REVIEW OR CRITICAL ASSESSMENT

Application of cores and binders in metalcasting

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This paper offers an overview of fundamentals and recent global developments of cores and binders used in metalcasting operations. The basic technical characteristics of salt and sand cores are provided along with organic and inorganic binder systems. A particular attention is paid to inorganic binders, receiving recently a renewed interest. The description of research and development efforts is accompanied by history and present status of commercial solutions used by the casting industry. The new development directions, aimed at meeting the growing complexity of the component design requirements and ever-more stringent environmental regulations, are emphasised.

Keywords: Casting, Die casting, Casting cores, Binders, Organic binders

Introduction

In metalcasting, cores are mould parts used to form internal holes and cavities in a cast product. Depending on casting technique, the core can be completely integrated into the casting die/mould or loosely laid therein. After solidification of the metal, the die is taken apart and the cast product is released. Then the core is broken, removed from the product and usually disposed of, although there have been applications for re-usable cores.[1] While some product cavities have functional purposes, such as cylinders in engine blocks, others are just for weight reduction. For example, some automotive engine parts such as camshafts or crankshafts have a designed hollow structure for a considerable weight reduction. Depending on casting methods which include gravity casting, low pressure or high pressure die casting, the cores may require a high strength as the pressure increases with each technique. Examples of components manufactured with casting cores are shown in Fig. 1.

In order to make the casting core structurally strong to withstand operating pressures, binders are used. The core binder refers to the chemical mixture which adheres the filler to provide the core strength. Hence, the core represents a composite comprising the filler and the binder. Since the typical volume of the latter is of the order of 1–3%, the filler is the predominant component of the core. However, despite such a low volume, conventional core binders emit up to 70% of a foundry volatile organic compound.[2] The binder chemistry is, therefore, of key importance.

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There are many types of cores in the casting industry; the primary focus of this paper is on sand cores with organic and inorganic binders as well as surface coatings for core strength increase. To provide the full picture, however, salt cores are also included. The objective is to provide an overview of fundamentals and the present status of commercial cores used by the global casting industry.

Core materials

The casting cores have to withstand tough requirements which depend on casting technique and alloy used. The temperature and its gradient represent one of many challenges. At the moment of casting the maximum temperature experienced by a core may exceed 1500°C on the metal side with a steep gradient through the core body. A specific challenge occurs during die casting of aluminium alloys, known for having light weight, relatively high strength, high productivity, and high dimensional accuracy. For these reasons, it is widely being used in applications such as the automotive industry. Since more complicated shapes are required for die casting parts, it becomes difficult to manufacture such geometries without breaking the core. In general, in high pressure die casting, the flow velocity used exceeds 30 m s^{-1} at gates and the hydrostatic pressure is more than 60 MPa. Such demanding casting conditions tend to cause high mechanical loading on the core.[3] Thus, a core that is able to withstand these conditions is required. However, increasing the core strength causes a decrease in its collapsibility which translates to longer time for core removal. Due to this, the total processing cost tends to increase, as well. To provide a solution, an extensive research has been conducted into producing the core that is able to withstand pressure and temperature, as required in die casting and at the same time it allows for its easy removal.

Two major types of cores are explored here, sand and salt cores. Historically, sand cores were first commonly

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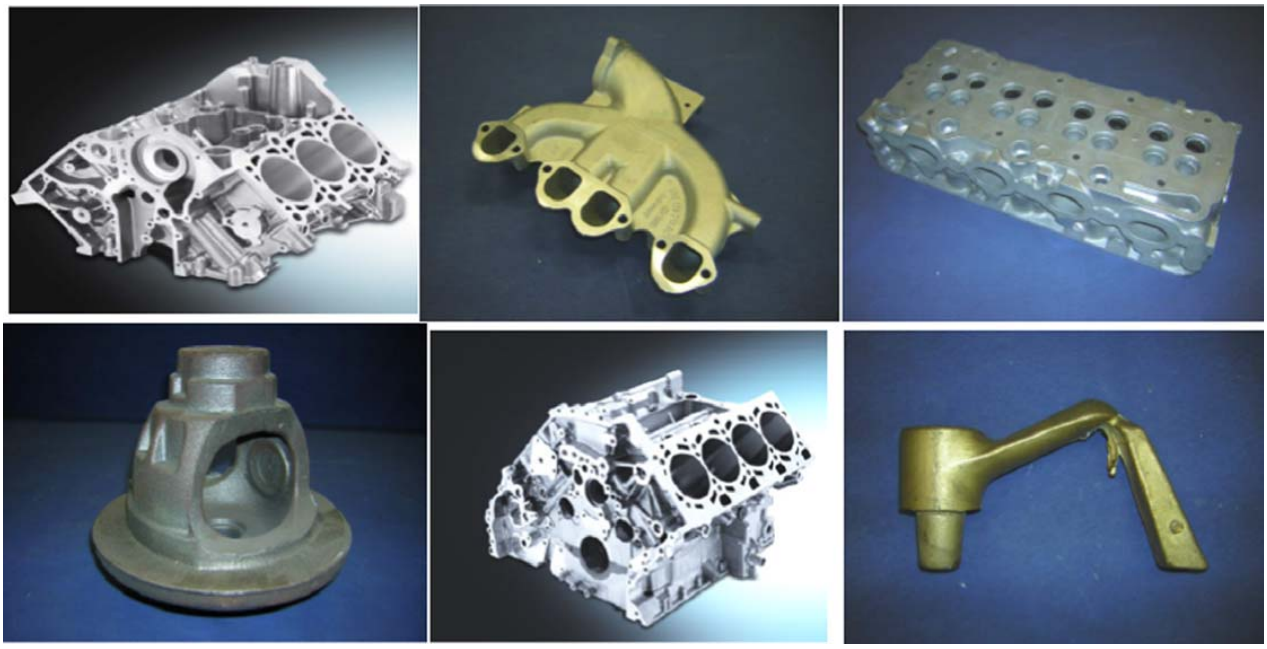


1 Examples of components manufactured with casting core[44]

accepted by the general casting industry. These cores are disposable ones, designed only to be used once. The problem with typical sand cores is that once the casting technique changes to that which requires higher pressure, the core becomes harder to remove from the cast product.[4] To address the issue of core removal, salt cores were introduced. The concept of salt cores is that once casting is completed, the core would not need to be broken down but rather dissolved with water.[5] Using salt cores also helped to simplify manufacturing the complex shapes due to the good castability of salt mixtures without reinforcements.[3] In applications where parts must be absolutely free of core sand residues, salt cores provide a solution. However, even the use of salt cores has some drawbacks. The growing demand for shape complexity, strength and easy removal cause the industry to divert its attention between sand and salt cores.

