Green Foundry LIFE project

LIFE17 ENV/FI/173

Action B3 Test series of molds, cores and casts produced by inorganic and organic binder systems

Deliverable DeB3A Test casts produced by inorganic binder systems in Karhula Foundry in Finland and Valumehaanika in Estonia

Authors:
Karhula Foundry Oy
Meehanite Technology Oy
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Content

1. Backround

This report combines the results and experiences from all the tests done with inorganic binder systems at Karhula Foundry during autumn 2018 to autumn 2020. Three different inorganic binder systems from three different manufacturers have been tested. Two binder systems are so called self-setting ie. they do not need any extra heat treatment. These binder systems achieve the required strength levels at normal room temperature. One binder system needs heating to about 150...200 C^{o} for example in a separate furnace or by blowing hot air into moulds and cores.

The results and experiences are presented separately for each binder system. In the end there is a chapter where the results are summarised and compared, and the suitability of each binder system for the production lines of Karhula Foundry are assessed.

Karhula Foundry had to withdraw from the project due to economic reasons caused by Covid-19 in 23th October 2020. Part of the planned tests were therefore missing. The remaining tests were made in a new pilot ferrous foundry Valumehaanika in Estonia during

Autumn 2021.

2. Karhula Foundry Oy

Karhula Foundry is over 120 years old foundry focused to produce demanding middle to large size special castings for global casting markets. The cast materials include wide variety of cast irons and steels, with the special emphasis on duplex, martensite, ferritic, austenitic and super-austenitic stainless steels.

At present the moulding lines of Karhula Foundry are using phenolic type organic binder system, Alphaset. The Alphaset System is a no-bake foundry binder system utilizing an alkaline phenolic resin cured by an organic ester. High quality silica sand is mainly used for moulds and cores. Zirconia based coating in alcohol solution is typically used to paint moulds and cores.

Karhula Foundry is located in Southern Finland, in the town of Kotka.

3. The inorganic binder system nr. 1.

This binder is based on modified alkali silicate. The hardener/promoter is 100 % inorganic, consisting of minerals and synthetic raw materials. After moulding, the moulds and cores must be dried by heating to temperature of 150...200 C^{o} to achieve the full strength.

(The brand name of the binder is Inotec EP 4703, Batch nr. 0000122367. The promotor is Inotec Promotor EP 4748, Batch nr. Hi190901. The agents were produced by ASK Chemicals and recommended for the planned tests by Oy LUX Ab Finland, which is a representative of

ASK Chemicals. LUX delivered the agents to Karhula Foundry)

3.1 Pretests with the binder system nr. 1

Preliminary tests were made in October 2018. These were made to study the effect of different compositions of binder and promotor on achieved strength as well as the effect of heating temperature and time.

The mixing was made by a small laboratory mixer made by Webac. New high-quality silica sand was used. Sand batches of 15 kg was mixed. Hand moulding was used and sand test bars were produced to measure the bending strength, photo 1.

Photo 1. Laboratory mixer, hand moulding and making of sand test bars.

The sand test bar mould weas heated in oven at 100 and 200 C° for 30 minutes. As a comparison one sand test bar mould was tested after two hours without heating. No strength could be measured from these test bars.

The bending strength was measured by machine made by GF, photo 2.

Photo 2. Bending strength test machine.

The results with different binder contents after heating in oven at 200 C° are below.

<u>2% binder, 30 minutes in 200°C oven</u> - Test bar 1: 280 N/cm2 - Test bar 2: 290 N/cm2

<u>1.5% binder, 30 minutes in 200°C oven</u> - Test bar 1: 140 N/cm2 - Test bar 2: 170 N/cm2

<u>1% binder, 30 minutes in 200°C oven</u> - Test bar 1: 35 N/cm2 - Test bar 2: 45 N/cm2

3.2 Chamber test with the binder system nr. 1

Chamber test was made in April 2019 to measure gaseous emissions from a test mould made by using inorganic binder system 1.

Mixing was made by the same laboratory mixer Webac as the preliminary tests. For the mould 7x 30 kg sand baches were mixed and binder and promotor was added to new silica sand. Binder was added after 10 s mixing and total mixing time was 80 s. Total sand + binder amount in the mould was 211 kg.

Cutted steel barrel was used as a pattern, photo 3, because a wooden pattern would have damaged in the needed heating.

Photo 3. Steel barrel as a pattern.

Photo 4. Hand moulding and heating oven. Temperature 160C^{o}, drying time four hours

After cooling, the mould was stripped and placed into a chamber. Holes for three thermocouples were drilled into the mould at 2,5, 5 and 10 cm distance from the steel surface, and at the depth of 25 cm, photo 5.

Photo 5. Test mould in the chamber, thermocouples installed.

Measurement arrangements are shown in photo 6.

Photo 6. Chamber test measurement arrangements.

Cast material was stainless steel and casting temperature was $1560C^{o}$, photo 7.

Photo 7. Chamber test casting.

