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Influence of Powder Additives on the Final Properties of Inorganic NoBake, Inorganic Cold Box, and Hot Box Binders

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ABSTRACT

In recent years, inorganic alkali silicate binders for hot box processes have gained significant attention within the foundry industry due to their environmental benefits and their potential in producing critical aluminum cast parts for automotive engines, e-engines, suspensions, and subframes. As waterglass-based systems, these binders produced no harmful emissions, aligning with stringent environmental standards. As regulations tighten, it is necessary to extend the experience gained from core- and mold-making with hot box processes to other segments of inorganic binder systems, specifically ester-cured nobake and CO_2-cured cold box. These technologies do not currently achieve the same performance levels as hot box-cured binders.

This study explores the use of custom-made powder additives to enhance the properties of these binder systems, facilitating the use of water-based coatings and improving the collapsibility and compaction of cores, resulting in superior casting surfaces in aluminum, brass, iron, and steel castings. Through a series of laboratory tests and casting trials, the study investigates the effects of powder additives on the performance of nobake and cold box alkali silicate binders, with the goal of enhancing the overall performance of these inorganic binder systems. The findings are expected to provide valuable insights for broadening the application of inorganic binders to nobake and cold box systems, offering an environmentally-friendly solution for non-automotive foundries that need to reduce their emissions or improve their environmental, health, and safety (EHS) footprint.

Keywords: inorganic, nobake, cold box, hot box, binders, emission-free, environmental, health, and safety, EHS, castings

INTRODUCTION

BACKGROUND AND MOTIVATION

The foundry industry is going through significant transformation driven by increasing environmental regulations and the demand for sustainable manufacturing practices. Inorganic binders, particularly modern alkali silicate-based systems, have emerged as a promising alternative to organic binders over the course of the last two decades. Due to their reduced environmental impact, the acceptance is high despite the more challenging process requirements. The hot box hot air process has been particularly successful in producing high-quality aluminum castings for automotive applications. The success of this process lies in its ability to produce strong, dimensionally accurate cores and molds within a similar range of cycle time as the polyurethane cold box (PUCB) process. At the same time, it emits zero harmful byproducts during coremaking, storage, casting, cooling, and shakeout. These upsides come with a few downsides like fragility, poor humidity resistance and collapsibility.

As the emission standards tighten, customers seek solutions in emission-reduced, organic binder systems as well as expanding the application of modern inorganic binders into other processes, such as inorganic nobake and CO_2-cured alkali silicate inorganic cold box (ICB). With these developments several challenges have emerged. These processes, while environmentally friendly, do not currently match the performance levels of the established, organic processes in terms of neither initial nor final strengths, cycle times, collapsibility, and surface finish. Furthermore, foundries producing smaller batches or lot sizes tend to supply a high number of different castings to their customers. Hence, their coreboxes cannot be replaced with heated tooling due to exorbitant costs. Jobbing foundries, whether machine or hand molding, need a different approach to solve or at least mitigate the effects of the new emission standards. The primary motivation of this study is to address the performance gaps of organically and inorganically bonded cores and molds by investigating the use of powder additives in nobake and ICB binders.

OBJECTIVES OF THE STUDY

The primary objectives of this study are:

- To evaluate the effects of custom-made powder additives on the properties of inorganic nobake and water glass CO_2 binders.
- To improve the collapsibility and compaction of cores and achieving superior casting surfaces as seen within the inorganic hot box process

- To compare the performance of enhanced nobake and ICB systems with traditional organic binder system alternatives like furan nobake or PUCB.
- To provide insights for extending the application of inorganic binders to non-automotive foundries, thereby supporting the industry's transition to more sustainable practices outside permanent mold aluminum die casting.