Moreover, a hybrid ceramic-sand core technology was developed for highly demanding applications.[6] A casting process that combines aerospace ceramic cores with automotive sand cores was recently developed by Southwest Research Institute.[7] This hybrid core is specifically suited for the purpose of allowing precision casting of extremely small passages in the automotive cast iron/steel components. It was designed to enable the production of heavy-duty diesel engines with the higher peak cylinder pressure capability than current state of the art engines. The ceramic section in the core is used where coolant passages between the engine gas exchange port walls and the fuel injector or spark plug are formed.

Salt cores

There are different mixtures to prepare a salt core. The most common use sodium carbonate (Na_2CO_3), potassium chloride (KCl) and sodium chloride (NaCl), melting these components and applying the moulding technique to create a core.[8] This helps the core to obtain a high static compressive strength and dimensional stability, required during casting. The detrimental features of salt mixtures are shrinkage cavities, microporosity and heat creaks. The latter may be created in the salt core when a volume change takes place such as during solidification.

Development directions of salt cores

An example of the salt core chemistry includes bromine ions, carbonate ions, and at least one of sodium ions or potassium ions. As ion precursors, sodium bromide NaBr and sodium carbonate Na_2CO_3 are used. Since applications often require complex shapes than could be achieved by dry-compaction method, the ingredients are rather melted by heating to obtain a melt and then injected into the metal mould under high pressure. After solidification, the salt core is removed from the mould. An application of this core includes die casting and gravity casting.[9,10] Another possible process to make a salt core uses a sodium chloride mixture, which is preheated to a temperature of maximum 30°C above liquidus and then poured into a mould. The core is formed by solidifying the melt inside the mould.[11]

A semisolid processing technique was used in a concept to produce salt cores with a mixture of sodium carbonate, potassium carbonate, sodium chloride and potassium chloride.[5] Since the salt core is formed by solidification in a metal mould after high pressure injection, having a precursor of semisolid mixture of sodium and potassium salts, instead of full liquid with a liquidus temperature of 700°C, allowed for precise reproduction of the shape required. To generate a semisolid slurry, the molten salt was undercooled into the 595–645°C temperature range, directly before injection. The pressure applied on the cavity remained constant until mould opening, in order to obtain high strength. The concept was tested with the expendable salt cores used for water jacket in a closed-deck type, 4-cylinder engine block. To remove the core, the engine block was submerged into a dissolution tank which contains liquids such as hydrochloric acid and hot water.

Four binary systems for high pressure die casting cores, tested by Yamaha included NaCl–Na_2CO_3, KCl–K_2CO_3, KCl–NaCl, and K_2CO_3–Na_2CO_3.[3,12] To determine the core

2 Casting core made of salt mixture[9]

3 Intake manifold casting using Cordis binding system (core is shown on top)[39]

strength, a four point bending test was carried out. It was found that the strength of NaCl–Na_2CO_3 was over 20 MPa in the Na_2CO_3 content region between 20 and 30 mol.-%, as well as 50 and 70 mol.-%. The highest strength for this system was 30 MPa at the composition of NaCl–70 mol.-%Na_2CO_3. For KCl–K_2CO_3 the strength was over 10 MPa in the K_2CO_3 region at 20 mol.-%, and between 50 and 60 mol.-%. The highest strength for this system exceeded 25 MPa in between the K_2CO_3 content of 50 and 60 mol.-%. It was noticed that the strength of the systems KCl–NaCl and K_2CO_3–Na_2CO_3 was below 6 MPa. The reason was the solidification structure and the solid state phase transformations. It was also found that, in the NaCl–Na_2CO_3 system, the hardness value of the primary particles was higher than in the KCl–K_2CO_3 system, explaining why the NaCl–Na_2CO_3 strength was higher than that of KCl–K_2CO_3.

The salt cores for cast pistons produced by CeramTec AG and Austrian Foundry Institute have similar advantages as cores mentioned above. Their gas emission during core storage and casting is minimal, making it environmentally friendly as well (Fig. 2). The cores are manufactured using a fully automated process.[13] Another type of salt core that has a soluble and insoluble portion was developed by Brunswick Corporation.[14] The aim was to make the soluble portion of the core to dissolve after casting was completed thus allowing removal of the insoluble portion. Fraunhofer IFAM, is also researching salt cores, focusing attention on pressing, compaction and sintering. The density distribution and a selection of casting parameters are considered to control flow peaks in the salt core.[15]

The salt core technology was explored to produce a cylinder crankcase.[16] To provide cooling, a water jacket usually surrounds a cylinder sleeve and is often open at the top on the cylinder side with crankcases. The salt core is fixed when it is placed near the end of the cylinder sleeve on the cylinder head side. This increases the stability of the core during casting process. The salt core in Daimler's patent[16] comprises of a crown which is attached to a core shroud with the cylinder head. It is placed in the cylinder sleeve so that the crown covers one end of the sleeve on the cylinder head. As a result the salt core is connected to both the cylinder sleeve and the die casting tool. This helps the core to withstand the high pressure. Based on the solution proposed, the salt core can be placed in different arrangements during the casting process thus changing some of the characteristics of the core.

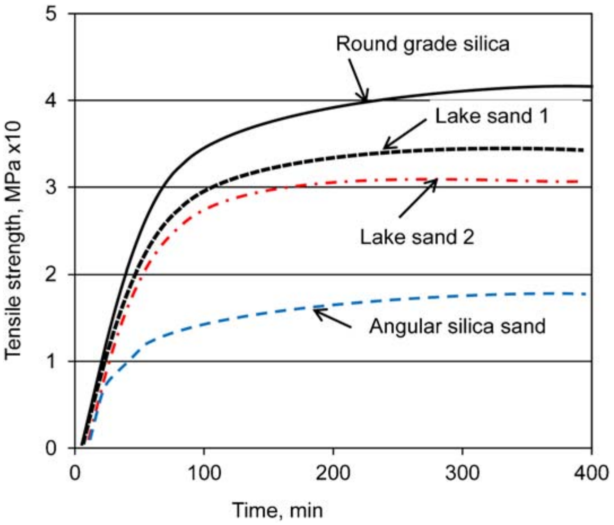
Besides improving the salt core properties, placement of the salt core can also help the process of casting a cylinder crankcase. According to Daimler's research,[17] the salt core is able to support the water jacket against casting pressure and it is able to prevent undesired penetration of melt into the cavities at incorrectly sealed casting–mould contact surfaces. Since the salt core remains in the cylinder crankcase during the pressure die casting, this improves the stability of the cylinder liner during the encapsulation, where higher pressure occurs and increases the process safety. The media connections of the coolant in the water jacket make it easier to dissolve the salt core as well when the casting process is completed.