After casting the cover of the chamber was closed and the measurement of the gaseous emissions and the temperatures inside the mould were started. Measurements were made for five hours. As a conclusion it can be said that the amount of gaseous emissions was drastically smaller compared to the organic binder chamber test: “*DeB1B Results of emission measurements of organic binder system chamber test casts in URV Foundry in Finland*.”

The results of this chamber test are presented in another document: “*De.B1A Results of emission measurements of inorganic binder system chamber test cast in Karhula foundry in Finland”*

The test mould was broken manually and the amount of loose material was collected and measured. There was around 1,5 mm thick burned black sand area around the casting, see photo 8.

Photo 8. Chamber test mould after cooling. Black burned sand around the casting.

The breaking of the mould was easy and the sand did not fix to the flasks, photo 9.

Photo 9. Breaking of the chamber test mould.

Loose material from the mould was collected and its weight was measured: 2,86 kg.

The surface quality of the casting was quite good, in spite that no coating was applied for the mould. Coating is a heat resistant material in a solution, and it is “painted” to the mould surfaces which will be in contact with melt metal. The solution is typically alcohol and heat resistant material is zirconia. The coating prevents the reactions between melt and mould.

Photo 10. Surface quality of the chamber test cast.

3.3 Production scale tests with the binder system nr. 1

Production scale tests with the binder nr. 1 were made in October 2019.
Sand used in these test moulds and cores was: 70 % recycled sand and 30 % new high quality silica sand.
The mixer was max. 500 kg mixer produced by Rojo, photo 11, and it was rented for this project purposes.
The sand amounts were measured by putting the mixer on a weight scale wagon, see photo 11.

Photo 11. The mixer and the method for measuring the amount of sand

Each time the aimed sand amount was 500 kg. Two different binder recipes were used. The amounts of the binder and the promotor were measured by accurate scale weight, see photo 12.

Photo 12. Measuring of binder weight

After filling the mixer by 500 kg silica sand solid promotor was added and mixed with sand for 3...5 min. After this the liquid binder was added and the mixer was used another 3...5 min.

The moulding

The moulding was made by pouring the sand mixture directly from the mixer into modelling rings or core packages, see photo 13. The moulds were patted by hand.

Photo 13. Moulding

Totally 15 different moulds were produced, some of them included cores.

The demand to dry the moulds and cores by heating at temperature 150…200C°, and the size of the available furnaces limited the size of production moulds to max 500 kg casting. The drying was made by using four core drying furnaces, see photo 14.

Photo 14. Core heating furnace.

The first moulds and core packages produced were heated for two hours at 160 C^o and then removed from the furnaces into the working area of the foundry. Temperature inside the foundry was about 16 C^o and relative humidity 65%. After cooling it was discovered that the drying time was not long enough for bigger moulds and core packages. Bigger moulds broke during opening or when removing the patterns, see photo 15.

Photo 15. Breaking of a core, due to lack of proper drying

Core packages are made of wood or polystyrene materials which are good insulation materials. Thereafter it was decided that the minimum drying time for cores and moulds is three hours. To ensure the complete drying most of the moulds and cores were left inside the furnace overnight. The furnaces were shut down and furnaces cooled to about 40 C^o by morning. Part of the moulds and cores were painted using TENO ZIR 78 coating. Industrial alcohol was used as a solvent. Drying of the paintings was made by flame burning and keeping them in core drying furnace for 15 min.

The moulds were placed on a casting wagon before casting, see photo 16.

Photo 16. Part of the test moulds on a casting wagon.

Test cast material in the first test cast was a special stainless steel grade acc. to ASTM A747 Cb7Cu-2. This grade was produced by the 8-tonselectric-arc-furnace and treated in AOD converter. In addition to test moulds there were enough production moulds made by Alphaset organic binder system, so that the full 8-tons charge could be used. The casting of the test moulds is shown in the photo 17. The pouring temperature of the steel was about 1515 C^{o}. Totally with this inorganic binder system 59 production scale moulds were produced by the foundry personnel. The weights of the castings varied between 30…500 kg, and total produced volume was 8,5 tonnes of castings.


Photo 17. Pouring of melted metal into the inorganic test moulds.

Findings and remarks

- Drying of the moulds and cores produced by inorganic binder system nr. 1 must be made well enough to reach the strength levels required. The size of moulds and possible insulations of core packages must be taken into consideration when heating times are decided. In these tests three hours at 160 C^{o} + cooling in furnace was enough for all tested moulds and cores.

- Wooden or plastic core packages cannot be heated to 160 C^{o} for several hours! They are more or less destroyed. The core packages should be made of metal.

- Binder nr. 1 sand shrinks during drying, about 1 cm in 500 cm high mould. This should be taken into consideration in pattern and core package design

- The amounts of binder and promotor used in the beginning of the tests seemed to lead very high strength levels after complete drying and caused heavy sticking on pattern or core package surfaces. This caused some cracks, see photo 18.

Photo 18. Cracks in the test mould due the high strength.

