LIFE17 ENV/FI/000173

Green Foundry

1/7/2018-30/6/2022

Action B5 Replication and transfer of the project results

DeB5.2 Conclusions and outcomes of the Green Foundry project

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1. Content

2. Introduction

The main objective in the Green Foundry LIFE Project (LIFE17 ENV/FI/000173) was to evaluate the possibility of transferring such benefits to the casting of iron and steel. The application of modern sand moulding systems based on inorganic binders would have a significant positive environmental and economic impact leading to increased competitiveness of the industry.

So far new silica based inorganic binders have been established in few aluminium foundries which have demonstrated to contribute to a decrease in hazardous air emissions and an improvement of indoor air conditions at the workplace when compared to organic binder systems. Besides, the reduction of harmful substances in foundry sand that goes with the use of these types of binder has a major influence on the possibilities for treatment of such wastes and accordingly reduces the amount of foundry sand to be landfilled.

In the Green Foundry LIFE project the use of various inorganic binder systems were experimentally tested in three pilot foundries and the impact on product quality as well as the integration in established process chains were evaluated. Dedicated emission measurements were performed in small scale chamber tests and foundry conditions with different organic and inorganic binder systems to measure the emission reduction and improvement in indoor air quality when exchanging to inorganic binder systems.

Furthermore, the treatment of inorganically and organically bound waste sands were demonstrated and investigated focussing on techniques like composting as well as thermal reclaiming and washing. Mechanical, hydromechanical and ultrasonic methods were tested with inorganic binder system waste sands on laboratory scale tests. For the implementation of the inorganic binder system in ferrous foundries one of the critical issues is to find a suitable treatment method or reuse applications for the waste sand. The findings of the project are fed into the currently running process of developing a new best available technology reference document (BREF) for the smitheries and foundries industry.

In this report the experiences and main results of the Green Foundry LIFE project are presented and the sustainability and technical readiness of the demonstrated technologies are evaluated.

In this report following themes are discussed:

- Applicability of inorganic and organic binding systems in different sand foundry types
- Results of the test casts carried out in the pilot foundries in the Green Foundry LIFE project
- Results of the small scale chamber tests and emission measurements carried out with organic and inorganic binding systems
- Solutions to improve foundry ventilation systems. Practical solutions for general and local ventilation systems and solutions for the sand mould shake-out system.
- Solutions for inorganic and organic surplus foundry sand cleaning and reuse methods. Reuse options of foundry waste sands in partner country are also presented.

2.1 Main concern and state of the art

The **European ferrous foundry industry** is the third largest in the world for ferrous casting (www.caef.eu/downloads-links)**, after China and India,** and are responsible for **15% of the global production**.
Iron and steel industries belongs to the energy intensive industries (EIIs) groups which are considered to be highly energy intensive. In 2020, the European ferrous foundry sector was composed by **1652 ferrous foundries** which produced **9,1 million tons of casting** (www.caef.eu/downloads-links). Higher figures are expected to be reached for 2021, closer to the ones from 2019, as a drop was clearly seen due to Covid crisis (In 2019: Production reached 11,5 million with a number of more than 1700 foundries).

The ferrous foundry industrial sector is central for Europe economy and production, it covers many crucial and needed activities such as automotive (>50% of the market share), railway systems, mechanical engineering, shipyards, wind turbines etc. With the will to enhance the strength of the industrial sector, be more competitive and less dependant of third countries, **supporting changes in this traditional foundry sector towards greener and more sustainable production processes is a core issue and a big challenge.**

Nowadays the majority of European foundries use **green sand system (bentonite sand) for moulding** with **chemical cores**. Only **1% of the foundries use inorganic system for mould and core manufacturing in Europe** (Huttenes Albertus, 2018) and most of those foundries correspond to light metals, mainly aluminium. The opposite Figure 1 shows the share of use between green sand and chemical binders (in the red circle).

The classification of the chemical binders is based on **how they are hardened physically**, the following three categories appear: SELF-SETTING (also call NO BAKE), COLD BOX and HOT BOX. And the Figure 2 depicts the nature of the chemical binders.

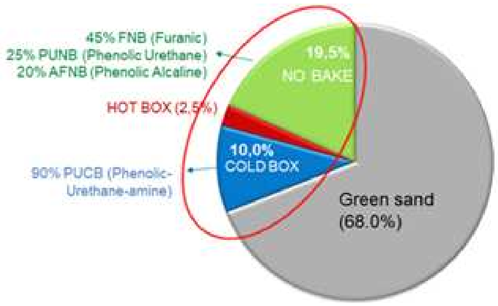

Figure 1: All foundry moulding systems, including green sand. Source: Courtesy of Huttenes Albertus Ilarduya

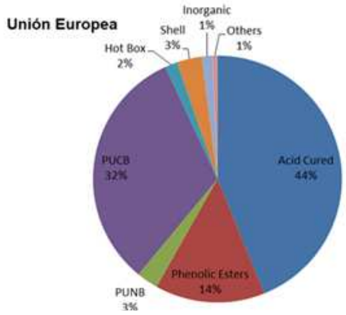

Figure 2: Chemical binders composing the groups (hot box, cold box, self-setting) in EU. Source: Huttenes Albertus Ilarduya

Inside each category of the chemical binders, there are plenty of them. The Table 1 below gathers the most used ones classified per categories.

Table 1 Most used binders from each binder families

Families	Description	Mostly used binders
SELF SETTING (No bake)	Chemical process where the mixture of silica sand and resin/binders is mixed with a liquid catalyst that reacts at room temperature. In Europe, approximately 70% of the foundries that works with chemical binders uses NO BAKE processes for mould and core making.	PUNB: Phenolic Urethane No Bake Acid cured: Furanic binders Phenolic Esters: Phenolic Alkaline (also called ALPHASET)
COLD BOX (Gas-Hardening process)	The mixture of silica sand and resin is hardened with the contact of a vaporized catalyst (CO2, amine...etc.). Example: Silicate-CO2, isocure system...etc.	PUCB: Phenolic Urethane Cold Box, (also called ISOCUPE) is used and widely for core making in green sand processes.
HOT BOX (Heat Curing Process)	The mixture of silica sand and resin reacts with a heat source. it is called "Hot box" when the temperature ranges between 180 - 280 ºC and "Warm box" between 100-160ºC	UREA-modified furfuryl alcohol resin and phenolic resin

The chemical binders, depicted in the Figure 2 above (mostly furanic/phenolic resins) and also green sand moulds bonded with bentonite and charcoal undergo thermal decomposition when exposed to the very high temperatures. During casting, the temperature is typically in iron and steel casting between 1.400ºC and 1550ºC, where pyrolysis or an incomplete oxidation of the binders occurs forming hazardous (GHGs, NOx, Fine Dust), carcinogenic (Polycyclic Aromatic Hydrocarbons PAH) and mutagenic compounds (Benzene, Toluene, Ethyl Benzene and Xylene BTEX) which can cause even cancer. These compounds form because of the incomplete oxidation during casting.

Emissions produced during casting are the key environmental concern for the sector.

In addition to the undesirable emissions described, casting processes produce a huge amount of undesirable waste. **90% of ferrous foundries are using sand casting,** making and intensive use of sand as an inert primary material, and generating more than **6 million tons of spend foundry sand in Europe** per year, being most of them landfilled. Waste foundry sand represents approx. **60-85% of total solid waste from foundry industry (**BREF Smitheries and Foundries 2005). Thus, the regeneration and reuse of sand are crucial.

3. Applicability of inorganic and organic binding systems in different foundry sand types

Pressure to change from organic to inorganic binders

The inorganic binder technology for core and mould production has previously been limited to large-scale applications in light metal casting. In iron and steel casting, inorganic binder systems also have enormous potential as an emission-free system alternative to organic binder core and mould production processes.

Due to political and legislative measures, the provisions of Technical Instructions on Air Quality Control have already been tightened, likewise limits of DOC and other harmful elements concerning deponing and use of surplus sand have been already limited and will also be subjected to further restrictions in the future. However, there are still no large-scale applications for this technology from light metal to cast iron and steel since the transfer is associated with fundamental challenges in tooling and production processes.

Several materials science and technological hurdles must be overcome first. The processes and sand systems are more complex and the requirements for the thermal resistance of the binder are significantly higher: the casting temperature is 650…900^{o}C higher, which is inevitably associated with higher mechanical and thermal strain of the binder system.

Nevertheless, inorganic binder systems offer significant advantages. Primarily, no harmful and volatile compounds are released during the core production, core storage, or casting processes. As a result, no complex and cost-intensive air treatment systems are necessary. In addition, the risk of traditional casting errors, such as gas bubbles or veining, is reduced by inorganic binders, which eliminates post-processing steps of castings and potentially reduces scrap rates. The economic, ecological, and technological benefits are offset by an initial investment volume for the core shooting machines and heat standing core and moulding tools.

Limitations when applying inorganic binders to existing casting processes

The incompatibility of inorganic bound sand cores with water-based coatings, insufficient thermal stability and poorer decoring properties are material-specific weaknesses of inorganic binder systems that previously limited their use in iron and steel casting. In addition, there are process-related problems that must be clarified prior to implementation in series production. These include greensand compatibility, the handling of alkaline used sand and ensuring a productivity that is comparable to cold box technology.

During 1990's and earlier made feasibility studies of inorganic binder systems in iron casting have shown that the coating of inorganic bound cores is one of the biggest challenges. In the coating-drying process, the sand core is exposed to an aggressive climate with high humidity. Concerning earlier water glass binders, the mechanical properties (determined as transverse strength) of the mixtures, which are crucial for the cores to withstand the casting process, are significantly lower. Although the dosage of alkali silicate binders is higher, typical transverse strength values for moulding mixtures with inorganic binders are lower in comparison with organic binders.

NO BAKE waterglass CO2- method (self-hardening in room temperature like furan and alpha-set) is one of the most widespread technologies to produce moulds using inorganic binder systems. Although it is an environmentally friendly method of producing moulds and cores (only water vapor and carbon oxides are released from the mould/cores during casting), their significant expansion has been prevented by couple of technological disadvantages in comparison with organic resin binder systems.

If, for example, alkaline silicate cured with liquid hardeners is used the typical transverse strength values range from 1.0 up to 1.4 MPa. On the other hand, if the system Furan NO BAKE is used, the typical transverse strength values vary from 1.8 up to 2.2 MPa. Generally, NO BAKE systems with inorganic binder works with binder dosage ranged from 2.5% up to 3.5% in comparison with 0.8–0.9% for Furan NO BAKE. In the case of the production of cores cured with carbon dioxide gas, the final strength of the core and its shelf–life are significantly different.

The most significant disadvantage is deteriorated collapsibility of the moulding mixture after casting. The formation of glass residues (melting of glass) on the grain surface leads to the fact, that significantly higher strength after casting is achieved than the primary strength (strength after curing). Another significant disadvantage resulting from glass residue formation could also be worsen ability to reclamation. There is possibility to use limited amount of reclaim sand (50 to 85%) depending on the type of reclamation equipment and reclamation method.

Finally, the use of these binder systems may be limited by the technological parameter of shelf-life. To ensure the production of castings in the sense of “just in time,” it means for a particular casting to have the mould and core produced at a given time, it is advantageous to produce cores in stock and thus ensure their availability at any time. The cores stored in this way must still be of high quality, in the sense of sufficient mechanical strength, high wear resistance, etc. The time at which these properties fall below an acceptable level is referred to as their shelf-life.

In the dehydration process of curing inorganic binders, the rate of the curing reaction is given by the rate of suction of water vapor released from the cured binder. In general, thermosetting processes are, however, energy-intensive as well as increased costs for core boxes and other accessories; commonly used wood and other types of core boxes cannot be used in comparison with the COLD-BOX core production method.

Latest developments show promising opportunities

The production of cores for the pre-casting of holes in castings places high demands on the quality of the moulding mixtures used. For this reason, organic binders are still used to a significant extent, which, although they meet the technological requirements, are a source of pollutant emissions during the production of castings. The current trend towards greening production is therefore looking for a suitable alternative in ‘green’ inorganic binders. Although for many decades standard inorganic binders could not be compared with organic resins in terms of technological properties, new inorganic binder systems are currently being developed that can eliminate these disadvantages, which include significantly lower collapsibility and reclaimability, and lower mechanical strength values.

A significant milestone in the development and application of inorganic binder systems is dated at the turn of the millennium when new development ways in the field of inorganic binders began to be presented. Firstly, it is the application of new types of inorganic materials but also modified alkaline silicates.

The basic principle of these technologies is the curing of alkaline silicate by the effect heat, either with warm air or, for example, using microwaves. In contrast to traditional processes, the dehydration curing process of alkaline silicates results in significantly higher mechanical properties of moulding mixtures, even at significantly lower binder dosages.

As a new solution some companies have introduced to the market semi-inorganic binders. These binders are based on same binding mechanism as the fully inorganic binders, but include a small organic hardener component, which gives enough strength in room temperatures to be able to make stripping – removing of a core from a core-box or a mould from a pattern. Stripping times can be adjusted from a few minutes to half an hour with different hardener modifications. Adequate strength values are achieved at ambient temperature in 24 hours without heating or gas blowing.

The other application are salt cores, which can be taken out from a casting by water. This technology is used in low-pressure die and die gravity casting to produce AI cylinder heads and crankcases as well as chassis components, which need 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 at gates and the hydrostatic pressure is more than 60 MPa. Such demanding casting conditions tend to cause high mechanical loading on the core. Thus, a core that can withstand these conditions is required. However, increasing the core strength causes a decrease in its collapsibility which translates to longer time for core-removal.

This combination of sand and salt cores enables the production of complex and thin-walled cores typical for automotive production. In addition, these technologies maintain their environmentally friendly nature, the collapsibility of the mixtures is improved during cores shake-out (possibility of combining mechanical shaking out of the cores with water rinsing) and, because of the lower binder content a reclaimability is also improved. The productivity of core manufacture is also increasing, and the production cycle is approaching the speed of production of cores from mixtures with organic binders.

Applicability of Tested Inorganic Binders to Replace Organic Binders

In this Green Foundry Project, it was possible to test number of “new” inorganic binder systems in cast iron and steel casting production. We can say that inorganic binders are well adoptable into non-ferrous metals: concerning aluminum and for example copper and zinc alloys pouring temperatures are low enough. Bigger problem concerning non-ferrous castings is high pressure die casting, in which process the metal velocity and pressure are causing challenging situation. However, the new inorganic and salt binders are offering solutions.

As described above, there are many big issues when introducing inorganic binders to ferrous metals. It was very promising to see that by selecting right binder into each process it is possible to take inorganic binders into use in most cases of iron and steel casting applications. However, in most cases the foundries need to make major changes in their processes to be able to adopt inorganic binders into their processes in a productive and economical way.

In the attached tables 1 and 2 the results and recommendations have been put into nutshell: what are the most promising processes and what kind of impacts the replacement means to working environment, to emissions, to process investments and what kind of other benefits it will give.

Applications in which best opportunities to replace organic resins by inorganic binders:

- organic binders can be replaced in mould making in mechanized and hand moulding of iron and steel castings by using semi-inorganic binders. The major investment is adjusting the binder mixers to new materials.
- to replace resin binders by fully inorganic binders in mould making means major changes in curing process – curing of the mould before stripping and final hardening after coating need heat – warm air, ultrasonic heating etc.- which again needs investments into patterns and tooling and production lines.
- core making processes need most changes and new investments, but inorganic binders would bring the biggest benefits to all impacts.
- no-bake core making processes by resin binders have same challenges as mould making – semi-inorganic works easily, but fully inorganic is challenging.
- hot-box and shell-core core making can easily change into inorganic binder.
- cold-box-amin-process can be changed to inorganic by replacing amin gas hardening to warm/warm air hardening providing the core-boxes are made in metal.

Processes needing most changes:

- sand mixers must be re-programmed or otherwise justified for new binders,
- storage and transport of binders need attention,
- when using semi-inorganic binders, hardening times of moulds and cores is longer and needs more transport and storage capacity,
- warning and heating of moulds and core when using fully organic binders need completely new production lines and heat producers,
- when using warm air or other heat for hardening of cores and moulds, core-boxes and patterns must be metallic and not resin ones,
- coating of moulds and core by water-based coating must be done carefully according to instructions because high humidity weakens the surface – new solution could be finer ceramic sand without coating or ultra-wave drying,
- core making process must be just-in related to mould making especially when humidity is high, because cores do not stand long storage, more storage capacity
- shake-out, crushing, sand transport, reclamation can need some changes when targeting highest strengths in sand cores

Positive Green impacts:

- internal air and atmosphere in the foundry will change dramatically – no toxic gases
- external emissions almost zero from sand system
- casting defects caused by core and mould gases will be dramatically less and makes savings in finishing operations and make castings more competitive
- working conditions will improve so much that recruiting new personnel is easy
- ventilation is not needed in same extend – savings in equipment investment and energy costs
- re-using of surplus sand is easier saving costs.

