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Action B5.1 BAT Report

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1. General Introduction

The following text is a summary of those activities performed in the course of the Green Foundry LIFE project which developed into concrete proposals for uptake of the respective technologies and processes in the updated version of the Best Available Technology Reference Document (BREF) for the smitheries and foundries industries currently in preparation through teh established Seville process as either Best Available Technology (BAT) or Emerging Technology (ET) candidates. In the following, the respective technologies and processes will be described in detail based on a structuring which reflects the BAT template adopted for feeding such proposals into the Seville process.

The technologies in question are listed in Table 1 below together with the current status as BAT or ET. The related section in the present document is also indicated.

Table 1: Overview of technologies covered in this report, with current development and availability status.

Designation of technology	Report Section	Status
Use of inorganic binders for moulds in iron and steel casting	2	ET
Use of inorganic binders for cores in iron and steel casting	2	ET
Thermal reclamation of foundry sand	3.2	BAT
Composting of waste foundry sand	3.3	BAT
Washing of foundry sand	3.4	ET
Ultrasonic treatment of foundry sand	3.5	ET
Hydromechanical treatment of foundry sand	3.6	ET

In the text, where possible, a reference is made to the related section in the BREF document. This reference does not refer to the structure of the currently available first draft of the updated BREF document [EC_22], but to that of the currently valid version dating from 2005 [EC_05].

2. Implementation of inorganic binder system in mould and core making (UNIPG, Pekka Kemppainen/Hannu Pöntinen, Meehanite)

2.1. Introduction and Reference to BREF

Related section in current BREF document [EC_05]:

2. Applied Processes and Techniques in Foundries
    2.5 Mould and Core Production
        2.5.1 Raw materials
            2.5.1.2 Binders and other chemicals
        2.5.6 Moulding and core-making with chemically-bonded sand

3. Current Emission and Consumption Levels in Foundries

   3.9 Mould and core production

      3.9.4 Moulding and core-making with chemically-bonded sand

   3.10 Casting

      3.10.1 Casting, cooling and shake-out, using lost moulds

         3.10.1.4 Used foundry sand

Inorganic binder systems represent an established technology in aluminum casting, in which they are used for production of moulds as well as cores both using conventional and addititve manufacturing techniques. For this branch of the casting industry, replacement of organic binder systems with inorganic ones has led to several advantages, among which

- significant reduction in harmful emissions during casting (section 3),
- improvement of indoor air quality (sections 3 and 4)
- improved access to waste sand reuse in the foundry industry itself (sections 5 and 6) and
- major limitations of harmful substance (e.g. DOC, BTEX, phenols, fluorides) content levels in waste foundry sand (section 6)

are most prominent. Transfer of this technological approach to iron and steel foundries could make similar improvement accessible to these industries. The prerequisite of such a step, however, is the dedicated evaluation of processing characteristics of such types of binders in the foreseen application. This includes evaluating their match with established industrial procedures and their impact on the quality of the parts produced.

2.2. Description

The binder systems considered as alternative to conventional phenolic or furanic organic variants fall into two different main categories:

- fully inorganic systems typically based on aqueous sodium silicate solutions plus some additive to foster hardening (3 examples considered, in the following designated binder 1-3)
- hybrid, organic-inorganic systems which combine an inorganic binder with an organic, usually ester-based hardener (2 examples considered, in the following designated binder 4-5)

As reference and basis for comparison, organic systems were evaluated in parallel to the inorganic and hybrid ones under scrutiny. Such reference systems included self-setting phenolic and furanic systems as well as bentonite-based ones. The reader should note that not all systems were covered in all types of tests.

A main characteristic of the fully inorganic binder systems studied is the fact that in its case, hardening requires heat: For details, see section 2.4. This limits the possibility of wider introduction in brownfield approaches, favouring greenfield scenarios instead. In contrast, the hybrid systems evaluated are self-setting, which matches the phenolic Alphaset system commonly used by many iron and steel foundries and thus facilitates its possible replacement by these systems. For greenfield approaches, the situation is somewhat different as initial investment can be tailored to the needs of a fully inorganic solution. The added investment for non-self-setting binder systems is not limited to suitable furnaces, but also includes pattern, cores boxes etc., as common wood or polymeric solutions are not suitable for elevated temperature processes. This reservation does not apply if the respective entreprise already has the respective facilities and tools at hand, which might be the case if e.g. hot-box core making processes were applied. From an environmental point of view, the use of hybrid systems may already constitute a significant benefit when compared to fully organic systems, as in this case the content level of organics is reduced by roughly one order of magnitude. In-depth life cycle assessment (LCA) studies might be required to assess under which conditions energy consumption, CO_2 emissions etc. associated with the hardening process cancels out advantages of the fully inorganic nature of the respective binders when contrasted to hybrid solutions.

2.3. Achieved Environmental Benefit

The fact that when using fully or predominantly inorganic binder systems, moulds and cores and thus also waste foundry sands contain less harmful substances directly implies an environmental benefit. This relates to the release of such harmful substances during mould and core production, curing of these and casting as well as the later disposal of waste foundry sands. For the latter, use of inorganic binder thus opens up new paths for reuse as alternative to landfill. The respective investigations have been summarized in the dedicated sections of this report, adding further studies on methodologies for reclamation and reuse applicable to organically (thermal reclamation, washing) and/or inorganically bonded (washing, ultrasonic and hydromechanical treatment) sand.

The benefits that can be achieved using these methodologies individually or in combination are, in short:

- reduction in amounts of foundry waste suitable only for landfill disposal
- extension of the scope of reuse options for waste foundry sand thanks to
- reduction in workplace emissions

Beyond larger scale environmental benefits associated with the use of inorganic binders, organic components in conventional binder systems for use in iron and steel casting are the source of critical workplace emission in the casting industry. Due to the fact that inorganic and hybrid binder contain no to low levels of organic substances which can react or decompose at casting temperatures to form gaseous emissions and fumes, considerable benefit is expected from their use. The problem is illustrated in Figure 1 below, showing fumes emerging from an organically as opposed to a predominantly inorganically bonded mould shortly after casting. Quantitative analyses of the respective effects have been performed as part of Green Foundry action B2.1 and B2.2.

Figure 1: Emission from an Alphaset-bonded mould (left) and another one based on a hybrid binder (right, binder 5). Images were taken approx. 4 minutes after pouring in both cases.

In the course of the Green Foundry LIFE project, several measurement campaigns covering emissions during casting were performed. These are summarized in Table 2 below.

Table 2: Overview of casting experiments for emission measurements with binder systems evaluated, locations of casting experiments and size of castings.

Binder System	Location of Tests	Weight of Casting [kg]	Weight of Sand [kg]
binder 1	Karhula Foundry (FI)	200	200
	Hardkop Iron Foundry (PL)	23	65
	AGH-UST laboratory foundry (PL)	0.150	0.150
binder 2	Hardkop Iron Foundry (PL)	23	65
	AGH-UST laboratory foundry (PL)	0.150	0.150
binder 4	Karhula Foundry (FI)	200	200
binder 5	Hardkop Iron Foundry (PL)	23	65
	AGH-UST laboratory foundry (PL)	0.150	0.150
Alphaset[1]	URV Foundry (FI)	23	65
	Hardkop Iron Foundry (PL)	23	65
	AGH-UST laboratory foundry (PL)	0.150	0.150
Furan[1]	Hardkop Iron Foundry (PL)	23	65
	AGH-UST laboratory foundry (PL)	0.150	0.150
Green Sand[1]	Hardkop Iron Foundry (PL)	23	65
	AGH-UST laboratory foundry (PL)	0.150	0.150

[1] Included as reference organic systems.

The massive reduction in emissions is illustrated by the following two tables, of which the first (Table 3) refers to the Finnish, the second (Table 4) to the Polish test campaign.

Table 3: Results of the Finnish emission measurements campaign comparing organic, hybrid and inorganic binder systems.

Substance		Binder system		
		Alphaset	Binder 4	Binder 1
dust	[mg/kg sand]	210	56.1	7.05
CO	[mg/kg sand]	10069	361	122
SO2	[mg/kg sand]	202	6.51	3.14
VOC	[mg/kg sand]	3237	112	33.5
BTEX	[mg/kg sand]	661	8.5	1.00
acetaldahyde	[mg/kg sand]	80.8	8.8	0.69
formaldehyde	[mg/kg sand]	1.91	6.2	0.60
phenol	[mg/kg sand]	108	0.89	0.13
o-cresol	[mg/kg sand]	151	<1.50	<0.07
p-cresol	[mg/kg sand]	73,7	<1.50	<0.05

Table 4: Results of the Polish emission measurements campaign comparing organic, hybrid and inorganic binder systems.

Substance	Binder system					
	Alphaset	Furan	GS[1]	binder 1	binder 2	binder 5
total BTEX [mg/kg sand]	495	658	170	22	24	60
benzene [mg/kg sand]	464	602	161	14	16	51
total PAHs [mg/kg sand]	9.87	12.09	5.8	1.99	2.18	3.14
benzo(a)pyrene [mg/kg s.]	0.17	0.24	0.15	0.02	0.01	0.06

[1] Green sand (reference)

2.4. Operational Data

Results of practical experiments

- Pilot plant I (Karhula Foundry):

Karhula Foundry produces medium to large scale castings between 1 kg and 30 tons apiece in weight for a global market. The foundry relies on a large range of available patterns which e.g. allow for economic production of spare parts. In this and other cases, series sizes are typical small and may go down to single parts being cast. Standard process is Alphaset (self-setting, alkaline phenolic resin with organic ester for curing) combined with pure high quality silica sand. Chromite sand is used in cases demanding highest surface quality in direct contact with the melt. Typical ratio of used and new sand is 70:30. Moulds and cores are typically covered in alcohol-based zirconia coating. Main casting materials are several grades of steel (e.g. duplex, martensitic, ferritic, austenitic and super-austenitic stainless steels), but cast iron is also offered.

At Karhula Foundry, one inorganic („binder 1“) and two hybrid binder systems („binder 4 & 5“) were evaluated. Moulding/core making tests as well as casting and shake out/decoring tests were performed with all binders.

Binder 1 required heating to temperatures of 160-200°C for drying and ascertaining the required strength levels. The time in the furnace was set to 30 minutes for production of bending test bars. For larger moulds and cores, additional allowance for soaking has to be made. Table 5 below provides data on bending strength levels as a function of binder and hardener content for all three binder systems. Strength data is based on two test bars each which were moulded manually. Levels of binder and hardener content are given in wt.% relative to the mixture of sand and binder components.

Table 5: Overview of bending strength levels achieved with reference and different inorganic and hybrid binder systems in relation to curing conditions.

binder system	content level [wt.%]		curing		bending strength [N/cm^2]
	binder	hardener	time [h]	temperature [°C]	
reference (Alphaset)	-	-	24	RT	250-300
binder 1	1	0.3	0.5	200°C	40
	1.5	0.45	0.5	200°C	155
	2	0.6	0.5	200°C	285
binder 4	3	0.3	1	RT	-
	3	0.3	4	RT	180
	3	0.3	24	RT	540
binder 5	1.8	0.32	1	RT	25
	1.8	0.32	4	RT	60
	1.8	0.32	24	RT	115

Data on binder 1 show that reference strength levels are easily met and surpassed, but that the exact curing conditions need to be thoroughly determined to avoid unnecessarily high strength levels which could hinder demoulding/decoring and have led to cracking of moulds during the experiments (hence the reduction in binder content in production scale tests described below to 1.5 wt.% and in curing temperature to 160°C, which proved successful).

The following casting experiments using binder 1 were perfomed:

- Chamber tests for emission measurement using 2 wt.% binder and 0.6 wt.% promoter, mixing in batches of 30 kg (mixing time 80s, addition of promoter after 10s). Curing was done for 4 hours at 160°C. Hand moulded Moulds remained without the usual coating. Stainless steel was cast at 1560°C.
- Production scale tests using mixtures of 500 kg each containing 70% recycled and 30% new high quality silica sand and two different binder content levels, namely
    - 2 wt.% binder and 0.6 wt.% promoter and
    - 1.5 wt.% binder and 0.45 wt.% promoter.

Mixing was done for 3-5 minutes before adding the promoter, after which mixing continued for another 3-5 minutes. Curing was done for 3 hours at 160°C, followed by overnight cooling in the closed furnace to approx. 40°C. Moulds were coated with TENO ZIR 78 (Foseco), flame burnt and kept for 15 minutes under an induction heating system positioned above the moulds. ASTM A747 Cb7Cu-2 stainless steel was cast at 1515°C pouring temperature.

In the case of the chamber tests, manual demoulding proved facile. No critical adhesion of sand to flasks was observed. Around the casting, a 1.5 mm thick shale of burned black sand was observed. Surface quality of castings was good despite the decision to abolish the coating. Production tests showed adverse effects of the higher binder content levels in terms of cracking of moulds and significant adhesion of sand to flasks and patterns which were linked to unfavourably high strength levels of the binder under the aforementioned conditions. Binder content was thus adjusted accordingly.

Binder 4 required no heating for hardening but showed self-setting behaviour. Strength data as function of curing time is given in Table 5 above. The data was gathered based on batches of 25 kg. It underlines that binder 2 easily surpasses the standard set by the reference Alphaset system, implying that binder content and curing time should be well adjusted to avoid potential problems caused by excessive strength.