- Therefore the last mould series were made by using lower amount of binder and promotor. The strength levels of different compositions of inorganic binder systems nr. 1 will be tested in the Thesis work made by Mr Kalle Kekäläinen
- The personnel making the test moulds experienced some irritation, causing nasal discharge. The possible health risks involved in using Inotec should be clarified.

Conclusions with the tests made at Karhula Foundry by inorganic binder system nr. 1.

- It would be possible to produce proper moulds and cores with the binder system nr. 1.
- Gas formation is minimal compared to the current organic phenolic binder system Alphaset
- However the need for drying the moulds and cores in ovens at elevated temperature makes it practically impossible to use this binder system at Karhula Foundry:
    - The size of available furnaces would limit the casting size to under 500 kg, Big part of Karhula's present production is in size range of 1...10 tons castings.
    - Current wooden patterns and core boxes could not be used because they would be damaged at elevated temperatures.
    - Production capacity would be much smaller, if all moulds and cores should be dried in ovens.

4. The inorganic binder system nr. 2.

Binder system nr. 2 is inorganic sodium silicate solution-based binding and organic ester mixture based hardening agent system. Combined by ester hardener (catalyst) the binder system is "self-setting". This means that the binder + hardener reaches the required strength levels at normal room temperature and moisture without additional drying by heating. Typical composition is 2...3% binder of the sand volume. The amount of the hardener is 10% of the binder, accordingly 0,2...0,3% of the sand volume. The hardener being ester mixture the combination is not 100% inorganic.

(The brand name of the binder is Clean Cast S27. The hardener is Clean Cast K4. The agents were produced by Peak Deutschland GmbH and they were delivered as a free sample by Dr. Polzin from Peak.)

4.1 Pretests with the inorganic binder system nr. 2

Preliminary tests were made in December 2019. The representative of the binder system manufacturer was present. Tests were made to study the effect of recommended compositions of the binder and the hardener on achieved strength as well as the effect of coating on the surface quality.

The mixing was made with a small laboratory mixer made by Webac. New high-quality silica sand was used. Hand moulding of two test bar moulds was made and sand test bars were produced to measure the bending strength. The volume of one mixture sand lot was 25 kg. The compositions of the different recipes were tested.

Sand test bars were tested after 1, 4 and 24 hours. The first tests after 1 hour did not give any results because sand test bars were cracked during the stripping. After four hours the strength was 180 N/cm^2. After 24 hours the strength was 540 N/cm^2 which is higher than with the current organic Alphaset binder system used at Karhula Foundry (about 250...300 N/cm^2).

The test block moulds were stripped about 24 hours after moulding. Other moulds were coated with the normal alcohol based Zr coating (Solitec ST 901, ASK) Part of moulds were uncoated, photo 18.

Photo 19. Coated mould, left and uncoated mould, right.

Test casts

Test block moulds were kept in the working area for six days before casting. The casted steel grade is duplex stainless steel CD4MCuN ASTM A890 Grade 1B. The casting temperature of this steel about 1565C^{o}.
The surfaces of the test blocks are shown in photo 19. The surface quality of test bar from coated mould is

much better.


Photo 19. Test cast from coated mould, left, and from uncoated mould, right.

The results of the pretests with inorganic binder system nr. 2 were promising. The needed strength levels were achieved without any excess drying or heating treatment and the surface quality with alcohol based Zr coating was good. It was decided to proceed with this binder nr 2 into production scale test casts. It was also decided to make a chamber test to measure the total gaseous emissions from the mould, because this binder system includes organic agent, ester-based hardener. The representative of the binder manufacturer expected that the gaseous emissions would be under 10% of the emissions compared to the organic Alphaset moulds.

4.2 Production scale tests with the binder system nr. 2

Covid-19 pandemic prevented some test arrangements at Karhula Foundry during spring 2020 because no external personnel were not allowed to visit the foundry. The personnel continued test casts with the existing binder systems. The production scale test with binder system nr 2 were made in September 2020 when the pandemic situation in Finland was calmer. Mixing of the sand and binders were made by a 350 l size test mixer, photo 20. The mixer has normally been used to produce concrete and mixing efficiency and speed is slower than with typical foundry mixers.

Photo 20. Test mixer

(The binder used was “Clean Cast S27” and the hardener “K5”, photo 21.)

Photo 21. Cast Clean S27 binder and K5 hardener)

The volume of mixture sand lot in the test arrangements was between 350…400 kg, Different recipes were tested.

Mixing time was min. four minutes before the start of the moulding (after adding binder 2 min mixing + after adding hardener 2 min). Totally 60 production scale moulds were produced by hand moulding method, with the total produced castings volume of 13,9 tonnes. Due to experiences at preliminary tests, all moulds were coated with Zr + alcohol solution coating. Part of one mould is shown in photo 22.