Table 2. Applicability of inorganic in non-ferrous foundries

FOUNDRY TYPE	CASTED METAL	POURING TEMPERATURE IN C	CASTING SIZES AND WEIGHT	PRODUCTION SERIES	COREMAKING TECHNOLOGY	BIDERSYSTEM	INORGANIC OPTION	MOULDMAKING TECHNOLGY	BINDERSYSTEM	INORGANIC OPTION	DEMANS FOR EQUIPMENT	IMPACT ON WORKING COREMAKING	IMPACT ON WORKING MOULDING SHAKE-OUT	IMPACTS ON WASTE	IMPACTS ON EMISSIONS
DIECASTING HIGH AND LOW PRESSURE	NON-FERROUS ALUMINUM	400-800	500X500X300 0,01 - 100 KG	LONG SERIES	HOT-BOX CORE SHOOTING	FENOLIC	FULLY INORGANIC	AUTOMATED LINE METALLIC MOULDS	NONE	NOT NEEDED	SAND MIXED RE-PROGRAMMING LESS VENTILATION	NO HAZAEDOUS GASES	NO HAZARDOUS GASES	NO SAND TREATMENT	NO TOXIC GASES
GRAVITY DIE CASTING	CU-ALLOYS				COLD-BOX CORE SHOOTING	ALCALIC	SEMI-INORGANIC	AUTOMATED LINE METALLIC MOULDS	NONE	NOT NEEDED	SAND MIXED RE-PROGRAMMING LESS VENTILATION	LESS HAZARDOUR GASES	LESS HAZARDOUR GASES	NO SAND TREATMENT	VERY LITTLE TOXIC GASES
RESIN SAND MECHANIZED	NON-FERROUS ALUMINUM	400-800	1000X1000X500 1-400 KG	SHORT SERIES	HOT-BOX CORE SHOOTING	FENOLIC	FULLY INORGANIC	SEMI-AUTOMATED FAST-LOOP	FURAN RESIN	SEMI-INORGANIC	SAND MIXED RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION	NO HAZARDOUS GASES	LESS HAZARDOUR GASES	NO SAND TREATMENT	VERY LITTLE TOXIC GASES
	CU-ALLOYS				COLD-BOX CORE SHOOTING	ALCALIC	SEMI-INORGANIC	SEMI-AUTOMATED FAST-LOOP	ALCALIC RESIN	SEMI-INORGANIC	SAND MIXED RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION		LESS HAZARDOUR GASES	NO SAND TREATMENT	VERY LITTLE TOXIC GASES
RESIN SAND HAND MOULDED	NON-FERROUS ALUMINUM	400-800	1000X1000X500 10-1000 KG	SHORT SERIES	RESIN HAND FILLED	FENOLIC	FULLY INORGANIC	SEMI-AUTOMATED FAST-LOOP	FURAN RESIN	SEMI-INORGANIC	SAND MIXED RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION	NO HAZARDOUS GASES	LESS HAZARDOUR GASES	NO SAND TREATMENT	VERY LITTLE TOXIC GASES
	CU-ALLOYS		2000X5000X1000 100 - 10000 KG	SINGLE CASTINGS	RESIN HAND FILLED	ALCALIC	SEMI-INORGANIC	SEMI-AUTOMATED FAST-LOOP	ALCALIC RESIN	SEMI-INORGANIC	SAND MIXED RE-PROGRAMMING LESS VENTILATION LONGER CURING LINES		LESS HAZARDOUR GASES	NO SAND TREATMENT	VERY LITTLE TOXIC GASES

Table 3. Applicability of inorganic binders in ferrous foundries

FOUNDRY TYPE	METAL	POURING TEMPERATURE IN C	CASTING SIZES AND WEIGHT	PRODUCTION SERIES	COREMAKING TECHNOLOGY	BIDERSYSTEM	INORGANIC OPTION	MOULDMAKING TECHNOLGY	BINDERSYSTEM	INORGANIC OPTION	IMPACT ON EQUIPMENT	IMPACT ON WORKING COREMAKING	IMPACT ON WORKING MOULDING AND SHAKE-OUT	IMPACTS ON WASTE SAND	IMPACTS ON EMISSIONS
RESIN SAND MECHANIZED	IRON	1280-1500	1500X1500X800 1-500 KG	SHORT SERIES	HOT-BOX CORE SHOOTING	FENOLIC	FULLY INORGANIC	SEMI-AUTOMATED FAST-LOOP	FURAN RESIN	SEMI-INORGANIC	SAND MIXER RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION	NO HAZARDOUR GASES	LESS HAZARDOUS GASES	NO THREATMENT	VERY LITTLE TOXIC GASES
					COLD-BOX CORE SHOOTING RESIN HAND FILLED	ALCALIC	SEMI-INORGANIC	SEMI-AUTOMATED FAST-LOOP	ALCALIC RESIN	SEMI-INORGANIC	SAND MIXER RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION		LESS HAZARDOUS GASES	NO THREATMENT	VERY LITTLE TOXIC GASES
RESIN SAND HAND MOULDED	IRON	1280-1500	1200X1200X1000 100-1000 KG	SHORT SERIES	RESIN HAND FILLED	FENOLIC	FULLY INORGANIC	SEMI-AUTOMATED FAST-LOOP	FURAN RESIN	SEMI-INORGANIC	SAND MIXER RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION	NO HAZARDOUR GASES	LESS HAZARDOUS GASES	NO THREATMENT	VERY LITTLE TOXIC GASES
			1000X5000X4000 1000 - 10000 KG	SINGLE CASTINGS	RESIN HAND FILLED	ALCALIC	SEMI-INORGANIC	SEMI-AUTOMATED FAST-LOOP	ALCALIC RESIN	SEMI-INORGANIC	SAND MIXER RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION		LESS HAZARDOUS GASES	NO THREATMENT	VERY LITTLE TOXIC GASES
RESIN SAND MECHANIZED	STEEL	1400-1650	1000X1000X800 10-400 KG	SHORT SERIES	HOT-BOX CORE SHOOTING	FENOLIC	FULLY INORGANIC	SEMI-AUTOMATED FAST-LOOP	FURAN RESIN	SEMI-INORGANIC	SAND MIXER RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION	NO HAZARDOUR GASES	LESS HAZARDOUS GASES	NO THREATMENT	VERY LITTLE TOXIC GASES
					COLD-BOX CORE SHOOTING	ALCALIC	SEMI-INORGANIC	SEMI-AUTOMATED FAST-LOOP	ALCALIC RESIN	SEMI-INORGANIC	SAND MIXER RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION		LESS HAZARDOUS GASES	NO THREATMENT	VERY LITTLE TOXIC GASES
RESIN SAND HAND MOULDED	STEEL	1400-1650	1200X1200X1000 50-1000 KG	SHORT SERIES	RESIN HAND FILLED	FENOLIC	FULLY INORGANIC	SEMI-AUTOMATED FAST-LOOP	FURAN RESIN	SEMI-INORGANIC	SAND MIXER RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION	NO HAZARDOUR GASES	LESS HAZARDOUS GASES	NO THREATMENT	VERY LITTLE TOXIC GASES
			1000X5000X4000 100 - 10000 KG	SINGLE CASTINGS	RESIN HAND FILLED	ALCALIC	SEMI-INORGANIC	SEMI-AUTOMATED FAST-LOOP	ALCALIC RESIN	SEMI-INORGANIC	SAND MIXER RE-PROGRAMMING LONGER CURING LINES LESS VENTILATION		LESS HAZARDOUS GASES	NO THREATMENT	VERY LITTLE TOXIC GASES
GREEN SAND AUTOMATED	STEEL	1400-1650	1000X1500X800 0,01 - 300 KG	LONG SERIES	HOT-BOX CORE SHOOTING	FENOLIC	FULLY INORGANIC	AUTOMATED LINE	CLAY BONDED	NONE	SAND MIXER RE-PROGRAMMING SAND RECLAMATION TRIMMING	LESS HAZARDOUS GASES	NO HAZARDOUR GASES	NO THREATMENT	LESS TOXIC GASES
	IRON	1280-1500	1000X1500,X800 0,01 - 300 KG	LONG SERIES	COLD-BOX CORE SHOOTING	ALCALIC	SEMI-INORGANIC	AUTOMATED LINE	CLAY BONDED	NONE	LESS VENTILATION	LESS HAZARDOUS GASES	LESS HAZARDOUS GASES	NO THREATMENT	LESS TOXIC GASES

4 Results of test casts and cores in pilot foundries

In Green Foundry LIFE project we tested four inorganic binders available on the market in three ferrous pilot foundries. Karhula Foundry in Finland and Valumehaanika foundry in Estonia use currently phenolic Alphaset binder system and FOM Tacconi foundry in Italy uses bentonite sand (green sand) binder system.

The aim of these tests was to demonstrate the feasibility of inorganic binders in production scale in the manufacture of moulds and cores in ferrous foundries.

Demonstrated inorganic binder systems:
The tested inorganic binders were from four different binder producers, with the brand names of:

- InotecTM from ASK Chemicals GmbH
- Cordis from Huettenes-Albertus Italy S.p.A.
- Cast Clean from Peak Deutschland GmbH
- Geopol® from Sandteam spol s.r.a.

Inotec TM and Cordis binder systems consist of fully inorganic binders and hardeners. The hardening processes in these systems need drying at elevated temperature at 150…200°C. Geopol® and Cast Clean binder systems consist of fully inorganic binders and organic hardeners (ester solutions). These binder systems harden at ambient temperature, and they are therefore called as “self-setting”.

4.1 FOM Tacconi foundry in Italy

FOM Tacconi foundry has changes its name to Fonderie di Assisi. The foundry is located near the centre of Assisi, which is one of the Unesco’s world heritage towns. It is obvious that emission reductions are necessary for the foundry to continue production in future at its current location.

FOM Tacconi produces both iron and steel castings for automotive industry, mainly parts for engines, such as castings for turbos and exhaust manifolds. FOM Tacconi demonstrated Cordis and InotecTM inorganic binders in core making. The cores were manufactured by the sup-supplier, 2VI S.r.l., producing test cores with both tested inorganic binder systems. The core shooting equipment used was equipped by hot air blower, enabling the heating to 150…200 °C. Most of the cores were painted by alcohol-based zirconium coatings. The cores were then transported to Assisi.

Before casting, the cores were inserted into green sand moulds before casting. The weight of the test cores was ca. 3 kg. The casting material was grey cast iron, and the casting temperature was ca. 1390 °C.

Figures 3-5. Cores with inorganic binders were produced at FOM Tacconi foundy.

Experiences:
The cores of inorganic binder system had the equal quality properties, as well as the quality of the test castings, compared to the current organic phenolic Cold-Box method cores and castings. The gas formation, measured in laboratory by loss of ignition method, was significantly reduced compared to Cold-Box cores, resulting less emissions and better indoor air quality in the foundry.

FOM Tacconi was satisfied with the results, and they are planning to proceed in application with inorganic binders. The implementation of core making by the demonstrated inorganic binder systems at the foundry requires investment of core shooting device equipped with heating or hot air blowing possibility. The foundry has made preliminary studies on suitable equipment available.

4.2 Karhula Foundry in Finland

Karhula Foundry produces 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.

Karhula Foundry demonstrated InotecTM, Clean Cast and Geopol® inorganic binders in mould and core making by using separate test mixers and hand moulding. Pretests were made first by all inorganic binders to find the most suitable recipes of binders and hardeners for the production.

Several full production scale series of tests with all three demonstrated inorganic binder moulds and cores were made. Typical foundry’s products with casting weight range of 15…2500 kg was produced. Most of the moulds were painted by alcohol-based zirconium coatings. Casting materials were different types of stainless steels, and casting temperatures varied between 1500…1540 ^{o}C.

Figures 6-8. Castings with three different inorganic binders were produced at Karhula foundry.

Experiences:
It is possible to produce the moulds and cores by the tested inorganic binder systems having the equal quality properties with the moulds and cores made by the current organic, phenolic Alphaset, method. The quality of the castings was as good as with the current products made by organic binder system. The harmful emissions from the moulds were greatly decreased by all the tested inorganic binder systems, compared to the moulds made by fully organic Alphaset binder system.

The inorganic binders which require heating to elevated temperatures as not feasible for the current production. There is a risk that in high temperatures that Karhula Foundry's current wooden or plastic core boxes and patterns would deform and be destroyed as unusable. The patterns and core boxes should be made of metallic materials, which would be very expensive. The production times would also be extended, especially with the bigger moulds. Necessary investment for heating equipment would increase costs, too.

The self-setting inorganic binder systems are better suited for the current production and product range. The implementation of these inorganic binders in full scale production would, however, require investment of separate mixer line.

4.3 Valumehaanika foundry in Estonia

Valumehaanika AS is an iron foundry locating in Tartu, Estonia.The current organic binder system is phenolic Alphaset system. Typical casting sizes vary between 5…100 kg, and they are used eg. in machines, generators, furnaces and other heating equipment. The self-setting Clean Cast and Geopol® inorganic binders were tested, by using the current modern continuous mixer line. Several production scale test series were made by both binder systems with different recipes of binders and hardeners, to find the most feasible ones for the prevailing production conditions and the produced castings. The moulds and cores were painted by alcohol-based zirconium coatings. The size range of the castings was 5…200 kg. Casted material was the grey cast iron EN GJL-250 and casting temperature was ca. 1450 ^{o}C.



Figures 9-11. Test casts with two different inorganic binders were produced at Valumehaanika foundry.

Experiences:
The demonstrated self-setting inorganic binders could be used instead of organic Alpahset in the continuous mixer line, without any need for changes in the equipment. The feasible recipes of the binders and hardeners are dependent on circumstances, especially ambient temperature, in the foundry. The cooler the temperature is, the slower is hardening, and faster hardeners must be used.

With the proper recipes, the properties of inorganic binder moulds and cores was satisfactory and comparable with current organic binder moulds. The quality of the castings was also comparable with the casings made by current organic binder system.

Valumehaanika was willing to continue with the application of inorganic binders. For the full-scale production, they are planning to invest a separate moulding line for inorganic binders.

Summary and sustainability of the project results:
The results in production scale test casts with inorganic binder systems in three ferrous foundries were promising, the emission reductions were significant and the quality of the castings was comparable with the castings made by organic binder systems. The project, however, learned that the extensive use in these and other ferrous foundries requires:

- Vast knowledge about different inorganic binder systems and their proper implementation into current or new production lines
- In most cases investments for moulding, core making and sand regeneration methods are needed and broad testing should be carefully carried out before commitment
- Traditional nature of the branch: 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

5. Current use of foundry waste sand and legislation

The summary of the actual and potential reuse applications of different types of spent foundry sand in Europe is shown below.

Table 4. Reuse applications of different types of spent foundry sand

Summary of the possibilities of reusing foundry waste	Spent Foundry Sands (SFS)					
	Green sand	Alkaline phenolic	Phenolic urethane	Furan resin	Shell resin	Sodium silicate
Asphalt	X	X	+	O	+	O
sand and gravel ballast						
Manufacture of blocks	+	X	+	+	X	+
Brick production	X	X	+	+	+	
Cement	X	X	+		X	X
Coarse aggregate substitute						
Concrete		X	+	+	+	
A substitute for fine aggregate	X	X	+	+	+	+
Foam concrete	X	X	+			
Insulation / glass / mineral wool	+	+	+	+	+	+
Production of lightweight aggregate						
Mortar production						+
Substrate for road structures		X	+		+	X

X - confirmed use of reuse
+ - a re-use application that has been theoretically proven, but there is no ongoing research project,
O - not suitable for re-use unprocessed

Finland: Currently over one third of annual foundry waste sands (approx. 94.000 tons) is landfilled, 64.896 tons is used for geo-construction purposes and 10.000 tons is treated by the Figure 12. thermal reclamation and recycled back to foundry processes.

Spain: Currently over half of annual foundry waste sands (approx. 150.000 tons) the major applications are the following: landfill (58%), in cement production as silica carrier in mortar (38%), kiln (2%), in the brick industry low-quality ceramics (1%) and in asphalt as a filler (1%), see Figure 12.

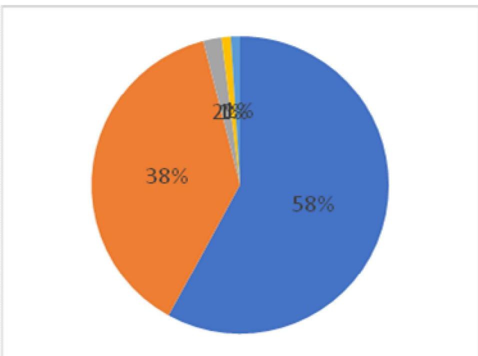

Figure 12. The applications of foundry waste sand in Spain (Source: FEAF, Spanish Federation of Foundry Associations)

Identification of reuse options for foundry waste sands

According to the documents provided by the project partners, there are several options for the reuse of foundry sands.

In Finland, there are seven reuse categories for foundry waste sand in the "Governmental Decree 843/2017" in geo-construction applications:

- Roadway, covered
- Roadway, paved
- Field covered
- Field paved
- Embankment
- Floor structure of industrial or storage building
- Road constructed of crushed stone and ash

In the table 5 the limit values for differen reuse options are presented.