CURRENT APPLICATION OF INORGANIC BINDERS IN THE FOUNDRY INDUSTRY

HOT BOX INORGANIC BINDER SYSTEMS

The hot box process with hot air purging has been particularly successful in producing high-quality aluminum castings such as engine components, e-engine parts, suspensions, and subframes. The success of this process lies in its ability to produce strong, dimensionally-accurate cores and molds within a similar range of cycle time as the PUCB process, whilst emitting zero harmful byproducts during coremaking, storage, casting, cooling, and shakeout. These upsides come with a few downsides like fragility of the cores, poorer humidity resistance as well as collapsibility of the cores and molds. Fragility leads to a higher need for dedicated support on racks, different acceleration of robot movements, when handling cores and the demand for pristine core box condition. The smallest resistances during the opening, ejection, or extraction of the core from the core box can lead to defects.

As this process is a physical and chemical reversible dehydration and condensation process, the curing time increases exponentially with the volume of the cores. It leads to poor humidity resistance when compared to the only chemically cured, organic polyurethane cold box process, limiting the application to a certain range of geometries and sizes. Due to the high investment cost for heated tooling, the application is further limited to high-volume castings that rectify the investment; hence, high-volume automotive applications are the most common end-market.

Despite these downsides, the range of application has spread from cores of several hundred grams to core packages comprised of several different cores weighing 200 kg in total that were mostly part of internal combustion engine components. In the last decade, modern e-vehicle suspension parts with large volumes and steep changes in cross-section areas emerged that raised challenging cycle time expectations for the technology. The market for hot-cured inorganic binder systems is still growing, but slower than in prior years.

The success of modern inorganic hot box binder systems lies within the knowledge in compounding the right liquid binder with the appropriate powder additive to meet expectations for cycle time, flowability, initial/final strength, collapsibility, humidity resistance, surface quality and several more.

Applications for iron and steel are the goal for the near future, yet the expectations are high, and the use of organic shakeout aids not tolerated as many customers have an “all or nothing” approach. This black and white approach prevents a steeper learning curve from serial applications with an initial pareto-approach: Solve 80 % of the task in 20% of the time and try to overcome the last 20% within the next 80% of the time.

INORGANIC NO-BAKE APPLICATIONS

Inorganic nobake binders enable foundries to produce large and complex cores and molds for aluminum, iron and steel applications with highly reduced emissions. However, the performance of alkali silicate binders in these processes is often limited by issues such as insufficient strength, bench life, flowability, poor collapsibility, suboptimal surface finish, and reclamation with higher losses and lower utilization rate. These limitations are particularly pronounced when compared to the performance of organic counterparts like furan, phenolic or polyurethane nobake (PUNB).

Historically developed expertise in either organic process is found in major foundry markets all over the world. For example, Spanish jobbing foundries like PUNB systems, while their German competitors will probably use furan systems. Inorganic nobake applications are currently limited by the range of casting temperature. This is due to the varying residual strength levels that are highly dependent on the casting temperature of the alloy. In addition, a sintering process takes place above a certain casting temperature when alkali silicate-based binders are used, which leads to increased solidification. Only the use of organic additives improves the decomposition, especially in iron casting applications. This accounts for all inorganic processes with alkali silicate water glass alike.

INORGANIC COLD BOX APPLICATIONS

The inorganic alkali silicate CO_2 cold box process was widely used in the 1900s for a large variety of applications. The ease of use and curing with relatively harmless CO_2-gas was pushed out of many applications by high-performing organic binders like resin-coated sand (RCS) as a first major step and with the invention of catalytically cured polyurethane cold box, the number of foundries forgetting about this technology rose rapidly as PUCB solved many of the disadvantages of RCS and ICB with disadvantages like veining defects.

However, the performance of alkali silicate binders in these processes is often limited by issues such as insufficient strength, poor collapsibility, and suboptimal surface finish. These limitations are particularly pronounced when compared to the performance of the above mentioned.

The use of water-based coatings was possible due to the severe loss in strength and the potential to have sand layers peel off. Using alcohol-based coatings is acceptable, yet, reducing the overall positive influence on the EHS impact on green production.