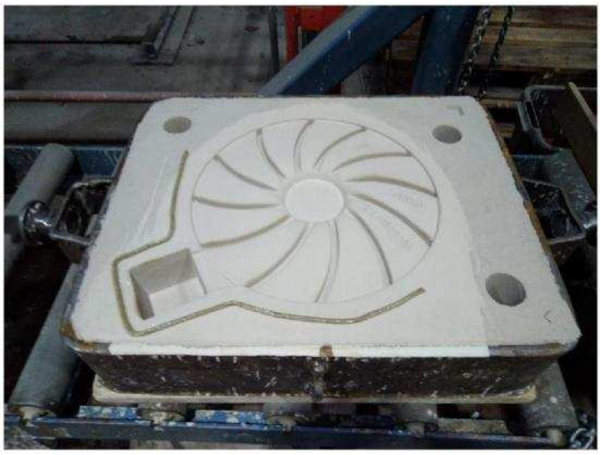
Photo 22. An example of coated mould.

Test moulds were kept in the working area at the temperature of 18...20C° for ca. 24 hours before casting. The casted steel grade of the first test cast was ASTM A 297 HH, which is a heat resistant austenitic stainless steel. The measured analysis of the test cast steel material: C 0,056%, Mn 1,37%, Cr 23,2%, Ni 12,4%. The measured casting temperature was 1501C°. The method of pouring can be seen in photo 23.

Photo 23. Pouring from a ladle

Practically no fumes were emitted from the moulds after casting, see photo 24, which is taken ca. four min after the pouring.

Photo 24. No fumes from the mould

Photo 25. Manual opening of moulds

There was a clear difference between the moulds which were filled first and which last from the mixer lot. Last moulds were much easier to broke (photo 25). Part of the waste sand was collected for recycling test purposes to be done in France by CTIF.

Quality of the test castings

The castings were sand blasted before cutting samples from them. The surface quality was checked by visual comparison using reference surface models. This system is used at Karhula Foundry, photo 26.

Photo 26. Reference surface quality models at Karhula Foundry

The surface quality of all test castings was A2 or A3, which is fully acceptable. Examples of the surface quality of test castings and typical casting made by organic Alphaset binder system is shown in photo 27.

Photo 27. Surface quality of castings made by using inorg. binder nr.2 (left) and Alphaset (right)

Possible defects and cracks were measured by dye penetrant inspection (DPI), photo 28.

Photo 28. Dye penetrant inspection (DPI)

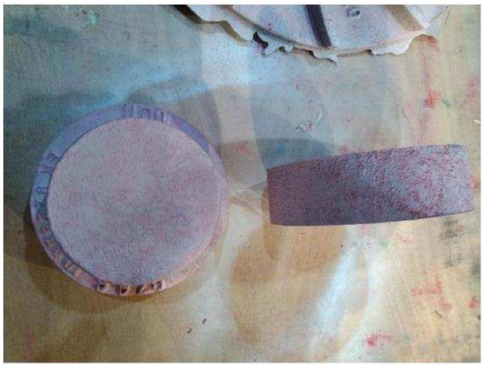

Photo 29. Dye penetrant inspected test castings. No cracks or gas porosity holes existed.

4.3 Chamber test with the binder system nr. 2

The chamber test was made to measure the total gaseous emissions using the inorganic binder system nr. 2. Based on the results from the test casts with this inorganic binder nr 2 it turned out to be more promising binder system for Karhula Foundry’s production than binder system nr. 1. Therefore the total emissions and environmental impacts were relevant to measure. This was an additional chamber test measurement but important for pilot foundries and for potential use in the future.

Chamber test with the inorganic binder system nr. 2 was made in October 2020.
Mixing of the sand and binders were made in a test mixer size of 500 kg, photo 30. Binder and hardener were added manually.

Photo 30. Test mixer, adding of binder during mixing

Photo 31. The binder and hardener used in the chamber test)

The measured volume of mixture sand lot was 287 kg. Different recipes were tested.

The pattern for the test mould is shown in photo 32. The diameter of the pattern is 350...330 mm and height ca. 350 mm and accordingly the estimated weight of the cast is ca. 210..220 kg.

Photo 32. The pattern for the chamber test mould

The moulding was made manually in about three minutes. The amount of the sand in the mould was measured: 204 kg, photo 33.

Photo 33. The amount of sand in the test mould

The temperature in the foundry was only 15Cº. The mould was therefore placed in the furnace for three hours with temperature of 25...32 Cº. Thereafter the pattern was stripped from the mould. Next day the mould was placed into the chamber and three thermoelements were located into drilled holes in the mould at the depth of 25 cm and they were at 2,5 cm, 5 cm and 10 cm distance from the steel surface, photo 34.

Photo 34. Test mould inside the chamber. The locations of the thermoelements.

The steel was poured into the test mould about 22 h after moulding. The cast material was duplex stainless steel of the grade ASTM A890 3A. The analysis of the test cast steel material: C 0,03%, Si 0,79%, Mn 0,5%, Cr 24,5%, Ni 5,2% Mo 1,9%.

The temperature of the steel was measured just before pouring: 1564 C^{o}. The pouring is shown in photo 35.