Table 5. Limit values to be respected for the reuse of foundry waste sand in geoconstruction applications

Finland	Reuse options in geo-contruction						
Channels	Roadway covered[1)]	Roadway paved[1)]	Field covered[1)]	Field paved[1)]	Embankment	Floor structure of industrial or storage building	Crushed stones and ash[2)]
Setting	Limit values mg/kgMS	Limit values mg/kgMS	Limit values mg/kgMS	Limit values mg/kgMS	Limit values mg/kgMS	Limit values mg/kgMS	Limit values mg/kgMS
As	1	2	0,5	1,5	0,5	2	2
Ba	40 à 80*	100	20	60	20	100	80
Cd	0,04	0,06	0,04	0,06	0,04	0,06	0,06
Cr	2,00	10	0,5	5	1	10	5
Cu	10	10	2	10	10	10	10
Hg	0,03	0,03	0,01	0,03	0,03	0,03	0,03
Mo	1,5	6	0,5	6	1	6	2
Ni	2	2	0,4	1,2	1,2	2	2
Pb	0,5	2	0,5	2	0,5	2	1
Sb	0,7	0,7	0,3 à 0,4*	0,7	0,7	0,7	0,7
Se	1	1	0,4	1	1	1	1
Zn	15	15	4	12	15	15	15
Chloride (Cl-)[3)]	3200 à 3600*	11000 à 14000*	800	2400	1800	11000	4700
Fluoride (F-)[3)]	50	150	10	50	30	150	100
Sulphate (SO_4^{2-})[3)]	5900 à 6000*	18000 à 20000*	1200	10000	3400	18000	6500
Phenolic compounds[6)]	10	10	5	10	10	10	10
Soluble fraction							
DOC / Eluate	500	500	500	500	500	500	500
DOC / raw							
Σ BTEX							
Σ TEX[4)]	25	25	25	25	25	10	25
Benzene (LOQ 0,01 et 0,05 mg/kg dm)	0,2	0,2	0,02	0,2	0,06	0,02	0,2
PCB-7 compounds[7)]	1	1	1	1	1	1	1
Petroleum hydrocarbons C10-C40	500	500	500	500	500	500	500
PAH compounds[5)]	30	30	30	30	30	30	30
Nitrates							
Cyanides							
Be							
Co							
V	2 à 3*	3	2	3	2	3	3
Asbestos							
Naphthalene	5	5	5	5	5	5	5
MAJ du 11.01.2022							
PRJ1700885 Green Foundry Life							

***Exceptions to the limit values, if the maximum thickness of the executed structure is 0,5 m (mg/kg L/S 10 l/kg)**

Roadway covered : Ba=80, V=3, Cloride (Cl^-)=3600, sulphate(SO_4^{2-})=6000

Roadway paved : Cloride (Cl^-)=14000, sulphate(SO_4^{2-})=20000

Field covered : Sb=0,4

1) The maximum amount of recovered asphalt chippings and crushed asphalt at an earth construction site is 1,000 tonnes

2) The layer thickness of a road constructed of crushed stone and ash is set at the calculated thickness of the filler layer

3) The limit values set for chloride, sulphate and fluoride in Table 1 do not apply to a structure that meets all the following requirements: situated at a distance no greater than 500 m from the sea; the direction of discharge of water draining through the structure is into the sea; and there are no wells used for domestic water intake between the structure and the sea

4) Toluene, ethylbenzene and xylene (cumulative content)

5) Polyaromatic hydrocarbons: anthracene, acenaphthene, asenaphthylene, bentz(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(g,h,i)perylene, benzo(k)fluoranthene, dibenzo(a,h)anthracene, phenanthrene, fluoranthene, fluorene, indeno(1,2,3-cd)pyrene, chrysene, naphthalene and pyrene (cumulative content)

6) Phenol, o-cresol, m-cresol, p-cresol and bisphenol-A (cumulative content)

7) Polychlorinated biphenyl congeners 28, 52, 101, 118, 138, 153 and 180 (cumulative content)

<u>In France</u>, there are three options presented in the CEREMA guide "Environmental acceptability of alternative materials in road techniques - Foundry sands", in the case of reuse of foundry waste sands as alternative materials in road techniques:

- Usage of type 1 : see guide CEREMA on web site www.cerema.fr
- Usage of type 2 : see guide CEREMA
- Usage of type 3 : see guide CEREMA
-

In the table 6 the limit values to be respected for the reuse of foundry waste sand in road technology in France.

Table 6. Limit values for the reuse of foundry waste sand in road technology

France	Reuse options in road ingeneering		
Channels	Alternative material for type 1 use	Alternative material for type 2 use	Alternative material for type 3 use
Setting	Limit values mg/kgMS	Limit values mg/kgMS	Limit values mg/kgMS
As	0,6	0,6	0,6
Ba	25	25	25
Cd	0,05	0,05	0,05
Cr	0,8	0,6	0,6
Cu	3	3	3
Hg	0,01	0,01	0,01
Mo	0,6	0,6	0,6
Ni	4	2	0,5
Pb	0,6	0,6	0,6
Sb	0,7	0,4	0,08
Se	0,1	0,1	0,1
Zn	20	20	5
Chloride (Cl-)	1000	1000	1000**
Fluoride (F-)	60	30	13
Sulphate (SO_4^{2-})	10000	5000	1300**
Phenolic compounds	2	2	1
Soluble fraction			5000**
DOC / Eluate	500	500	500
DOC / raw	30000 / 60000*	30000 / 60000*	30000 / 60000*
Σ BTEX	6	6	6
Σ TEX			
Benzene (LOQ 0,01 et 0,05 mg/kg dm)			
PCB-7 compounds	1	1	1
Petroleum hydrocarbons C10-C40	500	500	500
PAH compounds	50	50	50
Nitrates			
Cyanides			
Be			
Co			
V			
Asbestos			
Naphthalene			
MAJ du 11.01.2022	*A limit value of 60000 mg/kgDM can be accepted, if the TOC/eluate value does not exceed 500 mg/kgDM		
PRJ1700885 Green Foundry Life	**To be compliant, either the chlorides and sulphates VL or the soluble fraction VL must be respected		

Leaching test results of inorganic waste sands:
Based on the results of the leaching tests carried out with inorganic binder system waste sands; CTIF IE, INOTEC, GEOPOL W37-20 and PEAK W37, and taking into account the limit values provided by the project partners, the table below summarises all the possible reuse options for the samples tested. Comparison with waste sands treated with different cleaning methods were carried out, and results were compared with the untreated waste sand samples. All tests were carried out with inorganic binder system waste sands samples received from project test casts.

As a summary, there are different reuse options for inorganic binder system waste sands instead of landfilling, table 7.

Table 7: Possible reuse options for inorganic sands tested during the project

Process	Options	Accepted in center	Use of the material in geo-contruction (document from Finlande)						
	Samples tested	waste inert	Roadway covered[1)]	Roadway paved[1)]	Field covered[1)]	Field paved[1)]	Embankment	Floor structure of industrial or storage building	Crushed stones and ash[2]
Untreated sands	INOTEC	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	CTIF IE	No	No	No	No	No	No	No	No
	GEOPOL W37-20	No	No	No	No	No	No	No	No
	PEAK W37	No	No	Yes	No	No	No	Yes	No
Mechanical processing	INOTEC	No	Yes	Yes	No	Yes	Yes	Yes	Yes
	CTIF IE	No	No	No	No	No	No	No	No
	GEOPOL W37-20	No	No	No	No	No	No	No	No
	PEAK W37	No	No	Yes	No	No	No	Yes	No
Hydro mechanical processing	INOTEC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	CTIF IE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	GEOPOL W37-20	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	PEAK W37	Yes except in Italie	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MAJ du 12.01.2022									

Process	Options	Accepted in center	Use of the material in road ingeneering (2019 Cerema guide France)		
	Samples tested	waste inert	Alternative material for type 1 use	Alternative material for type 2 use	Alternative material for type 3 use
Untreated sands	INOTEC	No	Yes	Yes	Yes
	CTIF IE	No	Yes	Yes	Yes
	GEOPOL W37-20	No	No	No	No
	PEAK W37	No	No	No	No
Mechanical processing	INOTEC	No	Yes	Yes	No
	CTIF IE	No	Yes	Yes	Yes
	GEOPOL W37-20	No	No	No	No
	PEAK W37	No	No	No	No
Hydro mechanical processing	INOTEC	Yes	Yes	Yes	Yes
	CTIF IE	Yes	Yes	Yes	Yes
	GEOPOL W37-20	No	Yes	Yes	No
	PEAK W37	Yes except in Italie	Yes	Yes	Yes
MAJ du 12.01.2022					

<u>Conclusion</u> :
The above results show that the waste from the inorganic sand "INOTEC" can be reused in all geo-construction and road engineering options. The waste from the inorganic sand "PEAK" is only reusable for two geo-construction options, and the waste from the inorganic sand "INOBAKE" (CTIF IE) can be reused for all road engineering options.
After mechanical treatment of these inorganic sand wastes, there are fewer options for reuse in geo-construction and road engineering. This shows that the mechanical treatment is inefficient.
Instead of cleaning the sand grains, the mechanical treatment has "released" pollutants captured by the new sand during the steel manufacturing process (these pollutants are contained in the residual gangue and in the fine elements of the sand).
The presence of these pollutants in too large quantities is the cause of poor leaching results (e.g. fluorides, soluble fraction, DOC, Cr, Ni).
On the contrary, it appears that all the options of reuse in geo-construction and road techniques are possible for inorganic sand wastes treated by hydromechanical technology,

except for the option of reuse in road technique of type 3 in the case of the "GEOPOL" sand where the phenol index and fluorides are slightly above the acceptance limits in the partner countries.
This shows that hydromechanical technology is effective in treating inorganic sands.
To conclude, at this stage of the development of the different inorganic binders tested during this project, we cannot deduce that such or such process of inorganic sand is the best placed for a reuse in geo-construction or in road techniques, because it is the parameters of production and the industrial history of the sand which have an important impact on the quality of a waste sand.
Indeed, new sand will pick up more or less polluting substances during the production process of the parts used by the foundryman. Thus, the conditions of use of the sand, the metallurgical methods of elaboration, the types of parts produced, the means, the methods and the raw materials used by the foundryman will have a greater or lesser impact on the results of leaching analyses.
Concerning the different inorganic processes, the formulations of the chemical binders will impact the physico-chemical characteristics of the sand so that it behaves during the operations of the manufacturing process of the parts (good fluidity of the sand for core making and moulding, good flexibility of the moulds and cores at de-coring, good mechanical resistance during handling, transport and the operations of assembly and re-moulding, controlled mould/metal reaction, low emissions during casting, etc...).
In general, products developed for inorganic binder processes comply with REACH regulations and contain no or very few SVHC (Substance Very High Convern).

6. Cleaning the foundry waste sand and dust by composting method

When exchanging the binding system in foundries, it is relevant to solve the foundry waste problem and to find a feasible reclamation or cleaning methods. Therefore different surplus foundry sand purification and reuse methods were tested and demonstrated. The aim is to reduce the amount of waste sand to be landfilled and find new reuse applications.

By the composting method is possible to degrade the harmful organic substances of the foundry waste sand and produce clean soil material which can be reused in green construction purposes. This method was first piloted with organic binder system foundry waste sands in the Foundry sand LIFE project (LIFE13 ENV/FI/285) in 2015-2017. It has not yet been tested with foundry dust specimens and inorganic binder system waste sands. The results demonstrated that hazardous organic compounds (like phenols, DOC, BTEX, PAH, and sulphide and fluoride) were well degraded and the soil material met the limit values and it was suitable for green construction and landscaping applications.

6.1 Regulations in Finland and Spain for the Fertiliser Product

Finland:
The mature and clean compost end-product to be used in geo-construction and green construction purposes as *mixture soil material* must fulfil the national regulations and limit set in the *Decree of the Ministry of Agriculture and Forestry on Fertiliser Products (24/2011): Substrate – Mixture soil material (5A2).* This regulation sets limit values and demands for heavy metals of the end-product, pathogens (Salmonella and E. coli) and impurities (weeds, garbage). The following demand concerns foundry waste sands in composting:

"In case mineral soil from metallurgical industry is used as raw material for mixture soil, such as waste foundry sand, it must meet the criteria of harmful metals and organic harmful substances for positioning to the inert solid landfills". This demand applies when the foundry sand is mixed with the composting material *in the end of the composting process*.

Foundry waste sand or dust rarely fulfil all the limit values set in the *Government Decree of landfills (331/2013)* and therefore waste sands must be cleaned by composting method. There the foundry waste sand is *mixed with composting material in the beginning of the composting process* and harmful substances will be degraded by the microbiological activity during the composting process. The cleaning process will take approximately 5-6 months.

For mixture soil material there are no limit values for organic substances (Decree 24/11) because the compost end-product is used as organic soil material. Organic substances (DOC, TOC, sulphate) in the compost end-product do not cause any problems in utilizing the soil material in green construction purposes. Concerning *harmful metals* *the cleaned soil material must fulfil limit values set for the non-hazardous inert waste in the Government Decree of landfills (331/2013).*

Spain:
As the pertinent laws and guidelines on compost, fertilizer and organic substances are Europe wide, the Spanish legislation and limit values are in line with the Finnish legislation(http://www.euskadi.eus/web01-a2inghon/es/contenidos/informacion/leg_residuos/es_def/index.shtml).

6.2 Results of composting tests in Finland

In Finland we have carried out composting tests with
1) Phenolic Alphaset binder system waste sand and dust (organic)
2) Furan binder system dust (organic)
3) Inorganic binder system waste sand (inorganic)

In total 360 tons of composting materials were treated and cleaned in composting tests in Finland. The proportions of foundry waste sand / dust in the test heaps varied between 20-30%. Analyses were gathered during the tests from the composting materials and wastewaters.

Figures 13-14. Composting test heaps and sample collection.

Results of composting tests with *organic binder* system waste sands and dusts in Finland

Degradation of harmful substances of the foundry waste sands or dusts are followed by analysing the composting materials during the test. Duration of composting test was on average 5-6 months in different test heaps. Additionally, the post-maturing will continue about 6 months. In total the cleaning and maturing process will take at least 12 months.

In table 8, composting test results of the organic binder system (Phenolic sand) waste sands and dusts are presented. The composting test heaps were started in July 2019 and completed in June 2020.

The degradation of harmful substances of organic binder system dust (compost heap number 1) and waste sand (compost heap number 2) during the composting tests are illustrated below.

Table 8. Degradation of the harmful substances of organic binder system waste sands and dusts during the composting test (L/S=10)

	Dust	Silo sand	Limit value for non-hazardous inert waste	Compost heap 1 (dust) START	Compost heap 2 (sand) START	Compost heap 1 (dust) END	Compost heap 2 (sand) END	**Compost heap 1 (dust) Degradation efficiency**	**Compost heap 2 (silo sand) Degradation efficiency**
DOC, mg/kg dm	4500	1600	500	7800	4700	2100	1700	**73 %**	**64 %**
Phenol index, mg/kg dm	1,20	2,10	1	5,5	1,4	<0,10	<0,10	**98 %**	**93 %**
Fluoride, mg/kg dm	180	23	10	39	6	21	<5,0	**46 %**	**17 %**

DOC, phenol and fluoride concentrations exceeded the non-hazardous inert waste limit values before the composting tests. All the compounds were degreased during the composting process.
In the end of the composting tests *all concentrations were under the limit values set for mixture soil material (Decree of Fertilisers 24/11).* After post-maturing period of 6 months the mixture soil materials were mature and ready to be reused in green construction purposes.

In table 9, composting test results of the organic binder system (Furan sand) foundry dusts are presented. The composting test heaps started in June 2019 and completed after 12 months.

TOC, DOC, BTEX, fluoride and sulphite concentrations exceeded the non-hazardous inert waste limit values before composting tests. After composting process BTEX, fluoride concentrations were below inert waste limit values. Nickel and zinc concentrations exceeded the non-hazardous limit values in dust samples but after composting process these were below the limit values.

As a conclusion the compost end-products fulfilled the Fertiliser Decree 24/11 limit values and the harmful metals were under limit values set for inert waste (Decree 331/2013). After post-maturing the mixture soil material can be used for green construction applications.

Table 9. Degradation of the harmful substances of organic binder system foundry dusts during the composting process (L/S=10)

	Dust	Limit value for non-hazardous inert waste	Compost heap 1 (25%) START	Compost heap 2 (30%) START	Compost heap 1 (25%) END	Compost heap 2 (30%) END	**Compost heap 1 (25%) Degradation efficiency**	**Compost heap 2 (30%) Degradation efficiency**
TOC, % dm	12	3	23	25	20	20	**13 %**	**20 %**
DOC, mg/kg dm	2700	500	10000	9800	970	930	**90 %**	**91 %**
BTEX, mg/kg dm	7,38	6	2,60	2,50	0,30	0,29	**88 %**	**88 %**
Fluoride, mg/kg dm	36	10	17	12	8,9	8,9	**48 %**	**26 %**
Sulphate, mg/kg dm	3200	1000	3700	3500	2000	2000	**46 %**	**43 %**

Industrial size composting tests were carried out in a new site with organic binder system foundry dust specimens in 2020-2022. This was made because due to the COVID it was not possible to continue tests at Karhula Foundry and we did not get waste sands anymore for the composting tests. A new composting site and a new pilot foundry, interested in industrial size composting cleaning process was found in Northern Finland. New environmental permit was applied. This foundry uses furan binder system and produces iron castings.

Furan dusts had high sulphate, DOC, fluoride, nickel and zinc concentrations and very low pH of 3-4. During the composting process harmful substances were degraded and the soil material fulfilled the limit values set for the Fertiliser Product and the soil material could be used in landscaping purposes nearby. During these composting tests we also tested the influence of the heating and aerating to the quality of the material and to speed up the process.



Figures 15-17. Industrial scale demonstrations in Finland 2020-2022.

Results of *inorganic and organic binder system* waste sands in Finland:

At Karhula Foundry *three inorganic binder systems* were tested and all samples were analysed. There were no major differences between these inorganic binder system waste sands.

As a conclusion, the results demonstrate that there are much less harmful organic compounds present in the inorganic binder system waste sands compared with the organic binder sands and therefore the degradation of the harmful substances during composting process was minor and the compost end product (soil material) fulfilled the limit values set.

6.3 Results of composting tests in Spain

In Spain composting tests were carried out with following binder systems:

1. Silicate binder system (inorganic) - combined waste foundry sand and dust (75% and 25% respectively)
2. Bentonite binder system (organic) - washed green waste foundry sand (partially cleaned prior to composting)
3. Inotec ecological binder system (inorganic) - waste sand from cores

The total weight of compost materials was 120 tons of which WFS (Waste Foundry Sand) compromised approx. 20%.

Analysis of WFS was carried out prior to use. Subsequent analysis was carried out at the start, in the middle, and at the end of composting (timing based on temperature readings). Overall time 5-6 months. Prior to use as fertilizer, the 5-6 month old compost needs to be matured (minimum 6 months) and further analysed.

