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ARCHIVES of FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2025
Issue 1/2025

159 – 168

19/1

10.24425/afe.2025.153786

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

Use of Cores with Inorganic Binder to Produce Thin-Walled Nodular Iron Castings

G. Fratta [a, *], A. Kmita [b], I. Stefani [c], S. Saetta [a], S. Tapola [d]

[a] Department of Engineering, University of Perugia, Via Duranti 93, 06125 Perugia, Italy
[b] AGH University of Krakow, Academic Centre for Materials and Nanotechnology, al. A. Mickiewicza 30, 30-059 Krakow, Poland
[c] F.A. Engineering S.r.l., Via Protomartiri Francescani, 111, 06081, Assisi, Italy
[d] Meehanite Technology Oy, Kuokkamaantie 4, 33800 Tampere, Finland
* Corresponding author: E-mail address: gianluca.fratta@unipg.it

Received 30.07.2024; accepted in revised form 08.12.2024; available online 26.03.2025

Abstract

One of the primary issues in foundries is the emission of components that arise from the pyrolysis of organic substances during the pouring phase. This issue is particularly relevant in ferrous foundries. For this reason, the European Community has promoted the project Green Casting LIFE 21-ENV-FI-101074439, which aims at the industrial-scale implementation of the use of inorganic binders for the production of cast iron or steel castings. The work described in this paper shows that producing thin-walled castings in SIMO cast iron (a type of nodular cast iron characterized by high silicon and molybdenum content) using sand cores made with inorganic binders is possible, thanks to a new generation of products. In particular, the study is centered on an analysis of the results obtained from four tests conducted in a ferrous foundry with the aim of evaluating the feasibility of using inorganic cores in the production of exhaust manifolds for the truck sector.

These experiments highlighted that, even when used at temperatures above 1400 ºC, inorganic binders can guarantee satisfactory results in terms of the mechanical and technological properties of the cores, especially during the de-coring phase of the castings.

Indeed, the castings obtained presented a quality that is comparable with those produced using other traditional technologies; this could represent a valuable opportunity for ferrous foundries interested in resolving or mitigating the problem of odors and pollution reduction; moreover, it confirms that inorganic binders, indicated as BAT (Best Available Technology) in the BREF Final Draft (released in February 2024), can be used to manufacture cores intended for the green sand molding process in cast iron foundries.

Keywords: Ferrous foundries, Inorganic binders, Green casting, Green practices, Sand core manufacturing

1. Introduction

In recent years, the attention given to environmental pollution caused by industries has significantly increased. As a result, companies have begun looking for more eco-friendly solutions in order to minimise their impact. Governments and institutions have developed and implemented several measures to regulate and sustain companies during this transition. Regarding Europe, starting in the mid-90's, the European Union released Directive 96/61/EC, also known as the IPPC Directive (Integrated Pollution Prevention and Control), which aimed to prevent, reduce, and, as far as possible, eliminate pollution by intervening at the source of polluting activities. Later in 2003, the European Union released the first of a series of papers known as BREF (Best Available Techniques Reference Document) [1] that contain indications and guidelines concerning the use of the best available techniques (BAT) for each of the main industrial sectors. In addition to this, in 2010, the European Commission issued "The Industrial Emissions Directive (IED) (2010/75/EU)" [2], which incorporated the IPPC Directive and laid down the rules on integrated prevention and control of pollution from industrial activities. The Directive aims to prevent or, where that is not practicable, reduce emissions and waste arising from large agro-industrial installations. To this day (2024), the commission is revising this directive to keep it updated with the innovations introduced in recent years.

Regarding the foundry industry, the BREF in Annex 1, point 2.4, indicated different applicable BATs [3] for ferrous metal foundries with a production capacity exceeding 20 tonnes per day. These BAT can contribute to enhancing the effectiveness of the plants while also reducing emissions. Over time, numerous plants have successfully implemented some of these BATs. However, for others, the application proved challenging due to the presence of critical features that restricted their use. This is the case of inorganic binders, a group of chemical substances usable in the production of foundry cores and moulds that has been indicated in the BAT as a potential substitute for organic binders, nowadays widely used in foundries. The typical organic core binders are petroleum-based, containing the urea- and phenol-formaldehyde groups and furan resins [4]. Therefore, even if the efficiency of organic binders is high, they are responsible for emitting significant levels of polluting compounds, such as BTX, phenols, and aldehydes, in addition to greenhouse gases (i.e., CO, CO2, and methane) [5, 6, 4]. During metal pouring, organic binders tend to release large volumes of harmful vapours such as formaldehyde, benzyl, phenol, or toluene (BTX). [7].