Photo 35. Pouring into the chamber test mould

After pouring the open top surface of the molten steel was covered by exothermic powder.

Thereafter the hole in the cover of the chamber was closed and the measurements of gaseous emissions and temperatures inside the mould were started, photo 36.

Photo 36. Chamber test after closing the cover.

When the temperature in the mould was dropped to under 200 C^{o} about 24 hours after the pouring the test casting was lifted from the mould. Loose sand from the mould was collected and the weight of it was 5,3 kg photo 37.

Photo 37. The amount of loose sand

The test casting was sand blasted and the weight 204 kg. The surface quality of the test casting was poor, photo 38. The reason was that no coating was used. Previous tests have shown that by using alcohol-based zirconia type coating in the moulds made by inorganic binder system nr 2. the surface quality was as good as the castings made by using organic Alphaset binder systems and the same coating.

Photo 38. Surface quality of the chamber test casting (after sand blasting), no coating was applied.

Measurement arrangements and the results from this chamber test will be presented in a separate report.

5. Inorganic binder system nr. 3.

This binder is an inorganic geopolymer precursor with a low degree of polymerization. Liquid hardeners added to the mixture are used for hardening. During the hardening reaction polymerization increases and an inorganic polymer is formed. Inorganic binder system nr. 3 is used for the production of moulds and cores from self-hardened mixtures.

Photo 39. Geopol 618 binder and SA73 hardener

5.1 Production scale test with the inorganic binder system nr. 3

The same mixer was used as with the inorganic binder system nr. 2. The volume of mixture sand lot in the tests was ca. 300 kg. Different recipes were tested.

Mixing time was min. four minutes before the start of moulding (after adding hardener 2 min mixing + after adding binder two min). Totally over 60 production moulds were produced by hand moulding. The gross weights of the steel needed for moulds were between 28….2500 kg, and total produced volume of test castings was 19.8 tonnes. One pattern of the production test cast is shown in photo 40.

Photo 40. The patterns of one test mould

In addition to production scale test moulds also 6 sand test bars were produced. Mixed sand for sand test bars was taken from mixer after moulding all production moulds, ie. 9..10 min after start of the mixing.

Sand test bars were bend tested after 1, 4 and 24 hours. The results:

- 1h: ca. 25N/cm2
- 4h: ca.60N/cm2
- 24 h: ca 115 N/cm2, see photo 41.

Photo 41. The result of sand bar bending test after 24 h.

Normally Alphaset binder system is used at Karhula Foundry and it gives the result at sand bar bending test after 24 h about 250 N/cm^2.

The test block moulds were stripped about 24 hours after moulding. During stripping it was discovered that the moulds that were filled first from one sand batch were clearly harder compared with the moulds which were filled last. If the sand test bars would have been made just after 4...5 min mixing would have given higher strength values. To see the effect of mixing time sand tests were later repeated at FinnRecycling laboratory. The sand samples for test bars were taken after 1 and 10 min mixing in kg laboratory mixer. The results:

After 1 minutes mixing:
- 2 h: 79 N/cm
- 24 h: 131 N/cm^2

After 10 minutes mixing:
- 2 h: n/a
- 24 h: 30 N/cm^2

Accordingly bench time with this recipe is under 10 minutes. The actual bench time must be studied before continuation of production scale tests.

The previous tests with organic and inorganic binders have shown that moulds made of silica sand need the coating to achieve the acceptable surface quality in steel castings. Therefore all test mould were coated with typical alcohol based zirconium type coating Tenozir 78 (Foseco), photo 42.

Photo 42. Coating of the test moulds

Test cast materials

Test moulds were kept in the working area at the temperature of 18...20C^o for ca. 24 hours before casting. The casted steel grade in the first test casting was ASTM A 297 HH which is a heat resistant austenitic stainless steel. The measured analysis of the test cast steel material: C 0,056%, Mn 1,37%, Cr 23,2%, Ni 12,4%. The measured casting temperature was 1501C^o. Practically no fumes were emitted from the moulds after casting, photo 43, taken ca. four min after the pouring.

Photo 43. No fumes from an inorganic mould

As comparison, gaseous emissions are much bigger when using organic Alphaset binder system. Photo 44 shows how much fumes are emitted from an Alphaset mould (four minutes after pouring).

Photo 44. Fumes from an Alphaset mould

Breaking the test moulds

Moulds were broken manually using hammer, photo 45.

Photo 45. Manual crushing of moulds

There was a clear difference in moulds which were filled first and last from a mixer lot. Last moulds were much easier to broke. Part of the waste sand was collected for recycling test to be done in France by CTIF.

The quality of the castings

The castings were sand blasted before cutting samples from them. The surface quality was checked by visual comparison using reference surface models. This system is used at Karhula Foundry, see reference tables in chapter 4.2.

The surface quality of test castings was A2 or A3, which is fully acceptable. Examples of the surface quality of test castings and typical casting made by organic Alphaset binder system is shown in photo 46.