Sand cores

Sand cores are made using chemically bonded sands such as silica, zirconia, olivine and others.[18] When using silica sand, the grains have different polygonal shapes which create spaces between them during core moulding. Due to this, the sand core is prone to cracking under high pressure. To prevent infiltration of the molten metal into the core body and to allow easy separation of the sand core from the cast product, core coatings are used. The coating contains a binder in order to connect main components, such as fire resistant powdered materials to each other. The binder aids also in connecting the coating layer with the core body.[19] Organic or inorganic binders are used to coat the sand in order to withstand the high casting pressure. An example of core produced with Cordis' binding technology is shown in Fig. 3.

Development directions of sand cores

Although sand cores were used for decades, there is still an opportunity to improve their basic structure. According to recent findings, the type of sand used to mould a casting core affects the flowability of the core mixture and the core density. To control the core moulding process and resultant core strength, the shape of the sand grains is critical. According to Honda's patent,[20] in order to solve the core quality, the sand used should include a mixture of both the spherical (silica



4 Effect of sand type on tensile strength of core manufactured using sodium silicate binder[21]

sand) and the non-spherical sand grains (lake sand) – polygonal or angular. Typically, the silica sand content should be about 60% and the lake sand content another 40%. The above cores have advantages over cores produced from sands with uncontrolled grain morphology. An example of differences in tensile strength of cores produced with different sand grades is shown in Fig. 4.[21]

Doehler Jarvis invented its own sand core called Doehlercore. The core is used in aluminium cylinder blocks for a closed deck design, since it is capable to handle high pressures and high thermal stress.[22] The expendable die casting cores used for engine blocks were researched for years, since they present many challenges. Cores used for forming jackets around cylinders in engines have printout portions in their cylindrical sides and not at the ends. As a result, there is no connection between the sides of the cores for cylinders of a multiple cylinder core. The only connection between opposite sides of the core is at its ends. One of several solutions which did not weaken the core was to use a mandrel holder.[23] To execute this, the mandrel and core are assembled together and placed into the die. When the die is closed, the core does not break since a certain space is created from the mandrel between the printout portion of the core and the cavity. However, adding an extra component to the core is costly. To improve the process economy, another solution is proposed to hold the core bridging ends of each groove as webs or by using a printout portion integrally connected to the core but extending outwardly and spaced away from the periphery of the cavity.[24,25]

An inventive approach by Honda was to develop cores for thin wall hollow castings such as camshafts or crankshafts in an automotive engine.[26] The challenge was the overall length of the core which easily causes deflections and fracturing under flow of molten metal. The core body proposed has on its outer diametrical position a groove for inserting the entire arcuate portion of a chaplet. Such a change solves failures of adhesion between a chaplet and a core body as well as failures in melt flow due to a chaplet.

Core coatings

Another inventive direction is oriented towards the functional core coatings. The key attempt is to develop a capability by a core not only to withstand a high pressure, typically of $6{\cdot}9\times10^6$ Pa but also to have a good shake-out property, good wash-out resistance, good shelf life and no surface penetration. As a solution the double-layer coating was invented by Doehler Jarvis.[27] The first layer of the coating represents a base composed of hard refractory ingredients and the second layer is soft to provide easy release. The best release properties are obtained with particles of anhydrous powdered alumina, graphite, talc, titanium dioxide and zirconia.

During casting, as a result of high temperature, the organic binder combusts, decomposing into gases such as CO, CO_2 and, in the case of incomplete combustion, also tar or soot. The solid tar may clog the gas drains. In order to prevent generation of clogging in gas drains, the core was developed by Honda, where the outermost coating layer of an organic binder has an addition of the tar reducing agent.[28–30] The core production process is shown in Fig. 5. As a result a complex surface structure is created. The task of the first coating layer, marked as H in Fig. 6, is to close the pores of the core surface, thus preventing infiltration by molten metal. The second coating layer marked as T, with a typical thickness of 0·1 mm, is composed of mica, providing high lubricity and helping to remove the cast component, and agents reducing tar generation. It may also include an organic binder such as phenolic resin to increase its adhesion to the first layer.