While inorganic binders are nowadays successfully employed in aluminium foundries, their use in the production of ferrous castings is still limited due to the problematic behaviour of these substances at high temperatures. In fact, cast iron and steel require around 1400°C and 1600°C to melt, which is double the temperature required by aluminium. In consequence of this, the sand cores and moulds produced using sodium silicate (also referred as Water Glass), one of the most used inorganic binders in the last decades, tend to increase their strength, making them hard to remove from ferrous castings once they are solidified [8]. In addition to this, sand cores produced using inorganic binders tend to reduce their strength if exposed to humidity [9]. Due to their high sensitivity to environmental moisture, foundries using them in casting production must implement "just in time" strategies. However, in recent years, the development of new additives and innovative binders has played a significant role in reducing the occurrence of this problem. This progress can be reconducted to the development of new silicate-based binders, which demonstrate several advantages over conventional water glass [10, 11].

These issues are well documented in the literature. Works such as the one presented in [12] describe in detail the use of inorganic binders in ferrous foundries, analysing the logistic and technical problems related to their introduction in substitution of organic binders. In particular, the tests described in the paper revealed problems such as broken cores, defected castings, and sand remains. However, the results obtained were satisfying enough to believe that inorganic binders could be used on a large scale in ferrous foundries. Nevertheless, all previous research lacks systematic experimentation with inorganic binders to compare their environmental, economic, and production performance, particularly when compared to organic binders.

To fill this gap, a large-scale trial has been carried out to definitively evaluate the possibility of using inorganic binders. To do this, a series of tests were carried out to test and evaluate the performance of different inorganic binders produced by different manufacturers. Then, a qualitative comparison was conducted using the performance of an organic binder, nowadays widely employed in ferrous foundries, as a benchmark. These challenging activities were conducted with the aim of obtaining dependable and conclusive insights into the feasibility of employing inorganic binders in the industrial production of ferrous castings, a topic of extreme interest for industries but poorly represented in the literature. In terms of results, it seems that the experimentation provided a positive response. In the tests conducted, thin-walled castings made of ductile SiMo iron for truck applications were successfully produced. The choice of manufacturing thin wall castings is not casual, given the challenges associated with using inorganic cores in the production of cast iron pieces. Indeed, thin-walled castings refer to any castings that have walls with a thickness value around 5 mm [13, 14]. This means that the pieces are fragile, and during the manufacturing they have to be treated carefully, avoiding hits during the handling and the mechanical processes. But because inorganic binders are bad at de-coring, collisions are purposely used to get rid of the sand residues on the castings, which puts them at risk of breaking or getting damaged. Given this and the complexity of the pieces chosen, the case described is intriguing.

In the four tests, a total of six inorganic binders produced by four different manufacturers (Sand Team, Peak, Foseco, and Ask Chemical) were tested to evaluate their performance when used in the production line of the F.A. s.p.a., an Italian foundry that is specialised in the manufacturing of cast iron pieces for the automotive and truck sectors. Testing such a variety of products was necessary to understand which type of inorganic binders better suit the foundry's needs, which are unique to each plant. Indeed, as expected, not all products were suitable for the production type under test, as they differed from each other for composition and additives employed. However, the testing phase was useful for understanding how to maximize their efficiency and reliability, and the encouraging result obtained suggests that ferrous foundries can concretely adopt inorganic binding agents under certain conditions.

2. Description of the approach, work methodology, materials for research, assumptions, experiments etc.

This paper describes the impact of introducing inorganic binders in a ferrous foundry. The introduction happened in an experimental context, which allowed for testing and evaluating the performance of different products. This activity was part of the project Green Casting LIFE 21-ENV-FI-101074439, which aims to evaluate the feasibility of introducing a new generation of inorganic binder in European ferrous foundries. To achieve this goal, the project promoted an intense experimental campaign that directly involved six foundries from different European countries (Spain, Poland, Italy, Finland and Estonia). The foundries presented different features in terms of the casting produced (size, weight) and the manufacturing process adopted. This allowed for testing the inorganic binders in a wide range of conditions. This paper describes the analysis and results of experiments conducted over the past year and a half at the F.A. s.p.a., an Italian foundry. The foundry, situated in Assisi (Italy), specialises in producing iron and steel castings for the automotive and truck industry using the green sand process and shell-moulding. To produce the cores needed for the internal production, the foundry has several core shooters that use a cold box process involving urethane phenol resins, an organic binder. The experimental activity consisted of three steps: organisation of the test, measurement, and analysis of the collected data.