Photo 46. Surface qualities of castings made by inorganic binder nr.3 (left) and Alphaset (right).

Possible defects and cracks were measured by dye penetrant inspection (DPI).

DPI did not reveal any cracks or gas porosity holes in the test casts. Examples of the test castings are shown in photo 47.

Photo 47. Dye penetrant inspected test castings. No cracks or gas porosity holes.

6. Conclusions from the tests in Karhula Foundry

The planned actions of Karhula Foundry in Action B1 “Emissions of different binder systems during small-scale test casts” are fully completed. Chamber test with two different inorganic binder systems has been accomplished instead of planned one chamber test.

In action B3 “Test series of molds, cores and casts produced by inorganic and organic binder systems” targeted actions of Karhula foundry are completed by ca. 60%.

The reasons are eg. the problems with the first tested inorganic binder system which required drying at elevated temperature in oven. Karhula Foundry does not have moulding line which is equipped with such ovens. Drying was made in separate small ovens and due to incomplete drying many of the test moulds and cores were broken already during stripping, before casting. Several tests were made with the test mixer to find the optimum parameters for mixing time and the contents of the binder and promotor. Part of the moulds did not harden enough due to improper parameters, and they had to be scrapped. The size of the available ovens also limited the sizes of the test moulds so that the maximum weight of the test casts was 500 kg with this binder. The sizes of the test casts were smaller than planned, but more moulds were produced than originally was planned. Totally over 60 tests moulds were produced by this binder, but ca. 25 % of them had to be scrapped before casting. The quality of the successful tests casts was however good.

The tests continued with two other inorganic binder system. With these inorganic binder systems there were not such problems as with the first one because they were so called “self-setting” and achieved required hardness levels at room temperature and did not require separate drying at elevated temperature. Several mixing tests to find proper parameters for mixing time and compositions of binder and hardener was made also with these inorganic binder systems. Ca. 10% of the moulds had to be scrapped due low hardness caused by too long mixing + moulding time or due to wrong recipe of binder and hardener. It was decided to produce much more, but smaller, tests cast than originally was planned. This was made to achieve statistically more reliable results. Totally over ca. 60 test moulds were produced by each of these inorganic binders. The weight of the test casts varied between 15 kg to 2500 kg. Surface quality of the tests casts was good, similar to the casts made by organic Alphaset binder system, when the same coating was used for mould surfaces.

Aim was to find the potential and feasible inorganic binder system to be introduced in future at Karhula Foundry. Test casts were first produced under supervision of the binder system manufacturers and Meehanite personnel and emission measurements were carried out by AX Consulting. After the pretests the foundry personnel continued tests with the suitable inorganic binders. More small scale test casts with different inorganic binders were tested and therefore also more personnel work was needed. In total 180 production scale test moulds were produced during test periods. Volume of test castings with inorganic binder moulds was 42,2 tonnes. At the same time comparative castings with the volume of 39,2 tonnes were made by current organic binder system.

Due to positive results with inorganic binders Karhula Foundry planned to go on working with them to be able to implement inorganic binders in everyday practices. Two of the tested inorganic binder systems would not need any major investments in addition to the moulding line. However, the inorganic binder system which requires drying at elevated temperature, would necessitate an investment into a new moulding including on-line heating ovens.

Due to economic reasons Karhula Foundry had to withdraw from the project in 23th October 2020. Therefore the still remaining tests were carried out in a new pilot ferrous foundry, Valumehaanika AS in Estonia.

7. Valumehaanika AS

Valumehaanika AS (VM) is small iron foundry locating in Tartu, Estonia. The foundry has been founded already in 1966 but is has been recently renovated. VM has now modern equipment, including 3 years old induction furnace with the melting capacity of 750 kg, photo 48, and continuous mixer line, photo 49.

Photo 48. Induction furnace

Photo 49. Modern continuous mixer.

The current binder system is the same as in Karhula Foundry, phenolic Alphaset system.
The used foundry sand is silica sand and it is from Estonian origin. The datasheet of the sand is in Annex 1.
The moulds and cores are made by hand. Typical casting sizes vary between 5…100 kg, and they are used eg. in machines, generators, furnaces and other heating equipment. Total annual production is ca. 200 tons of castings, and work force is ca. 10 employees.

8. Tested inorganic binder systems in Valumehaanika

The currently used organic binder system, phenolic Alphaset, is so called self-setting. It means that the hardening happens at ambient temperature, without any need for heating or gas blowing. VM has no equipment for heating or gas blowing of moulds and cores. Therefore, the only feasible inorganic binder systems are self-setting or "no-bake". These systems harden at ambient temperature because the used hardener is organic ester.

Tested two no-bake systems were:

- Cast Glean S 27 binder and Cast Clean K4…K6 hardeners, made by Peak Deutschland GmbH, see photos 50 and 51.
- Geopol 618 binder and SA73 hardener, made by SandTeam, photo 52.