The following casting experiments using binder 2 were performed:

- Test casts using moulds made from mixtures of 3 wt.% binder and 0.3 wt.% hardener prepared in batches of 25 kg partly painted with alcohol-based Zr coatings (Solitek ST 901 by ASK). Stripping took place 24 hours after moulding, and moulds were left in the production area for another 6 days before casting the duplex steel CD4MCuN ASTM A890 Grade 1B at 1565°C.
- Chamber tests for emission measurement (see section **Virhe. Viitteen lähdettä ei löytynyt.**) using 3 wt.% binder and 0.3 wt.% hardener, mixing in batches of approx. 300 kg (three mixing steps of 1 minute each were alternated with, first, addition of binder and, second, addition of hardener). Manual moulding followed immediately afterwards, stripping after 3 hours in a furnace at 25-32°C. Casting with grade ASTM A890 3A duplex stainless steel took place 22 hours after moulding at 1564°C (weight of casting as measured after demoulding 204 kg).
- Production scale tests using mixtures of 350-400 kg each with two different binder content levels (a faster variant of the hardener/promotor was used in this case), namely
    - 2 wt.% binder and 0.17 wt.% hardener and
    - 2.5 wt.% binder and 0.21 wt.% hardener.

  Mixing was done for 2 minutes after adding the binder and another 2 minutes after adding the hardener. Hand moulding followed immediately afterwards. All moulds were painted with alcoholic Zr solution. Curing was done for 24 hours at 18-20°C in the working environment before casting. ASTM A297 HH austenitic stainless steel was cast at 1501°C pouring temperature. Demoulding was done manually (lifting, hammer blows).

Test casts showed no adverse characteristics associated with the binder system. Surface quality was good, but clearly improved by the Zr coating. No problems with demoulding were noticed.

Chamber tests resulted in casting of poor surface quality, as in this case, no coating of the mould was foreseen. Standard coating has been shown to be able to remedy this effect during the test casts. With coating, surface qualities matching those obtained with the reference Alphaset system can be obtained.

Production scale tests showed differences in terms of demoulding between moulds produced first and last from one mixing batch, with the latter proving tob e easier to break. Surface quality of test casts was determined based on comparison with reference surface models and proved to be fully acceptable and comparable to Alphaset based castings. Dye penetration inspection was used to detect possible surface cracks or porosity: None were found.

Binder 5, like binder 4, is self-setting. Strength data as function of curing time is given in Table 5 above, showing that binder 3 falls short of the reference system in terms of strength. Further experiments with a focus on the influence of mixing time led to slightly improved strength (131 N/cm^2 after 24 hours curing) at a reduced mixing times of 1 minute, suggesting a low bench time of the system of less than 10 minutes (samples mixed 10 minutes reached 30 N/cm^2 bending strength after 24 hours).

- Production scale tests using mixtures of 200-300 kg each with 1.8 wt.% binder and 0.32 wt.% hardener. Mixing was done for 2 minutes after adding the binder and another 2 minutes after adding the hardener. Moulding followed immediately afterwards. All moulds were painted with alcoholic Zr solution (Teno Zir 78, Foseco). Stripping was done 24 hours after moulding, during which time the moulds were kept at 18-20°C in the working environment. ASTM A297 HH austenitic stainless steel was cast at 1501°C pouring temperature. Demoulding was done manually (lifting, hammer blows).

As in the case of binder 4, demoulding was possible in all cases, but proved easier for moulds filled last from one mixing batch. Surface quality was acceptable in all cases and matched results for binder 4 and the Alphaset reference system. Dye penetration investigations showed neither cracks nor surface porosity.

- Pilot plant II (Valumehaanika AS):

Valumehaanika AS is a small iron foundry established in Estonia in 1966 and recently renovated and provided with new equipment. The standard binder system is Alphaset as in the case of pilot plant I (Karhula), while silica sand is acquired from local sources. 10 employees produce 200 tons of castings in a size range from 5 to 100 kg annually. Moulds and cores are produced manually. As Valumehaanika has no facilities for curing via heating or gas blowing, only self-setting binder variants can be processed. Two such binders were tested at Valumehaanika, namely the systems evaluated as binder 4 and binder 5 at pilot plant I. The same designation will be maintained in this section.

Binder 4 was mixed with sand at 3 wt.% binder and 0.3 wt.% hardener content using a continuous mixer. Moulding was done manually. Hardening was slowed down by low ambient temperatures of 12°C, allowing stripping only after 45-60 minutes, compared to 15-30 minutes typical for the Alphaset reference system. For this reason, an alternative composition with 3 wt.% binder and 0.36 wt.% of a faster hardener variant was introduced, allowing a slight reduction of stripping time to 30-45 minutes. All moulds were painted using alcoholic Zr coating (Teno tec 5800 B, Foseco). Curing time was 18-24 hours at the aforementioned, comparatively low ambient temperature. Casting was done using gray cast iron according to EN GJL-250 at a pouring temperature of 1450°C. Demoulding was done manually by hammer blows, subsequent cleaning by shot blasting.

Surface quality of the test casts matched that of Alphaset-based casts. The sand’s tendency of sticking to casting surfaces was slightly increased compared to the reference system: As as consequence, short blasting times had to be increased.

Binder 5 was mixed with sand at 1.8 wt.% binder and 0.32 wt.% hardener content using a continuous mixer. As in the case of binder 4 at pilot plant II, and in contrast to actions at pilot plant I, a faster hardener variant was selected to compensate for low ambient temperatures (8-11°C in the case of test casts using binder 3). Nevertheless, stripping times exceeded those of Alphaset systems. All moulds were painted using alcoholic Zr coating (Teno tec 5800 B, Foseco). Casting followed 3-27 h after moulding. Casting was done using gray cast iron according to EN GJL-250 at a pouring temperature of 1450°C. Demoulding was done manually by hammer blows, subsequent cleaning by shot blasting.

Surface quality and the adherence of sand to the castings matched observations made for binder 4.

- Pilot plant III (Fonderie di Assisi):

Fonderie di Assisi produces both iron and steel castings for the automotive industry, among them mainly engine components. In the course of the project, Fonderie di Assisi evaluated two fully inorganic binder systems (binder 2 and binder 3) for cores. The cores themselves were produced by a sub-supplier, 2VI S. R. L. (see following section below).

Cores received from pilot plant IV were subjected to 2 hours at 900°C in a muffle furnace to determine loss on ignition resp. loss on calcination. Calcined residue was visually evaluated, sand residue analysed by optical microscopy. For comparison, an organically bonded core (cold box, phenolic isocyanide resin, 1.6%) was subjected to the same test procedure as the binder 2 and binder 3 variants produced at pilot plant IV. Figure 2 depicts the three types of cores.

Figure 2: Comparison of the three different types of cores (left to right, organic binder, inorganic binders 2 and 3).

Tests were perfomed upon arrival/production of the cores and after 6 day of storage in (a) lab and (b) production environment.

Calcination tests left samples bonded with organic and the Inotec systems in a non-aggregated state, while the binder 2-based sample did not fully disintegrate. Loss on ignition was measured at 1.6 wt.% initially and 1.57 resp. 1.54 wt.% after 6 days of storage in lab resp. production environment for the organic reference. The respective values for the Binder 3 variant were 0,42, 0.40 and 0.27 wt.% and 0,57, 0.44 and 0.40 wt.% for the binder 2 system. The tests indicate no adverse hygroscopic behaviour on the part of the inorganic systems. They furthermore confirmed the assumption (based on the lower weight loss) that the use of inorganic binders should lead to lower gas release during casting and thus a chance to reduce casting defects. Besides, available knowledge on the nature of the inorganic systems implies that gas release is likely mostly water, so formation of harmful emissions is expected to be lowered further. Some residual strength and aggregation is seen in inorganic binders. Shakeout of sand is thus impeded – however, shot blasting allowed facile removal of the cores.

Casting experiments were performed with grey cast iron (GJL 250) using cores based on both inorganic binder systems at a casting temperature of 1389°C. Altogether 320 castings were produced. In 96 cases, mould and core were manually removed, in 224 cases, this was done using an automated, vibration-based system. This operation did not lead to removal of the cores (no difference observed between both types of inorganic binders). However, this matches typical results for organically bonded cores. Subsequent two-step shot blasting of 10 minutes per step fully removed the core in the first step, though for both binders, some residual sand remained in the internal cavity. After the second sand blasting, external and internal surfaces are clean. Of the 224 automatically demoulded castings, 5 could not be associated with a binder due to core breakage. Of 135 castings produced using the Binder 3 system, 106 were in good condition, while in 29 (21.5%) cases, core breakage was observed. The corresponding figures for the Binder 2 system are 84 and 83 (1.2% failure).

- Pilot Plant IV (2VI S.R.L.):

Cores for further investigation and use in casting experiments at pilot plant III where produced using two different inorganic binders by means of a core blowing machine and an adapted core box originally designed for a cold box process but fitted with a resistive heating system.

The binders used were both inorganic two-component systems (binder 2 and 3, based on the designation system chosen for this report). In both cases, the binder itself is an aquaeus solution of modified sodium silicates. The additives required for hardening are mixtures of synthetic and natural powders, likely refractory oxides, of which the exact composition is not known. An alcoholic paint is used for coating the cores with refractory plaster following the core blowing process.

Figure 3: Example of a core with visible surface defects.

Despite the core box not having been specifically designed for use of the inorganic binder, cores of good quality were achieved, showing surface cracks and a tendency towards surface crumbling only in very few cases. Besides, cores produced using Binder 2 showed less resistance to handling and mechanical loads during transportation.

2.5. Cross-Media Effect

As discussed above, some inorganic binders require curing at elevated temperatures. The energy consumption associated with this additional process step - when matched against organic cold-box or similar processes in terms of hardening conditions – have to be taken into account when judging the overall environmental balance of using an individual inorganic binder for which this need applies.

2.6. Applicability

Fully as well as hybrid inorganic binders are available from several producers and already well established in light metal casting today. It was predominantly these binders which have been evaluated in the course of the Green Foundry LIFE project for iron and steel casting. The overall outcome of these experiments in terms of the quality of castings did show that there are indeed commercially available inorganic binder systems which can be transferred to the casting of iron and steel. Thus from a technological point of view, applicability can be confirmed.

2.7. Economics

Typical cost of inorganic binder systems is higher than that of organic ones. Relationships of roughly 1:15 are reported in this respect. Furthermore, switching from established room temperature processes to those inorganic binder variants requiring elevated temperatures of approximately 160-200°C for hardening would incur considerable investment costs, as patterns and core boxes not suitable for such processes would have to be replaced and furnaces or other heating equipment like hot air blowing lines set up. Costs for core boxes and patterns for typical castings like large pump housings or impellers as produced at pilot plant (see section 2.4) in a weight range between 30 kg and a few tons could amount to 50 to 100 k€ per part. In addition, additional investment costs of approximately 500 k€ would have to be covered for appropriate drying systems, i. e. furnaces of suitable dimensions for this range of product sizes. For foundries addressing the market for small scale series production in this area relying on the use of several hundreds of patterns, such an investment is impossible to realize. Thus the respective types of binders can only be introduced economically in foundries which already have hot box core lines up and running.

As an alternative for foundries relying entirely on cold box processes, hybrid types of binders can be considered. Although these are not entirely inorganic, they can help reduce the amount of organic compounds by up to 80% and allow processing according to a scheme similar to the established Alphaset process.

For greenfield applications, the aforementioned higher cost of inorganic binders remains a barrier. Increasing use of these binders due to environmental regulations and waste disposal costs may induce a reduction in prices based on economy of scale effects. If these can not fully compensate the cost advantage of organic systems, further developments in this area should also be aimed at establishing technological advantages of inorganic binder systems.

2.8. Driving Force for Implementation

- Economic considerations currently hinder the broad introduction of inorganic binders (see section 2.7). Reduction of purchase prices could support market growth and thus economy of scale effects.
- Further increases in disposal costs for waste foundry sand could lead to adoption of less harmful inorganic binders when considered on a total cost basis. However, this may require adaptation of local/national regulations, as in some cases, waste foundry sand is apparently generally categorized as waste irrespective of the binder system, and thus of the actual harmful substance content.
- Stricter regulations for workplace safety and allowable levels of airborne harmful substances may prove hard to reach when using organic binders, while inorganic binders have been proven to be significantly less critical in this respect during the current project. Thus the choice between complex secondary technical measures for air quality improvement when continuing to use organic binders and switching to inorganic binders could promote introduction of the latter.
- Carbon footprint and comparable environmental considerations are gaining in importance for many OEMs specifically in the automotive, but also in other industrial sectors. In this context, supply chains are increasingly being scrutinized, turning the environmental positioning of a supplier into an argument in favour of buying from this company.

2.9. Reference

3. Waste cleaning systems of surplus foundry sand: thermal reclamation, composting, washing, ultrasonic cleaning, hydromechanical treatment (TI, CTIF, Tecnalia/Araba, Meehanite)

3.1. Introduction and Reference to BREF
(Smitheries and Foundries, Version 2005)

Related section in current BREF document:

3. Current Emission and Consumption Levels in Foundries

3.9 Mould and core production

3.9.4 Moulding and core-making with chemically-bonded sand

3.10 Casting

3.10.1 Casting, cooling and shake-out, using lost moulds

3.10.1.4 Used foundry sand

The disposal of used foundry sand has become an increasingly critical issue for the casting industry, as e.g. critical values for VOC content are being increased, disallowing specific types of disposal for foundry waste which had earlier been commonly practised, such as landfill or use in construction works. Use of inorganic binder in the iron and steel casting industry, which is not an established practice yet. could significantly reduce harmful substance and specifically VOC content levels in waste foundry sands originating from this industry. As a consequence, additional paths for reuse and recycling could become available, or established ones now limited by increasingly strict regulations made accessible again.