POWDER ADDITIVES IN INORGANIC BINDER SYSTEMS

Powder additives have been explored as a means of improving the properties of inorganic binders for decades. Whether it was certain organic compounds like wax, starch, or sugars. Most of these organic materials were added in significant volumes to improve strength levels, shakeout properties, etc. and lead to emission levels not far from organic binder systems.

With the knowledge acquired with modern hot box inorganic binder systems, the goal of these experiments is to show the potential benefits of using modern, inorganic powder additives to improve the performance of standard products, creating modern emission-free, environmentally friendly inorganic cold box and nobake systems. These additives are known to enhance strength, improve collapsibility, and enable better compaction of cores, leading to superior casting surfaces. Will this be true in the context of nobake and cold box processes? Different curing mechanisms, chemical vs. physical curing, may lead to different results. Nevertheless, the use of custom-made powder additives presents a promising approach to overcoming the current performance limitations. They transfer knowledge accumulated within the use of hot box hot air applications and possibly help to impact further casting applications outside the automotive industry. The focus was directed at the fast-growing applications with high volumes and high demands for the last two decades. As these target markets are slowing down, business development focuses on opening new markets for modern inorganic waterglass binder systems. This is the goal of several experiments conducted during customer projects, to understand the potential within old technology resurrected and re-thought.

CURRENT RANGE OF APPLICATION

When looking at organic and inorganic binder systems, the relevant binder systems cover certain areas of application for specific reasons. Table 1 shows the common range of application for the binder systems considered for this study. The left column indicates the binder systems. The headers show the size of the annual series size from single, individual castings to mass production and the indication inside each field indicates the size of castings produced with the respective binder system and quantity produced. The goal is to expand these areas of application to reduce the use of organic binder systems as shown in Table 1.

Table 1. Range of Application Overview of Different Binder Systems – Pre Study

	Single castings	Small series	Medium series	Large series	Mass production
Inorganic Hot Box				S-M	S-M
Polyurethane Cold Box		S-L	S-L	S-L	S-M
Inorganic Cold Box		S-M	S-M	S-M	
Inorganic No-Bake	S-L	S-L	S-L		
Furan No-Bake	S-XL	S-XL	S-XL		

EXPERIMENTS

TRIAL AND ERROR APPROACH

As foundry processes are influenced by many uncontrollable variables like weather conditions, reclaimed sand quality, new sand quality, mixing equipment, casting process etc., the focus of these initial trials was to solve real life issues of customers. By having a constant back and forth of lab work and real casting trials, tests were altered over the course of the experiments to try and understand how lab test setups were able to indicate results in the foundry.

Two customers, one with a traditional alkali silicate CO_2-process and another one with a furan nobake process, were partners to develop a new generation of inorganic cold box and nobake binder systems.

Three binder systems were initially chosen: hot box, ester-cured nobake, and CO_2-cured cold box, all based on alkali silicates. First, the well-known effect of powder additives on inorganic hot box results were documented. The next step was to use these and transfer them to the other processes with inorganic alkali silicate binders to have a reference as base line. Custom-made powder additives were then developed specifically for the experiments and selected based on their potential to enhance binder properties. The selected additives were mixed with the binder systems in varying proportions to determine the optimal formulation for the specific application.

LABORATORY TESTING

A series of laboratory tests were conducted to evaluate the performance of the modified binder systems. The results found in these tests were the basis for first casting trials with industry partners.

Without the constant alignment of laboratory and industrial scale results, the whole intention of leveraging an old technology cannot succeed, as the real understanding grows with actual castings.

Bending Strength

Measured to assess the mechanical strength of the cores and molds based on initial and final strength levels.

Flowability

Measured by comparing the weight respectively density of standard cores in standard laboratory core production. CO_2-cores shot in a core shooter and nobake cores tamped and then weighed before being stored or measured.