Photo 50. Binder Cast Clean S27

Photo 51. Hardener Cast Clean K6

Photo 52. Geopol 618 binder and SA73 hardener from SandTeam

8.1 Tests with Peak's inorganic binder system

Peak Deutchland GmbH in Nossen, Germany is producing a variation of sodium silicate solution binding and ester based hardening agents. Cast Clean S27 is designed for ferrous castings. Combined by ester hardener (catalyst) Peak's inorganic system is self-setting. This means that this binder + hardener reaches the required strength levels at normal room temperature and moisture without additional drying or heating.
Typical composition is 2…3% binder of the sand volume. The amount of the hardener is 10...12% of the binder, accordingly 0,2…0,3% of the sand volume. The hardener being mainly ester, the combination is not 100% inorganic. Based on Peak's experience, the gas formation is, however, expected to be only 10…15% compared to alpha set type phenolic binder system. The chamber test made in Karhula Foundry in autumn 2020 proved that this is true.
There are 7 types of hardeners K1…K7. The bigger the number, the faster is the hardener. Working times are 30 (with K1) …2 (with K7) minutes. The stipping time is 2…2,5 times the working time.
The tests were made in the production line using the continuous mixer. In the mixer, there are four pumps, one for the binder, two for different "speed" hardeners and one for water (for cleaning). Peaks binder and hardener can be connected to the pumps, which normally are pump Alphaset binder and hardener, without any changes or modifications. The binder and hardener are injected to the sand stream continuously in the mixer. Different recipes of the binder and hardener were tested, to find the most feasible for the current production and production conditions (ambient temeperature).

The moulding was made by hand, see photo 53.

Photo 53. Hand moulding in Valumehaanika

The hardening times with this binder system are dependent on ambient temperature: the lower the temperature, the slower is hardening. The ambient temperature was only 12 ºC, and hardening time with the first recipe was too slow for the normal production rate. The stripping could be made 45…60 minutes after moulding, and the roller track filled with moulds waiting for stripping. Due to slow hardening rate, more faster recipes of binders and hardeners were later used. Examples of the moulds after stripping are shown in photo 54.

Photo 54. Test moulds after stripping

The moulds were coated by alcohol-based zirconium coatings. The coatings were dried by flame burning. The examples of the coated moulds are shown in photo 55.

Photo 55. Coated test moulds made by Peak's binder system

The test castings of the moulds made by Peak's binder systems

Normally the test castings were made next day and accordingly the moulds had 18…24 h time to harden. The target composition of the melted gray cast iron: C: 3,3%, Si 1,7%, Mn 0,9%. The grade of this cast iron type corresponds to the norms EN GJL-250 and GG25 in DIN 1691. The casting temperature was ca. 1450 ^{o}C. The photo 56 shows one example of the pouring into test moulds.

Photo 56. Pouring into test moulds made by Peak's binder system

Practically no fumes were emitted from the mould after pouring the melt into the moulds. The moulds were broken next day by hand hammering and cleaned by shot blasting machine, photo 57. In photos 58 and 59 are shown some of the test castings before and after shot blasting.

Photo 57. Shot blasting machine in Valumehaanika.

Photo 58. Test castings before shot blasting.

Photo 59. Photo 58. Test castings after shot blasting.

The surface quality of the test castings was comparable with the castings made by organic Alphaset moulds. The sticking of the sand to surface was, however, slightly stronger with test castings, and somewhat longer shot blasting times were needed.

8.2. Tests with SandTeam inorganic binder system

SandTeams inorganic binders are based on Geopolymers. Geopolymers are purely inorganic materials; they belong among alkaline aluminosilicates. These materials contain silicon, aluminium and an alkaline element such as sodium or potassium. In nature, such materials occur as zeolites. Geopol, however, is not formed by geological processes, but is artificially prepared. Geopol is called geopolymer because its composition is close to the composition of natural rocks.

The hardening material is similar as with Peak,s binder system, ester, and Geopol binder system is also self-setting ie. “no-bake”.

SandTeam has developed different modifications of Geopol and SA hardeners. The tested binder is Geopol 618, which is recommended for ferrous castings. SA hardeners are classified so that SA 71 is the slowest and SA 76 is the fastest.

The hardening time is dependent on ambient temperature also with Geopol binder systems. The measured ambient temperature was very low, only 8…11 ºC, during the moulding with Geopol binder system. Different recipes of hardeners were used to find the most feasible combination, but due to low ambient temperature, only the fastest hardener available SA 75 was used.

Geopol binder and SA hardeners can be used with the same mixer pumps as Alphaset binder and hardener, without any modifications and adjustments. The Geopol 618 binder and SA 75 hardener were connected by pipes to mixer pumps similarly as with Peak's binder and hardener, without any problems. Only the setting values were set to give the planned recipe.

The hardening happened slower than expected, even taking into account the low ambient temperature. Some of the bigger moulds broke during or after stripping, due to too slow hardening, photos 60 and 61.