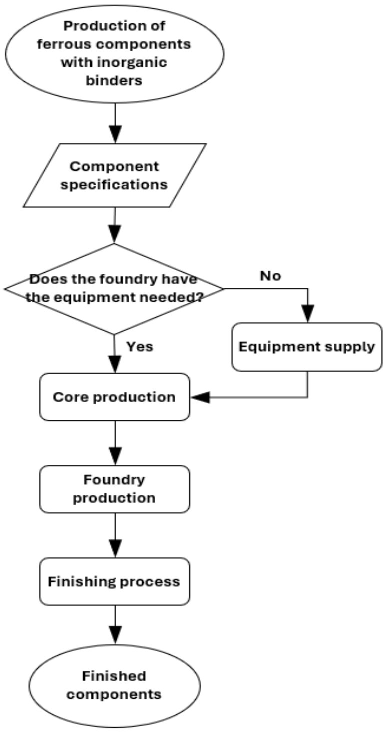


Fig. 1. Essential steps of the manufacturing process

2.1. Organisation of the test

For the experimental phase, the foundry tested a series of inorganic binders from different producers (Sand Team, Foseco, Peak and Ask Chemicals) in substitution for the organic binder. Further information about the manufacturers and their inorganic binding systems can be found in the bibliography [15, 16, 17, 18]. However, producing cores with these binders forced the foundry to introduce some modifications in the manufacturing process that they usually adopt. These inorganic binders, in fact, present the following features:

- These binders, unlike organic binders commonly used in F.A., require heat for the curing process.
- The cores and moulds manufactured with inorganic binders are humidity-sensitive, so in light of his, the stocking and coating processes were modified in order to avoid their destruction.
- Inorganic binders increase their strength due to high temperatures, so the de-coring process is more difficult in comparison to what happens with organic binders.

It is clear that, in addition to the typical steps that commonly characterise the production of cores with organic binders, further steps were added to fulfil the necessities coming from the use of inorganic binders.

The total number of tests carried out is four. The first was carried out under different conditions compared to the next three, and the results were not satisfactory. However, the experience proved beneficial, as it facilitated the identification of the problematic features previously described and allowed for the adaptation of the production process in the following tests. This work focuses on describing the final test, which yielded the best results in terms of production feasibility and casting quality. Figure 1 illustrates the casting manufacturing process using inorganic bonders, while the steps are detailed below.

a. Component specifications

For the first test, it was decided to manufacture a grey iron truck discharge pipe. This decision was taken with the intention of reusing an aluminium-core box among the ones already in place at F.A. in order to adapt it for the warm box process. However, no specific criteria regarding the shape and size of the sand cores to produce were taken into account.

However, during the test, it became evident that the length and weight of the produced cores (a kit of three pieces) could significantly influence the manufacturing process and the results. For instance, the high thickness of one of the cores made completing the curing difficult because the heat couldn't reach the inner part of the piece properly. This caused a significant increase in the time needed for the process.

Consequently, for the following tests, some modifications were implemented. First of all, to prevent issues during the curing process, a component that needed cores of small dimensions was selected. The casting was chosen among the ones regularly produced by the foundry. A kit of five cores was used for the manufacturing of this component, resulting in two castings of different sizes (4.8 kg and 12.9 kg) that, once assembled, form a truck exhaust manifold. Table 1 illustrates the core box and the cores produced. Regarding the metal, these castings were realised in nodular cast iron with high silicon and molybdenum content (SIMO cast iron). This piece is considered as thin walled because of its thickness, that in certain point is around 6 mm.

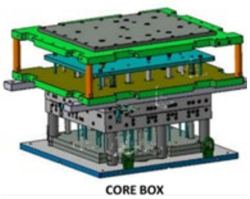
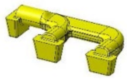
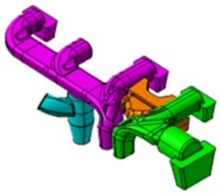
In addition to this, the foundry commissioned the manufacturing of a specific steel core box suitable for the warm box process and capable of ensuring a correct curing process. The next section provides a further description of this point.

b. Equipment supply

Generally, the cold box process uses core boxes made of various materials, like resin and wood for small-scale production or aluminium or steel for large-scale production. After the first test of the four carried on, it was clear that the aluminium core box, originally used for the cold box process and specifically modified for the warm box process, was not suitable for this new purpose. The aluminium core box was adapted by adding internal electrical resistances, which provided heat through the Joule effect, but the negative results in terms of the strength of the cores produced made it clear that a new core box was necessary.

For the manufacturing of cores using the hot box process or the warm box process (as required by the inorganic binders tested), core boxes are usually realised in steel. Steel, in comparison to aluminium, is characterised by a lower coefficient of thermal expansion ($\alpha = 11.7 \times 10^{-6}\,K^{-1}$ for steel and $\alpha = 23.2 \times 10^{-6}\,K^{-1}$ for aluminium [19]) that ensures adequate dimensional stability. Additionally, core boxes feature specific internal channels that allow pre-heated diathermic oil to flow, ensuring homogeneous heat diffusion. Moreover, core boxes must present channels for filling and evacuating the air, as hot air is necessary to aid in the curing process of the sand-binder mixture. It goes without saying that, to fulfil all these needs, F.A. had to design a new steel core box and contract manufacturing to a trusted supplier.