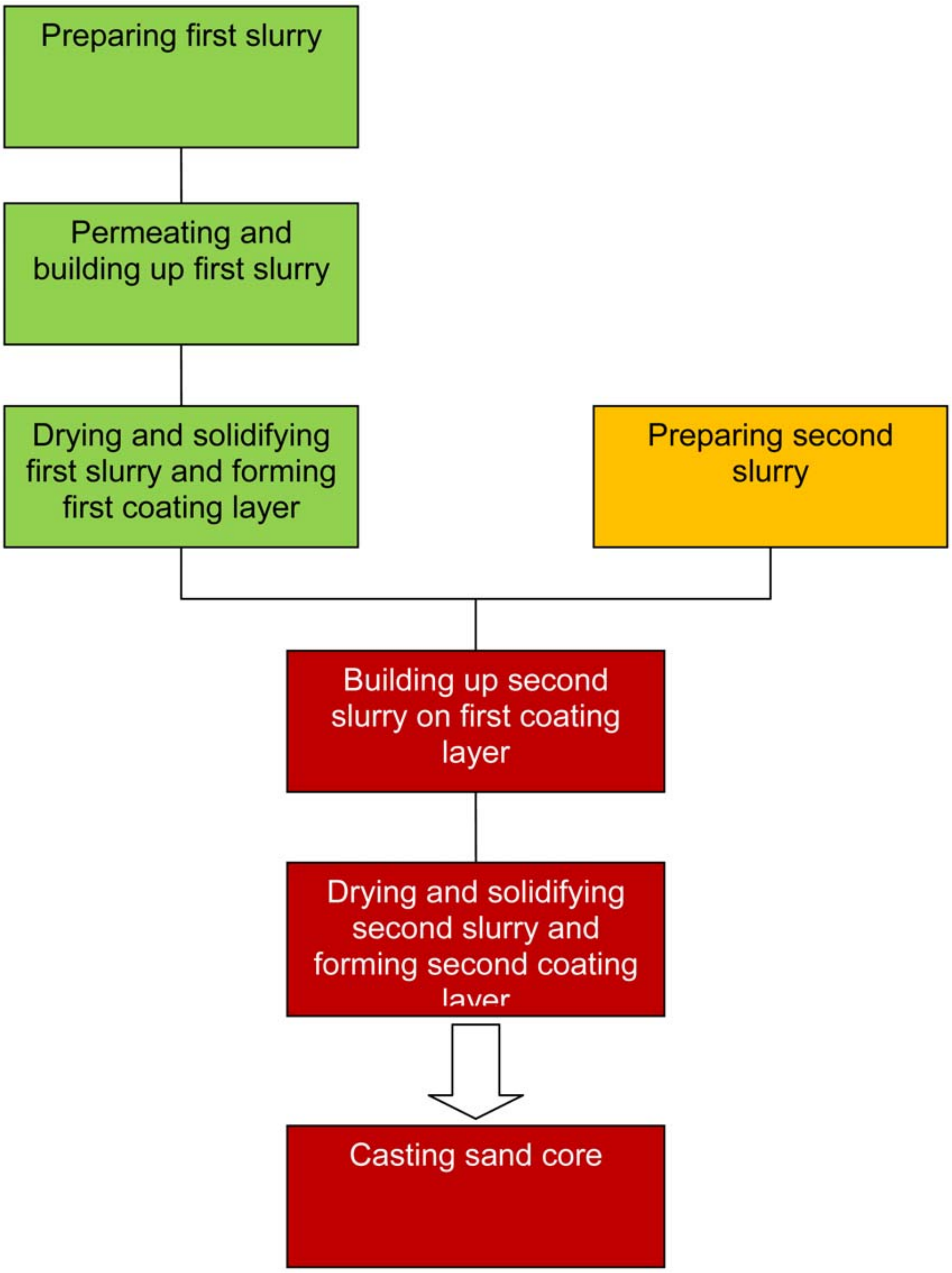
Core binders

The purpose of a core binder is to provide strength to a core and hold the sand grains together. Hence, binders prevent the core from falling apart. A basic description of core binders is that they are finely pulverised or liquid materials with binding capabilities used to provide green strength, hot strength and baked strength to a core.[31] Although some requirements of binders are specific for cores, very often their application covers moulds as well.

Organic core binders

Historically, inorganic binders were the first ones used to strengthen cores during casting but the automotive industry expressed interest in organic binders, thus the demand on the former declined. The typical organic binders are petroleum based such as phenolic urethanes and furans. It is generally known that the organic binders tend to release during exposure to cast metal the large volumes of harmful vapours such as formaldehyde, benzyl, phenol or toluene. These gases represent hazardous air pollutants and some fractions are of health concern.[32] In addition, volatile species contribute to gas induced type of porosity, adversely affecting the casting structural integrity. Examples of commercial organic binders include Ecolotec, GMBond, or SigmaCure.

The GMBond, an environmentally friendly binder, manufactured by Hormel Foods, consists of two ingredients: protein and catalyst.[33] Its chemistry includes 50% carbon, 17% nitrogen, 7% hydrogen, 25% oxygen and the rest are trace minerals. The reason for using protein is to improve the core removal, to lower the hazardous emissions, and a waste stream reduction. The essential steps of the core manufacturing, using organic binders, are shown in Fig. 7. The tensile strength of the core ranges from 1·7 MPa and higher, depending on the



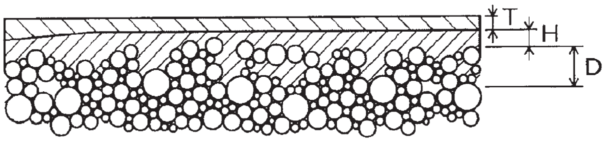
5 Flow chart showing production steps of sand core with surface coating[30]

aggregate medium. As shown in Fig. 8, as the surface tension changes, a bridge is formed between neighbouring sand grains. An advantage is that the easier core sand removal and the tighter dimensional accuracy allows the thinner casting walls to be employed, leading to reduced weight of the cast part, and further to the lower component cost.[34]

A core making process exploring organic binder, referred to as Resin-CO_2, was developed by Honda to produce sleeve cores for gray iron cylinder liners for a number of aluminium engines. It shows benefits as compared with the previous process of Phenolic-Urethane Cold-Box amine gas cured (Tables 1 and 2). The process starts from a high intensity mixing of sand and the binder components. Then the mixed sand is discharged into a hopper that supplies the core blower. Following gas curing the cores are extracted and moved to a transfer container section. The essence of core manufacturing is shown in Fig. 9. The resin–CO_2 process uses a patented water based phenolic resin binder that is cured with safe CO_2 gas. There are no flammable components and the process is odorless. The key additional benefits include:

(i) the elimination of a curing gas scrubber system, with the CO_2 curing gas being vented directly to the outside atmosphere, where it dissipates harmlessly
(ii) sand preparation equipment and core box tooling are easily cleaned with water
(iii) respirators are no longer required during maintenance activities.[35]

Foseco released several inorganic binders that are silicate based but the most frequently used is the organic binder Ecolotec.[36] The Ecolatec process is based on the use of a proprietary water-soluble phenolic resin, condensed under alkaline conditions. The binder contains a special resin, which is free of nitrogen, phosphorus or sulphur. All sand types such as silica,



6 Cross-sectional view of surface region of sand core with surface coating H shows first coating layer; T is second coating layer; D is core body[30]

chromite or chamottes can be used successfully. In order to harden the mixed sand, CO_2 gas has to be supplied into the core-box. It is known that CO_2 acts as a reaction component with the resin, not as a catalyst.

Inorganic core binders

Due to the health and safety guidelines, and increasing environmental impact caused by gas emissions, more companies have been trying to implement inorganic binders since they are odorless and emission free. Inorganic binders are typically made out of synthetics such as sodium silicate, cement, phosphate and sulphite lye. The natural inorganic binders are clays and bentonites. Besides being environmentally friendly, inorganic binders when attached to cores also improve the casting quality. There is a growing interest in developing an inorganic binder that has the same structural capabilities as organic ones in terms of the core structural integrity, shake-out properties and casting quality.

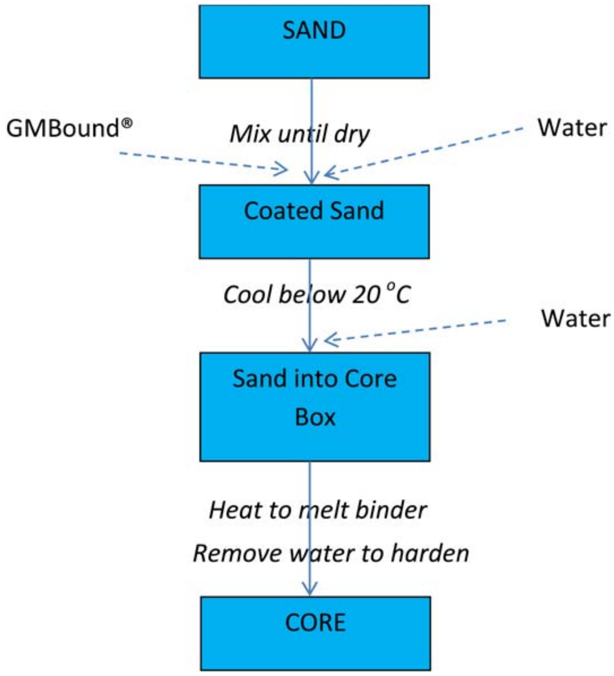
There are many companies focused on developing inorganic core binders for the automotive industry, including Minelco GmbH, ASK Chemicals, HA International, BMW, Foseco, and Honsel. In addition to individual effort, there are also joint ventures involving clusters of companies.