Photo 60. Mould made by Geopol, broken during stripping

Photo 61. Mould made by Geopol, broken after stripping

One factor in hardening rate is foundry sand quality. Before the tests in Karhula Foundry, a sample of 10 kg foundry sand was sent to SandTeam's laboratory, and they cave the recommendations of the recipe based on laboratory studies. It was now assumed, that Valumehaanika's sand quality is similar as the sand quality in Karhula Foundry.

Several test series were, however, made also with Geopol binder system, with a slower production speed, to allow the moulds to harden enough before stripping. The Geopol moulds were also painted by alcohol-based zircon coatings. The coatings were dried by flame burning, figure 62.

Photo 62. Drying of the coating of Geopol moulds with flame burning.

The test castings of the moulds made by SandTeam binder system

The test casts were made 3…27 h after the producing the moulds. The iron quality was the same as with Peak’s moulds, gray cast iron type corresponding to the norms EN GJL-250 and GG25 in DIN 1691. The casting temperature was ca. 1450 ºC.
In one mould there was a small leakage between the mould parts, see photo 63. It was expected to be caused by unproper sealing of the mould parts, not by breakage of the moulds.

Figure 63. Example of pouring into tested Geopol moulds. Small leakage in one mould, left.

The fume emissions were negligible also with Geopol moulds, see photo 64.

Photo 64. Geopol test mould. No visible fumes were emitted (5 min after pouring).

The moulds were broken next day by hand hammering and test castings were cleaned by shot blasting machine, similar way as with Peak’s test castings. Surface quality was comparable with castings made by Alphaset moulds. Due to slightly stronger sand sticking longer shot blasting times were needed. Figure 65 shows examples of the test castings made by Geopol binder system.

Figure 65. Test casting made by Geopol binder system.

9. Continuation of the tests in Valumehaanika

During the supervision on the tests, totally 2,9 tons of test castings were produced by using these two inorganic binder systems. At the same time totally 4,5 tons of comparison castings were produced by using organic Alphaset binder system. The sizes of the test castings were 20…550 kg.
Production personnel of Valumehaanika continued the tests with these two inorganic binder systems during the autumn of 2021. Totally 19,7 tons of test castings were made by using inorganic binders. This volume includes the test castings made during supervision. Totally 16,5 tons of comparison castings made by using organic Alphaset binder system. The total volume of test castings with inorganic and organic binder systems is 36,2 tons. The size range of the test castings was 20…870 kg.

10. Findings and conclusions of the test in Valumehaanika

Both Peak's Cast Clean and SandTeams Geopol inorganic binder systems are suitable for Valumehaanika's current production line equipped with modern continuous mixer. The mixer pumps can be used without any modifications with both inorganic binder systems, instead of the current phenolic organic Alphaset binder system hardening rate with both inorganic binder systems was slower that with Alphaset low ambient temperature, 8…12 ºC, was the main reason for slow hardening rate. Also Alphaset hardens slower in cool temperatures, but the rate can be adjusted by using faster hardeners. Both inorganic binder systems have also fast hardener types. However, the hardening rates with the fastest hardeners available were slower than anticipated by the binder producers one factor of the slow hardening rate could be the used sand quality. The Valumehaanika's sand sample must be sent to SandTeams's laboratory for studying it's effect on hardening rate the quality of the test castings was comparable with current Alphaset castings.

Valumehaanika is willing to go on with the demonstrations with inorganic binders. They are a potential partner in the new LIFE project proposal "Green Casting LIFE". The idea is to invest a separate moulding line only for inorganic binders.

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11. Experiences and lessons learnt from test casts in Karhula Foundry and Valumehaanika

The main experiences from the production scale tests:

- Inorganic binder systems can be used in ferrous foundries instead of phenolic Alphaset binder system
- The quality of the moulds and castings is comparable with castings made by Alphaset moulds
- The self-setting inorganic binder system behave quite similarly as Alphaset, and in some cases same moulding equipment can be used
- Inorganic binder systems which need a drying at elevated temperatures are not feasible for production of bigger ferrous castings. The patterns and core boxes should be made of heat resistant material such as metal. This is extremely expensive. Moreover the production speed would slow down due to the long time needed for heating big moulds and core boxes thoroughly. The time needed could be up to several days.

To implement inorganic binders in full scale production in ferrous foundries, the following must be taken into account:

- Vast knowledge is needed about different inorganic binder systems and their proper implementation into current or new production lines.

- Individual implementation plan for each foundry must be prepared including suitable inorganic binder systems for the foundry’s production lines and products, and technical and economic information about possibly needed investments
- In most cases investments for moulding, core making and sand regeneration methods are needed and broad preliminary testing should be carefully carried out before commitment.
- Traditional nature of the branch opposes reforms: there should be successful example cases of replacing the organic binder systems by inorganic binders, so that new ferrous foundries would dare to start the change and introduction of inorganic binder systems in full production scale.
- Suitable sand reclamation system should be tested for inorganic binder system waste sand. In case foundries take inorganic binders in use in part of the production or for some products it is necessary to solve the sand reclamation system because different waste sand