Table 10. Degradation of the harmful substances contained in inorganic binder system WFS during the composting process (L/S=10)

	Sand	Limit value for non-hazardous inert waste	Compost heap 1 (sand) START	Compost heap 1 (sand) END	**Compost heap 1 Degradation efficiency**
Chlorides, mg/kg dm	<50,00	800	928	841	9%
Mineral oil, mg/kg dm	<20,00	500	<34	<20	41%

Degradation occurred in all harmful substances, the minimum level of efficiency being 9% in chlorides and the maximum being 41% in Mineral oil.

Table 11. Degradation of the harmful substances contained in organic binder system WFS during the composting process

	Sand	Limit value for non-hazardous inert waste	Compost heap 1 (sand) START	Compost heap 1 (sand) END	**Compost heap 1 Degradation efficiency**
TOC, % dm	<0,10	3	1,65	1,18	28%
BTEX, mg/kg dm	<0,04	6	<0,15	<0,04	73%
Mineral oil, mg/kg dm	<20,00	500	67	<20	70%

Degradation occurred in all harmful substances. Note that there was a wider range between minimum and maximum efficiency compared to inorganic binder. Its higher carbon content lends itself better to biodegradation. The minimum level of efficiency being 28% in TOCs, and the maximum being 73% in BTEX. Mineral oil degradation efficiency was 70%.

Table 11. Degradation of the harmful substances of eco-inorganic binder system waste foundry sand during the composting process (L/S=10)

	Sand	Limit value for non-hazardous inert waste	Compost heap 1 (sand) START	Compost heap 1 (sand) END	**Compost heap 1 Degradation efficiency**
DOC, mg/kg dm	77,5	500	1000	640	36%
TOC, % dm	<0,10	3	21,3	16,8	21%

Degradation occurred in all harmful substances. Note that there was a smaller range between minimum and maximum efficiency compared to both organic and inorganic binders. The minimum level of efficiency being 21% in TOCs, and the maximum being 36% in DOC.

The results of the composting tests with inorganic binder system waste sands demonstrated successful composting and the soil materials fulfilled the limit values set for Fertiliser Product. Since the concentrations of harmful substances are lower with inorganic binder system waste sands, the cleaning efficiency rates are also smaller.

6.4 Constructing the composting field

The composting tests always need a permit from authorities. Also a waterproof surface layer is mandatory to avoid any contamination to surrounding environment. A waterproof double-layer concrete asphalt is normally used in permanent composting fields. One option is to install a waterproof film and natural sand is added on top of the film layer. Wastewaters from the site are collected to a container and transported to wastewater treatment center.

Fig. 18. Constructing the composting field.

Fig. 19. Wastewater collection pipelines, a container and overflow basin.

Composting materials were analysed according to the Ministry of Agriculture and Forestry on Fertiliser Products (24/2011) for Substrate – Mixture soil material (5A2). For harmful metals the compost material must fulfil the limit values set for the non-hazardous inert waste in the Government Decree of landfills (331/2013).

For successful composting process an *aeration system is recommended* to improve the oxygen content of the composting material. Therefore, an aeration pipeline was constructed inside the composting heap and equipped with a fan. Electric power is needed for the fan of the aeration system. Aeration is recommended in the beginning of the composting process to start the microbe activity effectively.

A *storage site for raw materials* (foundry waste sands and organic materials) is also needed. The raw materials can be stored next to the site only couple of weeks before constructing the composting heaps.

Odours and emissions. In case the composting site locates near the settlement there can occur smells while constructing the composting heaps or after mixing the heaps during the composting process. Mixing is made approximately 2 times during the composting period (app. 6 months).

Total emissions from composting heaps were measured during in the Foundry sand LIFE project (LIFE13 ENV/FI/285) in 2015-2016. Based on these results there were higher concentrations of ammonia, CO, formaldehyde, benzene and odours in the beginning of the composting process. After 5 months most of the emissions were even under the detection limits.

6.5 Costs of the composting process

Finland:

The cost calculation is based on a constructed, actual composting site in Finland. The cost calculation is based on the assumption that the composting site is constructed specially for the treatment of waste foundry sand. The used land area is 30x150 m = 4500 m^2 and the planned annual composting capacity is 1000 tons.

The construction costs involved:

- Cutting of the trees and cleaning the area by bulldozer: 3000 €
- Adding filler sand: 5000 €

- Covering foil: 4000 €
- Wastewater pipes: 1000 €
- Wastewater tank: 2000 €
- Pump for circulating wastewater: 1000 €
- Aeration equipment ie. fan and tubes: 15000 €
- Electric power line: 2000 €
- A cabin for aeration equipment: 5000 €
- Total construction cost: 35000 €.

The cost of the land area is not calculated. For the operating time of 10 years, annual fixed cost without interest is 3500 €.

The annual running and maintenance costs:

- Animal manure or similar organic material (only transportation cost): 1000 €
- Wood chips and sticks: 500 € (90 % of the sticks are circulating in the process)
- Electric power: 1000 €
- Turnover of the composting heaps (4 times a year, 4x2 days by excavator): 4000 €
- Emptying of the wastewater tank: 500 €
- Total annual running costs: 7000 €

Total annual costs are: fixed costs 3500 € + running costs 7000 € = 10500 €. On average about 30% waste foundry sand can be added to the compost. The annual capacity of 1000 tons of compost means that 300 tons of waste sand can be treated in this site. The ton wise cost of composting treatment for waste foundry sand is accordingly 10500 €/300 tons = 35 €/ton.

Waste foundry sand, on the other hand, substitutes screened natural sand which is added to compost which is used as soil improvement material. The cost of screened natural sand in Finland is ca. 5 €/ton. Thus **the actual cost of composting treatment for waste foundry sand is ca. 30 €/ton.**

The transportation cost of waste foundry sand is not included in the cost calculation. Normally it is not reasonable to transport sand over 100 km distance.

In the existing composting sites the cost of waste foundry sand treatment is be much lower. Typically, composting companies utilize local cheap (free of charge) organic materials such as animal manure, garden waste, collected biowastes, etc. To the vendible compost end products natural sand is normally added (40%). Instead of natural sand, they can add waste foundry sand, which is transported to the site at the cost of foundries. The composting companies would not have to purchase the natural sand. It would also be possible to collect a gate fee from the foundries that would be less than the deposit fees for the foundries.

Spain:

Costs are essentially the same in Spain as in Finland, with the exception of the transportation cost which is slightly lower in Spain (approx. 5-10% lower). In Spain, compost producers traditionally source ballast sand from train manufacturers, chicken farmers and pig farmers. Today, WFS (waste foundry sand) is also being used following the success of this project in the area of the Basque Country.

6.6 Capacity

The capacity of composting method depends on the area of the composting site.
Example. In the composting field size of one thousand square meters (1000 m^2), it is possible to treat 600-700 tons waste sand annually. To treat about 7000 tons of waste sand, it requires app. 1 ha (hectare) composting site.

7 Washing method

Cleaning foundry waste sand by washing method was studied by Research and Innovation Tecnalia, in Spain on the laboratory scale. Three binder system foundry waste sands were tested.

- Inorganic binder system waste foundry sand (lab scale washing trials by Tecnalia)
- Organic binder system waste foundry sand (industrial scale washing by Ecofond)
- Inorganic binder system foundry sand (industrial scale wet attrition by AKW Apparate + Verfahren GmbH Technical Laboratory & Trials)

7.1 Washing method

The closed Ecofond company supplied foundry sand which had been through their washing method and was later analysed by Tecnalia. The exact washing method of Ecofond is their intellectual property. Tecnalia carried out the washing tests in their laboratory.

Washing Method (Leaching)
The principle behind the method was that by using basic chemical products (5M hydrochloric acid and distilled water) contaminated moulding sand could be cost-effectively washed and made reusable.

The quantities of unwashed sand started at 30 grams, and as the experiments progressed, were scaled up to 450g. In all, approx. 100 kilos of sand were washed.

Step one was to wash the sand with distilled water in an Erlenmeyer flask. This was then analyzed for pH and rewashed using fresh water until the level obtained by washing in water stabilized, i.e. no further reduction. Once pH showed no further change, step two was to add the damp sand to another Erlenmeyer flask containing HCl (hydrochloric acid). This was then mixed with a magnetic agitator for eight hours. The solution was then filtered to separate the sand from the acid, and the pH level of the sand was checked. The sand was then returned to an Erlenmeyer flask containing fresh HCl to repeat the washing, agitation and analyzing process until the desired pH range was obtained twice, i.e. no further change.

The final stage was to dry the sand using a Mufla furnace. The dry sand was then ground for full chemical analysis.

The following figures show the different equipment used for washing sand.

Fig 20-21. Washing sand with distilled water and pH measurement

Fig 22-24. Büchner funnels equipment and filtering the sand after washing.

7.2 Washing method results

The tables below (12a and 12b) show the results of washing both organic and inorganic WFS. Note that inorganic WFS was washed at laboratory scale, while organic WFS was washed at industrial scale by Ecofond. The results from inorganic WFS trials were extrapolated for comparison purposes. These costs are based on the laboratory scale tests carried out in the Green Foundry LIFE project, not actual production size plant costs.

Table 7 describes the inorganic binder waste sand process before and after washing.

Table 12a: The following table shows the results of scaling up to 30g sand before and after washing

Total metal (mg/kg)	**Before washing**	**After washing**	**Washing efficiency**
Barium (Ba)	2.87	<2.00	30
Chromium (Cr)	16.80	<2.00	>100
Iron (Fe)	13,300.00	10,400.00	22
Molybdenum (Mo)	<1.00	<2.00	50
Nickel (Ni)	606.00	575.00	5
Zinc (Zn)	8.50	6.81	20

After washing 30g, the metal content of the WFS was reduced in all cases, most notably in Cr and Mo.

Table 12b. The following table shows the results of scaling up to 450g sand before and after washing

Total metal (mg/kg)	Before washing	After washing	Washing efficiency
Barium (Ba)	7.85	4.55	42
Chromium (Cr)	15,800.00	163.00	99
Iron (Fe)	15,800.00	13,400.00	15
Molybdenum (Mo)	3.24	<2.00	38
Nickel (Ni)	718.00	640.00	11
Zinc (Zn)	13.20	10.50	20

After washing 450g, the metal content the WFS was reduced in similar proportion to the 30g sample, demonstrating that the process is suitable for scaling up. Note that in the case of Ba, higher starting levels lead to a greater reduction after washing.

The following table 13 shows the values for Total Heavy Metals in WFS before and after washing by Ecofond and analysis by Tecnalia. Approx. weight 3 tons which was used for composting test heaps.

Table 13: Organic binder waste sand process before and after washing

Heavy metals (mg/kg)	Before washing	After washing	Washing efficiency
Aluminium (Al)	15,580.00	3,480.00	82
Barium (Ba)	70.60	24.70	65
Chromium (Cr)	31.20	14.70	53
Copper (Cu)	22.10	18.30	17
Iron (Fe)	11,500.20	5,750.00	50
Zinc (Zn)	106.00	55.90	53

The washing process reduced heavy metal values for Al, Sb, As, Fe, Ba, Cu, Cr, Se y Zn.
In the case of organic WFS there was sufficient quantity to analyse for other hazardous parameters.
Although it was not possible to analyse inorganic samples for the same, the premise is that the process would be similarly effective. Further trials should be carried out to demonstrate this.

Table 14. Other hazardous compounds.

Other hazardous parameters (mg/kg)	Before washing	After washing	Limit value for inert waste	Washing efficiency
Fluorides	7.80	<5.00	10.00	36
Phenol	0.80	<0.50	1.00	38
DOC	480.00	169.00	500.00	65
TOC	8,900.00	<1,000.00	30,000.00	89
BTEX	0.22	<0.04	6.00	100

Fluorides, Phenol, DOC and TOC values were found to be lower than in unwashed sand (Table 14).

7.3 Industrial scale washing process and set-up costs

Industrial scale process and set-up costs

To assess the industrial scale plant costs, following calculations were made. The plant could be of approx. 1,000 m2 divided into goods in (200 m2), process area (500 m2), laboratory (80 m2), office (80 m2) and storage (140 m2). This would be staffed by four full-time employees. And annual production would be 1000 ton per year.

Investment costs:
Three tons pneumatically linked stainless steel vessels for the three-stage process. The first for mixing the WFS with distilled water, the second for adding the acid, and the third for rinsing with distilled water.

Table 15. Investment costs

Equipment	Cost € /a
Stainless steel vessel distilled water	6,300
Stainless steel vessel mixer	6,300
Stainless steel vessel acid mixer	6,300
Water pipes	1,000
Pump for circulation	1,500
Aeration tubes and magnetics	15,000
Electric power line	4,000
Store silo 1 capacity 6 ton	3,500
Store silo 2 capacity 6 ton	3,500
TOTAL	47,400

Running costs of the washing process:
There are two main consumable costs to take into account: chloric acid and distilled water. The total HCl used would be aprox.1,400 l and distilled water 3,000 liters. (30,000€+20,000€) plus laboratory tests, such as, filters, 24,000€. If we recycled at least, 40% of the raw materials.

Total annual costs are fixed costs 3,500 € + running costs 17,000 € +raw materials 50,000+ 24.000= 94,500 €. If we recycled at least, 40% of the raw materials. The annual capacity of 1,000 tons of washing sand means that 1,000 tons of waste sand can be treated in this site. The ton wise cost of washing treatment for waste foundry sand is accordingly 94,500 €/1,000 tons = 9,45 €/ton. **The total cost will be 10 €/tn. In this cost there are no wastewater treatment costs included.** These costs are estimations (not based on actual construction costs).

Advantages and disadvantages of leaching methods (the above costs are calculated for the single acid and washing method), table 16.

Table 16. Advantages and disadvantages of leaching methods

Method	Advantages	Disadvantages
Single acid and washing	Acid solubilises most minerals such as phosphates, carbonates, sulphates depending upon the acid used	Not all the minerals are washed with just one acid
Stepwise acid Washings	Two acids could be used with the ability of one acid to remove those minerals which could not be removed in the earlier washings	The use HF, HCl and HNO3 would require special and rugged materials of construction of reactors.

7.4 Wet attrition method, results and cost estimations

These additional washing tests were made to get industrial scale results for inorganic binder waste sands. The used treatment method is specific, combing wet treatment and mechanical attrition. The interaction effects of this method and thermal reclamation treatment on the quality of reclaimed waste sand and treatment cost of is also discussed here.

Test procedure:
The tests were performed with so called AKA-DRUM, which is used for dissolving raw materials. The goal of these tests was to clarify the autogenous cleaning of inorganic foundry waste sands by removal of fines of the surface of grains by means of intensive wet stirring, see figure 25.

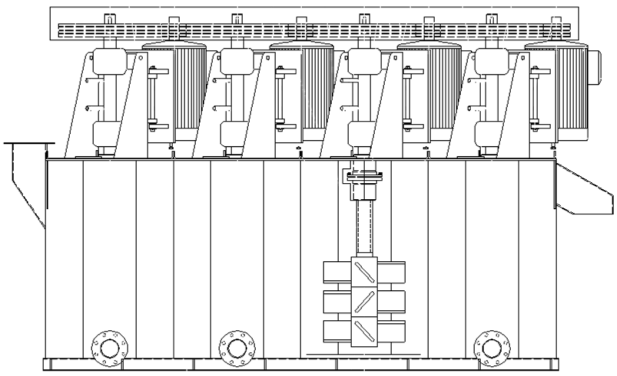

Fig 25. Principle image of the test apparatus.

The process of the wet attrition test consisted of four steps:
1. First the sample was classified with a 4 mm sieve
2. After sieving it was put through attrition. Solid content in this test was 1,3 kg sand/1 liters water. Attrition time was 5 minutes with 400 rpm
3. The sample was then deslimed
4. Sieved again with a 0,063 mm sieve

The grain size distribution and loss on ignition were then analysed in the lab. Microscopic pictures from the sand before and after the tests were also taken. The tests were conducted by AKW Apparate + Verfahren GmbH Technical Laboratory & Trials. Tests were done in June 2020.

Results:
<u>Screening:</u>
Results of the initial screening, 4 mm sieve, table 17.

Table 17. Results of initial screening.

Screening at [mm]	[mm]	4
Residue	[Ma.-%]	4,4
Undersize	[Ma.-%]	95,6

Attrition:
The parameters for the attrition test were as follows, table 18.

Table 18. The parameters for the attrition test

Solid content	[g/l]	1300
Rpm	[min^{-1}]	400
Attritioning time	[min]	5
Deslimed fraction < 0,063 mm	[Ma.-%]	0,9

The microscopic pictures taken from the samples show no visible change in the sample.

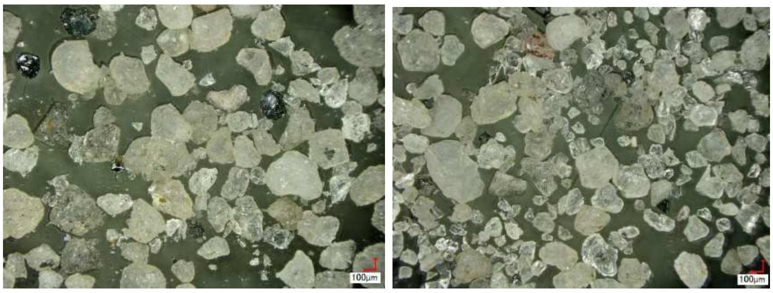

Fig 26-27. Samples before and after attrition

Loss of Ignition, LOI:
The results of the LOI stay within the measurement accuracy unchanged. The LOI test was conducted in a temperature of 550° C, table 19.