Collapsibility

Evaluated by assessing the ease with which the cores and molds break down after casting, the specimens were heat treated in a muffle oven to simulate temperature impact at the most critical temperature range of 2012F (1100C). This temperature simulates the average temperature of the molding material that pre-tests showed in a distance of 5-15 mm (0.2-0.6 in.) from the casting surface in iron casting applications, as the most difficult temperature range. The collapsibility is tested by weighing in a portion of the specimen before vibrating it on a sieve with a defined amplitude and frequency to have a reproduceable test environment. If the casting trials in foundries showed different behavior than the test, the frequency and/or total time of the test were adapted. This developed a good reference for the shakeout process.

Thermal Stability

Thermal stability was assessed by subjecting specimen to the standardized Hot Distortion test by the British Cast Iron Research Association (BCIRA).

Table 2. Initial and Final Strength of Cold Box and No-Bake Molding Mixtures

COLD BOX	Initial Strength [MPa]	Final Strength [MPa]	NO-BAKE	Initial Strength [MPa]	Final Strength [MPa]
classic organic (1,1% binder)	1,50 +/- 3%	2,20 +/- 4%	classic organic (1,2% binder)	1,27 +/- 3%	3,97 +/- 4%
classic inorganic (3,0% binder)	0,44 +/- 1%	0,59 +/- 4%	classic inorganic (2,5% binder)	0,49 +/- 1%	1,75 +/- 4%
new inorganic (3,0% binder + add)	0,65 +/- 1%	0,85 +/- 3%	new inorganic (2,5% binder + add)	0,87 +/- 2%	1,91 +/- 4%

RESULTS AND DISCUSSION

Bending Strength

The bending strength of both inorganic nobake and cold box systems increases with the addition of powder additives (Table 2). The initial strength levels show significant differences that distinguish a wider range of application. Final strength levels do increase, yet not in the same relative value as the initial strength. Inorganic cold box binders are showing significantly lower strength levels compared to PUCB results. Same shows when comparing furan nobake with inorganic nobake, whether with or without powder additive.

Flowability

The flowability of both, inorganic nobake and cold box systems, increases with the addition of powder additives, in the case of inorganic nobake + powder additive, the density is even higher than with traditional furan resin (Table 3).The flowability levels show significant differences that can make the difference in gaining a wider range of application, as the gap to PUCB and furan NB is closed.

Collapsibility

The results of the shakeout/collapsibility tests (Table 4) show that organic binders have a significantly better core collapse. This is due to the possible pyrolysis of the binder compared with the melting of alkali waterglasses. On the other hand, customers may want to separate waste sand streams, which is easier when screening for intact parts of an inorganic core. This can help to reuse acceptable volumes of used sand.

Thermal Stability

In the BCIRA method, the results of the latest powder additive development looked promising (Table 5).
The test shows the behavior of a specimen when heated up by a flame from one side. The PUCB specimen reaches a maximum deformation of approximately 1 mm with a complete softening of the binder bridges, hence collapse of the specimen, after 21 seconds. The standard inorganic cold box specimen has a lower expansion yet collapses after 14 seconds. The enhanced inorganic cold box system manages to stay at an even lower maximum expansion level of 0.625 mm and a total time until collapse at 23 seconds.

Table 3. Core Density of Cold Box and NoBake Molding Mixtures

COLD BOX	Core Density [g/l]	NOBAKE	Core Density [g/l]
classic organic (1,1% binder)	1589 +/- 0,5%	classic organic (1,2% binder)	1449 +/- 0,5%
classic inorganic (3,0% binder)	1486 +/- 0,5%	classic inorganic (2,5% binder)	1372 +/- 0,5%
new inorganic (3,0% binder + add)	1557 +/- 0,5%	new inorganic (2,5% binder + add)	1489 +/- 0,5%