Table 1. Core-box and casting manufactured in test 2, 3, and 4

Core-box	Cores	
	 1.05 kg	
		
	 0.46 kg	 1.08 kg
	 0.35 kg	 1.45 kg

Furthermore, the foundry had to commission an external core shop to manufacture the cores because it lacked any machinery suitable for the warm box process. The chosen core shopper is located in northern Italy, near Brescia, approximately 450 km from Assisi. For the manufacturing, a PRIMAFOND core shooter, specific for inorganic binders, was employed. PRIMAFOND is an Italian company that specialises in designing and manufacturing machinery and equipment for foundry sand core production. In recent years, with the spread of new inorganic binders, PRIMAFOND has developed, on the basis of the core shooters commonly used in the cold-box process, a specific machinery for the inorganic process. As previously described, the main difference is the presence of a metal core box heated to 150–200 °C and a drying system with hot air at about 200 °C to speed up the hardening process of the cores.

c. Core production

The production of the cores is composed of three main steps: the manufacturing, the coatings, and the drying.

As described in the previous section, for the manufacturing of the cores, a PRIMAFOND core shooter, specific for the inorganic process, was used. The values assigned to the production parameters (such as drying time, shoot pressure, hot air temperature, and others) were defined through an iterative process. Because every core presents peculiar features (shape, thickness, weight), the values needed for manufacturing can't be easily predetermined, so different attempts are carried out, evaluating each time the quality of the sand cores obtained until a satisfactory result is achieved. The production parameters can be monitored and modified directly through a monitor on the machinery. The final values used for manufacturing the cores used in the test are shown in the next paragraph, "Measurement".

The coating and drying processes required careful planification. The first test, carried out using both coated and uncoated cores, demonstrated the necessity of using coatings to ensure a satisfactory finish on the ferrous castings. However, due to the high sensitivity to humidity that the cores present, water-based coatings—widely used in foundries nowadays due to their lower VOC emissions—appeared unsuitable for the purpose. Therefore, alcohol-based coatings were used in the following three tests. The operation of coatings took place both in the core shop (alcohol-based coating) and the F.A. (water-based coating). For drying the coated cores, F.A. owns a continuous tunnel oven that generally operates at around 150 °C and can completely dry the coating in 20–25 minutes. Figure 2 shows the steps and elements required for manufacturing the cores using inorganic binders.

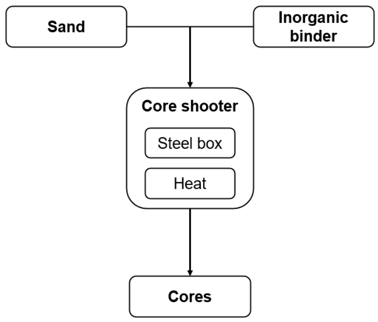


Fig. 2. Core manufacturing using inorganic binders

d. Foundry production

After manufacturing the inorganic cores, all the subsequent operations took place in F.A. As previously mentioned, the tests were carried out to evaluate the performance of inorganic binders in the production of ferrous castings. Each of the foundries involved in the Green Casting Life project uses a different manufacturing process, depending on their specialisation and needs. F.A. is a foundry specialising in manufacturing castings for the automotive and truck sectors, which require high volumes of castings of small or medium size. To match this demand, F.A. uses the green sand process, which is the most suitable for the purpose. The green sand process consists of creating a sand shell (composed of the mould and cores) where the liquid metal is poured and cooled, allowing for the desired shape. An automatic process realises the moulds, where a specific machine uses a metal die to shape a mixture of sand (90%), bentonite (a kind of clay, 7.5%), and coal dust(2.5%). Operators then manually arrange the cores in the moulds, creating the shell. Later, an automatic system moves the shells to the pouring zone, where they are filled with liquid metal. A shake-out machine extracts the rough castings from the shells once they have cooled. After this, the castings are processed to remove excess parts and improve their surface finishing, while the sand is collected and re-used for manufacturing new moulds. Figure 3 shows the steps of the process.