Table 19. The results of the LOI

Sample	Raw material	63-4000µm attritioned + deslimed
Loss on ignition in %	0,17	0,19

Final grain size distribution:

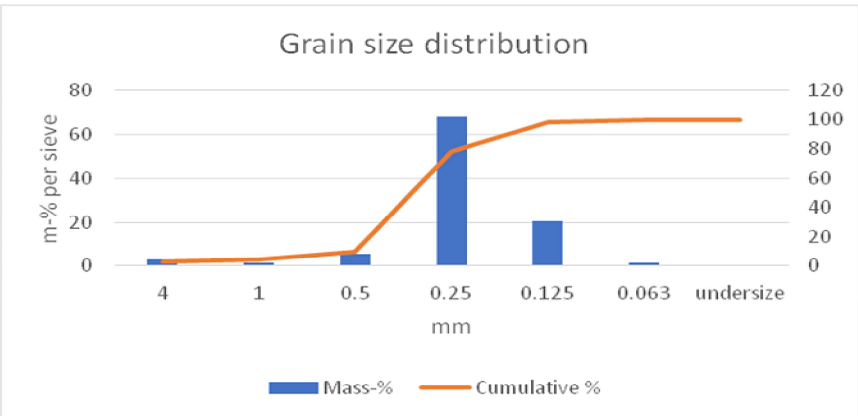

Figure 28. Grain size distribution after wet attrition.

Cost estimation:
In the case of ester cured phenolic resin sand wet scrubbing add costs approximately 20 % (electricity + water), but it saves at the same time in thermal process chemical additive amount significantly and also minimizes some gas consumption. Altogether the sum is about +- 0. The investment for water scrubbing unit is between 500.000 – 1.000.000 euros (scrubber, water treatment plant etc.).

In the case of inorganic waste sand the scrubbing unit investment is about the same, but there are no savings concerning chemical additives needed in ester cured phenolic resin sand types which means wet scrubbing of inorganic sands add costs approximately 10 % in thermal reclamation process.

Conclusions:
Wet scrubbing of used (waste) foundry sands before thermal reclamation is a technology used with organic foundry sands, especially with ester cured phenolic resin sands. Wet scrubbing of organic sands removes effectively harmful organic compounds of phenolic sands before thermal reclamation and also adjusts the pH level more suitable for thermal reclamation.

Wet attrition tests performed with the AKA-DRUM and with Inotec inorganic sands showed that there is no visible change in sand grain microscopy with untreated and treated samples. Also the loss of ignition of untreated and treated samples were the same within the measurement accuracy.

The separate results of **thermal reclamation of inorganic used foundry sands** in this Green Foundry project **showed slight improvement of mould strength properties compared to purely mechanically reclaimed sands**. Compared to those results these wet attrition tests of inorganic sands show that there is no advantage technically or economically to wet scrub these sand types before thermal reclamation.

8 Thermal reclamation method

Thermal reclamation tests were done with ester cured phenolic resin and furan bonded sand, two different inorganic binder systems and for green sand (bentonite).

8.1 Thermal reclamation process

Thermal reclamation tests were done at Finn Recycling Ltd´s existing thermal reclamation process plant in Urjala, Finland. The reclamation plant is used commercially for ester cured phenolic resin no-bake sands (APNB). The reclamation temperature i.e. the temperature of the sand leaving the thermal process was set to 650° C, which is the set temperature used with APNB sands. The process line consists of the feeder, thermal reclamation oven and a cooling screw. An additional automated sieve follows the process line so that the commercially deliveries conform to the requirements of the reclaimed sand. The following requirements have been set by Finn Recycling to the reclaimed sand together with its foundry customers, table 20.

Table 20. Requirements set by to the reclaimed sand

Dust content	Loss on Ignition
<1%	<0,3%

8.2 Results

The quality tests conducted on the sands were the Loss on Ignition (LOI) test and the 3-point bending strength test. The Loss on Ignition test is a standardized test which shows the level of organic matter or water of crystallization in the tested sand. The bending strength test is used the analyse the bending strength of a ready foundry sand mix to ensure that cores made of different sands can withstand the pressure the molten metal impacts to the cores during casting. Before the test were conducted, the samples were sieved with a 1mm sieve to remove the remaining coarse particles from the sand.

The tests were done by applying the standards AFS 5100-12-S and VDG Merkblatt P 33. The ignition temperature was 900° C and the time in the ignition temperature was 3 hours. The samples, seen in figure 29, of 25±5g were dried in 100° C before setting them in the hot laboratory oven.

Fig 29. Loss on Ignition samples

Test bars made according to the standard VDG Merkblatt M 11 with a cross section of 22,7 x 22,7 mm^2 were made following the instructions of the binder manufacturer. The bending strengths were the tested with a Morek Multiserw LRu-2e strength test machine for **test bars made of new sand, reclaimed sand and used sand.** Test bars and the bending machine are featured in figure 30.

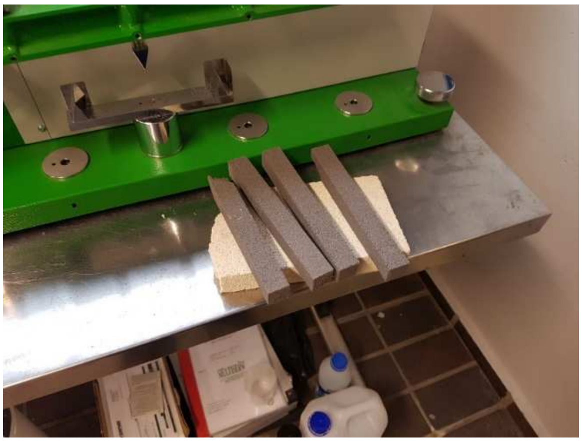

Fig. 30 Test bars and the bending strength test machine

8.2.1 Peak Inorganic

The results of the LOI tests are featured in table 21. The results show that the un-reclaimed sand had much more matter in it which was removed during the test compared to the reclaimed sand. This could be caused by water of crystallization, which did not evaporate during drying from the un-reclaimed sand but evaporated from the reclaimed sand during the thermal reclamation.

Table 21 Loss on Ignition results for Peak

LOI	Reclaimed	Used sand	New sand
Sample 1 before	23.162	22.510	24.11
Sample 1 after	23.152	22.397	24.07
Result 1	0.04%	0.50%	0.17%
Sample 2 before	20.663	20.597	22.87
Sample 2 after	20.66	20.538	22.84
Result 2	0.02%	0.29%	0.13%
Result average	**0.03%**	**0.39%**	**0.15%**

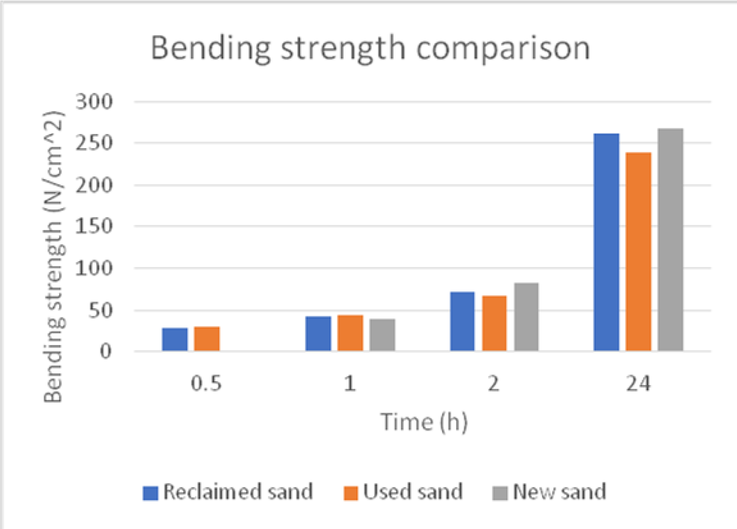

Fig. 31 Peak bending strength results

The bending strength test results (figure 31) show that the reclaimed sand has initially lower strength results compared to the used sand, but after two hours the reclaimed sand performs better. Same kind of trend is seen with new sand, which is the strongest of the three sands after two hours but is the weakest before that. The new sand was so fragile after 0.5 hours of hardening that the test equipment could not get a low enough reading. The amount of binder used was 2.5% of the sample mass and hardener was 12 % of binder mass.

The results show that thermal reclamation has some effect on the Peak Clean Cast Inorganic sand. The range of 2-24 hours is the realistic hardening time at least in Finnish foundries, so the bit lower strength in the start of the hardening time in not a huge problem. Mainly problems can rise especially with the new sand if a core must be removed from a core box too early when the sand has not hardened enough to endure it. Also, the bending strengths were comparably low when compared to APNB or other organic resins at least In the early stages of hardening. After 24 hours the bending strengths were in the same area as APNB sands.

8.2.2 Inotec Inorganic

The results of the LOI tests are featured in table 22. The results show that the un-reclaimed sand had much more matter in it which was removed during the test compared to the reclaimed sand. This could be caused by water of crystallization, which did not evaporate during drying from the un-reclaimed sand but evaporated from the reclaimed sand during the thermal reclamation. This is supported by the fact that the crushed un-reclaimed sand started to form blobs when stored but the reclaimed sand did not.

Table 22 Loss on Ignition results for Inotec

LOI	Reclaimed	Used sand	New sand
Sample 1 before	23.26	21.38	24.11
Sample 1 after	23.19	21.11	24.07
Result 1	0.30%	1.26%	0.17%
Sample 2 before	20.27	20.58	22.87
Sample 2 after	20.23	20.34	22.84
Result 2	0.20%	1.17%	0.13%
Result average	**0.25%**	**1.21%**	**0.15%**

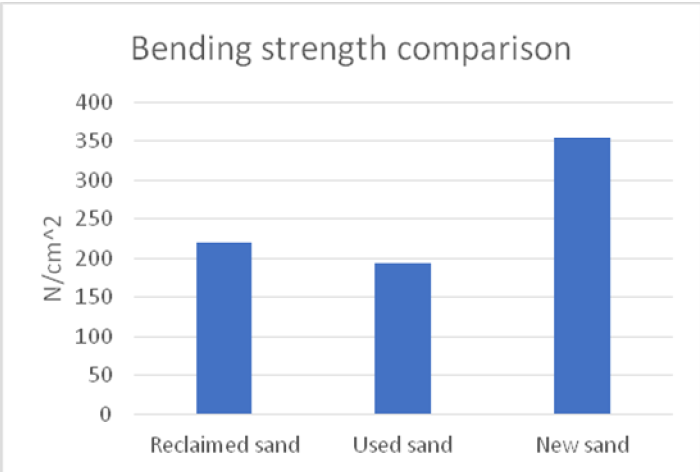

Fig. 32 Bending strength results of Inotec

The used amount of binder was 2 % and the amount of promoter was 0.6 %. The results (table 23) show that with only thermal reclamation no significant regeneration of the sand with Inotec takes place while the process consists only of thermal reclamation. On the other hand, the thermal reclamation of APNB sands works properly and is currently in use at Finnish foundries.

Table 23. Bending strength results for Inotec

Sample	Reclaimed sand	Used sand	New sand
N/cm^2	175.4	215.2	328.2
	221.4	189.4	373.3
	216.4	151.5	352.0
	253.8	228	349.6
	231.8	185.6	370.9
Average:	219.76	193.94	354.8

8.2.3 APNB

When the thermal reclamation project was started, for ester cured phenolic resin no-bake sands (APNB) the acceptable level of loss on ignition was set at 0.3%. As seen in table 24, the results of the quality assurance tests show, that the thermally reclaimed sand passes the requirements clearly.

Table 24. Loss on ignition for APNB sands

Loss on ignition	**Reclaimed APNB**
Goal	<0.3%
Sample 1 before	22.41
Sample 1 after	22.39
Result 1	0.09%
Sample 2 before	23.54
Sample 2 after	23.52
Result 2	0.08%
Average	**0.09%**

As comparison, the bending strength test conducted on reclaimed APNB sand show that reclamation by thermal reclamation only yields good results, as seen in figure 33. The reclaimed sand is mixed with new sand with a ratio of 70:30 as per request of the foundries. Further testing shows that the addition of new sand is not required. The amount of binder used was 1.5 % of sand mass and hardener was 25 % of binder.

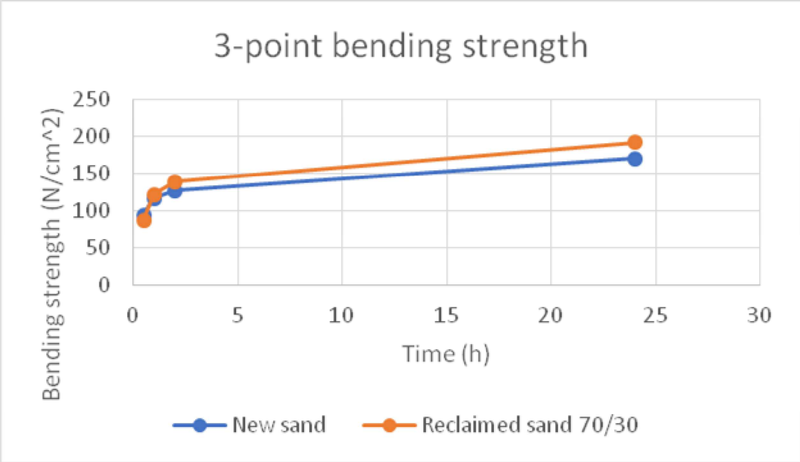

Fig. 33 Bending strength results for APNB sands

8.2.4 Furan bonded sands

Thermal reclamation of furan bonded sands has been tested at FinnRecycling in a small-scale production run of 5 tons which was then tested in a Finnish foundry. The tests were continued after a new production line in the FinnRecycling plant is installed during Q2/2021.

The results were good as expected, but the process needs a little more adjusting so that the bench and hardening times of the resulting reclaimed sands are equal to those of new sands. Overall, when comparing bending strengths, the reclaimed sand was a little bit weaker than new sand. Additional problems for the thermal reclamation of furan bonded sands are the sulfuric oxides which are formed during the thermal process. Compared to the reclamation process of APNB sands, reclamation of furan bonded sands needs additional filtration systems for the flue gases. The amount of binder used was 1.1 % and the amount of hardener 45 % of the amount of binder.

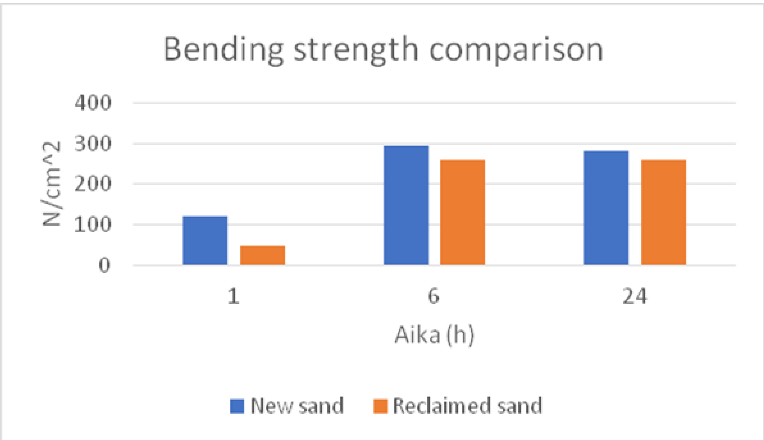

Fig. 34 Bending strength results for Furan bonded sand

The longer hardening time of reclaimed sand is probably due to the higher pH of the reclaimed sand, as the furan system uses an acid as hardener, so the higher pH acts like a buffer against hardening. This can be mitigated by foundries with the tuning of their mixer parameters.

Table 25. pH of reclaimed sand and new sand

Sample	mass (g)	pH
Reclaimed sand	25.023	7.15
New sand	25.014	6.83

Table 26. LOI of reclaimed furan sand

Loss on ignition	Reclaimed furan
Target	<0.3%
Sample 1 start	20.636
Sample 1 end	20.62
Result 1	0.09%
Sample 2 start	22.366
Sample 2 end	22.348
Result 2	0.08%
Average	**0.09%**

8.2.5 Green sand

Green sand (bentonite) by its nature is problematic for thermal reclamation as its bonding system is based on clay. For the product to be pure, the water of crystallization must be first removed thermally and then the remaining clay shell must be removed buy mechanical treatment. The process is under development at the moment at FinnRecycling. The aim is to develop a single machine capable of the mentioned combined thermo-mechanical treatment.

The purely thermal treatment tests were done for green sand. As a result, the loss on ignition of the sand got to bit over 0.3% which is not perfect but was still considered as a success. However, in further testing with a cold-box core shooter, the test bars hardened just nominally so overall the purely thermal reclamation process is not enough to successfully reclaim green sand, as was expected. The sand with the binder and hardener mixed in felt dry compared to normal cold box sand made from new sand. It seemed as if the remaining bentonite in the sand had sucked in all the binder. The amount of both cold-box binder agents were 0.6 % of sand mass.

Table 27. LOI results of greensand

Loss on ignition	Greensand
Sample 1 start	20.551
Sample 1 end	20.478
Result 1	0.36%
Sample 2 start	23.346
Sample 2 end	23.270
Result 2	0.33%
Average	**0.34%**

8.2.6 Summary

The results of thermal reclamation on the different sand systems are summarized in the table 28 below.

Table 28. Results of thermal reclamation on the different sand systems are summarized

Binder system	Results of Thermal reclamation
Peak	Small improvement
Inotec	Small improvement
APNB	Good results, in commercial use
Furan	Good results
Green sand	Development work needed, new mobile unit gives promising results

8.3 Costs of a concentrated reclaiming facility

The costs of a concentrated thermal reclamation plant can be divided into fixed and running costs. A single thermal reclamation oven's annual output is 8000 t so the amount of ovens depends of the amount and size of the customers.

Fixed costs:

- Thermal reclamation oven + cooler unit 950 000 €
- Gas tank 100 000 €
- Silos 50 000 €/unit
- Facility 1 000 000 €
- Sieve unit 60 000 €
- Conveyors 100 000 €

Running costs:

- Operator
- Gas
- Electricity
- Maintenance
- All together around 15 €/t depending on location
- 12 €+50 €/ton Saas* for a mobile treatment unit

*SaaS fee is an example for 20000 tons /year

The price of new sand depends for a big part of the logistical costs, as well as of the costs of landfilling the waste sand. Logistical costs of the sand also apply to a concentrated reclamation plant so the most important aspect which determines the profitability of a reclamation plant is the location in relation to its customers and on how much the customers have had to pay of their new sand, which determines how much they are willing to pay for the reclamation of their waste sand.