Table 4. Collapsibility of Cold Box and No-Bake Molding Mixtures

COLD BOX	Collapsed Core [%]	NO-BAKE	Collapsed Core [%]
classic organic (1,1% binder)	99,9 +/- 0,1%	classic organic (1,2% binder)	99,8 +/- 0,3%
classic inorganic (3,0% binder)	5,2 +/- 4%	classic inorganic (2,5% binder)	4,9 +/- 5%
new inorganic (3,0% binder + add)	59,4 +/- 3%	new inorganic (2,5% binder + add)	43,8 +/- 5%

Table 5. Hot Distortion Test (BCIRA) Comparing Cold Box Binders

	Max. deformation [mm]	Time till collapse [s]
Polyurethane cold box	1,0 +/- 0,1	21+/-1
Standard inorganic Cold Box	0,75 +/-0,1	14 +/-1,5
Enhanced inorganic Cold Box	0,625 +/- 0,1	23 +/-1

CASTING TRIALS

Following laboratory testing, casting trials were conducted at project partners' sites to evaluate the real-world performance of the modified binder systems. Aluminum castings using the enhanced inorganic nobake and iron castings using the enhanced cold box systems were produced to verify the findings. The castings were evaluated for dimensional accuracy, surface finish, and overall quality as well as the performance compared to the currently used organic binder systems.

Inorganic Cold Box Trial in Iron-Foundry

The foundry is struggling to meet their emission goals with the use of PUCB and a standard alkali silicate CO_2 cold box system. Both binder systems need additional additives with organic materials. Especially for the standard inorganic system, the organic components eliminate a huge portion of the environmental benefit. Thus, a trial was conducted with the enhanced inorganic cold box system using a powder additive and dropping the organic components step-by-step. There were two major goals. The first goal was to replace the existing inorganic system. The second goal was to replace polyurethane-cold box cores with the new inorganic cold box system.

The results were promising, as shown in Table 6:

- Potential reduction of binder level by 25% as shown in lab tests realized.
- Slight cost increase compared to the standard inorganic binder system, yet major cost decrease compared to the organic PUCB system.
- Reduction of total organic carbon by more than 90 % due to exchange of additive.

Table 6. Performance of Different ICB Systems

Development Steps	Binder addition [%]	Additive addition [%]	Initial strength [MPa]	Final strength [MPa]
Current Inorganic	3,3	1.0 (organic)	0,44 +/- 1%	0,50 +/- 3%
Enhanced Inorganic	3,3	0.8 (inorganic)	0,54 +/-1%	0,71 +/- 3%
Enhanced Inorganic	2,5	0.6 (inorganic)	0,48 +/-1%	0,61 +/- 4%

Inorganic NoBake Trial in Aluminum Foundry

The foundry is looking to replace their standard furan binder system with an environmentally-friendly alternative, especially with tightening regulations. This application comprises the back-fill of a coated lost-foam cluster. The fumes of the lost foam application are surely higher, but reducing the time in which emissions are generated can be significantly reduced when the back-fill does not smoke after casting and during cool-down of the castings.

A trial was conducted with the enhanced inorganic nobake system using a powder additive. The major goal was to create a test mold that held a test piece, simulating a lost foam casting. These results were promising but raised the question about reclamation of the used sand.
The difference between pure inorganic-ester process and the approach taken at the customer are not always fully aligned. Nevertheless, the results were promising and sand samples for reclamation trials are currently being worked on. This will bring new challenges as inorganic binder accumulates and e.g., bench life decreases:

- Reduction of total organic carbon by more than 95 %

EFFECTS OF POWDER ADDITIVES ON THE NO-BAKE AND COLD BOX BINDERS

The addition of custom-made powder additives significantly improved the performance of both nobake and cold box binders. Bending strength tests showed a notable increase in strength, particularly for initial strength levels. Collapsibility tests revealed that the modified binder systems were easier to break down after casting, mitigating the negative effects of these binder systems. For the inorganic cold box system in iron applications, there are further hurdles to be solved. Nonetheless, the direction is clear: exchange major volume of simple cores of PUCB where possible with enhanced inorganic cold box to reduce the total organic carbon load and meet emission standards.