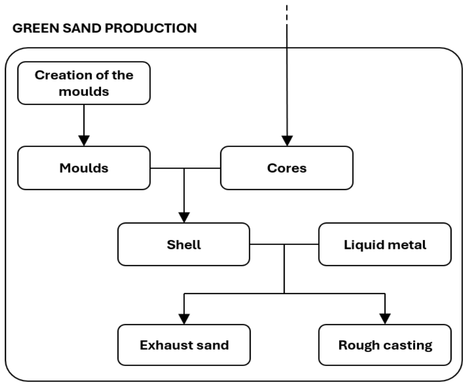


Fig. 3. Steps of the green casting process

e. Finishing process

After shaking out the rough castings, they go through a preliminary finishing process to eliminate the gating system, which consists of all the channels necessary during the pouring to correctly fill the sand shell. Operators manually carry out this process. Once completed, the castings undergo a second process to improve the surface finishing and remove the residual sand. As the inorganic cores presented a higher resistance in comparison to the organic ones, removing the sand was a difficult task that needed a few attempts to produce satisfying results. Under normal conditions, the standard production in F.A. consists of two steps to remove the sand from the castings and improve the surface quality. As indicated previously, firstly, a specific machine performs a shake-out process to remove the majority of sand. After that, the castings undergo shot blasting in order to improve surface quality and eliminate sand residues. To do so, the F.A. possesses a hook-type shot blasting machine and a tumble shot blasting machine.

The first machine consists of a chamber that fires metal shots onto castings positioned on a hook or a basket. Inside the machine, the hook runs and rotates, exposing all of the workpiece surfaces to the abrasive action of the shots. Nevertheless, this machine is not suitable for castings with deep cavities and curvatures, as the metal shoots cannot reach the inner surfaces. The tumble shot blasting machine, on the other hand, guarantees deeper action thanks to the presence of a rotating drum along with the shot blasting. The movement and impact generated help remove sand residues and improve surface quality. This process works well for pieces with cavities, but the impacts may damage castings made of fragile materials, such as grey iron, or with thin walls.

At the end of the process, the castings must present a sufficient finishing quality that makes them acceptable to the customers. The next paragraph details the results obtained from the test with inorganic binders.

2.2 Measurements

Once manufacturing was defined, the next step was to organise the experiment and define the more significant parameters to measure. To determine which process parameters were worth observing or measuring, the whole manufacturing process of the castings was decomposed into all its parts with the aid of the IDEF0 methodology. The IDEF0 is both a process modelling technique and an industrial standard, with extensive literature references in the analysis and design of projects in the fields of manufacturing, aerospace, business, and information systems science and technology [20]. For each sub-process or phase, the following features are identified: controls, inputs, mechanisms, and outputs. Figure 4 shows a representation of a generic process with IDEF0.

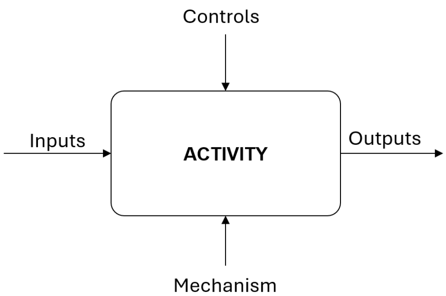


Fig. 4. Representation of a generic activity with IDEF0

IDEF0 is based on a hierarchical representation of the activities or processes; this means that each activity can be decomposed into sub-activities that present their own features, resulting in a complete and detailed representation of all the parts involved in the process. This means that an IDEF0 model is made up of a series of connected activity diagrams presented in node-number order that depict the issue under consideration. Each diagram is identified by a 'node number' that indicates its position in a model's hierarchy.

Figure 5 shows the IDEF0 representation of the main activities that compose the manufacturing of ferrous castings with inorganic binders, as it was organised for the test. The elements highlighted in red in Figure 5 are the process parameters and equipment's special features that are critical for quality (CTQs) and therefore require attention. Among the influent parameters, the CTQs were identified in accordance with the observations provided by the foundry's expert and technician. This, in addition to the deep analysis of the manufacturing process that was performed, allowed for a reduced number of parameters to monitor. For instance, environmental humidity and temperature, which are significant parameters for the conservation of the inorganic cores, were not monitored because the parts agreed that the storage time wasn't high enough to influence the resistance of the cores. In the following sections, these elements are detailed.