9 Treatment tests with inorganic binder system waste sands

The treatment processes selected by CTIF for the Green Foundry Life project are those capable of cleaning inorganic sand waste to obtain a quality of treated sand sufficient for reuse in foundries (moulding, core making), or for external reuse.

The processes using the emerging hydromechanical and ultrasonic technologies being the most efficient were selected for test purposes for comparison with a conventional mechanical technology currently used in industry (attrition mechanical process).

CTIF carried out following laboratory scale tests:

1. Mechanical treatment tests,
2. Hydromechanical treatment tests,
3. Ultrasonic treatment tests,
4. Characterisations of sand samples carried out before and after treatment, to observe the impact of the different technologies on inorganic sands, and to select sand batches to be tested in leaching (sand batches before treatment, least treated sand batches and best treated sand batches).

After the pre-treatment of the sand waste transmitted by the project partners, the sands to be treated were characterized and compared with the new reference sand (silica sand BE01). Detailed process descriptions can be found on deliverable DeB4.5 Feasibility studies of the reuse of inorgnaic surplus foundry sand in core making and geo-construction.

9.1 Summary of the mechanical treatment tests

Table 29. Summary of the mechanical treatment tests with different inorganic waste sand specimens

Laboratory checks on the sand samples	Ref SN BE01	INOTEC	CTIF IE	GEOPOL W37-20	PEAK W37
Fineness index	46	50	49	52	55
Distribution 50-70-100 (%)	95,03	92,00	94,68	90,27	90,75
Distribution 200-270-bottom (%)	0,18	0,92	1,04	1,89	2,28
Absence of residual aggregate (%)	0,00	0,00	0,00	0,08	0,04
Theoretical specific surface (cm2/g)	159	176	170	184	195
Breakage of sand grains observed under the light microscope (high/low/no)	no	low	low	significant	significant
Aggregate removal observed under optical microscope (yes/no)	no	yes	yes	yes	yes
Amount of fines produced by the treatment (no/low/significant)	no	significant	significant	significant	significant
Grain shape observed under light microscope (general trend: spherical/angular)	Spherical	Sph+Ang	Sph+Ang	Sph+Ang	Sph+Ang
Appearance of grains observed under the light microscope (general trend: smooth/rough)	smooth	smooth+Rug	smooth	smooth	smooth
Amount of black grains (general tendency: not/low/significant)	no	significant	low	low	low
Quantity of light-coloured grains with black spots (general tendency: not/low/significant)	no	significant	significant	significant	significant
Amount of light-coloured unstained grains (general trend: not/low/significant)	significant	no	low	low	low
Electrical conductivity of treated sand (µS/cm)	500 - 520	863	1262	997	842
pH of the treated sand	8,30 - 8,40	10,01	10,17	9,57	9,44
Acid demand of treated sand (ml HCL)	1,2 - 2,0	27,5	35,9	20,9	17,1
Samples retained for leaching test		X	X	X	X
Updated on 26/11/2021					

Initial findings:

- Grain breakage for the GEOPOL W37-20 and PEAK W37 sands,

- The production of fines is significant in all cases,
- For all the treated sand samples, conductivity, pH and acid demands are not in conformity with the new silica sand reference BE01,
- All sand samples are not well cleaned.

Explanations:

In order to compare the effects of the mechanical treatment with the hydromechanical and ultrasonic treatments, the settings of the mechanical module were set at V550T20 + 30 min of dedusting.

- To reduce grain breakage in GEOPOL W37-20 and PEAK W37 sands, the rotation speed of the module and the treatment time should be adjusted (e.g. set to V550T15 or V500T20),
- The 30 minute dedusting time was not sufficient to reduce the fines content,
- The mechanical treatment does not clean the inorganic sand well: the production of fines is high (dry attrition phenomenon), and a large quantity of residual gangue remains stuck to the surface of the grains (temperature rise phenomenon).

Note: after mechanical treatment, no clear unstained grain is found in INOTEC sand: this difference in behaviour compared to other sands is perhaps due to the nature, composition and/or quality of the binder and additives used for this process.

9.2 Summary of the hydromechanical treatment tests

Results of the sand characterization after hydromechanical treatment, table 30.

Table 30. Results of the sand characterization after hydromechanical treatment

Laboratory checks on the sand samples	Ref SN BE01	INOTEC	CTIF IE	GEOPOL W37-20	PEAK W37
Fineness index	46	49	47	48	49
Distribution 50-70-100 (%)	95,03	92,64	95,42	94,68	93,94
Distribution 200-270-bottom (%)	0,18	0,14	0,04	0,00	0,06
Absence of residual aggregate (%)	0,00	0,04	0,00	0,04	0,08
Theoretical specific surface (cm2/g)	159	172	160	169	172
Breakage of sand grains under the light microscope (significant/low/no)	no	low	low	low	low
Aggregate removal observed under optical microscope (yes/no)	no	yes	yes	yes	yes
Amount of fines produced by the treatment (no/low/significant)	no	low	low	low	low
Grain shape observed under the optical microscope (general trend: spherical/angular)	Spherical	Sph+Ang	Sph+Ang	Sph+Ang	Sph+Ang
Appearance of grains under the optical microscope (general trend: smooth/rough)	smooth	smooth	smooth	smooth	smooth
Amount of black grains (general trend: no/low/significant)	no	low	low	low	low
Quantity of light-coloured grains with black spots (general trend: no/low/significant)	no	significant	low	low	low
Amount of clear unstained grains (general trend: no/low/significant)	significant	significant	significant	significant	significant
Electrical conductivity of treated sand (µS/cm)	500 - 520	523	516	507	511
pH of treated sand	8,30 - 8,40	8,78	8,73	8,72	8,45
Acid demand of treated sand (ml HCl)	1,2 - 2,0	5,8	2,2	0,6	1,5
Samples retained for leaching test		X	X	X	X
Updated on 26/11/2021					

Initial findings:

- No breakage of the sand grains in all cases,
- All the parameters checked are in conformity with the reference sand BE01,
- The sand is well cleaned in all cases,
- Only the INOTEC sand has a slightly higher acid demand.

Explanations:

- The phenomena produced and the effects generated by the treatment are particularly effective in cleaning inorganic sands,
- The slightly high acid demand for INOTEC sand can be reduced by optimising the settings of the treatment module (rotation speed, treatment time, number of rinses).

9.3 Summary of the ultrasonic treatment tests

Results of the characterisation of the sands after ultrasonic treatment, table 31.

Table 31: Results of the characterisation of the sands after ultrasonic treatment

Laboratory checks on the sand samples	Ref SN BE01	InoEC	CTIF IE	GEOPOL W37-20	PEAK W37
Fineness index	46	50	47	49	50
Distribution 50-70-100 (%)	95,03	93,02	96,10	94,14	93,98
Distribution 200-270-bottom (%)	0,18	0,18	0,06	0,04	0,10
Absence of residual aggregate (%)	0,00	0,04	0,04	0,06	0,12
Theoretical specific surface (cm2/g)	159	176	162	171	175
Casse grains de sable observée au microscope optique (significant/low/no)	no	low	low	low	low
Sand grain breakage observed by optical microscope (significant/low/no)	no	yes	yes	yes	yes
Aggregate removal observed under optical microscope (yes/no)	no	low	low	low	low
Amount of fines produced by the treatment (no/low/significant)	Spherical	Sph+Ang	Sph+Ang	Sph+Ang	Sph+Ang
Appearance of grains under the optical microscope (general trend: smooth/rough)	smooth	smooth	smooth	smooth	smooth
Amount of black grains (general trend: no/low/significant)	no	low	low	low	low
Quantity of light-coloured grains with black spots (general trend: no/low/significant)	no	significant	low	low	low
Quantity of clear unstained grains (general trend: no/low/significant)	significant	low	significant	significant	significant
Electrical conductivity of treated sand (µS/cm)	500 - 520	525	521	515	518
pH of treated sand	8,30 - 8,40	8,76	8,77	8,79	8,58
Acid demand of treated sand (ml HCL)	1,2 - 2,0	7,5	4,5	1,5	1,6
Samples retained for leaching test					
Updated on 26/11/2021					

Initial findings:

- No breakage of the sand grains in all cases,
- All the parameters checked are in conformity with the reference sand BE01,
- **The sand is well cleaned in all cases**,
- Only the INOTEC sand has a slightly high acid demand and a low quantity of clear unstained grains,
- The acid demand of the CTIF IE sand is also a little high.

Explanations:

- The phenomena produced and the effects generated by the treatment are particularly effective in cleaning inorganic sands (with, however, poorer characterisation results of the treated sands, compared to the hydromechanical treatment process),
- The acidic demands that are still somewhat high for INOTEC and CTIF IE sands can be reduced by optimising the settings of the treatment module (treatment time and rinses).

9.4 Options for reusing inorganic sand waste

Identifying options for reusing inorganic waste sands, table 32.

Table 33. Identifying options for reusing inorganic waste sands

Process	Options	Accepted in center	Use of the material in geo-contruction (document from Finlande)						
	Samples tested	waste inert	Roadway covered[1]	Roadway paved[1]	Field covered[1]	Field paved[1]	Embankment	Floor structure of industrial or storage building	Crushed stones and ash[2]
Untreated sands	INOTEC	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	CTIF IE	No	No	No	No	No	No	No	No
	GEOPOL W37-20	No	No	No	No	No	No	No	No
	PEAK W37	No	No	Yes	No	No	No	Yes	No
Mechanical processing	INOTEC	No	Yes	Yes	No	Yes	Yes	Yes	Yes
	CTIF IE	No	No	No	No	No	No	No	No
	GEOPOL W37-20	No	No	No	No	No	No	No	No
	PEAK W37	No	No	Yes	No	No	No	Yes	No
Hydro mechanical processing	INOTEC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	CTIF IE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	GEOPOL W37-20	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	PEAK W37	Yes except in Italie	Yes	Yes	Yes	Yes	Yes	Yes	Yes
MAJ du 12.01.2022									

Process	Options	Accepted in center	Use of the material in road ingeneering (2019 Cerema guide France)		
	Samples tested	waste inert	Alternative material for type 1 use	Alternative material for type 2 use	Alternative material for type 3 use
Untreated sands	INOTEC	No	Yes	Yes	Yes
	CTIF IE	No	Yes	Yes	Yes
	GEOPOL W37-20	No	No	No	No
	PEAK W37	No	No	No	No
Mechanical processing	INOTEC	No	Yes	Yes	No
	CTIF IE	No	Yes	Yes	Yes
	GEOPOL W37-20	No	No	No	No
	PEAK W37	No	No	No	No
Hydro mechanical processing	INOTEC	Yes	Yes	Yes	Yes
	CTIF IE	Yes	Yes	Yes	Yes
	GEOPOL W37-20	No	Yes	Yes	No
	PEAK W37	Yes except in Italie	Yes	Yes	Yes
MAJ du 12.01.2022					

9.5 Conclusions

Treatment trials carried out on inorganic sand waste have shown that hydromechanical and ultrasonic technologies are particularly effective in obtaining an inert waste sand after treatment, or in allowing the treated sand to be reused in foundry, geo-construction or road engineering purposes.

10 Solutions to reduce emissions and improve indoor air quality

10.1 Assessment of the harmfulness of the moulding sands

The intensively developing foundry industry consumes large amounts of natural resources, energy and metals as well as generates significant amounts of gases and solid wastes, which influence the natural environment and work condition. In foundry plants metal casting can be done with various methods. One of the most important method preferred around the world is sand casting. Moulding sands, in which castings are produced, can be bound by organic binders (e.g. furan, phenol–formaldehyde resins), inorganic binders (water glass, aluminosilicates) or by bentonite. Under an influence of high temperatures of liquid metal there is a hazard of emitting from a mould dangerous substances: benzene, toluene, ethylbenzene, xylenes (BTEX) and Polycyclic Aromatic Hydrocarbons (PAHs) groups. The gas evolution performance of the mould is a very important index, which is directly related to the quality of casting. The main reason for testing the emission of compounds from the BTEX or PAHs group is that some of these compounds show carcinogenic and / or mutagenic properties, e.g. benzene (BTEX) or benzo (a) pyrene (PAHs). Moulding sands bound by organic binders (phenol formaldehyde; furan), inorganic binders and green sand, were subjected to investigations (RESEARCH ON THE RELEASE OF DANGEROUS COMPOUNDS FROM THE MOULDING SANDS, AGH University, ESMET 2021).

Two aspects should be considered at the assessment of the given moulding sand harmfulness.

1. Moulding sands harmfulness for employees and for the environment caused by emissions of gaseous and dust contaminations occurring during the sands preparation, producing cores and moulds as well as at moulds pouring with molten metal, cooling and castings knocking out:

- Evaporation of volatile compounds during producing moulds and cores (mixing, sands shooting, moulds making, storing, etc.);
- Evaporation of unreacted initial components of resins (e.g. in case of phenol-formaldehyde resin: monomers of phenol and formaldehyde) as well as solvents of higher boiling points at the first seconds after a mould filling with liquid metal;
- Emission of BTEX and other decomposition products occurred as the pyrolysis result of the main carbon chain of the polymer in further stages of the casting production.
- All chemically bound binders can create potential hazard for the health in case of long-lasting or recurring exposures to hazardous factors. The threat can occur both by inhalation and through the skin. Especially dangerous is a direct contact of an employee with unreacted resin or unhardened sand, during its preparation and during making moulds and cores. In extreme cases the skin contact with those substances can cause chemical burns, scars and allergies. Therefore using personal protection devices, such as gloves resistant to chemicals, safety goggles and protective clothing, is necessary.
- during moulds pouring with molten metal the binder thermal decomposition occurs. A majority of decomposition products occurs in trace amounts. Special dangerous are decomposition products of substances containing carbon applied as additions for green sands.

2. The sand harmfulness for the environment is caused by elution of dangerous substances from spent sands. In dependence of the concentration of eluted substances - determined in the elution test - the given sand can be classified to one out of dumping grounds. In the situation when the spent sand will be further economically utilized, performing the elution test is also necessary due to a possible contact with employees or with the environment.

The emission of inorganic dangerous substances occurs mainly during melting and cleaning processes of castings and mostly these substances are metal oxides. Hazardous substances at work places can be gaseous, liquid or solid. Their dangerous operations can take place by the skin contact, by breathing or eating together with food. The main source of dust and gaseous contaminations are operations of moulds pouring with liquid metal, moulds cooling and castings knocking out. In the case of moulding sands with bentonite these operations generate up to 90 % of contaminations from the Hazardous Air Pollutants (HAPs) group.

In order to assess each technology, including the moulding and core sands technology, in the aspect of its influence on the environment and working conditions, the analysis of life cycles of all products should be performed. This analysis should start from the raw materials output (sand, bentonite, coal) via the binders production (resins, water glass) then the whole process of sands preparations and moulds making, pouring and cooling processes of moulds, castings knocking out. The analysis should be ended on the spent sands reclamation process and these sands utilisation or storage. Only two elements of life cycles of moulding and core sands, the most important in considerations of their harmfulness, are taken into account:

- moulding sand preparation process, making of moulds and cores, moulds pouring with molten metals, moulds cooling and castings knocking out. This mainly concerns gaseous substances released to the environment during these processes.
- influence of spent moulding and core sands during their storage or recycling, the reclamation process, after reclamation wastes and possibilities of their utilisation, including storage. This concerns substances which could be eluted to the environment.

  The goal of this project was to demonstrate the new clean technology of moulding systems in practice. The new inorganic binder system is based on the sodium silicate (glass water) or aluminosilicate, which reduces the amount of harmful components indoor and in ambient air.

10.2 Emissions of inorganic and organic binding systems

Small scale chamber tests and emission measurements were carried out from the sand moulds made of organic and inorganic binder systems. Tests were carried out in Finland (AX-LVI Consulting) and Poland (AGH-University).

In Finland the emission tests were made by using a closed chamber, where the mould was placed in. The weight of the test casting was about 200 kg and the amount of sand in the mould was also ca. 200 kg. The tests were made in two ferrous foundries: URV and Karhula.

In Poland small scale chamber tests were made in the laboratory foundry of AGH-UST and in the ferrous foundry Hardkop. The weight of the test casting in the AGH-UST laboratory test as about 150 g and the amount of the sand in the mould was also ca. 150 g. The weight of the test casting in Hardkop was ca 23 kg and the amount of sand in the mould was ca. 65 kg.

The detailed test arrangements and the means of measurements are presented in separate reports.

Tested inorganic binder systems:
Totally four different inorganic binder systems were tested, table 34.

Table 34. Tested inorganic binder systems

Inorganic binder system: Brand name and manufacturer	Binder type	Hardener/promotor/additive type	Recommended contents of binder and hardener/promotor for steel casting	Need for separate drying
Cordis, Huettenes-Albertus	Liquid: Modified Silicate solution, 100 % inorganic	Solid Anorgit additive: 100 % inorganic mixture of synthetic and natural powders	Binder ca. 2% and additive 0,6..1,0 % of the sand amount	In oven at temperature of 130..180 C° or bý hot air
Inotec, ASK	Liquid: Alkali Silicate type, 100 % inorganic	Solid promotor: 100 % inorganic, consisting of minerals and synthetic raw materials	Binder 2..2.2% and promotor 0,6..1,0 % of the sand amount	In oven at temperature of 160..200 C° or by hot air
Clean Cast, Peak	Liquid: Alkaline Silicate type, 100% inorganic	Liquid hardener: organic ester mixture	Binder 2..3% and hardener 0,2..0,3% of the sand amount	Self-setting at room temperature
Geopol, SandTeam	Liquid: Modified silicate type: artificially prepared geopolymers, 100% inorganic	Liquid hardener: organic ester mixture	Binder 1.8%..2% and hardener 0,3..0,36% of sand amount	Self-setting at room temperature

For comparison, following organic binder systems were also tested:

- Furan: binder + hardener = furfuryl alcohol resin + phosphorus acid
- Alphaset: binder + hardener = phenol resin + ester acid
- Green sand: bentonite binder + carbon dust

These three organic binder systems are currently the mostly used binder systems in ferrous foundries.