A number of inorganic binders explore silicate, which enables the preparation of mould and cores without any need for drying or baking, and in certain cases even without ramming the sand. Silicate binders are one of the oldest core making binders used in the foundry industry, and are also known as water glass. The water glass method in a combination with CO_2 gas or esters as a liquid hardener has been used in iron, steel and nonferrous foundries. Self-setting sodium silicate binders have also been used for many years.[21]

Historically, sodium silicate binders with a cold-box or self-setting had lower tensile strength than traditional organic binders. To increase strength, various additives should be applied. This includes both the organic and inorganic materials at different levels of concentrations and also the type and morphology of sand. The common conclusion is the substantially low level of gases released. In case of carbon monoxide, the lowest emission level was achieved for no-bake and cold box sodium silicate binders.

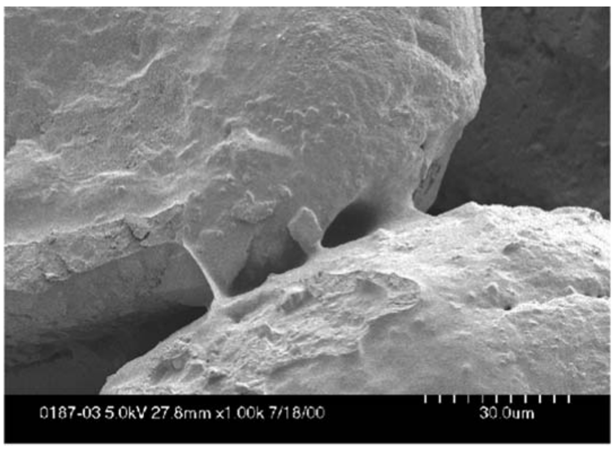
Collagen related binders

Collagen is the fibrous protein that strengthens skin, tendon and bones and is available in large quantities as a byproduct of the meat-packing industry. While at room temperatures it has strength comparable to steel, at high temperatures its strength is not sufficient to withstand a metal pressure. The inability of collagen alone to withstand temperatures of molten iron (1290–1510°C) is the key reason that it is not implemented by the industry.



7 Schematics of core manufacturing using GMBond organic binder[33]

An effort was made to produce a hybrid organic/inorganic binder by combining alkali-silicates with collagen.[37] A mixture included collagen, sodium silicate, C+K/Li silicate, C+Na silicate and traces of phenolic urethane. An extensive testing including TGA, hardness, dynamic mechanical analysis, hot distortion and molten iron erosion was conducted on collagen, hybrids and for a comparison also on sodium silicate and phenolic urethane. The results showed that collagen alone does not develop sufficient physical and mechanical properties to act as a core binder. However, the hybrids of collagen with lithium/potassium silicate or sodium silicate have favourable physical and mechanical properties. The hybrid properties are superior to those exhibited by conventional modified sodium silicate and phenolic urethane binders (Fig. 10).



8 Image (SEM) showing formation of bridge between silica sand grains in core, connected with GMBond organic binder[33]

Table 1 Comparison of core process parameters between Phenolic –Urethane Cold-Box (PUCB) and Resin–CO_2 from Honda[35]

Core process parameters, comparison

Parameter	PUCB process	Resin–CO_2 process
Binder (part I)	Phenolic resin/solvent	Phenolic resin/water
Co-reactant (part II)	MDI/solvent	None
Total binder component(s) addition	1·5% based on sand	2·5% based on sand
Curing gas	TEA (flammable)	CO_2 (non-flammable)
Total core box cycle time	No change	No change
Liquid parting used	Yes	No

α-starch composite binder

Starch is a high molecular polymer capable of swelling and retaining large volumes of water in a swollen state. It was found that the natural starch is not suitable for cores due to its high water absorption swelling and dehydration hardening during heating. As a result, the core strength is well below the level required. A new binder composed of α-starch, kaolin, sodium silicate, dextrin, phosphate and water in specific proportions was developed.[38] At high temperature the starch in the binder decomposes but the other components such as sodium silicate and phosphate react with kaolin, forming a heterogeneous network Al–O–Si, containing heat-resistant $AlPO_4$. Thus, the binder has good collapsibility and high temperature strength. The high temperature stability and stress–strain curves of the starch bonded sand in the heating process up to 1000°C are shown in Fig. 11. It looks that when the room temperature strength is sufficient, the starch content should be reduced to improve the high temperature properties of the core.

Commercial binders

The following inorganic binders are based on silicate compounds: Cordis, alternative warm-box binder (AWB), Inotec, Solosil, Amasilic, Nucelpon, Carsil, Amasilic and Geoset.

Cordis binders

Cordis is the inorganic binder developed by Hüttenes-Albertus (HA) Group. The development started in the 1990s with the basic goal to produce a binder system with water as the only solvent and a completely inorganic binder matrix, which, depending on the binder type, has a matrix consisting of a combination of phosphate, silicate, and borate. The idea is to use the binders in conventional core shooting machines and de-core the casting on equipment existing in the foundries.[39]

The Cordis consists of liquid silicate (Cordis resin) and a powder additive (Anorgit).[40] During processing, an irreversible cure is completed by a combination of dehydration and chemical reaction. The core boxes must be heated to approximately 149–177°C and the purged hot air accelerates cure to 38°C min^{-1}, where the system must be designed to maintain this temperature during cure to optimise the cycle time. Due to its good flowability, the Cordis binder can be used for cores with filigree contours, such as water jacket cores. According to HA, the Cordis binder can achieve cold bending strengths between 350 and 550 N cm^{-2}, depending on the sand and additive.[41] The binder is used for manufacturing of a cylinder head with gravity die casting of aluminium. No fumes or odors are released during the casting and there is no condensate in the die.

The unique feature of Cordis binder is a sequence of the gas release during casting. First, the gas is released only during a short period of time, approximately after 30–40 s of casting. As seen in Fig. 12*a*, hot-box cores release gas during the entire casting cycle. Moreover, the amount of gas released by Cordis depends on the grain size of the sand used (Fig. 12*b*). For the same amount of binder applied, the gas volume released from coarse grained sand is lower than that from the core made of the fine grained sand. Other benefits of Cordis binder include improved shake out, significantly reduced down-time required for casting dies cleaning, reduction of gas porosity from sand cores and better surface finish by using finer sand.[42] A comparison of gas emission for several binders is shown in Fig. 13.