For this reason, several tests have been performed regarding the reclamation, recycling and reuse of inorganically bound waste foundry sands sourced from the iron and steel casting industry. The methods studied were

	poposed as ...
• thermal reclamation of foundry sand (section 3.2)	BAT candidate
• composting of foundry sand (section 3.3)	BAT candidate
• washing of foundry sand (section 3.4)	ET candidate
• ultrasonic cleaning of foundry sand (section 3.5)	ET candidate
• hydromechanical treatment of foundry sand (section 3.6)	ET candidate

In order to evaluate the environmental impact of the aforementioned reclamation, recycling and reuse methods, life cycle assessments have been performed. These were based on results dating from 2014 until today gathered in the course of the GreenFoundry LIFE (LIFE17 ENV/FI/000173) and the LIFE Foundrysand project ((LIFE13 ENV/FI/000285), as well as others sourced from industrial scale application in Finland (thermal reclamation), the former ECOFOND company and lab scale experiments performed by the Tecnalia Research & Innovation centre. The results of these assessments will be reflected in the sections on achieved environmental effects (positive aspects) and cross-media effects (negative aspects) for each individual process covered.

Possibilities of reusing or disposal of foundry sand are subject to regulations on European level which classify wastes as inert, non-hazardous or hazardous. The respective leachate hazardous substance (inorganic and organic) content values delimitating these classes are related in the table below.

Table 6: Overview of waste classification based on leachate hazardous substance content.

Type of waste	inert		non-hazardous		hazardous	
Component	Limit value for leaching @ 10 l/kg [mg/kg of dry material]	Co (percolation test) [mg/l]	Limit value for leaching @ 10 l/kg [mg/kg of dry material]	Co (percolation test) [mg/l]	Limit value for leaching @ 10 l/kg [mg/kg of dry material]	Co (percolation test) [mg/l]
Metal components						
As	0.5	0.06	2	0.3	25	3
Ba	20	4	100	20	300	60
Cd	0.04	0.02	1	0.3	5	1.7
Cr	0.5	0.1	10	2.5	70	15
Cu	2	0.6	50	30	100	100
Hg	0.01	0.002	0.2	0.03	2	2
Mo	0.5	0.2	10	3.5	30	30
Ni	0.4	0.12	10	3	40	40
Pb	0.5	0.15	10	3	50	50
Sb	0.06	0.01	0.7	0.7	5	5
Se	0.1	0.04	0.5	0.2	7	7
Zn	4	1.2	50	15	200	200
Chlorides	800	450	15,000	8,500	25,000	25,000
Fluorides	10	2.5	150	40	300	500
Sulphates	1,000	1,500	20,000	7,000	50,000	17,000
Phenol	1	0.3	1	0.3	-	-
DOC	500	160	800	250	1,000	320
STD	4,000	-	60,000	-	100,000	-
Organic components						
TOC	30,000	-	50,000	-	60,000	-
BTEX	6	-	-	-	-	-
PCB	1	-	-	-	-	-
Mineral oil	500	-	-	-	-	-
PAH	55	-	-	-	-	-

3.2. Thermal reclamation of foundry sand

3.2.1. Description

Thermal reclamation of foundry sands was investigated at Finn Recycling’s plant dedicated to this purpose for commercial reclamation of self-setting (no bake) ester-cured phenolic resin sands. The plant applies reclamation temperatures, equal to the temperature of the sand leaving the furnace, of 650°C. The thermal treatment system consists of a feeder, the thermal reclamation unit (a rotary drum furnace), a cooling screw and a automated sieving unit. The procedure has been shown to be effective on this type of waste foundry sand, as will be demonstrated below. Besides, it can be applied to other types of organically bonded sand. It is not recommended for inorganically bonded sands, as these already reach or undercut the relevant limit values of pollutant and harmful substance content. For hybrid systems containing e. g. ester-based hardeners, a limited benefit linked to the remaining low content of organics may also be expected.

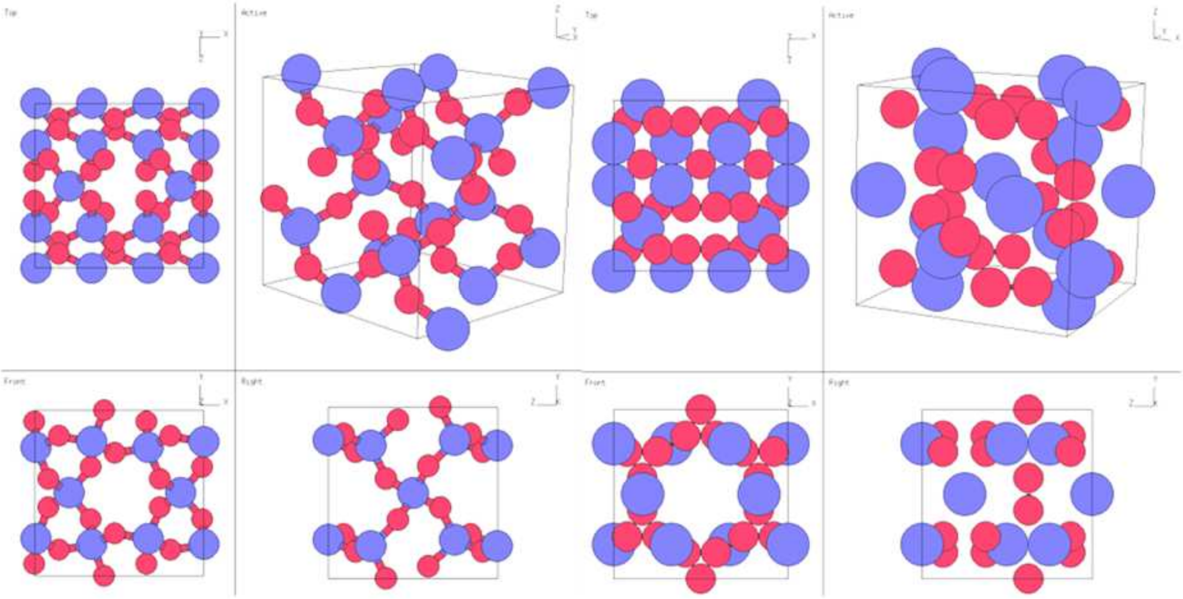

Figure 4: Crystal structure of high density, low volume and low-temperature α- (left) and the low density, high volume, high temperature β-quartz.

The fundamental principle of the process is based on pyrolysis of organic components and removal of any remaining residues by breaking-off in the course of the volume change associated with the transition in crystal structure experienced by quartz sand at elevated temperature, namely at 573°C, as shown in Figure 4. These latter residues are separated from the reclaimed sand in a subsequent dedusting step.

3.2.2. Achieved Environmental Benefit

Annual global amount of waste foundry sand reaches 100 Million tons. In addition to that, foundries produce 10 billion kg of sand-related CO_2 emissions per year. Of the aforementioned vast amount of sand, only 1% is currently being recycled. Large scale implementation of the suggested reclamation technology could cover 97% of the organically bonded waste sand (still the majority) included in the overall figure, which would drastically reduce the need for new landfills for the waste sand, as well as the need for sourcing virgin sand. Furthermore, net reduction of sand-related CO_2 emissions could reach 60%. This includes also transport-related emissions to/from the sand supplier and to/from the landfills. As the suggested technology is meant to be installed locally at the foundry (fully automated system), no transport emissions linked to a central reclamation site apply.

3.2.3. Operational Data

In order to evaluate the possibility of reusing the reclaimed sand for mould and core production, loss on ignition (LOI) as well as bending tests were performed on samples produced from reclaimed, used and new sand. LOI test samples of 25 g were dried at 100°C prior to being subjected to 900°C for 3 hours (based on AFS 5100-12-S and VDG-Merkblatt P33). Bending tests were performed on standard samples of 22.7 mm x 22.7 mm cross section according to VDG-Merkblatt M11. Samples using binder 1 and binder 2 as described in section 2.4 were produced based on the standard procedures and content levels prescribed by the manufacturers, leading to the following findings:

- **Binder 1** (requiring elevated temperature curing):
    - LOI data showed lowest loss figures in the new sand (0.15 wt.%), followed by reclaimed sand (0.25 wt.%) and used sand (1.21 wt.%).
    - In terms of bending strength, the reclaimed sand reached comparatively low strength levels around 220 N/cm^2 and thus fell short of the new sand by a margin of approximately 37%. With non-reclaimed used sand, bendings strength levels of approximately 190-200 N/cm^2 were reached.
- **Binder 4/5** (self-setting):
    - LOI data showed lowest loss figures in the reclaimed sand (0.03 wt.%), followed by new sand (0.15 wt.%) and used sand (0.39 wt.%).
    - In terms of bending strength, bending strength was highest in used sand for curing times of and below 1 hour. From 2 hours onwards until 24 hours, reclaimed and new sand both showed higher strength levels than used sand, with a slight advantage for the reclaimed sand. After 24 hours of curing, strength levels above 250 N/cm^2 were reached by both these specimen types, while untreated used sand fell short of this margin.

The results indicate that thermal reclamation allows reintroduction of reclaimed sand into the moulding and core-making process without restrictions only in the case of binder 2. With respect to binder 1, it must be assessed on a case-by-case basis whether the strength levels, which undercut the typical values of conventional, Alphaset-bonded sands (nominally 250-300 N/cm^2, however, in associated tests, only approx. 170-190 N/cm^2 were reached, which would move the binder 1 results into the region suitable for application, too), can nevertheless be employed. However, it must be noted that from the point of view of harmful substance content alone, inorganically bonded sand does not require the treatment, which means that in this case, strength levels for non-thermally reclaimed, inorganically bonded waste sands should also be determined for comparison.

Accompanying tests were performed on phenol and furan bonded sands, comparing new sands with mixtures of 70% reclaimed and 30% used sand. For phenol bonded sands (APNB), starting from 1 hour curing, the sand mixture exceeded the strength measured on pure new sand by about 10%. This picture was reversed for furan bonded sands, were the reclaimed sand (no mixture in this case) fell short of the new sand by a margin of roughly 70% after curing for 1 hour, >10% after 6 hours and <10% after 24 hours.

Additional tests were performed on (bentonite bonded) green sand. Here, thermal reclamation alone proved insufficient to restore usability. It is assumed that a thermomechanical rather than a exclusively thermal treatment would be required to also remove the clay shell formed around the sand particles.

3.2.4. Cross-Media Effect

The positive environmental effects have to be balanced against the energy and fuel consumption of the reclamation system. As detailed in the operational data section, these amount to 12-20 kg of propane gas and 13-25 kWh electrical energy per ton of sand processed. Additional resources needed include approx. 14.5 to 16.5 Nm^3/h of compressed air. In terms of requirements for gas, further sources beyond natural gas like biogas can be considered, changing the environmental balance. Depending on the type of binder contained in the treated sand, thermal reclamation can cause emission of sulfur oxides as flue gases. This requires appropriate filters to mitigate the effect.

3.2.5. Applicability

The thermal reclamation method has been successfully evaluated on organically bonded sands. It is commercialized in Finland by the company Finn Recycling. However, based on two different business models pursued by Finn Recycling, it can also easily be made available outside Finland. The two business models in question are the sale of dedicated equipment to foundries which intend to apply the process inhouse as opposed to centralized sand treatment as a service, as offered directly by Finn Recycling based on their available plant in Finland. The former option can easily be exported to practically any country. For either solution, Finn Recycling has implemented a sophisticated evaluation process which allows foundries interested in the process to evaluate the results achievable with their waste sand. In short, the procedure involves treatment of batches of waste foundry sand provided by the respective foundries at Finn Recycling's plant. During these experiments, parameter optimization is undertaken to ideally match the respective samples. These are sent back to the foundry together with data on any adaptation that might be necessary there in producing moulds and cores from the reclaimed sand. The foundry can thus gather first-hand experience on working with the modified sand and base the decision on acquiring or using the technology on this, thus limiting the risk in adopting it. In case the treatment process is set up within a foundry, supply of and connections for electricity, gas and compressed air have to be available.

3.2.6. Economics

Today, according to Finn Recycling, European foundries spend approximately 1.7 billion Euros per year for sand [Fin22]. An estimate of investment costs for a plant capable of annually reclaiming 8000 tons of waste foundry sand comes up with a sum of 2.26 million €. At typical prices of 100-300 €/ton of virgin sand plus fees for landfill disposal, acquisition of 8000 tons provides a good match with the assumed investment cost of a reclamation system. Consideration of the running costs, including logistics, leads to a figure of 17-25 €/t of reclaimed sand, which does not yet include write-off for the investment and is higher than the respective value for washed sand, which however has not been explicitly tested for reuse in moulding. The established price tag for Finn Recycling's services (when ordering Sand treatment as a Service, SaaS) is 50 €/ton, which still outmatches the market price range for virgin sand by a large margin and does not carry additional investment costs.