10.2.1 Chamber tests in Finland

One organic binder system and two inorganic binder systems were tested:

- Organic Alphaset in URV iron foundry
- Inorganic Inotec in Karhula Foundry
- Inorganic Peak in Karhula Foundry

The mould and other test arrangements are shown in figure 35.


Figures 35-36. Test arrangements in chamber tests in Finland

After pouring the melt into the mould, the chamber was closed by a cover, and the emitted gases were measured for 6 hours. Emission gases are formed in burning processes caused by the heat of the molten metal. Due to the porosity of the sand moulds, the gases flow through the moulds to the surface and mix into the surrounding atmosphere.

If the used binder or hardener include flammable organic material, harmful gases can be formed. These are eg. toluene, benzene, ethylbenzene, and xylenes concentrations (BTEX) and polycyclic aromatic hydrocarbons (PAHs). BTEX gases can be carcinogenic and long-term health effects of exposure to PAHs may include cataracts, kidney and liver damage, and jaundice. Other possible harmful gases formed are CO and SO_2. Gas formation in the moulds and especially in the cores can impair the quality of the castings due to risk of gas porosity formation. That is why the volumes of the mentioned harmful gases and total volume of gases were measured in the chamber tests.

The complete results of the measurements are presented in separate reports. Here are presented the measured gas volumes in correlation with the sand amount. These results give the best practical comparison, because the recommended contents of binders and hardeners in correlation with the sand amount are somewhat different, see table 35.

Table 35. All the calculated chamber test results in Finland

	Test	URV chamber	Karhula chamber	Karhula chamber
	Resin	Alpha set	Inorganic Peak	Inorganic Inotec
Emission per casting [g/ton casting]	dust	211	56,10	7,40
	CO	10 129	361	128
	SO_2	203,31	6,51	3,30
	VOC	3 256	111,6	35,2
	BTEX	665	8,50	1,05
	asetaldehyde	81,3	8,76	0,72
	formaldehyde	1,92	6,23	0,63
	phenol	109	0,89	0,13
	o-cresol	152	<1,50	<0,08
	p-cresol	74,1	<1,50	<0,05
Sum		14 883	563	177
Emission per sand [g/ton sand]	dust	210	56,1	7,05
	CO	10 069	361	122
	SO_2	202	6,51	3,14
	VOC	3 237	112	33,5
	BTEX	661	8,5	1,00
	asetaldehyde	80,8	8,8	0,69
	formaldehyde	1,91	6,2	0,60
	phenol	108	0,89	0,13
	o-cresol	151	<1,50	<0,07
	p-cresol	73,7	<1,50	<0,05
Sum		14 794	563	168
Emission per binder [g/kg binder]	dust	7,8	1,33	0,35
	CO	373	8,56	6,10
	SO_2	7,49	0,15	0,16
	VOC	120	2,65	1,68
	BTEX	24,5	0,20	0,05
	asetaldehyde	2,99	0,21	0,03
	formaldehyde	0,07	0,15	0,03
	phenol	4,02	0,02	0,01
	o-cresol	5,59	<0,036	<0,004
	p-cresol	2,73	<0,036	<0,002
Sum		548	13,3	8,4

Conclusions of the chamber tests in Finland:
The measured emissions from both inorganic binder moulds are only a fraction (3,8% and 0,8%) compared to the emissions of the organic Alphaset binder mould.

Inorganic binder 1 inorganic binder system uses organic hardener (ester compound). Thus it is understandable that some organic emissions are measured. The recommended amount of the hardener is small, and the emissions are only 3,8% compared to the emissions from organic Alphaset mould.

In inorganic binder 2, inorganic binder system both binder and hardener should be 100% inorganic, but minor organic emissions were found. There must be some organic matter added to the binder and/or promotor material to improve the technical performance of the binder system.

The emissions from both inorganic binder moulds are so small that a drastic decrease in harmful emissions from the foundries would be obtained by using these inorganic binders instead of organic binders. In addition, improvement in indoor air quality is expected, as well as in the quality of the castings due to the decreased risk of gas porosity.

Based on the emission measurements from chamber tests carried out at URV and Karhula foundries with organic Alphaset binder system and two inorganic binders, the results demonstrate remarkable emission reductions. BTEX emissions were reduced by 99%, VOC emissions by 98%, dusts by 96%, CO by 98% and phenols by 99%, when exchanging organic binder system to inorganic binder. Same kind of measurement results were also received at the Hardkop foundry in Poland.

10.2.2 Chamber tests in Poland

Three organic binder systems and three inorganic binder systems were tested both in small scale chamber tests in AGH-UST laboratory foundry and in Hardkop pilot iron foundry:

- Organic Alphaset (MA)
- Organic Furan (MF)
- Organic Green Sand (MB)
- Inorganic (MI)
- Inorganic (MC)
- Inorganic (MG)

AGH-UST laboratory foundry:
The test arrangements at the AGH University are presented in figure 37-38 and results in table 36.

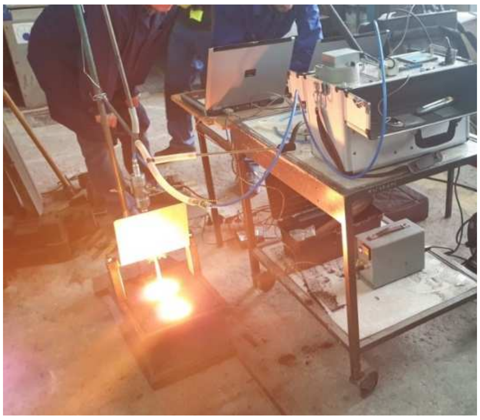

Fig 37-38. Chamber test arrangements in AGH-UST laboratory foundry

Table 36. Results of the lab scale tests at AHG University

CODE	Emissions per 1 kg of moulding sand, mg				
Compounds	Total BTEX	Benzene	Total PAHs	Benzo(a)pyrene	Total gas content ml per 100 g moulding sand
Organic MF	658	602	12.09	0.24	19.73
Organic MA	495	464	9.87	0.17	24.97
Organic MB	176	161	5.8	0.15	26.10
Inorganic MG	60	51	3.14	0.06	13.76
Inorganic MC	24	16	2.18	0.01	11.42
Inorganic MI	22	14	1.99	0.02	8.88

Conclusions from the chamber tests in laboratory scale in Poland:

Comparative studies of moulding sands with organic and inorganic binders exposed at high temperature (1350 ^{o}C) carried out on a laboratory scale have shown that:

- moulding sand with organic binder generated 2 to 3 times more gas volume than other mouding sands
- moulding sands with organic binder (MA and MF) showed significantly higher emission of compounds from the PAHs and BTEX group than moulding sand with inorganic binder (MI, MC, MG and MB); the difference was even 10 times;
- in the BTEX group, the main component emitted was carcinogenic benzene (up to 95%),
- in the PAHs group, the main component emitted was naphthalene, in addition, small amount of carcinogenic benzo (a) pyrene was also identified in these gases,
- the moulding sands with inorganic compounds, hardened with temperature (MI, MC), showed lower emissions of BTEX, whereas for moulding sands with inorganic binder, but hardened by organic hardener (MG),
- a particularly low emission from the group BTEX and PAHs were characterized by moulding sand with water glass (MI, MC) cured by hot air,
- green sand (MB) showed relatively low emission of compounds from the PAHs and BTEX groups because in the bentonite mixture the coal dust was partly replaced by more environmentally friendly components,
- in the case of moulding sands with organic binder (MF and MA) and green sand (MB), SO_2 was found in the tested gases. The presence of SO_2 in the gases from the moulding sand (MF) is the result of decomposition of benzenesulfonic acid which is used as a solvent, while the presence of SO_2 in gases from the MB moulding sand is associated with the sulfur content of carbon-containing additives introduced into bentonite,
- NOx oxides were found in gases released from MF and MA moulding sand, which are probably the result of the decomposition of compounds containing nitrogen e.g. urea, which is introduced to resin by manufacturers in order to extend resin life.
- Due to the grate fraction of green sand in the production of cast iron, work is underway to develop environmentally friendly sea coal replacements.

10.2.3 Hardkop pilot iron foundry tests

Research on the composition of gases (BTEX and PAHs groups) formed during pouring and cooling of moulds and knocking out of castings were conducted in the HARDKOP foundry in Trzebinia. Six types of moulding sands were selected for testing.
Ratio (mould sand:metal) was 2.8 – 3.0. Temperature of liquid cast iron was 1380 – 1420^{o}C. Prepared moulds were placed on a vibrating table, the construction of which, after the pouring and cooling of the mould, allow knocking out the casting, without having to dismantle the stand. The whole system was placed in a metal box with a flap opened in the upper part, through which liquid metal was poured into the mould. The box was equipped with a connector, through which gases generated in the process were sucked (Fig 39).

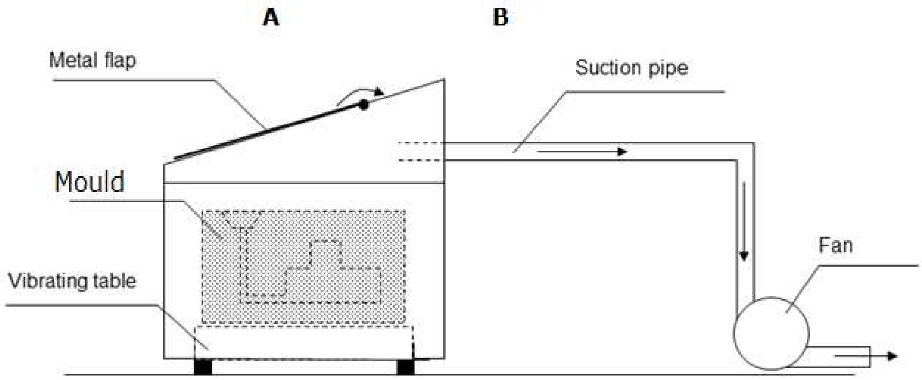

Figure 39. Test arrangements in Hardkop iron foundry.

Results of BTEX measurements carried out with 3 organic and 3 inorganic binder systems are presented in table 37.

Table 37. Test results from the chamber test in Polish pilot foundry Hardkop

CODE	Emissions per 1 kg of moulding sand, mg				
Compounds	Total BTEX	Benzene	Total PAHs	Naphthalene	Total PAHs+Total BTEX
Organic MF	84	18	0.15	0.12	84.15
Organic MA	34	23	1.8	1.43	35.8
Organic MB *	5.1	2,6	0.48	0.36	5.58
Inorganic MG	1.6	1,1	0.41	0.21	2.01
Inorganic MC	0.25	0.15	0.059	0.026	0.31
Inorganic MI	2.2	1.1	0.056	0.043	2.26

* part of coal dust was substituted by environment friendly additions

Conclusions:
In order to compare the harmfulness of the tested moulding sands, measurements of amounts of emitted substances from the BTEX and PAHs groups under an influence of high temperatures, were performed. Measurements were conducted for the whole cycle containing: pouring, cooling and knocking-out, within the Action B Tests in foundry plants – small scale laboratory. The obtained results were recalculated into the emission from 1 kg of the moulding sand and 1 kg of the binder applied in the given technology.

The following conclusions can be drawn on the bases of tests performed under the small scale chamber conditions:

1) Emissions of PAHs, as well as BTEX in case of moulding sands with organic binders is several dozen higher than the emission of these compounds from moulding sands with inorganic binders.
2) Green sands in respect of the PAHs emission are in the intermediate sphere, while in respect of the BTEX emission are comparable with moulding sands with inorganic binders.

3) From the comparison of moulding sands with organic binders it results, that the BTEX emission from the MA sand is more than two times lower than the emission from the MF sand, while benzene and toluene predominate in the composition of gases emitted from both sands.
4) Moulding sands with inorganic binders are comparable in terms of the emission amount of substances from the BTEX and PAHs groups. Higher values of the unitary emission from moulding sands with MG binder are the result of using the organic liquid hardener for this binder hardening, while for the hardening of the remaining two binders (MI, MC) high temperatures were used.
5) Moulding sands with inorganic binders (MG, MC and MI) are characterised by lower harmfulness for the environment and employees than moulding sands with organic binders.
6) Relatively environment friendly were green sands (MB), in which a part of coal dust was substituted by additions able to produce lustrous carbon.

11 Solutions to improve foundry indoor air quality

11.1 General and local ventilation systems

General ventilation:
The purpose of **general ventilation** in the foundry is to control the indoor air quality and temperature conditions. The higher process emissions are, the higher air flow rate is needed, to reach satisfactory indoor air quality. Foundry processes are highly polluting. Especially melting, pouring, cooling and shake-out processes need extra arrangements that is local exhaust systems to lower the emission load into indoor air. With the local ventilation should escape from 70..90% from process pollutants. The remaining 10..30% should be left to be controlled by general ventilation. Still the general ventilation is to be high always up to 10 times exchange rate per hour. The lower ventilation rated can be reached, the higher energy efficiency is achieved. In northern European conditions 15..25% of foundry energy use is consumed in ventilation systems.

The dimensioning of general ventilation is based in winter periods on control of contaminants and in summer periods on cooling the premises. The air flow for contaminant control is based on the mass balance equation.

$q = k_1 * k_2 * m * m / C_{tv}$, ($m^3/s$)

Where:
q is supply air flow, m^3/s
k_1 is emission source effect on exposure i.e. pollution spreading from the source to occupational zone, typically 2-10 factor
k_2 is the mixing factor of indoor air i.e. complete dilution means factor 1, with wall jet system 1..1,5 and the factor of displacing ventilation 0,2..1
m is the capture efficiency of local ventilation varying from 0,1..1
C_{tv} is the target value of indoor air quality usually 1/10.. 1/2 of threshold limit value, mg/ m^3

Table 38 gives the magnitude of general ventilation efficiency factor (k_2) which has essential effect on the air flow rate. The supply air distribution systems, illustrated in Figure 40, differ considerably. As a general rule it can be estimated that air exchange rate in foundry premises rises up to 10 times per hour.

Table 38. Ventilation efficiency i.e. mixing factor of different supply air distribution systems

Supply air distribution system	Ventilation efficiency of system
a) Anemostates on ceiling level	1,0 - 1,4
b) Supply air from ceiling with vertical jets	1,0 - 1,1
c) High impulse jet anemostates	1,2 - 1,5
d) Anemostates above occupation level	0,6 – 0,8
e) Thermal displacement ventilation	0,4 – 0,6
f) Nozzle ducts above occupation zone	0,5 - 0,7

g) Floor jets	0,3 - 0,6
h) Cold air jets on ceiling level	1 - 2

Example. In case of heavy load of heat and dust in foundries e.g. pouring, mould cooling, shake-out and melting unit processes, the displacement ventilation system is optimal method (where $k_2 \approx 0{,}3$) (Fig. 40). The equal air quality is reached with a third of air flow (q) compared to simple mixing ventilation ($k_2 = 1$) (Fig. 41). Optimal ventilation system saves remarkably energy of heating the supply air during the cold seasons.

When considering the performance of general ventilation one has to know the tightness of the building as well. The tightness of building envelope means that the air tightness of the structures through which the ventilation air is not supposed to flow, is good. The tightness of the building envelope is one of the most important factors affecting the co-operation of structures and HVAC engineering. It is also one of the most difficult factors to be controlled. The influence of uncontrolled air leakages has grown as one of the most usual facts behind draught complaints and poor energy economy as the insulation level of structures and heat recovery efficiency has improved.

The tightness of the building is important in considering good implementation of heat recovery, air purification and humidification. The air entering through leakages can not be filtered or utilized in heat recovery.

When defining the general ventilation efficiency one has to be aware of air leakages in air balance level in case the exfiltration air or infiltration is in question. Usually, when there is the zero pressure difference level in the room, both filtration types exist at the same time. The exfiltration air flows out through the building envelope above the zero level and the infiltration air flows in the below the zero level. The exfiltration air transports contaminant out from the hall thus improving the general ventilation efficiency.

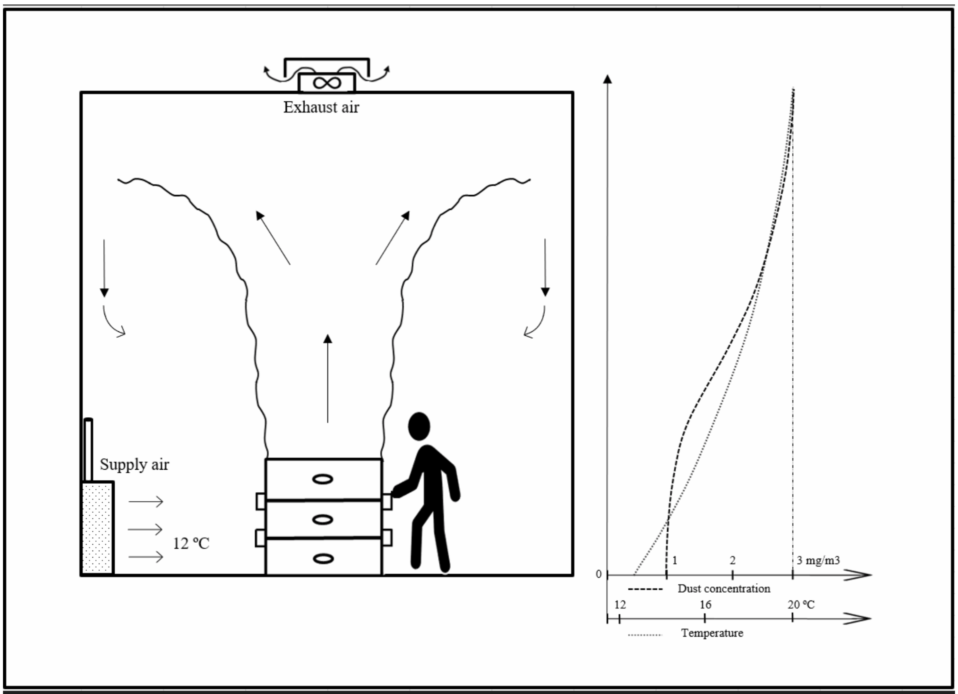

Fig. 40. In case of displacement ventilation $k_2 \approx 0,3$.