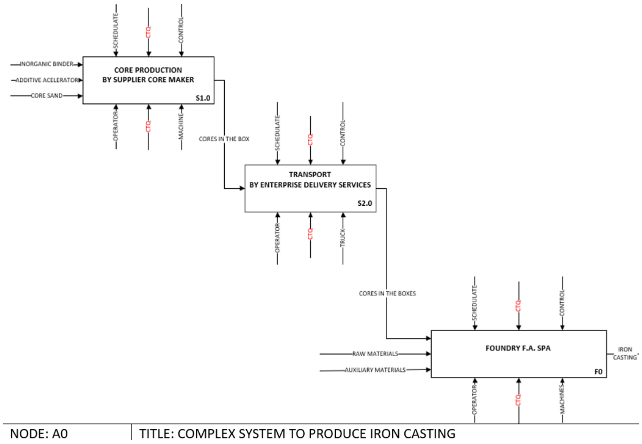


Fig. 5. IDEF0 representation of the tested process

a. Core production by supplier maker and shipping

This process is divided into three sub-processes: core production, handling, and storage. The first of these presents the highest number of CTQs, as shown in Figure 6. This is undoubtedly due to the fact that a large number of process parameters regulate automated core manufacturing. All these parameters were controlled and set directly by an operator on the core shooter. This allowed for real-time process control, allowing for adjustments to the parameters based on the quality of the produced cores, shoot by shoot.

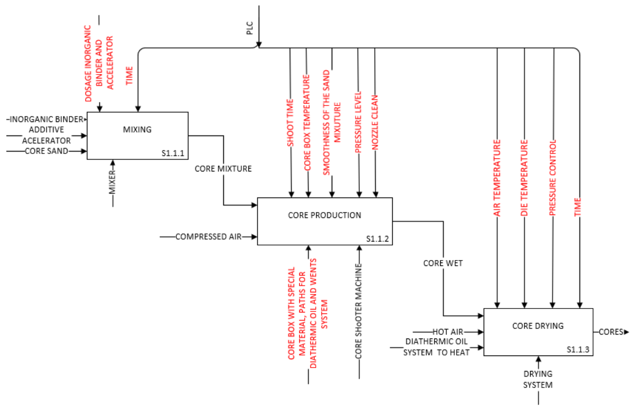


Fig. 6. Core manufacturing carried out in the core shop

In detail, the parameters that were measured are reported in Table 2, together with the values recorded. Another aspect that was controlled was the preparation of the sand-binder mixture. Each producer specifies the amounts of binder and promoter to mix with the sand (usually 2% for the first and 1% for the second), and it is crucial to follow this prescription to avoid adverse effects on core strength, collapsibility, and mixture viscosity. In light of this, the mixing parameters of the machinery were carefully supervised. Regarding the sand, the core shop employed silica sand that presented the features illustrated in Table 3.

Table 2. Values of the production parameters

Production parameter	Value
Firing pressure	6 bar
Drying air temperature	220°C
Die surface temperature	150/160°C
Drying time	70 s (test n.2 n.3) 35 s, 50 s, 70 s, 90 s (test n.4)

Table 3. Features of the sand employed in core manufacturing

Parameter	Value
Appearance	White
Grain form	Round
Specific weight	1,50 g/cm^3
Absolute weight	2,60 g/cm^3
Hardness	7 Mohs
Melting point	1750 °C
Specific surface	125 com^2/g
PH	7,5
Loss of ignition	0,10%

After manufacturing, the cores were immediately prepared for transport to F.A. The pieces were arranged in plastic boxes. To avoid damage during shipping, the cores were wrapped in paper, and to prevent that changes in humidity could reduce their strength, the box was sealed, and bags of silica gel were added near the cores. Indeed, because of the composition of inorganic binders, the cores tend to absorb humidity from the environment, so the time between their production and their employment on the foundry line should be less than 72 hours.

b. Core finishing

Once they arrived at F.A., the cores underwent a finishing process to prepare them for their final employment on the manufacturing line. As shown in Figure 7's IDEF0 diagram, this process consists of two steps: core coating and drying.

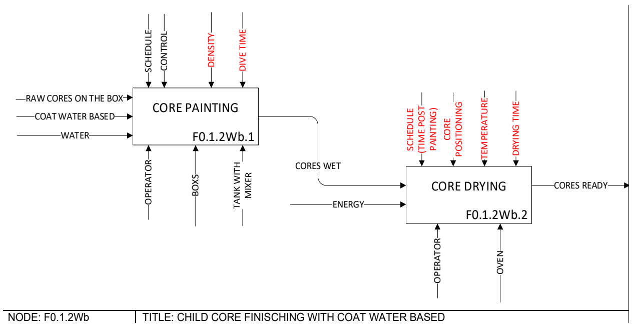


Fig. 7. Cores finishing performed at F.A.

For Tests 2, 3, and 4, some of the cores used in the pretests were coated. Painting with alcohol-based coatings did not cause any significant problems, whereas painting with water-based coatings highlighted some relevant issues. As stated previously, the cores produced using inorganic binders are highly humidity-sensitive, so the use of water-base coating is generally avoided. However, they were tested in Test 3 to evaluate their influence on the level of emissions released during the pouring of the molten metal. To avoid that the cores could suffer excessively in the presence of water, the length of the immersion in the coating and other parameters were modified specifically. Table 4 shows the CTQs measured during the coating and drying of the cores.