3.2.7. Driving Force for Implementation

- Scarcity of suitable natural sands as a resource for various applications is an ongoing issue. Recycling of sand, wherever possible, is thus a definite need to save available resources for such industries in which recycling or reuse is technically impossible.
- Increasing cost of new sands, including logistics cost, may positively affect economic viability of the thermal reclamation approach. The fact that the process is already established for alcalyne phenolic no bake (APNB) sands underlines that this is not only possible, but likely. Cost competitiveness has already been demonstrated in the preceding section.
- Further increase in the cost of waste foundry sand disposal may create an economic incentive for reuse.
- Public regulations aimed at enforcing stricter environmental standards may directly (implementation of waste minimization procedures) or indirectly (increase of disposal costs by re-categorization of waste foundry sand or lowering of harmful substance content limits) force foundries to implement this or other measures for recycling/cleaning of foundry sands.
- The variety of options for implementing this technology (as a service, on-site etc.) contribute to the flexibility of the approach and may thus influence decisions in favour of it.

3.2.8. Reference
(Experimental and Pilot Applications, Literature)

The technology in question is commercially available through Finn Recycling [Fin22]. Two ways of implementing the technology are available for interested foundries: Either equipment is bought from Finn Recycling and installed inhouse, or sand treatment is booked as a service. The latter option saves investment, but may slightly shift the environmental balance as transportation of sand between foundry and recycling plant may have to be accounted for.

[Sap18] Sappinen, T. Thermal reclamation of foundry sands in industrial symbiosis. MSc thesis, Aalto University, Jan 2018.

3.3. Composting of foundry sand

3.3.1. Description

Normally after the composting process natural sand is added into the composting end-product as mixture soil material. In the case of cleaning surplus foundry sand by composting method, the foundry sand is added to the composting material in the beginning of the process. During the composting process itself, microbiological activity can facilitate a reduction of harmful organic substance content in such additives. This applies specifically to waste sands from the foundry industry. Despite the fact that cleaning by composting is known to show positive effects, waste sands used as additives in this sense do have to fulfill certain requirements in terms of limit values of certain substances. These are typically defined on European level and taken over in national regulations. For example, in Finland, limits put down in the *Decree of the Ministry of Agriculture and Forestry on Fertiliser Products (24/2011): Substrate – Mixture soil (5A2)* have to be adhered to, a document which in turn demands that requirements for inert solid landfill deposition as laid down in *Government Decree of landfills (331/2013)* have to be met. Typically, there are no limit values for organic substances in decree 24/2011, as the end-product is used as organic soil material and organic components like DOC and TOC are not considered as causing any problems in view of the final purpose of the material. Instead, the focus is on heavy metals as well as pathogens (Salmonella and E. coli) and impurities (weeds, garbage). The cleaning is a by-product of the composting process and thus takes as long as this, typically 5-6 months, plus an additional 6 months for post-maturing. Besides its long-term nature, composting is an area-intensive process. To clean about 2200 tons of composting material containing about 20-30% of foundry sand or dust, a composting site size of approximately 1200 m^2 is required. To treat 22,000 tons of composting material (including once again 20-30% of foundry sand or dust), a composting site size of 10,000 m^2 is needed.

Figure 5: Setting up a composting plant. A watertight film was installed and waste water collected from the sitein a separate water tank.

3.3.2. Achieved Environmental Benefit

- Composting of foundry waste sands and dusts showed major reduction of content levels for most harmful substances listed in section 6.1, including

    - DOC: reduction between 36 and 91%
    - TOC: 13-28%
    - BTEX: 73-88%
    - Fluorides: 17-48%
    - Mineral oil: 41-70%
    - Sulphates: 43-46%

- While foundry waste sands and dusts based on organic binders do not necessarily reach the limits set for inert waste or the limit values set for foundry waste sands reuse in geo-construction in the *Government Decree on the Recovery of certain wastes in earth construction in Finland (943/2017)*, tests summarized below indicate that inorganic binders do.
- In the case of inorganic binders, with the exception of the DOC levels measured for two types of binders, the waste sand already meets inert waste limits prior to composting. DOC content of the respective samples with slightly elevated levels (on average 29 % above the limit value) may be assumed to be suitable reduced by composting, as cleaning efficiency in case of organic binders was between 36 and 91% in this category across all tests.

A further major advantage of cleaning by composting, if directly applicable based on initial harmful substance content levels and relevant regulations, is that the foundry waste sand in this case replaces the natural sand commonly added in the end of the composting process and thus does not cause an extra use of resources or energy, but instead saves resources (here: natural sand) which would otherwise have to be sourced elsewhere. This may constitute a double benefit of the procedure as such.

3.3.3. Operational Data

Results of practical experiments

Two composting test campaigns were undertaken in the course of the project, one in Finland, another in Spain. These are described sequentially below.

Finnish test campaign

Table 7: Overview of binder systems covered in the Finnish test campaign.

Binder system		Material	Composting		
Designation	Type	waste sand	no of heaps	size of heaps	total weight
Different inorganic binder waste sands.	inorganic	waste sand	1	20 tons	360 tons
phenolic Alphaset	organic	waste sand and dust	2 (1 dust, 1 sand)	each about 20 tons	
Furan	organic	waste dust	4 (dust contents between 20-25%	test heaps from 20-to 180 tons	

In the project both the organic and inorganic binder system waste sands were tested. The proportion of waste foundry sands in the composting heaps varied. Prior to the composting process, the waste sand or dust considered were analyzed in terms of their harmful substance content levels. The results are summarized in the table below [DeB4.4]:

Table 8: Characterization of sample waste foundry sand (WFS) and waste foundry dust (WFD) batches prior to composting, Finnish campaign.

Binder type	Sample	DOC [mg/kg dm]	Fluoride [mg/kg dm]	Phenol index [mg/kg dm]	Molybdenum [mg/kg dm]
inorganic	WFS sample A1	90	<5	<0.1	0.04
	WFS sample A2	37	5.5	<0.1	0.002
	WFS sample A3	230	<5	0.11	0.03
	WFS sample B1	640	<5	<0.1	0.03
	WFS sample B2	680	41	<0.1	<0.01
	WFS sample C	610	32	<0.1	<0.01
organic	WFS sample D	1600	23	2.10	0.02
	WFD sample E	4500	180	1.20	1.08
n.a.	limit value non-hazardous inert waste	500	10	1	0,5

The data illustrates the expected higher content levels of critical substances in organic binder waste sands and dusts, whereas waste sands with inorganic binders in some cases can be treated as non-hazardous inert waste even without employing cleaning operations.

Degradation of the harmful compounds is presented in the table below for the composting tests performed in Finland.
After the composting process, the **composting end product** must, **as soil material,** meet the limit values set in the *Decree of the Ministry of Agriculture and Forestry on Fertiliser Products (24/2011): Substrate – Mixture soil (5A2).* This regulation sets limit values and demands for heavy metal contents of the end product, pathogens (*Salmonella* and *E. coli*) and impurities (weeds, garbage).
When foundry waste sand is added to the composting material, the compost must as fertilizer products (soil material) also meet the limit values set for heavy metals and harmful organic substances according to the *Government Decree of landfills (331/2013)* for non-hazardous inert waste.
It should be noted that no limit values are set for organic substances like DOC, TOC and sulphite for fertiliser products. Yet the degradation of these compounds were analysed during the process because these are normally the high in surplus foundry sands and the key issue when considering the landfilling or other reuse applications (e.g. road construction, geo construction).

Table 9: Degradation of harmful compounds during the composting tests, Finnish campaign.

Binder	Sample from ...	TOC [% dm]	DOC [mg/kg dm]	BTEX [mg/kg dm]	Fluoride [mg/kg dm]	Phenol index [mg/kg dm]	Sulphate [mg/kg dm]
Phenolic Alphaset, dust and sand	comp. heap #1 (dust), START	12	7800	n.c.	39	5.5	130
	comp. heap #1 (dust), END	12	2100	n.c.	21	<0.1	98
	comp. heap #2 (sand), START	n.a.	4700	n.c.	6	1.4	49
	comp. heap #2 (sand), END	-9,4	1700	n.c.	<5.0	<0.1	57
Furan, dust 2019-2020	comp. heap #1 (25%), START	23	10000	2.60	17	<0,01	3700
	comp. heap #1 (25%), END	20	970	0.30	8.9	<0,10	2000
	comp. heap #2 (30%), START	25	9800	2,50	12	n.a.	3500
	comp. heap #2 (30%), END	20	930	0,29	8.9	<0,10 ?	2000
Furan, dust 2020-2021							
	comp.heap #1 (20%) START	13	710	0,48	15	n.c.	2600
	comp.heap #1 (20%) END	14	370	0,31	14	n.c.	2600
	comp.heap #2 (20%) START	10	550	0,45	12	n.c.	2400
	comp.heap #2 (20%) END	14	440	0,28	9,3	n.c.	2700

n.c. under detection limit value
n.a. not available

Results with phenolic Alphaset sand and dusts (Composting test heaps 1 and 2):

DOC concentrations of dust and waste sand were above the limit value of non-hazardous inert waste before the composting test started. During the tests, DOC concentrations were reduced. As there are no limit values for DOC for the end-product (soil material), the envisaged use as soil material is possible.

Fluoride concentration was high in dust specimen and waste sand samples. The fluoride is probably coming from the fluoride containing feeders used in the moulds for all sand systems. At the end of the composting process the concentration was below the limit value.

Phenol concentrations of dust and waste sand exceeded the inert waste limit value before the composting test. In addition to the sand mould's binder system, phenols can also originate from the core production, if the latter was done according to the cold-box system. Phenols were degraded during the composting tests, so that in the end, the concentrations were below the inert waste limit value. For fertiliser products there are no limit values concerning phenols, so use of the end product for this purpose is possible.

Suphate concentrations were very low and there is no limit value enforced for the fertilizer product. Also BTEX concentrations were below detection limits.

Based on the results of the summer 2019-2020 small scale composting tests, it can be concluded that the tests were successfully completed and the innovative composting end-product fulfilled the limit values set in the Decree of the Ministry of Agriculture and Forestry on Fertiliser Products 24/2011 and The EU Degree on Fertiliser Product (2019/1009) and the end-product can be re-used as substrate and for gardening and geo-construction purposes.

Degradation of the harmful substances during the composting tests demonstrate very good cleaning efficiency rates (Table 1). The composting method can thus be considered an effective approach to cleaning of waste foundry sands.

	Organic dust	**Organic waste sand**	Limit value for non-hazardous inert waste	Compost heap 1 (organic dust) START	Compost heap 2 (organic waste sand) START	Compost heap 1 (organic dust) END	Compost heap 2 (organic waste sand) END	**Compost heap 1 (organic dust) Degradation efficiency**	**Compost heap 2 (organic waste 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 %**

Results with inorganic binder system foundry waste sand (not included in the table):

Based on the analyses results the analysed inorganic binder system waste sand was very clean already without the composting treatment. The “waste” sand did not contain any organic or inorganic harmful compounds or metals.

Analysis results demonstrate that the inorganic binder system foundry sand could be re-used without any additional cleaning method e.g. for geo-engineering purposes, as it fulfills the requirements of the *Government Decree on the Recovery of Certain Wastes in Earth Construction 843/2017*.

Results with furan sand system dusts:

Small scale tests in 2019-2020 (composting heaps 1 and 2)

Small scale composting tests of about 20 tons with foundry dust specimens were carried out in Northern Finland. Dust portions varied in test heaps.

In the beginning of the composting tests the dust samples were analysed. Limit values exceeding concentrations of BTEX, fluoride, nickel and zink were detected. pH of foundry dust was about 4. During the composting tests all these compounds and concentrations were reduced and in the end of the composting tests all concentrations had fallen below the limit values set for non-hazardous inert solid waste.

DOC and TOC concentrations of dust specimens exceeded the limit values for non-hazardous solid inert waste. After mixing the dust with other organic materials, the concentrations of organic compounds were naturally higher in the beginning of the composting tests. During the composting tests, TOC and DOC concentrations decreased. In the end the concentrations were not under the limit values set for the inert waste, but as there are no limit values for organic substances in the Decree for Fertiliser Products 24/2011 because the product is used as soil material in geo-construction purposes, such usage is facilitated also in the case of these wastes.

High sulphate concentration was detected in dust specimens. Sulphate typically originates from use as hardener in foundry processes (p-Toluenesulfonic acid). Such hardeners are used in hardening sand molds and cores. Sulphate is a salt of sulphuric acid and it will degrade during the composting if the conditions are aerobic. Therefore, aeration is needed during the composting process. Based on the test results obtained, more mixing and turning of the heaps is needed to further reduce sulphate concentrations. However, sulphate is not considered a harmful substance and there are no limit values for it in Fertiliser Product Decree 24/11. However, sulphate concentration affects maturation of the composting material because plants cannot grow in high salt concentration.

Based on the results obtained, the harmful organic compounds were degraded and metal concentrations decreased during the composting tests. The end products fulfilled the limit values set in the *Decree of the Ministry of Agriculture and Forestry on Fertiliser Products 24/2011* set for soil material mixtures. The post-maturing of about 6 months is always needed to ensure that the end-product will be mature. The mature soil material mixture can be used as substrate and for gardening purposes.

Industrial scale tests in 2020-2022 (composting heaps 1 and 2)

Two test heaps of 91 tons and 182 tons were constructed where the foundry dust (furan sand system) proportion was on average 20-25%. During the composting process, DOC concentrations decreased in both heaps. There are no limit values for DOC, but the concentrations at the end of the composting tests were below the limit values specified for inert waste (500 mg/kg dm).

The fluoride content of the foundry dust initially exceeded the limit value set for inert waste (10 mg / kg dm), but at the end of the compost tests the concentrations were close to the limit value in both heaps taking.