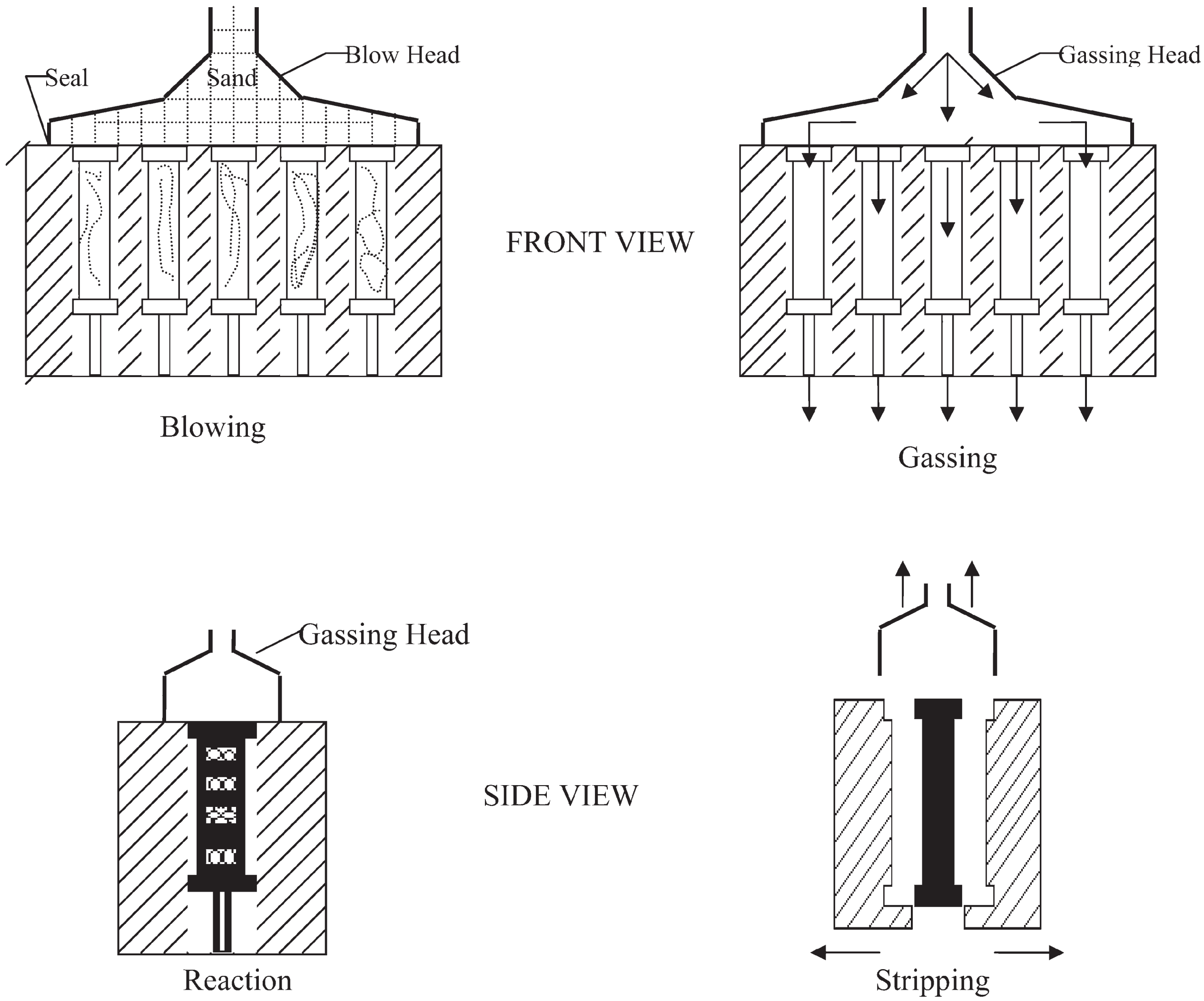
AWB binder

The AWB is an inorganic core binder developed by Nemak Dillingen, Audi and Minelco. As with most companies attempting to make an inorganic core binder, the objective was to develop an environment friendly and technically effective process for the production of

Table 2 Comparison of environmental performance between Phenolic-Urethane Cold-Box (PUCB) and Resin–CO_2 processes from Honda[35]

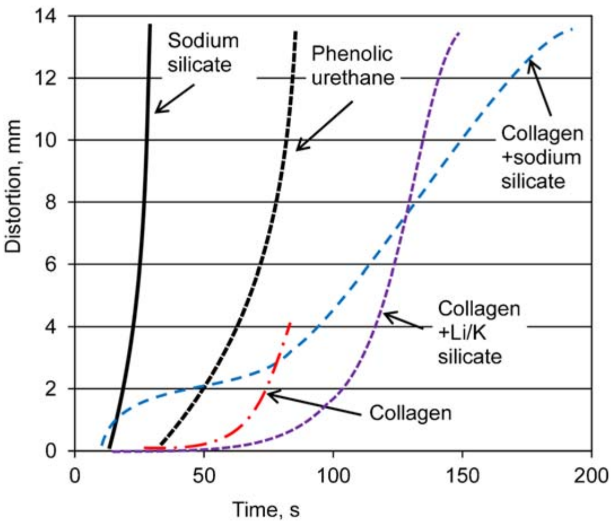
Environmental performance

Criteria	PUCB process	Resin–CO_2 process
Raw materials used per annum	227·7 ton	0·093 ton
Gas scrubber required	Yes	No
Respirator required	For TEA generator servicing	None
Tooling cleaner	Organic solvent	Water
Flammable binder system component(s)	Yes	No
% Free phenol in binder	6·6% Maximum	0·05% Maximum
% Free formaldehyde in binder	Less than 0·1%	0·15% Maximum

