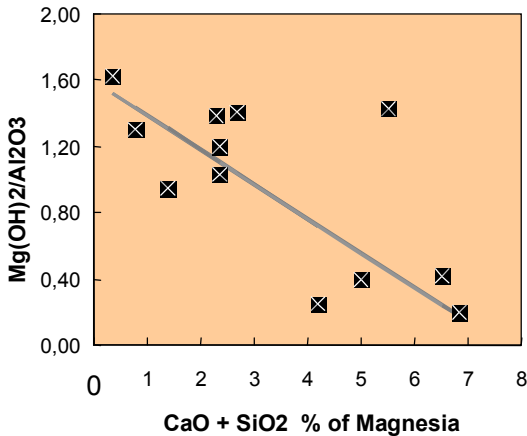


Fig 14. Hydration resistance of selected magnesia

The difference in hydration resistance is shown with the higher purity magnesia types (lower impurities) showing generally lower hydration resistance. The choice of magnesia would also be made after due consideration of the impact on spinel formation, microstructure and thermal expansions. Thus the situation becomes one of managing an inevitable compromise with conflicting demands rather than optimising a single parameter.

6 Installation flexibility

The development of higher performance castables suitable for metal contact applications resulted in products that were more sensitive to placing, particularly in terms of vibration energy and technique, water addition tolerance, sensitivity to ambient temperature and curing/dry out rates¹⁵. Subsequent research into castable rheology during the 1980's focussed upon the aspect of ease of placing¹⁶. The objective was to improve installation flexibility whilst still maintaining target installed properties. Within this context it was realised early on that the reactive fine fillers and particle size distributions played a major role in determining castable rheology. Thus was born the notion of facilitating castable placing by reducing the inter-particle contact and allowing the fine particles to move more

freely. Castable flow was shown to be related to particle size distribution. This concept gave rise to the advent of free flow and pumpable castables which could be placed without the need for vibration^{17,18}.

More recent work has again shown the importance of particle size distribution in determining placing characteristics¹⁹. In order to increase inter particle spacing and decrease particle contact careful selection must be made of the reactive fine fillers such as alumina and fume silica²⁰. An example of this effect is shown in Table VIII and graph 15. The graph shows the calculated particle size distribution, based on particle volumes for two model castable systems SFC A and B using the Dinger and Funk equation as the model. Equation 1 shows the calculation basis. The particle size distribution of SFC A was targeted to have a distribution modulus, n , of between 0,22 and 0,25. These distributions could only be achieved through the addition of super fines. For each choice of fillers the optimum additives and dosage rates need to be selected to ensure sufficient dispersion of the fines. Thus castable flow will be governed by particle packing effects as well as dispersion effectiveness of the fines. The table VIII shows the resulting flow values of these two systems. The self flow value is determined²¹ using an ASTM flow cone and is the difference in final diameter compared to the initial diameter and expressed as a percentage. It can clearly be seen that the model system which follows the target n value has self flow characteristics whilst SFC B is only suitable for vibration placing.

Table VIII Characteristics of two self flow castables

	SFC A %	SFC B %
Alumina aggregate	79	90
Binder phase		
Fume silica	6	3
Reactive Alumina	10	
70% CAC	5	7
Additives	+0,06	+0,06
Volume of <100micron	38	23
Initial self flow value %	90	30

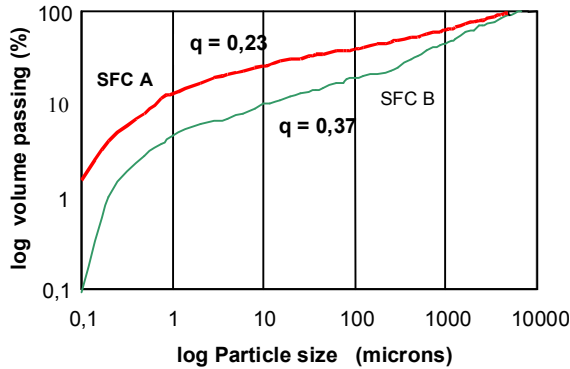


Fig. 15. Calculated particle size distributions of two model castable systems

Particle shape also has a significant impact upon castable self flow properties and the flow can be significantly modified by using raw materials with a different morphology. Using a rounded sintered alumina as the fine aggregate fraction in place of an angular sintered alumina grain gave an improvement in flow of over 40% without compromising the flow profile and flow decay²².

$$\% \text{ passing} = \frac{d^n - d_s^n}{d_m^n - d_s^n} * 100 \quad (1)$$

n = distribution modulus

d = particle diameter

d_s = smallest particle

d_m = max particle size

It is clear that the self flow characteristics are only a small part of total formulation considerations. Issues such as sedimentation and segregation control have to be addressed along with final physical and mechanical properties. Thus it is not unusual to find that self flowing and pumpable castables are composed of more than 10 different raw material components, each fulfilling a specific function controlling placing as well as final installed properties. There exists today a multitude of self flow products based upon different mineral systems with and without silica and magnesia for a variety of ladle

applications²³. The development of installation technology has continued with these types of products paving the way for the latest shotcreting techniques^{24,25,26}.

7 Summary

A wide range of castable systems and installation techniques are available today for application in ladles. A significant part of this progress has been due to development of the 'binder phase' of these high technology refractory castables.

It is possible to adjust castable placing characteristics by modifying the binder phase components which include calcium aluminate cement, reactive fine fillers and additives. Due to the interdependence of these components they must however be optimised simultaneously. Furthermore this can only be done within the context of each specific castable type. This must be always be done with consideration to the target final installed properties.

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