The sulphate concentration in the foundry dust also exceeded the inert waste limit value (1000 mg / kg dm), but since there is no limit value for sulphate in soil material (*Fertiliser Regulation 24/11*), this does not prohibit usage of the material in this application. Mixing and turning the heaps regularly is generally suggested as means to effectively reduce sulphate concentratoins.

The concentrations of soluble nickel and zinc in the foundry dust exceeded the limit values for inert waste enforced by the *Decree on landfills 331/2013*. However, at the end of the composting experiments, the concentrations of these metals were below the limit valuesof both the inert waste and the fertilizer regulation.

Results demonstrated that the soil material as end product meets the limit values set for in the *Fertilizers Regulation (24/11)* and concerning the harmful metals and organic pollutants in the *Decree of inert waste landfills (331/2013)*.

Spanish test campaign

Table 10: Overview of binder systems studied in the Spanish test campaign.

Binder system		Material	Composting		
Designation	Type		no of heaps	size of heaps	total weight
silicate	inorganic	waste sand, dust	2	20 tons each	120 tons
eco-inorganic	inorganic	waste sand from cores	2	20 tons each	
bentonite	organic	washed green waste sand	2	20 tons each	

Again, the conventional binder system (here: bentonite/green sand) included in the test served as reference. The amount of waste foundry sand was approximately 18-20% by weight in all cases.

The table below contains data on harmful substance degradation from beginning to end of composting trials [DeB4.4]:

Table 11: Results of composting trials, Spanish campaign.

Binder	Sample from ...	TOC [% dm]	DOC [mg/kg dm]	BTEX [mg/kg dm]	Chloride [mg/kg dm]	Mineral oil [mg/kg dm]
inorganic	comp. heap #1 (sand), START	-	-	-	928	<34
	comp. heap #1 (sand), END	-	-	-	841	<28
eco-inorganic	comp. heap #1 (sand), START	21.3	1000	-	-	-
	comp. heap #1 (sand), END	16.8	640	-	-	-
organic	comp. heap #2 (30%), START	1.65	-	<0.15	-	67
	comp. heap #2 (30%), END	1.18	-	<0.04	-	<20
n.a.	limit values non-hazardous inert waste	3	500	6	10	1

Using the nitrate/ammonium ratio as indicator, which should be >1 for mature compost, it was found that based on green sand and on silicate binder containing sand reached maturity after 3 months, while inorganic eco-binder sand based compost required extended maturing times.

3.3.4. Cross-Media Effect

Cross-media effects concern the need for gathering and disposal, including possible treatment, of waste water, the degradation of harmful substances, and odour. Studies in the course of the Foundrysand LIFE and Green Foundry LIFE project have yielded the following results in this respect:

- Odour emissions are to a large part not related to the waste foundry sand content of the composting heap, but rather to other organic materials involved. They typically occur at the beginning of the composting process and decrease significantly in its course.
- Gaseous emissions observed include CO_2, CO, methane, ammonia, formaldehyde and benzene. As in the case of odours, emissions are greatly reduced in the middle of the composting process. At the end of the process, most emissions fell below the detection limits. Continued methane and CO emissions are an indication that the composting heap needs additional maturation time.
- Waste water samples did not show exceptionally high contamination levels. However, waste water has to be collected and transferred to the local treatment plant for further processing.

In the case of the relevant measures like sealing of the site against groundwater contamination and waste water treatment being implemented, it can be concluded that composting of waste foundry sand does not pose additional environmental risks. As a further aspect, however, the pros and cons of area usage (plant footprint) as well as the fact that the establishment of such a plant automatically implies creation of impervious surfaces with implications for several environmentally relevant aspects such as lack of rainwater infiltration and thus also of groundwater recharge should be considered.

3.3.5. Applicability

The composting process has been evaluated for several different binder systems waste sands in real world scenarios and composting heap sizes since 2015. Meehanite Technology Ltd has patented this method. Previous studies have been performed in the course of the FoundrySand LIFE project. As a result of this, the use of waste foundry sand as natural sand replacement is already established commercially e.g. in Spain. In general, as the process has a considerable footprint, it requires availability of sufficiently large areas for setting up the treatment (site size ranges from 1,000-10,000 m^2). With respect to these areas, it must also be considered that due to the fact that waste water has to be recovered, the respective area must be sealed, and thus setting up of a composting plant contributes significantly to total impervious surface coverage, which is associated with environmentally malign side effects. Furthermore, earlier studies have shown that during inital stages of the composting process, smell can be emitted which may forbid location of composting sites in the vicinity of human settlements. It must be noted, however, that this is typically not a problem related to the use of waste foundry sands in the composting process, but rather a general issue.

3.3.6. Economics

Establishment of a composting site requires environmental permits and suitable measures to protect the surroundings against contamination. This includes e. g. the construction of water-tight layers for protection of ground water against contaminants leached out from the composting heap. Accordingly, waste water originating from the composting site has to be gathered in dedicated tanks, and leackages or oozing out of any other harmful effluents has to be prevented. This increases the cost of a composting plant, it is, however, a measure that is generally required and not directly linked to the use of waste foundry sand as source of mineral soil additions.

The costs of setting up and running a composting facility with a capacity of handling approx. 2,400-2800 tons of surplus foundry sand or dust annually (base figure is 600-700 tons per 1000 m^2 of composting area), requiring a total area of 4,500 m^2 (including waste water treatment area, raw material storage and roads, assuming that 500 m^2 are required for the latter), have been evaluated as follows below. However, as the report clearly shows, waste foundry sand processing does not necessarily require dedicated new facilities, but can be handled by existing ones serving the compost market.

Table 12: Overview of cost factors and associated costs with respect to setting up a composting plant.

Cost factor		Estimated cost [€]
Construction costs	site preparation (cutting of trees, levelling, addition of filler sand etc.)	8,000
	foil coverage	4,000
	wastewater handling (pipes, tank, circulation pump etc.)	4,000
	aeration equipment (fans, tubes etc.)	15,000
	cabin for aeration equipment	5,000
	electric power connection	2,000
	TOTAL CONSTRUCTION COSTS	38,000
Annual running and maintenance costs	transportation costs animal manure or similar organic materials	1000
	wood chips and sticks (90% circulation rate assumed)	500
	electric power	1000
	turnover of composting heaps (4 times/year)	4000
	emptying of waste water tank	500
	TOTAL ANNUAL RUNNING COSTS	7000
TOTAL ANNUAL COSTS (BASIS 10 YEARS OF OPERATION)		10,800

As a results, for a newly established composting site, the treatment costs per ton of waste foundry sand add up to 36€/ton. For an existing composting site, the costs are reduced to 23,33 €/ton, if the plant's operation has already earned its investment costs and thus any write-off costs can safely be ignored. Taking into account that acquisition of screened natural sand carries a price tag of approximately 5 €/ton, for the most optimistic scenario, the cost of treating waste foundry sand by composting is lowered to 18,33 €/ton.

3.3.7. Driving Force for Implementation

- Waste foundry sand, specifically if based on inorganic binders, can directly be used for composting. In this role, it replaces a natural resource which would actually have to be acquired by the composting enterprises and would thus constitute a cost for them which typically amounts to roughly 5 €/ton of screened natural sand.
- At the same time, costs for waste foundry sand disposal are rising. Thus the removal of excess waste foundry sand via composting may become economically attractive for foundries even if prices should remain well below those typically paid by composting enterprises for natural sand addition.
- Thus it is very likely that a price for waste foundry sand in composting may establish itself which effectively results in an economic benefit both for foundries and composting companies.

3.3.8. Reference

(Experimental and Pilot Applications, Literature)

Composting of foundry sand does not require setting-up specific plants, but can in principle be done in existing, conventional composting sites provided that the necessary regulations are in force that allow for treatment of foundry sand in this respect. As this is apparently the case as long as waste foundry sand meets harmful substance limit values in place, any operational composting plant qualifies as exemplary application of the process.

3.4. Washing of foundry sand

Washing of foundry sands should originally have been performed by Ecofond, who unexpectedly went out of business at the onset of the GreenFoundry project. Their task was thus taken over by Tecnalia, with Econfond-washed sand introduced into the investigation for comparison only. The advantage of this rededication of tasks is that it allows to relate the details of the washing procedure, whereas Ecofond's method is protected by intellectual property rights and could not have been disclosed in full in the present report. The drawback is that the scale on which these procedures could actually be tested is reduced compared to what would have been possible for an industrial partner.

3.4.1. Description

The washing process adopted by Tecnalia is based on rinsing with distilled water and leaching using 5M hydrochloric acid (HCl). The method was initially evaluated manually on batches of 30 g, then scaled up to batches of 450 g. The individual steps of the procedure are (data given for 450 g of sand):

- Step 1: Rinsing the waste foundry sand with distilled water, followed by determination of the pH value. Repetition of this step until in two consecutive steps, no further change of pH was detected.
  (Ratio of sand to water 1:2, target pH value <= 9.35).
- Step 2: Filtering to separate sand from water followed by air-drying.
- Step 3: Mixing of the sand with hydrochloric acid. Leaching for 8 hours under mixing by a magnetic agitator at 300 rpm.
  (7.5 mol => 747.16 g HCl)
- Step 4: Filtering to separate sand from hydrochloric acid.
- Step 5: Washing of the sand with distilled water (ratio 1:2 as before) and measurement of the pH value. Repetition of until the desired pH values (neutrality, pH = 7) is reached and no change in pH observed in two consecutive cycles.
- Step 5: Drying of the sand in a muffle furnace for 3 hours at 105°C.

Prior to analysis, the dried sand is ground. For scale-up of the process, a proportional increase in chemical quantaties is possible.

3.4.2. Achieved Environmental Benefit

Quantitative benefits of washing which were identified include:

- elimination of 36-100% of hazardous elements achieved
- content of fines is reduced by 80% through washing compared to raw foundry sand
- content of respirable crystalline silica (RCS, < 0.05 mg/m^3) is reduced by 50% through washing compared to raw foundry sand

Further qualitative benefits may be named:

- Washing of waste foundry sands could free up landfill space for other materials for which no alternative treatment exists, or available treatment options are cost intensive and/or less environmentally friendly in themselves.
- Area footprint of a washing plant is only 50% of that of a comparable composting area.
- Washed waste foundry sand can replace new raw sands in production of cores and potentially molds. This would limit the need for extraction of new sand.
- As chemical washing plants afford no combustion processes, they would be CO_2 neutral on a local basis.
- The plant works quietly and odour-free, the process is efficient and equipment requires little maintenance.
- Location of a washing plant at optimum distance to several foundries might reduce CO_2 emissions associated with transport (greenfield approach). So might location of small-size washing plants at the foundries.

The following potential drawbacks of the washing procedure must be taken into account:

- Washing as performed in the present study requires 1.4 litres of HCl and 3.0 litres of distilled water per kg of waste foundry sand.
- HCl as cleaning agent needs neutralization itself.
- Of the water, only 75% can be reclaimed, leading to a net amount of 0.75 litres of waste water per kg of waste foundry sand.
- Operation with HCl requires personal protective equipment (PPE).

3.4.3. Operational Data

The washing technology as described here has been evaluated in laboratory-scale experiments. It is not yet commercially available on larger scale. Detailed esults of these experiments are summarized below.

Individual washing efficiencies obtained for certain elements (predominantly heavy metals) contained in waste foundry sand originating from inorganically bonded moulds, as well as the change of these efficiencies with scaling up from 30 g to 450 g, are related in Table 13 below:

Table 13: Washing efficiencies achieved on inorganically bonded waste foundry sand - comparison of batch sizes of 30 g and 450 g. Also included is are results of washing experiments performed by Ecofond.

metallic contaminant	washing efficiency 30 g [%]	washing efficiency 450 g [%]
Barium (Ba)	30	42
Chromium (Cr)	> 88	99
Iron (Fe)	22	15
Molybdenum (Mo)	-	38
Nickel (Ni)	5	11
Zinc (Zn)	20	20

The following Table 14 summarizes washing efficiencies achieved by the Ecofond process on organically bonded sand:

Table 14: Washing efficiencies achieved by the Ecofond process on organically bonded (phenolic) waste foundry sand (focus on metallic contaminants).

metallic contaminant	content level [mg/kg]		washing efficiency [%]
	before washing	after washing	
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

Table 15 summarizes efficiencies obtained in terms of organic contaminants, and puts them in perspective with regulatory limits allowing consideration of the waste foundry sand as inert waste. As in Table 14, the data is based on the cleaning of organically (phenolic) bonded sand.

Table 15: Washing efficiencies achieved by the Ecofond process with respect to organic contaminants, including a comparison with limit values to allow consideration of the sand as inert waste.

contaminant type	content level [mg/kg]		inert waste limits [mg/kg]	washing efficiency [%]
	before washing	after washing		
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

Note that highest washing efficiency was achieved with organically bonded sand. Despite the lower efficiency of the washing process, based on its generally lower content of harmful substances, inorganically bonded sand remains the ecologically favourable choice. However, as organic binders still are more widespread in the industry, applying the method to these, too, could generate a significant environmental impact.

3.4.4. Cross-Media Effect

See comments in section 3.4.2 on potential drawbacks: A considerable amount of water is used in the process, which cannot be reclaimed in full (loss/waste water is 0.75 litres/kg of foundry sand, with the water originally provided as distilled water). Furthermore, an amount of 1.4 litres of HCl/kg of foundry sand has to be neutralized. A detailed LCA of the process would have to consider these process fluids and their production, too, e.g. in terms of energy needs associated with their production, and balance the outcome against the positive environmental effects.