Table 4. Coating and drying of the cores coated with water-based coating in Test 3

Parameter	Value
Coating density	23 °Bè
Immersion time	1-2 s
Time between coating and drying	30 min
Oven temperature	125 °C
Drying time	60 min

Nevertheless, after drying in the oven, the cores coated with water-based coatings presented cracks and damage to the surface (Figure 8). Water absorption in the surface layers during the coating process likely caused this issue, which affected the bottom side of the cores that were drying on a paper-covered shelf. During the drying process, the water, having transformed into steam, may have attempted to come out, but the presence of the coating layer and the paper may have impeded its proper evacuation. As a result, the steam began to accumulate, increasing the pressure. When the pressure reached a critical value, the cores cracked, releasing the vapour.

Fig. 8. Cracked cores after drying

As a consequence of this, in Test 3, the castings were manufactured using only uncoated cores, whereas in Test 4, only an alcohol-based coating was employed.

c. Ferrous castings production

The use of inorganic cores didn't affect the regular casting manufacturing process, so it wasn't necessary to introduce any significant modifications. In this phase, to evaluate the potential benefits of using inorganic binders, it was decided to measure the amount and composition of the gas emitted during the metal pouring. To do so, in pretest 1 and pretest 3, the iron was poured first into flasks containing cores made with organic binders (regularly employed in F.A. production) and then into flasks containing the cores made with inorganic binders. The gases released during and after the pour were directed towards a gas analyser, enabling the recording of the emissions in both cases. Table 5 shows the values obtained from the measurement. The measurement was carried out by analysing the emissions coming from flasks containing both coated and uncoated cores in the different combinations indicated in Table 5. For each combination, the gas detector analysed the emissions coming from 10 flasks in order to obtain acceptable and coherent values.

Table 5. Composition of the gaseous emissions recorded during the pouring in Test 3

	Organic Binder		Inorganic Binder	
Coat	AB	WB	No	WB
V.O.C. [g/Nm^3]	45.8		53.1	
Methane [g/Nm^3]	23.5		32.6	
Benzene [g/Nm^3]	0.79		0.61	
Phenols [g/Nm^3]	< 0.18		< 0.17	
Formaldehyde [g/Nm^3]	0.89		0.69	

Observing the values in Table 5, it is evident that the results obtained differ significantly from what was expected. In fact, the emissions coming from the flasks containing inorganic cores are almost the same, or even higher for some compounds, in comparison to the flasks containing cores produced with the traditional process. Theoretically, the use of inorganic binders should help reduce the emissions produced during pouring, as they do not contain organic compounds that decompose through pyrolysis at high temperatures. However, it is important to consider that in the green sand process, the moulds that compose the shell together with the cores are made by mixing sand, bentonite, and coal dust, an organic compound. Generally, coal dust represents 2.5% of the total weight of the moulds. According to F.A. indications, the moulds that are generally involved in their manufacturing process weigh around 600 kg, so this means that for each flask, 15 kg of coal dust are used. This number is significantly higher in comparison to the amount of binder used for manufacturing the cores. For instance, the cores produced for the test weigh around 4 kg and contain around 2% of inorganic binder, which is equal to 0.08 kg. Considering this, it is clear that the benefit in terms of emissions generated by the use of inorganic binders is negligible in this particular kind of process. However, their use can contribute to a safer work environment in the core shop, where hazardous emissions produced by organic binders represent a significant problem.

Once cooled, the flasks were emptied on a shakeout machine that enabled the removal of the sand from the rough castings. After that, the castings were moved to the finishing department.

d. Castings finishing

After the shakeout, the castings still had their cavities filled with sand residue. Therefore, the rough castings underwent a preliminary degating process to remove the sand and excess metal parts. The treatment improved the situation, removing most of the sand, but a significant amount of core residue persisted on the castings' surfaces. To definitely remove the sand, the castings were shot-blasted. For this purpose, the tumble-shot blasting machine was employed. After 13 minutes in the machine, the castings were completely sand-free. Figure 9 shows the castings through the various steps of the process.

Fig. 9. Clockwise from top left: Castings after shakeout, after degating and after shot blasting

3. Results

3.1. General remarks

Analysing the data and observations collected during the tests, it is possible to say that the use of inorganic cores for manufacturing ferrous castings presents both advantages and disadvantages.