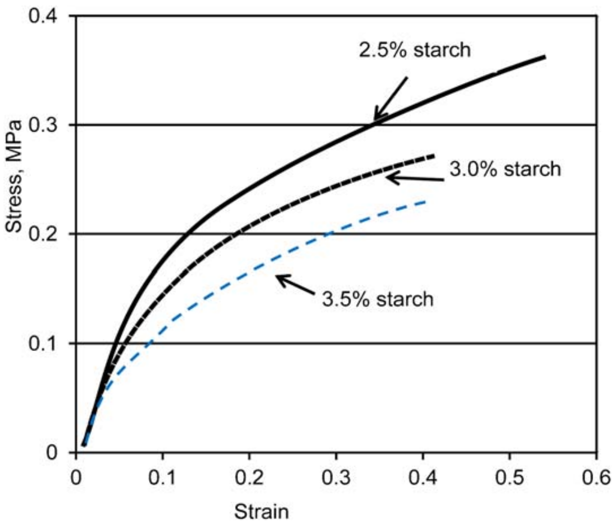


9 Core production cycle with organic binder Phenolic-Urethane Cold-Box (PUCB) by Honda[35]

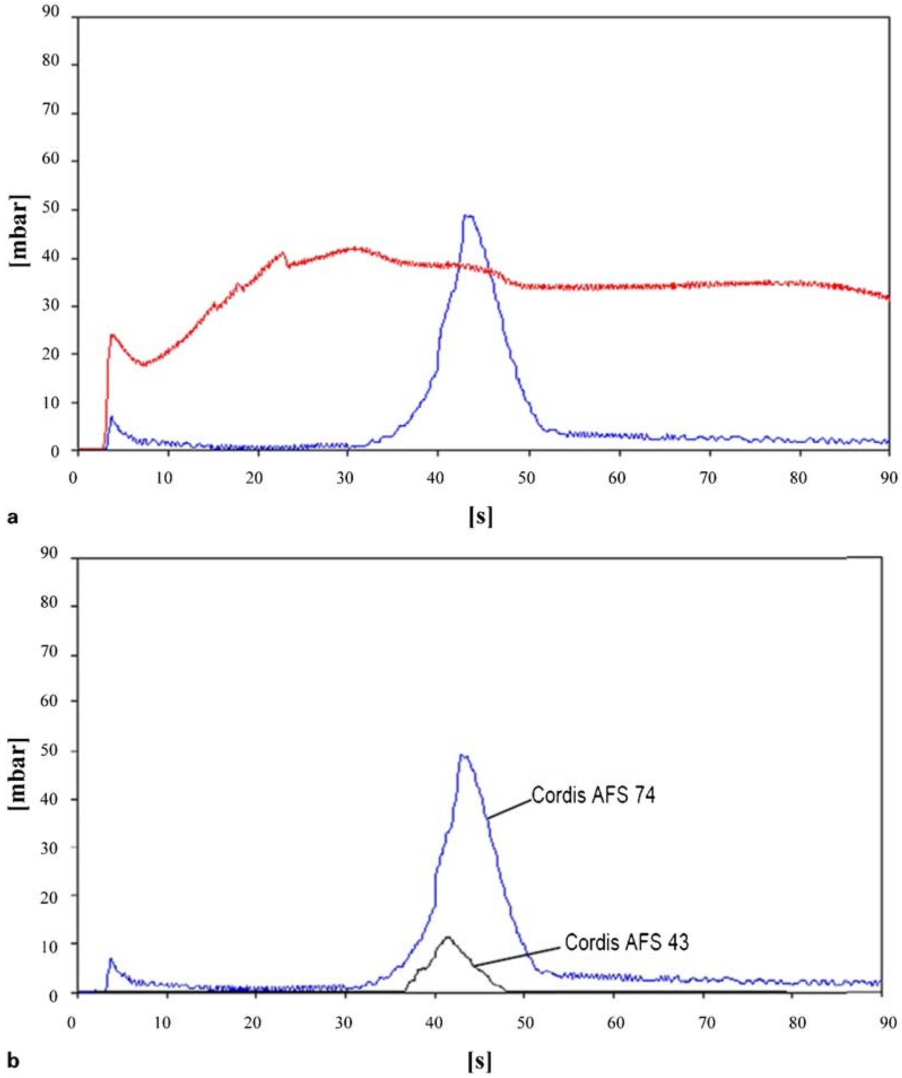
aluminium engine blocks. This casting consumes 30% less energy and reduces greenhouse gases emissions, deposits and waste water when using an inorganic binder.[43] Alternative warm-box binder is a sodium silicate binder with an additive of NaOH to optimise the process. The temperature used is approximately 138–200°C and there is a negative pressure within the core during shooting and curing. It uses a reversible sol-gel and the sand/binder mixture and can be stored for a long period of time if sealed properly. The AWB binding



10 Hot distortion test for cores manufactured with several types of binders[37]



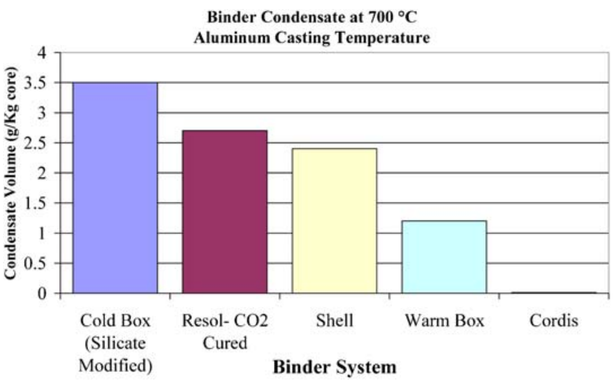
11 High temperature stress–strain curves of cores manufactured with binder containing α-starch[38]



12 ***a*** **release gas comparison between Hot-box (red) and Cordis (blue) cores and** ***b*** **release gas pressure curves of two Cordis cores with different grain sizes: AFS 74 – fine grain sand; AFS 43 coarse grain sand[39]**

process works by forming silicate bridges (Fig. 14). Alternative warm-box binder cores release less gases during casting compared to organic cores, therefore no gas cavities are formed.[44]

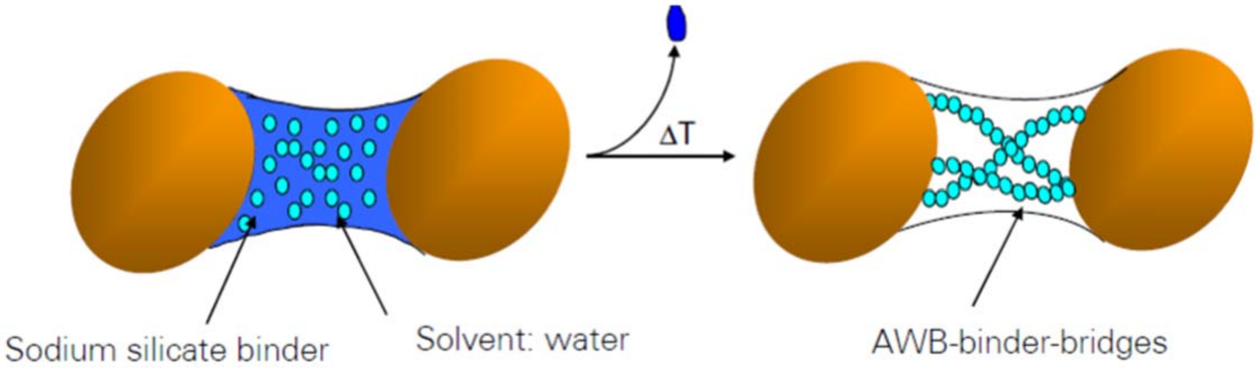
The AWB binder has an easy shake-out characteristics and the silica sand cores can be de-cored with already existing mechanical equipment. When using high quality sands, the cores start to disintegrate when the casting product is cooled down.[45] The bending strength of the binder depends on core material and core storage time under open storage conditions.[46] A comparison indicates a loss of core stability as storage time increases which is due to the loss of moisture. The shortcomings of the AWB binder include that the sand should not be mixed with organic systems and the core sands itself can get attached to casting since they tend to bind easily.[47]