3.4.5. Applicability

A general technological readiness of this or a similar washing method for industrialization and commercial application has been demonstrated in the past in Spain by the Ecofond company. However, the endeavour has apparently not been a commercial success, since the company is out of business at this moment. This said, it is completely unclear whether this is in any way related to the economic viability of the process, or to other, external circumstances. What is more, with changes in economic or regulatory boundary conditions, the process may become economically attractive again in the future. Some dependency on locality may arise in this respect due to the need for considerable amounts of water in the course of the treatment.

3.4.6. Economics

<u>Personal Protective Equipment (PPE):</u>

- Use of HCl for leaching requires dedicated personal protective equipment (PPE).
+ Reduction of fines and RCS may limited the need for PPE.

<u>Machinery/processing equipment:</u>

- Implementing the process on industrial scale requires some investment in processing equipment, e.g. for mixing sand with fluids (distilled water, leaching agents), for filtering out the sand, and for drying the sand (furnaces). Assuming a processing capacity of 1000 tons a year, investment costs will run up to 47.4 k€, while processing costs will be 3.5 k€ fixed costs plus variable costs of altogether 91 k€, in which waste water treatment is not included. This leads to a cost per ton 0f 9.45 € for washing the sand.

- Use of leaching agents will require acid resistant materials in components in contact with the sand during washing/leaching, or with the leaching agents in general. This incurs additional costs which are further heightened if several acids like HF and HNO_3 are used in a stepwise process aimed at eliminating further unwanted components not readily attacked by HCl.

\+ In contrast to e. g. thermal reclamation, the equipment used needs only limited maintenance efforts. Besides, the process is highly efficient.

<u>Plant size/required area:</u>

\+ The plant footprint is 50% smaller than the area needed for composting of comparable amounts of waste foundry sand.

3.4.7. Driving Force for Implementation

- Further increase in the cost of waste foundry sand disposal may create an economic incentive for reuse.
- There is competition between this and other cleaning methods for waste foundry sand. Depending on local conditions like available space, availability and cost of electricity and other resources like water and boundary conditions w. r. t. investment may tip the scales in favour of this method in some places, against it in others.
- Public regulations aimed at enforcing stricter environmental standards may directly (implementation of waste minimization procedures) or indirectly (increase of disposal costs by re-categorization of waste foundry sand or lowering of harmful substance content limits) force foundries to implement this or other measures for recycling/cleaning of foundry sands.

3.4.8. Reference

(Experimental and Pilot Applications, Literature)

[Bal16] S. Balbay. Removal of Pollutants from Waste Foundry Sand by Chemical Washing Method a. International Conference on Agricultural, Civil and Environmental Engineering, Kuala Lumpur, Malaysia, January 5th-6th, 2016.

[DeB4.4] Green Foundry LIFE Deliverable DeB4.4: Conclusions of the results of the waste sand cleaning methods

3.5. Ultrasonic cleaning of foundry sand

Ultrasonic treatment of waste foundries sands was evaluated on lab scale by CTIF, comparing four different inorganic and hybrid binder variants.

3.5.1. Description

The fundamental principle of the process is graphically described in the figure below:

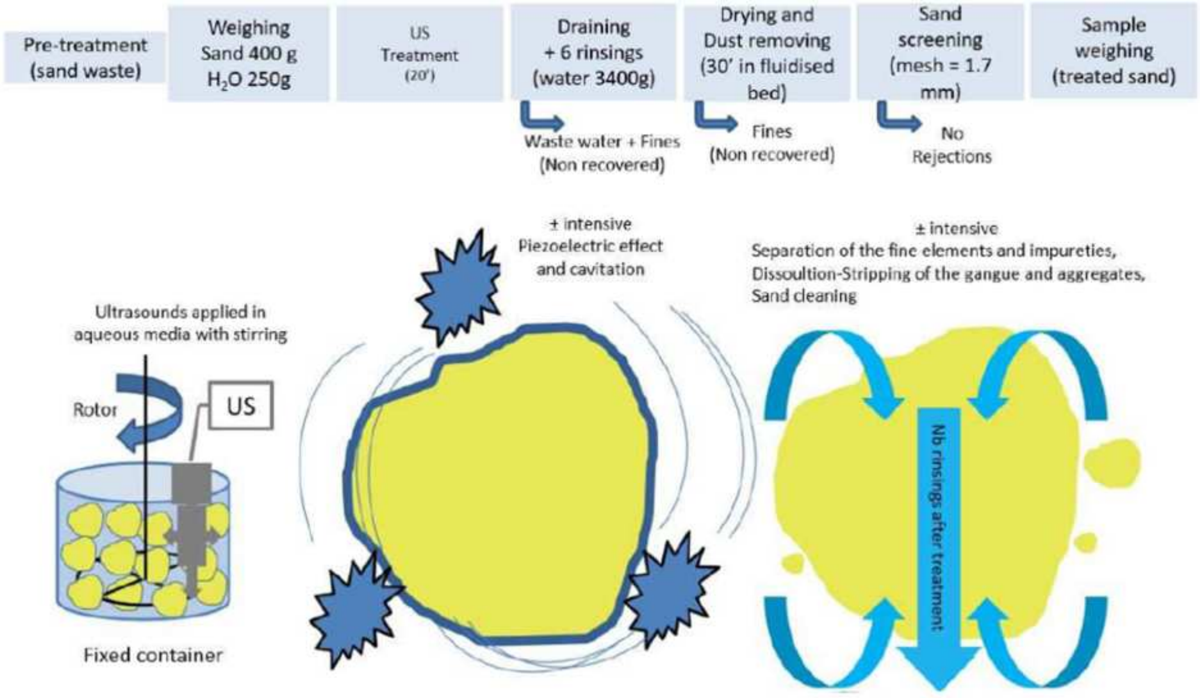

Figure 6: Stages and fundamental principle of the ultrasonic treatment process.

The process is comprised of several steps, starting with mixing the sand with water as carrier medium for the ultrasound agitation. The agitation achieved thus in combination with the stirring operation plus the influence of cavitation and piezoelectric effects observed in quartz lead to the destruction and thus stripping of surface layers covering the individual grains of sand. Immersion in water and rinsing facilitate separation of fine elements and impurities as well as dissolution of certain elements, compounds and aggregates. A subsequent drying in a fluidized bed is used to further remove fines, as is a final sieving.

3.5.2. Achieved Environmental Benefit

Positive environmental impacts include the following points:

Ultrasonic cleaning in general

- reduces the need of new sand at foundries by 95-96% by facilitating sand reuse, with the remaining 4-5% corresponding to processing losses,
- accordingly reduces the amount of sand which needs to be landfilled by 95-96%
- reduces net lifecycle greenhouse gas emissions from foundry sand by 50-70%,
- reduces shipping and transportation for sands as these can be circulated locally,
- makes it possible to reuse the sand in geoconstruction or road engineering besides recycling it internally,
- allows further reduction of environmental impacts by integrating modern filtration techniques for treatment of the water used for rinsing and
- alllows further reduction of the amount of water needed for rinsing per unit weight of waste foundry sand if closed loop techniques are applied.

From an operational perspective, the following benefits are achieved:

- The ultrasonic treatment does not generate dust or fumes in the atmosphere.
- The ultrasonic process is CO_2 and odour free.
- The water discharged after filtration complies with the standards – this has been checked for aluminium, but needs verification for steel castings.

3.5.3. Operational Data

Experimental studies on ultrasonic treatments using lab scale samples (400 g of sand) have been performed by CTIF comparing altogether four different inorganic or hybrid binder systems:

- **Binder 6** is a fully inorganic, commercially available binder system
- **Binder 7** is a fully inorganic, commercially available binder system
- **Binder 8** is a mostly inorganic, hybrid, commercially available binder with organic hardener
- **Binder 9** is a mostly inorganic, hybrid, commercially available binder with organic hardener

Figure 7 illustrates the appearance of sand grains after the cleaning process in comparison to the virgin sand.

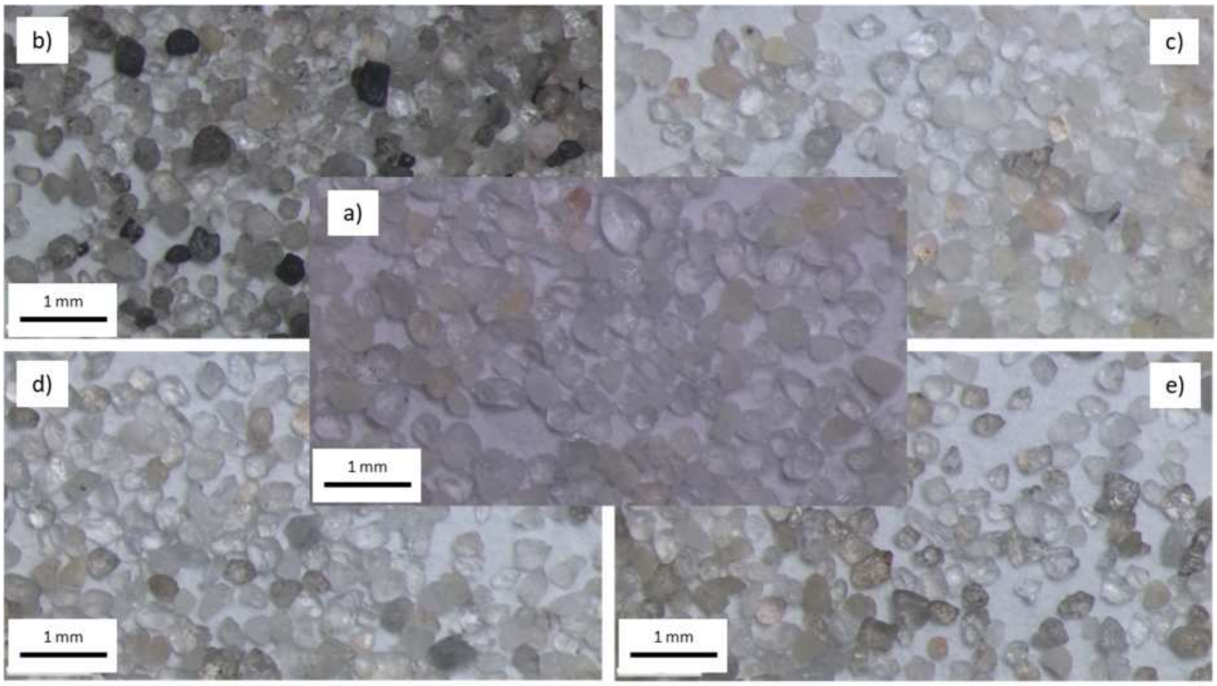

Figure 7: Comparison of (a) virgin sand of grade SN BE01 and (b-e) differently bonded sand after ultrasonic cleaning; (b) ***binder 6****, (c)* ***binder 7****, (d)* ***binder 8*** *and (e)* ***binder 9****.*

Figure Y exemplarily depicts the appearance of grains of sand in virgin state, after use with inorganic binder of type INOTEC, and after the ultrasonic treatment.

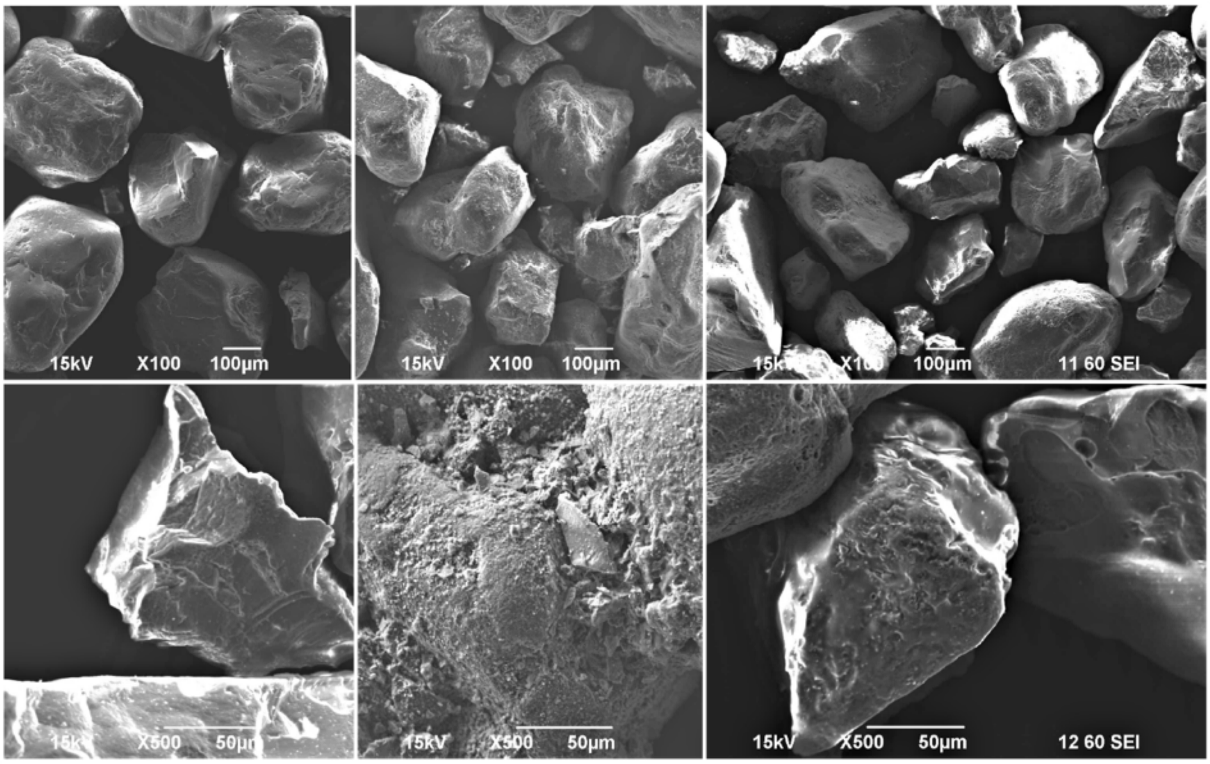

Figure 8: Effect of treatment on BE01 sand - appearance of the grains of sand in virgin state (left column), after use with inorganic ***binder 6*** *(center column) and after ultrasonic treatment (right column).*

The effect of the treatment has been evaluated in terms of the resulting characteristics of the sand in contrast to the virgin material. The results in terms of sand characteristics are summarized in the table below:

Table 16: Effect of ultrasonic treatment on sand characteristics.