ENHANCED INORGANIC VS. CURRENT ORGANIC BINDER SYSTEMS

While the enhanced nobake and cold box systems still did not fully match the performance of organic binder systems in all aspects, the gap was significantly reduced. The modified systems demonstrated comparable casting results with reduced environmental impact.

The goal is not to replace all organic binder systems with inorganic binders yet grow awareness within the industry that replacing high-volume, low-complexity cores with inorganic binders can be a great opportunity to lower emissions and total organic carbon without harming the stability of existing processes like green sand. This applies especially for the cold box process.

In terms of the nobake application, reclaimed sand streams will be a major focus of further research as the negative influence of acid-cured and ester-cured waste streams are not yet solved without investing significantly in reclamation equipment and sand-mixing machinery. Most nobake foundries are not able to introduce powder additives into their continuous mixers. Furthermore, the addition rates for inorganic binders are higher which would lead to an increased frequency of changing the drum/industrial bulk container (IBC) or building larger tank silos.

CONCLUSION AND FUTURE WORK

SUMMARY OF FINDINGS

This study demonstrated that custom-made powder additives can significantly enhance the performance of inorganic nobake and alkali silicate-CO_2 cold box binders. The modified binder systems exhibited improved strength and flowability as well as collapsibility, and surface finish, bringing their performance closer to that of their organic counterparts. These findings have important implications for the foundry industry, particularly for non-automotive foundries seeking to reduce their environmental impact.

Surely, there are no straight-forward plug-and-play solutions but working on change leads towards innovation and henceforth an emission-reduced future in further applications in the metalcasting industry, including all type of sand foundries casting a diverse range of iron, steel, and aluminum alloys. These results suggest that a hybrid approach could well be a solution for reducing emissions quickly and meeting local requirements. A foundry does not have to exchange all cores but can focus on voluminous, simple geometries for the beginning – quick wins with hybrids. The future is (partially) inorganic.

EXPAND RANGE OF APPLICATION

Looking at the results of the experiments in the laboratory and at project partners foundries, the adaptation of inorganic cold box application seems closer to the start of production than the introduction of revolutionary inorganic nobake systems. With the enhanced inorganic cold box systems, one could utilize higher strength levels to produce more filigree cores or reduce binder levels to enhance shakeout properties and cost structure. Better flowability may lead to pristine surfaces without the need for a coating. Looking at the enhanced inorganic nobake system, increased flowability and higher strength levels are the obvious advantages compared with the traditional inorganic nobake system. Nevertheless, strength levels and elasticity of organically-bonded molding materials like with furan resins are not within reach. Table 7 shows the judgment of potential expansion of range of application in the shaded areas– metric as in Table 1. For an inorganic cold box from M to L and for inorganic nobake from L to an enhanced L+.

WHAT'S NEXT?

Future research should focus on further optimizing the formulation of powder additives to maximize their benefits. Additionally, long-term studies should be conducted to evaluate the durability and consistency of the enhanced binder systems in various foundry applications and their influence on the existing processes, e.g., compatibility with other organic binder systems to use all available technology for a hybrid-approach to environmental, social and governance (ESG) and EHS challenges of the upcoming years. Finally, the potential for scaling up the use of these additives in industrial settings should be explored to assess their economic viability. Separation of sand streams is a major challenge that will determine the success of any changes.

Nevertheless, foundries should not look at the binder system only and chemical companies not only at the existing processes. This seems to be the easiest way, yet it might keep the industry from finding different solutions quicker, when being open to innovation and new approaches.

Table 7. Range of Application Overview of Different Binder Systems – Post Study

	Single Castings	Small Series	Medium Series	Large Series	Mass Production
Inorganic Hot Box				S-M	S-M
Polyurethane-Cold Box		S-L	S-L	S-L	S-M
Inorganic Cold Box		S-L	S-L	S-L	
Inorganic No-Bake	S-L+	S-L+	S-L+		
Furan No-Bake	S-XL	S-XL	S-XL		