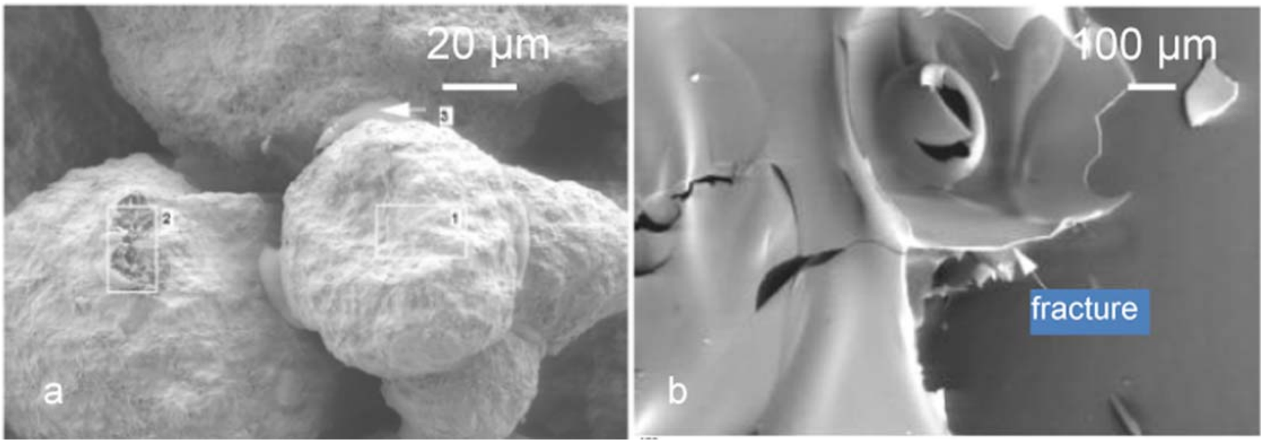
13 Comparison of condensate volume of Cordis binder with several other binders systems[40]

Inotec binder

Ashland, WD-Giesserei, Sud-Chemie, and BMW have successfully been using the Inotec binder. The Inotec plant produces a package consisting of various cores, including those to be used for the casting of cylinder blocks for the new highly efficient 6-cylinder diesel engine of BMW Group.[48] The Inotec binder developed by Ashland–Südchemie–Kernfest GmbH, is an inorganic and emission-free, based on silicate used for aluminium casting. Since air extraction and amine washing are expensive and time-consuming processes they substantially affect the core cost. The task of the binding agent is to bind the quarry sand used in the production of casting cores so it can withstand extreme temperatures of up to 900°C encountered in aluminium casting. This enables precise and faultless casting of



14 Schematics of bond formation by AWB binder[44]



15 *a* connection bridge between sand grains in AWB binder and *b* binder morphology after core fracturing[44]

complex mouldings such as cylinder heads and water cooling jackets.

According to investigation performed by International Foundry Research the use of the Inotec inorganic binder system not only increases the tool production but by reduced cleaning intervals for the core box and mould, it significantly reduces the cleaning costs for castings, where condensation of phenol binders is a key factor. The role of the Inotec binder in casting porosity is still under investigation.[49] Another inorganic binder, developed by Ashland, is called Ecoset. It is a phosphate binder and is made up of two components, a low viscosity liquid and a powdered hardener.[50] Ashland has other inorganic binders, as well, such as GeoSet.

Comparison of organic and inorganic binders

An investigation of inorganic and organic binders was a subject of Casting Emission Reduction Program.[51] The

Table 3 Tensile strengths of selected binders, NT – not tested[51]

Manufacturer/binder	Tensile dtrength in MPa at specific intervals			
	5 min	2 h	24 h	24 h humidity
Foseco Ecolotec 750	0·485	0·613	0·609	0·591
Hormel GMBond	33·431	344·171	47·238	4·235
HA International Cordis 8266 with Anorgit 8393	39·696	47·208	44·266	18·318
HA International Cordis 8323 with Anorgit 8370	28·630	37·594	39·262	4·583
Ashland GeoSet	32·155	45·933	46·833	5·482
HA International SigmaCure	NT	47·296	NT	NT

Table 4 Results for shake out test of selected binders[51]

	Foseco Ecolotec 750	Hormel GMBond	HA International Cordis 8266 W/ Anorgit 8393	HA International Cordis 8323 W/Anorgit 8370	Ashland GeoSet	HA 1·1% SigmaCure Phenolic Urethane	HA Cordis 4820BF
Average shake out rate (sand grams per second)	3	7·1	73·1	57·5	48·2	3·8	37·5

binders compared included Foseco's Ecolotec 750, Hormel's GMBond, HA Internationals Cordis (8266, 8323, 4820BF) and SigmaCure and Ashland's GeoSet. The summary is shown in Table 3. Of binders examined the Foseco's Ecolotec had the lowest tensile strength and the Cordis binder 8266 with Anorgit additive was the strongest. In the presence of humidity, the same Cordis binder still had the highest tensile strength. Ecolotec had the second highest and it did not lose strength at all. GMBond, Cordis, and GeoSet are all water soluble binders that are set based on a dehydration process. This is the main reason that they are affected by a presence of humidity. SigmaCure and Ecolotec are both phenolic urethane binders, which are not sensitive to humidity.

The shake-out test showed the inorganic based cores GeoSet and Cordis performed very well, as shown in Table 4. These cores completely shook out in an average of about 9 s. The organic based cores SigmaCure, GMBond, and Ecolotec did not shake-out at a rate as high as the inorganic based cores. The inorganic based binders shook out at a rate 10 times greater than the shake-out rate of the organic based binder. In absence of high humidity, the tensile strength performance of these binders was satisfactory.

Summary

The cores and binders are the important components of metalcasting operations. For decades the design and manufacturing of casting cores has created a constant challenge for foundries around the world. The growing complexity of core shape, high strength and core removal requires new materials for the core base, binders and coatings. In a quest for the perfect solution, the inorganic binders are receiving recently a renewed interest. At the same time the pressure on development better cores magnifies with increasingly stringent environmental as well as health and safety regulations.

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