Parameter	Reference	BE01 sand with binder no.			
	BE01				
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 area [cm^2/g]	159	176	162	171	175
Grain breakage observed	n.a.	low	low	low	low
Aggregate removal observed	n.a.	low	low	low	low
Appearance of grains	spherical	spherical & angular	spherical & angular	spherical & angular	spherical & angular
Grain surface appearance	smooth	smooth	smooth	smooth	smooth
Amount of black grains	none	low	low	low	low
Amount of black-spotted grains	none	significant	low	low	low
Amount of unstained grains	significant	low	significant	significant	significant
El. conductivity [µS/cm]	500-520	525	521	515	518
pH	8.3-8.4	8.76	8.77	8.79	8.58
Acid demand [ml HCl]	1.2-2.0	7.5	4.5	1.5	1.6

3.5.4. Cross-Media Effect

Negative environmental impacts include the following:

- The sand rinsing operations, when carried out in an open loop during the ultrasonic treatment generate a quantity of wastewater that must be filtered (6 to 8,5 m^3 per ton of treated sand, depending on the number of rinses, of which at least four are required, as otherwise the pH of the wastewater must be regulated).
- The sand must be dried after the rinsing operations. The sand drying operation requires a considerable amount of energy (fluidized bed drying system).
- Wastewater filtration treatment generates 4 to 5% waste (not analyzed to date).
- Ultrasonic treatment is noisy and may require additional individual environmental protection means for this reason.

The ultrasonic treatment requires 8.5 l/kg waste foundry sand of water mainly for the rinsing step. This is important, because the rinsing operations in the laboratory tests were carried out in an "open loop". An industrial pilot equipped with a "closed loop" sand rinsing system with an integrated water filtration and treatment system would significantly lower water consumption and reduce the volume of ultimate waste (which will no doubt be recoverable). This water contains fines and must be subjected to treatment and filtration. Analyses of the quality of rinsing water carried out by CTIF within the framework of another project have shown that the pH, the chemical oxygen demand and the soluble fraction contained in the rinsing water must be monitored. The presence of Carbon, Aluminum and Iron have been identified and are probably due to the composition of the powder additives used in the inorganic binder systems. CO_2 pH regulation is an environmentally friendly process that could be used in this case.

3.5.5. Applicability

The ultrasonic treatment process is currently not commercialized. Its effectiveness has so far only been demonstrated on lab-scale samples of 400 g. A transfer to industrial scale is still pending. In this sense, ultrasonic treatment of waste foundry sand is not an available technology and can thus not figure as BAT. It should however be considered as emerging technology the progress of which towards commercialization deserves to be monitored. This is justified by the results obtained on lab scale, which indicate that the process is particularly effective in comparison to other treatment techniques.

3.5.6. Economics

No sound analyses of the economics of industrializing this treatment are available at this stage. For a better understanding of the economic viability of the process, the development of an industrial scale pilot plant is necessary and recommended.

3.5.7. Driving Force for Implementation

- Scarcity of suitable natural sands as a resource for various applications is an ongoing issue. Recycling of sand, wherever possible, is thus a definite need to save available resources for such industries in which recycling or reuse is technically impossible.
- Increasing cost of new sands, including logistics cost, may positively affect economic viability of the ultrasonic reclamation approach.
- Further increase in the cost of waste foundry sand disposal may create an economic incentive for reuse.
- Public regulations aimed at enforcing stricter environmental standards may directly (implementation of waste minimization procedures) or indirectly (increase of disposal costs by re-categorization of waste foundry sand or lowering of harmful substance content limits) force foundries to implement this or other measures for recycling/cleaning of foundry sands.

All the above statements have to be seen as tentative, as currently no detailed study on the economic viability of a scaled-up process is available.

3.5.8. Reference

As stated above (see section 3.5.6), neither industrial application nor pilot plant implementation of the technology is currently available.

3.6. Hydromechanical treatment of foundry sand

Hydromechanical treatment of waste foundries sands was evaluated on lab scale by CTIF, comparing four different inorganic and hybrid binder variants.

3.6.1. Description

The fundamental principle of the process is graphically described in the figure below:

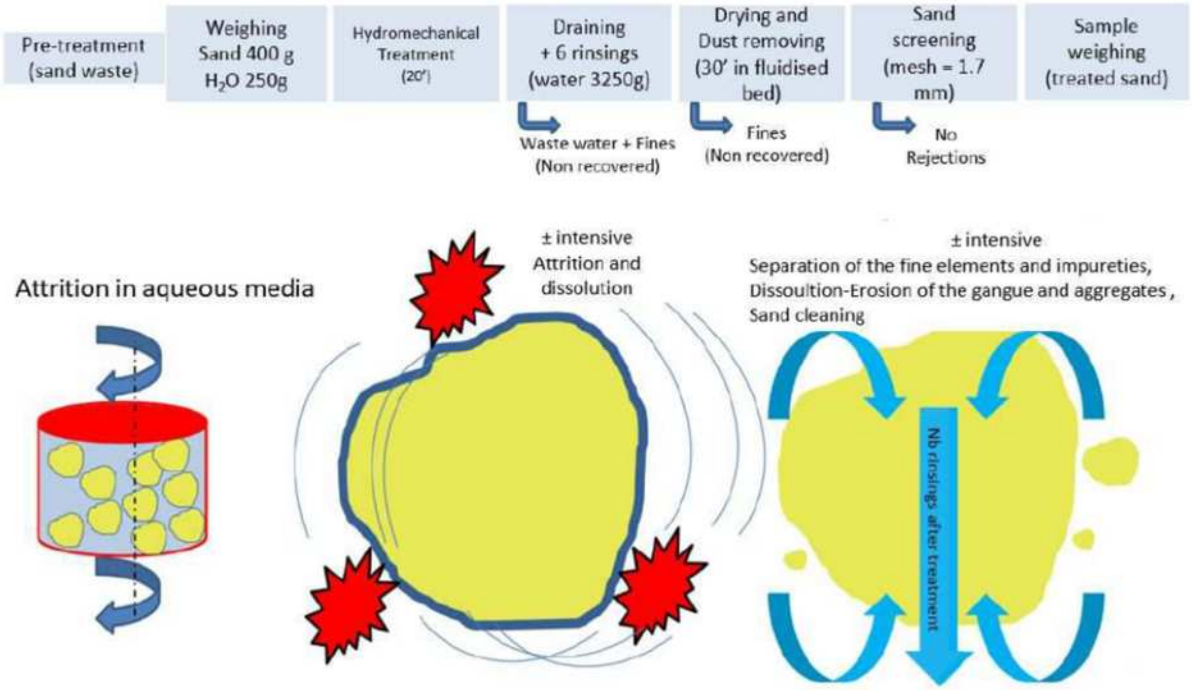

Figure 9: Stages and fundamental principle of the hydromechanical treatment process.

The process consists of the following steps (also depicted, with typical parameter settings, in the Figure above):

- Step 1: Weighing of the samples before treatment.
- Step 2: Moistening of the sand prior to the treatment.
- Step 3: Hydromechanical treatment (typical treatment time approx. 20 min.)
- Step 4: Draining and rinsing of the sand, the latter repeated 6 times.
- Step 5: Drying and dust removal in a fluidized bed.
- Step 6: Screening and weighing of the remaining sand.

During the core hydromechanical treatment step, combined attrition and dissolution lead to the removal of remainders of the binder on the grain surface. Immersion in water and rinsing facilitate separation of fine elements and impurities as well as dissolution of certain elements, compounds and aggregates.

3.6.2. Achieved Environmental Benefit

Positive environmental impacts include the following points:

Hydromechanical treatment in general

- reduces the need of new sand at foundries by 95-96% by facilitating sand reuse, with the remaining 4-5% corresponding to processing losses,
- accordingly reduces the amount of sand which needs to be landfilled by 95-96%
- reduces net lifecycle greenhouse gas emissions from foundry sand by 50-70%,
- reduces shipping and transportation for sands as these can be circulated locally,
- makes it possible to reuse the sand in geoconstruction or road engineering besides recycling it internally,
- allows further reduction of environmental impacts by integrating modern filtration techniques for treatment of the water used for rinsing and
- alllows further reduction of the amount of water needed for rinsing per unit weight of waste foundry sand if closed loop techniques are applied.

From an operational perspective, the following benefits are achieved:

- The hydromechanical treatment does not generate dust or fumes in the atmosphere.
- The hydromechanical process is quiet as well as CO_2 and odour free.
- The water discharged after filtration complies with the standards – this has been checked for aluminium, but needs verification for steel castings.

3.6.3. Operational Data

Experimental studies on ultrasonic treatments using lab scale samples (400 g of sand) have been performed by CTIF comparing altogether four different inorganic or hybrid binder systems:

- **binder 6** is a fully inorganic, commercially available binder system
- **binder 7** is a fully inorganic, commercially available binder system
- **binder 8** is a mostly inorganic, hybrid, commercially available binder with organic hardener
- **binder 9** is a mostly inorganic, hybrid, commercially available binder with organic hardener

Figure X illustrates the appearance of sand grains after the cleaning process in comparison to the virgin sand.

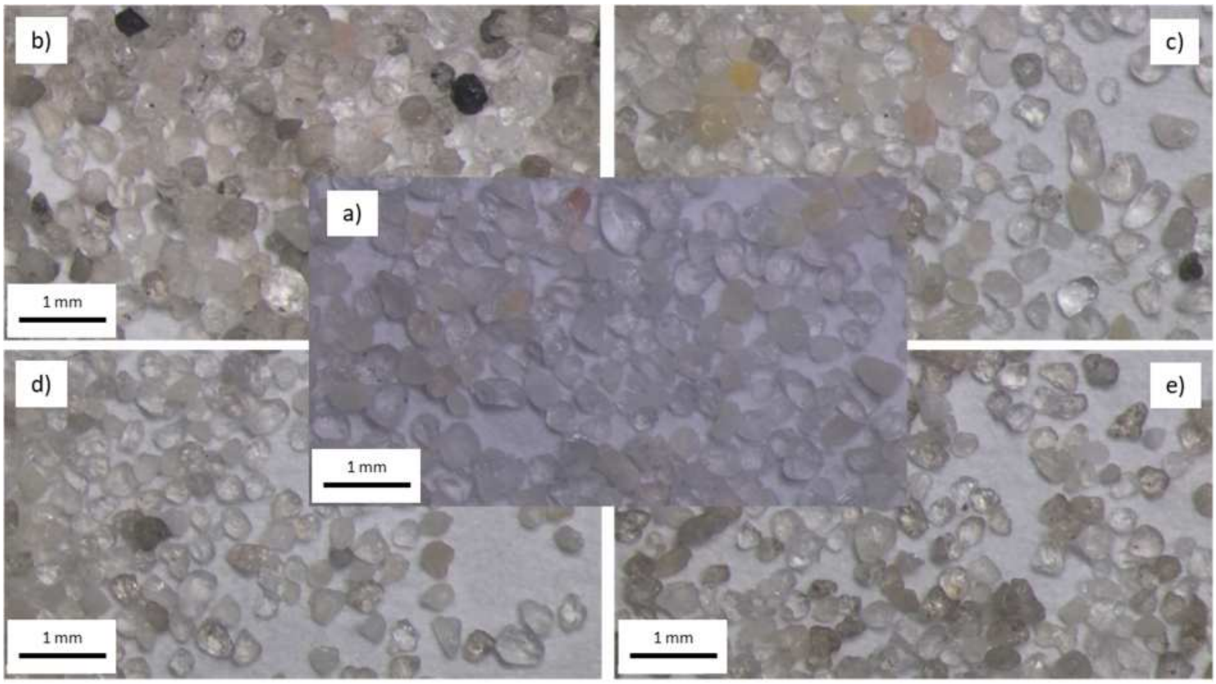

Figure 10: Figure 6: Comparison of (a) virgin sand of grade SN BE01 and (b-e) differently bonded sand after ultrasonic cleaning; (b) ***binder 6****, (c)* ***binder 7****, (d)* ***binder 8*** *and (e)* ***binder 9****.*

Figure Y exemplarily depicts the appearance of grains of sand in virgin state, after use with inorganic binder 6, and after the ultrasonic treatment.