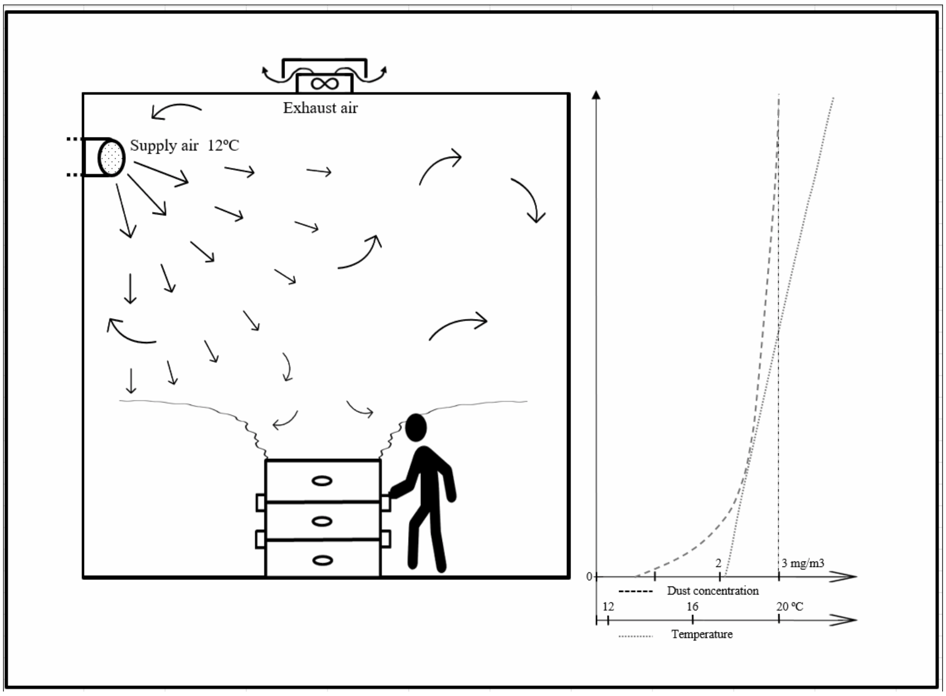

Fig 41. In case of displacement ventilation $k_2 \approx 1,0$ (mixing ventilation).

Next to the figures are the illustrations of thermal stratification of indoor air temperature and dust concentration.

Local ventilation:

The purpose of **local ventilation** in foundry premises is to minimize impurity emissions and heat load from contaminant source into indoor air by capturing contaminants as effectively as possible (Fg. 42). In this way local ventilation reduces the load of general ventilation, m, to control quality and temperature conditions of indoor air. The efficiency of local ventilation is defined as capture efficiency:

$E = m/M$

Where
E is capture efficiency of local ventilation; 0 – 1
m is emission flow of contaminants into indoor air, mg/s
M is total emission flow of contaminants from the source, mg/s

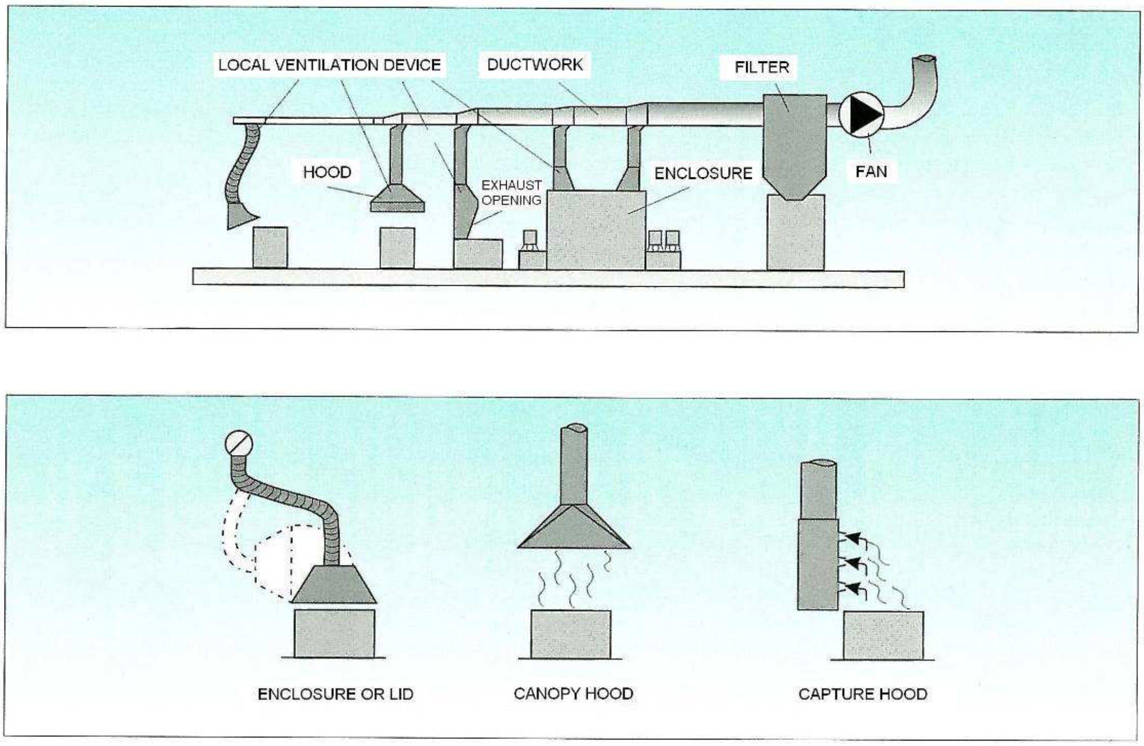

*Figure 42**:** Local ventilation efficiency is the capture efficiency of contaminants from the emission source.*

Enclosing local exhaust system for shake-out:
One of the most polluting unit processes is the shake-out of sand moulds. It contains highly dust and gaseous emissions. The shake-out table can be enclosed with drivable heat resistant curtains when shaking (Fig 43). The curtains will be driven down under loading stage and risen up for shake-out stage. With the system a low air flow of 1-3 m^3/s is needed for the grille and dedusting system. Instead the open grille shake-out needs 5-10 times higher air flow without any enclosure (Fig 44).

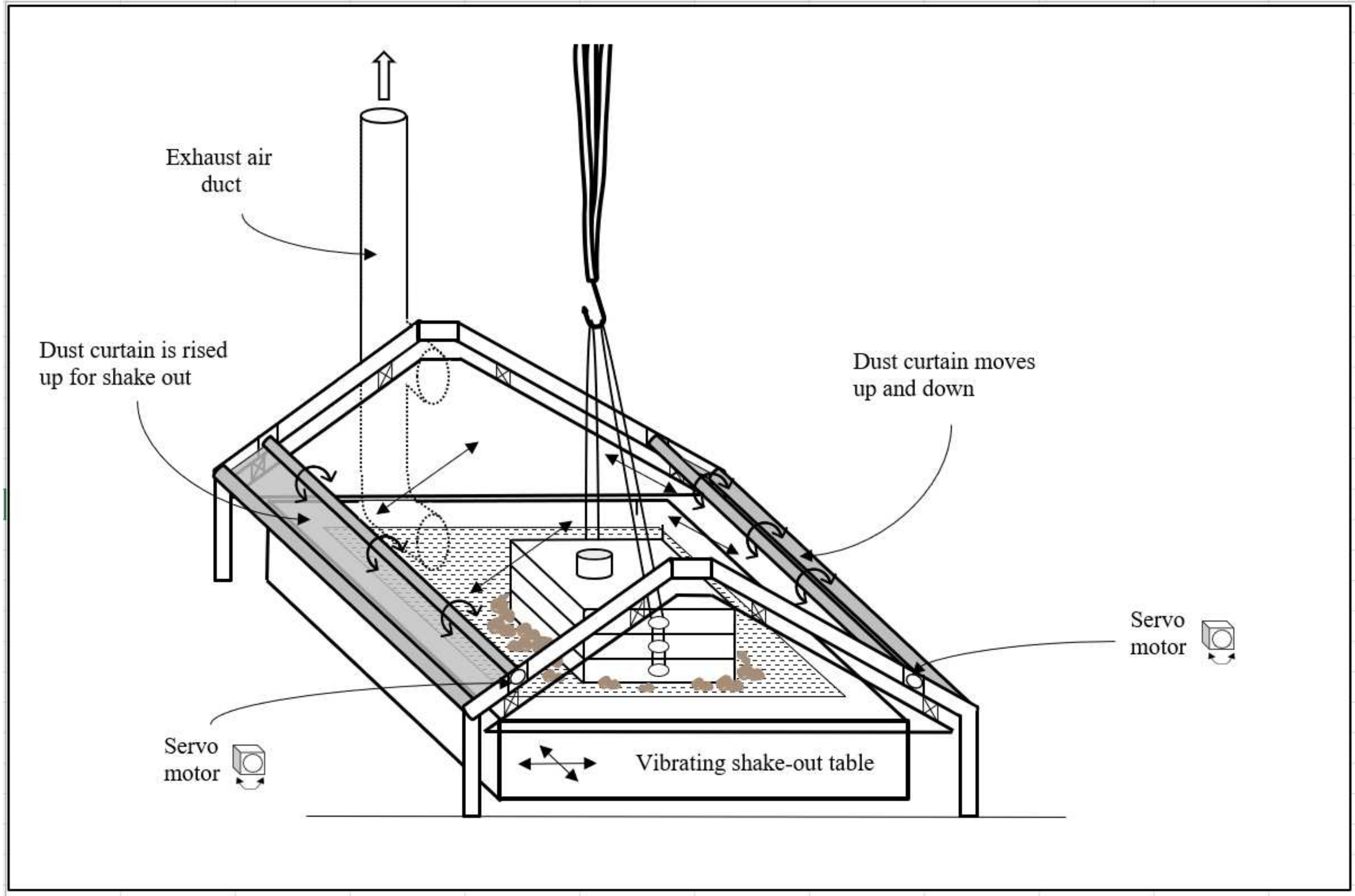

Fig 43. Local exhaust system of the shake-out.

Fig 44. Shake-out with local ventilation but without any enclosure.

Dedusting and filtration:
In foundries, the ventilation exhaust air usually contains various amounts of dust. This must be taken into account if exhaust air circulation or heat recovery is considered. In both cases, the exhaust air must be filtered first in order to prevent problems in occupational hygiene and to ensure that the heat recovery surfaces stay clean.

Energy cost of ventilation:

Ventilation uses heating energy in the heating of supply air and electricity in operation of fans. As an example in two shift production the supply air heating of 10 m^3/s ventilation unit uses annually heating energy some 670 MWh/a in Finnish climate and in South Germany some 480 MWh/a this corresponds. This corresponds to the cost of 34,000 €/a and 24.000 €/a with the energy price of 50 €/MWh. By choosing the most efficient ventilation (supply air distribution system) the saving may rise up to 50 % when comparing displacement system to complete mixing ventilation system, see table 3 still both systems perform equal air quality in occupation zone and other occupational hygiene conditions. This shows 17,000 €/a saving in Finland and 12,000 €/a saving in Germany.

By applying efficient local ventilation system one may save even more remarkably. For example a poor local exhaust system of a induction furnace may capture only 90 % of furnace fumes. This means 10 % of the fume mass is emitted into indoor air. This means hourly the extra load of some 0.1 kg fume mass from 3 ton furnace to be diluted into indoor air and exhausted out via general ventilation exhaust air flow of 33,000 m^3/h in normal foundry indoor concentration of 3 mg/m^3. This means almost equal extra use of general ventilation and the same energy cost annually as we had in the chapter above *i.e.* 34,000 €/a.

12 Summary of the Green Foundry LIFE project

The main objective in the Green Foundry LIFE Project (LIFE17 ENV/FI/000173) was to evaluate the possibility of transferring such benefits to the casting of iron and steel. The application of modern sand moulding systems based on inorganic binders would have a significant positive environmental and economic impact.
The aim of the Green Foundry LIFE project was to demonstrate the feasibility of inorganic binders in ferrous foundries by following actions: emission measurements with different organic and inorganic binders and emission reductions expected, full-scale test casts and cores with different inorganic binders in three pilot foundries and waste sand treatment and reuse methods.

Small scale chamber tests were made in Finland and Poland to measure total emissions of the casting processes. Different organic and new inorganic binder systems were tested both in small scale chamber tests in AGH-UST laboratory foundry and in Hardkop pilot iron foundry. In order to compare the harmfulness of the tested moulding sands, measurements of amounts of emitted substances from the BTEX and PAHs groups under an influence of high temperatures, were performed. Moulding sand with organic binders generated 2 to 3 times more gas volume than inorganic. Green sand showed relatively low emission of compounds from the PAHs and BTEX groups because in the bentonite mixture the coal dust was partly replaced by more environmentally friendly components.
In Finland the small scale chamber tests were carried out at Karhula and URV foundries with organic and inorganic binder systems. The results demonstrated remarkable emission reductions of 90-98 % related to BTEX, CO, VOC, PAH, SO_2 compounds when using inorganic binders.

Full production scale test series with inorganic binder system moulds and cores were made in three ferrous pilot foundries in Finland, Italy and Estonia. Karhula Foundry in Finland and Valumehaanika foundry in Estonia use currently phenolic Alphaset binder system and FOM Tacconi foundry uses bentonite sand (green sand) binder system. The aim of these tests was to demonstrate the feasibility of inorganic binders in production scale in the manufacture of moulds and cores in ferrous foundries. The tested inorganic binders were from four different binder producers, with the brand names of:

- InotecTM from ASK Chemicals GmbH
- Cordis from Huettenes-Albertus Italy S.p.A.
- Cast Clean from Peak Deutschland GmbH
- Geopol® from Sandteam spol s.r.a.

The results in production scale test casts with inorganic binder systems in pilot foundries were promising, the emission reductions were significant and the quality of the castings was comparable with the castings made by organic binder systems. The project, however, learned that the extensive use in these and other ferrous foundries requires:
- Vast knowledge about different inorganic binder systems and their proper implementation into current or new production lines

- In most cases investments for moulding, core making and sand regeneration methods are needed and broad testing should be carefully carried out before commitment
- Traditional nature of the branch: 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

Various foundry sand reclaiming options with different inorganic binder waste sands were tested. The aim was the clean the foundry waste sands and recycle back to foundry processes. **Washing, mechanical, hydromechanical and ultrasonic reclamation techniques** were tested on laboratory scale. **Thermal reclamation tests** with organic and inorganic binder system waste sands were performed in industrial scale tests at the thermal reclamation plant in Iitala, Finland owned by FinnRecycling Ltd.

Purifications and reuse methods were demonstrated in the project. Industrial scale composting tests were demonstrated in Finland and Spain**.** By composting method the harmful organic substances of the foundry waste sands will be degraded and the clean soil material can be reused in new applications as in geo-construction and landscaping. The aim is to reduce the need of natural sand to be mixed with the soil material after the composting, and replace it with foundry waste sand which is added in the beginning of the composting process. Most importantly, the aim is to reduce the amount of foundry waste sand to be landfilled in the future.

13 Publications

(2016) S. Balbay. Removal of Pollutants from Waste Foundry Sand by Chemical Washing Method a. International Conference on Agricultural, Civil and Environmental Engineering

(2017) Wang, L. Investigation of parameters and mechanism of ultrasound-assisted wet reclamation of waste sodium silicate sands. International Journal of Cast Metals Research, Vol. 31 (3).

(2016) Chaparro, A.L., et al. Desarrollo y validación de un método ambientalmente amigable para determinación de metales pesados en pastos. REVISTA DE CIENCIAS AGRÍCOLAS, Vol. 33, 3-15.

(2014) Alves, S. Q.B. et. al. Metals in Waste Foundry Sands and an Evaluation of Their Leaching and Transport to Groundwater, Water Air Soil Pollute, 225,1963.

(2013) Czapla, P. The State of Art of the Mechanical Reclamation of Used Foundry Sands. Archives of Foundry Engineering, Vol. 13, 15-30.

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(2007) Belli, M., et. al. The role of different soil sample digestion methods on trace elements analysis: A comparison of ICP-MS and INAA measurement results. Accred. Qual Assur (2007) Vol. 12, 84-93.

(2006) Acosta, Y., et al. Análisis comparativo de dos técnicas de digestión para la determinación de metales pesados en lodos residuales. MULTICIENCIAS, Vol. 6, Nº 3, 2006 (234 - 243).
Handbook of Environment & Waste Management, Volume 2: Land and Groundwater Pollution Control

Expired patents:

Purification of sand (US2952516A) Current Assignee: International Minerals and Chemical Corp
Process for purifying silica sand (US4401638A) Current Assignee: Materias Primas Monterrey SA
Process for leaching sand or other particulate material (US4042671A)

A method for treating surplus foundry sand by composting and a compost (patent number 20165289, 15.8.2018). Meehanite Technology Ltd.