Regarding the benefits, it was observed that:

- All the inorganic binders used in the tests allowed for the production of SiMo castings with an internal surface quality similar to that achieved by employing cores produced using organic binders.
- Even though the sand coming from the cores was not completely removed during the shakeout, the castings were thoroughly cleaned after a few minutes of shoot blasting in a tumble shot blaster.
- The fact that most of the cores do not break down during the shakeout can be an advantage, as it prevents contamination of the exhaust green sand. In fact, the exhaust sand from the cores presents properties that render it unsuitable for reclamation and re-use in the moulding process. By preventing contamination, the physical and mechanical characteristics of the reclaimed sand can be kept more stable.
- The cores manufactured using inorganic binder are characterised by a curing time (35 s) that is approximately equal to the time required by organic binders with the cold box process. This means that these two processes present the same production rate.
- The results obtained confirm that inorganic binders can be adopted for manufacturing cast iron castings using the green sand process, as suggested by the Best Available Techniques (BAT) contained in the BREF Final Draft (February 2024).

Concerning the shortcoming, it was observed that:

- Coating the porous surface of cores made with inorganic binders improves surface finishing and prevents defects like penetrations from forming on the castings. The use of alcohol-based coatings doesn't present any issues, whereas water-based coatings, due to the humidity sensitiveness of the cores produced with inorganic binders, can't be used without damaging the sand cores. However, the use of water-based coatings is unavoidable to eliminate polluting and hazardous emissions, so further studies and experiments are necessary to understand how to industrialise their use.
- Introducing the use of inorganic binders in a ferrous foundry requires a significant initial investment, especially for binders that require heat for curing, such as the ones used in the tests. In particular, the manufacturing of steel core boxes represents an important cost. Unlike the aluminium core boxes that are usually used for the cold box process, the warm box process requires core boxes equipped with internal channels, which can be obtained through expansive processes.
- Specific core shooters are required for the manufacturing of cores with inorganic binders, which require heat for curing. These machines, different from the core shooters used in the cold box process, present features and functionalities that are specific for inorganic binders.
- Cores manufactured with inorganic binders are highly humidity sensitive, so they have to be used within 72 hours of manufacturing.
- The reduction in pollutant emissions achieved by using inorganic binders is more significant as the weight of the cores employed is higher. However, in the green sand process, the main source of emissions is coal powder, which is used as an additive in the molds. In light of this, the use of inorganic binders doesn't help to reduce the emissions produced during the pouring of the metal but, anyway, represents an important solution for the creation of a safe work environment, as it allows for eliminating hazardous emissions and odours during core manufacturing.

4. Conclusions

The experimental study described in this article aims to evaluate the possibility of using inorganic binders for the production of ferrous castings on an industrial scale. For several years, this innovation has piqued the interest of companies because of its potential, but to this day, the literature still lacks an accurate and complete description of the advantages and problems related to the use of inorganic binders in large scale production in ferrous foundries. Given this, the hope is that this article can serve as a starting point for broadening knowledge of the subject.

In particular, the experimental activity focused on evaluating the performance of various inorganic binders for the manufacturing of cores employed in the production of SiMo ductile iron thin-walled castings for the truck sector. The experiments were organised and carried out at the F.A., an Italian foundry that takes part in the Green Casting Life project and that adopts the green sand process for its production. The analysis of the results and observations collected during the test showed that the tested inorganic binders, by applying the necessary changes to the production process regularly carried out in the foundry, enable the successful production of good-quality and defect-free castings with characteristics entirely similar to castings produced using classic inorganic binders.

Furthermore, the research highlighted secondary aspects that could serve as the basis for further investigations and research to improve the application of inorganic binders in casting. For example, in the green sand process (used to perform the tests), the low collapsibility of the cores produced with inorganic binders can represent a potential advantage. In fact, by avoiding mixing the sand from the cores with that of the moulds, it is possible to keep the latter clean and obtain reclaimed sand with optimal physico-chemical characteristics.

However, some problematic aspects warrant further consideration. In particular, consider the problems with water-based coatings and the emissions generated during casting in the green sand process.

Regarding the former, it is obvious that, to date, water-based paints are not yet suitable for coating sand cores produced with inorganic binders. To overcome this problem, a solution could be to reduce the humidity sensitivity of the cores by using specific additives or to industrialise the coating process with techniques not commonly used in foundries. Concerning the second problem, as discussed earlier, it is clear that in the green sand process, the main source of BTEX emissions during casting is represented by the pyrolysis of the coal dust present inside the moulds. The introduction of inorganic binders, therefore, would not solve this problem but would undoubtedly help to eliminate polluting and hazardous emissions produced within core shops during the manufacturing of the cores. In order to reduce emissions released during casting, further research could help identify technologies that, in combination with the inorganic binders used for the cores, could reduce, if not eliminate, the emissions produced in the green sand process.

Acknowledgements

The searches mentioned in this paper are funded by the European Union LIFE Program, Green Casting LIFE Project (LIFE21-ENV-FI-Project101074439). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

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