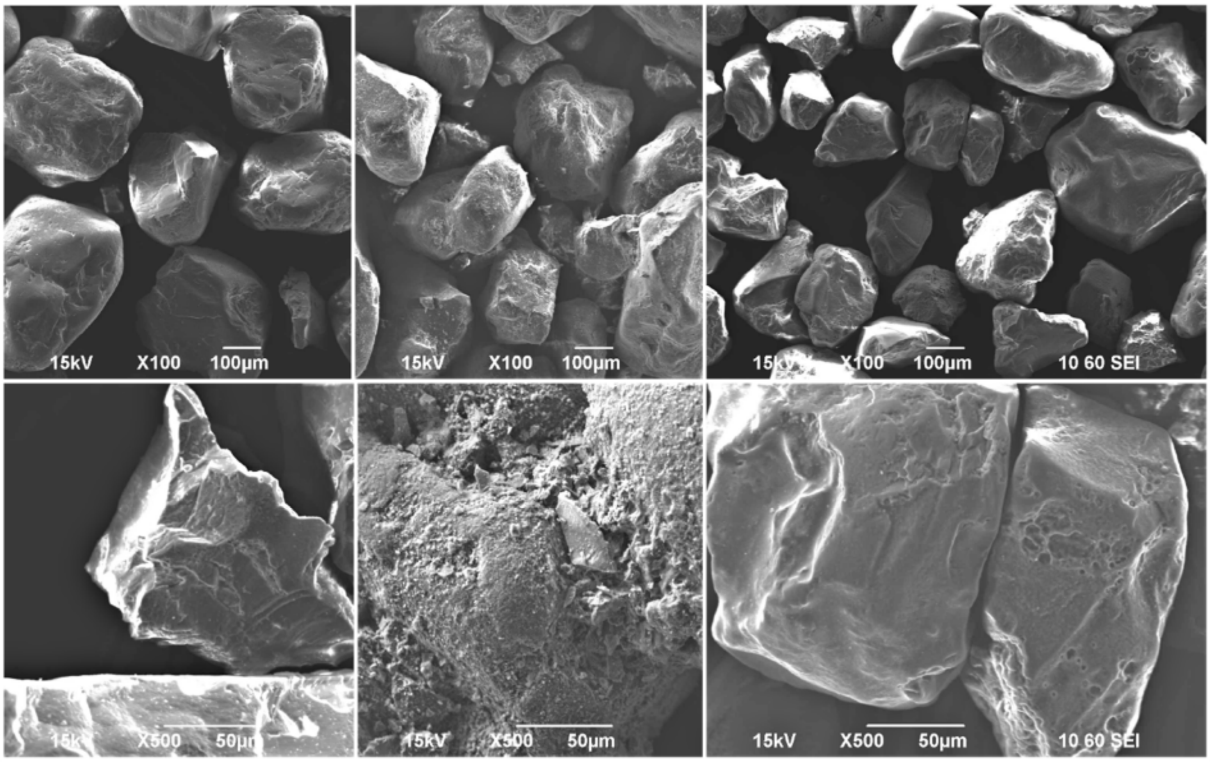

Figure 11: Effect of treatment on BE01 sand - appearance of the grains of sand in virgin state (left column), after use with inorganic ***binder 6*** *(center column) and after hydromechanical treatment (right column).*

Table 17: Effect of hydromechanical treatment on sand characteristics.

Parameter	Reference	BE01 sand with binder no.			
	BE01	Binder 6	Binder 7	Binder 8	Binder 9
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 area [cm^2/g]	159	172	160	169	172
Grain breakage observed	n.a.	low	low	low	low
Aggregate removal observed	n.a.	yes	yes	yes	yes
Amount of fines produced	n.a.	low	low	low	low
Appearance of grains	spherical	spherical & angular	spherical & angular	spherical & angular	spherical & angular
Grain surface appearance	smooth	smooth	smooth	smooth	smooth
Amount of black grains	none	low	low	low	low
Amount of black-spotted grains	none	significant	low	low	low
Amount of unstained grains	significant	significant	significant	significant	significant
El. conductivity [µS/cm]	500-520	523	516	507	511
pH	8.3-8.4	8.78	8.73	8.72	8.45
Acid demand [ml HCl]	1.2-2.0	5.8	2.2	0.6	1.5

The tables below provides the corresponding data on leaching tests for binder 6-9, comparing the respective parameter values before and after hydromechanical treatment.

Table 18: Results of leachte tests, showing the effect of the hydromechanical treatment for ***binder 6****.*

	BE 10 sand/binder6		% change
	untreated	treated	
	[mg/kgMS]	[mg/kgMS]	
As	0.11	0.02	-82
Ba	0.07	< 0.05	-30
Cd	< 0.002	< 0.002	-
Cr	0.07	0.04	-43
Cu	0.05	< 0.02	-60
Hg	< 0.0005	< 0.0005	-
Mo	0.03	< 0.02	-33
Ni	< 0.03	< 0.03	-
Pb	< 0.02	< 0.02	-
Sb	0.067	< 0.02	-70
Se	< 0.02	< 0.02	-
Zn	0.30	< 0.10	>
Chloride	< 10	< 10	-
Fluoride	8.9	2.3	-74
Sulphate	76	< 10	>
Phenolic compounds	<0.10	0.46	+360
DOC (on eluate)	40	34	-15
Soluble fraction	4930	1100	-78
DOT (on raw)	< 2000	< 2000	-
BTEX (sum)	< 0.10	< 0.10	-
TEX (sum)	< 0.10	< 0.10	-
Benzene (LOQ 0.01 / 0.05 mg/kg dm)	< 0.02	< 0.02	-
PCB-7 (sum)	< 0.007	< 0.007	-
Petroleum hydrocarbons C10-C40	< 20	< 20	-
Sum 16 EPA-PAH, excl. LOQ	< 0.16	< 0.16	-
Naphthalene	< 0.01	< 0.01	-

*Table 19: Results of leachte tests, showing the effect of the hydromechanical treatment for **binder 7**.*

	BE 10 sand/binder7		% change
	untreated	treated	
	[mg/kgMS]	[mg/kgMS]	
As	0.01	<0.01	-
Ba	<0.05	<0.05	-
Cd	<0.002	<0.002	-
Cr	<0.01	0.03	+200
Cu	<0.02	0.02	-
Hg	<0.0005	<0.0005	-
Mo	<0.02	<0.02	-
Ni	<0.03	<0.03	-
Pb	<0.02	<0.02	-
Sb	<0.02	<0.02	-
Se	<0.02	<0.02	-
Zn	<0.10	<0.10	-
Chloride	<10	<10	-
Fluoride	<2	<2	-
Sulphate	<10	<10	-
Phenolic compounds	0.23	0.19	-17
DOC (on eluate)	770	28	-96
Soluble fraction	7000	561	-92
DOT (on raw)	<2000	<2000	-
BTEX (sum)	<0.10	<0.10	-
TEX (sum)	<0.10	<0.10	-
Benzene (LOQ 0.01 / 0.05 mg/kg dm)	<0.02	<0.02	-
PCB-7 (sum)	<0.007	<0.007	-
Petroleum hydrocarbons C10-C40	<20	<20	-
Sum 16 EPA-PAH, excl. LOQ	<0.16	<0.16	-
Naphthalene	<0.01	<0.01	-

*Table 20: Results of leachte tests, showing the effect of the hydromechanical treatment for **binder 8**.*

	BE 10 sand/binder8		% change
	untreated	treated	
	[mg/kgMS]	[mg/kgMS]	
As	0.03	<0.01	-67
Ba	<0.05	<0.05	-
Cd	<0.002	0.003	+50
Cr	0.03	0.10	+333
Cu	<0.04	0.02	-50
Hg	<0.0005	<0.0005	-
Mo	<0.02	<0.02	-
Ni	<0.03	<0.03	-
Pb	0.02	<0.02	-
Sb	<0.02	<0.02	-
Se	<0.02	<0.02	-
Zn	<0.10	<0.10	-
Chloride	<10	<10	-
Fluoride	76	4.1	-95
Sulphate	13	<10	-23
Phenolic compounds	<0.10	1.10	+1100
DOC (on eluate)	810	36	-96
Soluble fraction	4160	<500	-88
DOT (on raw)	<2000	<2000	-
BTEX (sum)	<0.10	<0.10	-
TEX (sum)	<0.10	<0.10	-
Benzene (LOQ 0.01 / 0.05 mg/kg dm)	<0.02	<0.02	-
PCB-7 (sum)	<0.007	<0.007	-
Petroleum hydrocarbons C10-C40	<20	<20	-
Sum 16 EPA-PAH, excl. LOQ	<0.16	<0.16	-
Naphthalene	<0.01	<0.01	-

Table 21: Results of leachte tests, showing the effect of the hydromechanical treatment for ***binder 9****.*

	BE 10 sand/binder9		% change
	untreated	treated	
	[mg/kgMS]	[mg/kgMS]	
As	0.02	<0.01	-50
Ba	<0.05	<0.05	-
Cd	<0.002	<0.002	-
Cr	0.01	0.08	+800
Cu	0.02	<0.02	-
Hg	<0.0005	<0.0005	-
Mo	<0.02	<0.02	-
Ni	<0.03	<0.03	-
Pb	<0.02	<0.02	-
Sb	<0.02	<0.02	-
Se	<0.02	<0.02	-
Zn	<0.10	<0.10	-
Chloride	23	<10	-57
Fluoride	110	7.1	-94
Sulphate	20	<10	-50
Phenolic compounds	<0.10	0.10	-
DOC (on eluate)	300	29	-90
Soluble fraction	3080	<500	-84
DOT (on raw)	<2000	<2000	-
BTEX (sum)	<0.10	<0.10	-
TEX (sum)	<0.10	<0.10	-
Benzene (LOQ 0.01 / 0.05 mg/kg dm)	<0.02	<0.02	-
PCB-7 (sum)	<0.007	<0.007	-
Petroleum hydrocarbons C10-C40	<20	<20	-
Sum 16 EPA-PAH, excl. LOQ	0.20	<0.16	-20
Naphthalene	<0.01	<0.01	-

The evaluation of the leachate tests show that significant reductions can be obtained for some of the substances under scrutiny. Following the hydromechanical treatment, waste foundry sand bonded using **binders 6-9** conform to the limit values for inert waste applicable in most countries. An exception is the stricter limit value in Italy for fluorides, which is not met by **binder** 6 after the treatment, and, in the case of **binder 8** after the treatment, the slightly exceeded limit value for the phenol index valid in all countries

Based on **binder 7**, the effect of reuse on bending strength of bonded sand was evaluated against reference samples using the same binder, but new sand. The tests showed no statistically significant difference between both sample series, proving that the hydromechanical treatment is indeed suitable for reclaiming waste foundry sand for reuse in core making.

3.6.4. Cross-Media Effect

Negative environmental impacts include the following:

- The sand rinsing operations, when carried out in an open loop during the hydromechanical treatment generate a quantity of wastewater that must be filtered (5.5 to 8 m^3 per ton of treated sand, depending on the number of rinses, of which at least four are required, as otherwise the pH of the wastewater must be regulated).
- The sand must be dried after the rinsing operations. The sand drying operation requires a considerable amount of energy (fluidized bed drying system).
- Wastewater filtration treatment generates 4 to 5% waste (not analyzed to date).

Similar to the ultrasonic treatment, the hydromechanical treatment requires 8.125 l/kg waste foundry sand of water mainly for the rinsing step. This is important, because the rinsing operations in the laboratory tests were carried out in an "open loop". An industrial pilot equipped with a "closed loop" sand rinsing system with an integrated water filtration and treatment system would significantly lower water consumption and reduce the volume of ultimate waste (which will no doubt be recoverable). This water contains fines and must be subjected to treatment and filtration. Analyses of the quality of rinsing water carried out by CTIF within the framework of another project have shown that the pH, the chemical oxygen demand and the soluble fraction contained in the rinsing water must be monitored. The presence of carbon, aluminum and iron have been identified and are probably due to the composition of the powder additives used in the inorganic binder systems. CO_2 pH regulation is an environmentally friendly process that could be used in this case.

3.6.5. Applicability

The hydromechanical treatment process is currently not commercialized. Its effectiveness has so far only been demonstrated on lab-scale samples of 400 g. A transfer to industrial scale is still pending. In this sense, ultrasonic treatment of waste foundry sand is not an available technology and can thus not figure as BAT. It should however be considered as emerging technology the progress of which towards commercialization deserves to be monitored. This is justified by the results obtained on lab scale, which indicate that the process is particularly effective in comparison to other treatment techniques.

3.6.6. Economics

No sound analysis of the economics of industrializing this treatment are available at this stage. For a better understanding of the economic viability of the process, the development of an industrial scale pilot plant is necessary and recommended.

3.6.7. Driving Force for Implementation

- Scarcity of suitable natural sands as a resource for various applications is an ongoing issue. Recycling of sand, wherever possible, is thus a definite need to save available resources for such industries in which recycling or reuse is technically impossible.
- Increasing cost of new sands, including logistics cost, may positively affect economic viability of the hydromechanical reclamation approach.
- Further increase in the cost of waste foundry sand disposal may create an economic incentive for reuse.
- Public regulations aimed at enforcing stricter environmental standards may directly (implementation of waste minimization procedures) or indirectly (increase of disposal costs by re-categorization of waste foundry sand or lowering of harmful substance content limits) force foundries to implement this or other measures for recycling/cleaning of foundry sands.

All the above statements have to be seen as tentative, as currently no detailed study on the economic viability of a scaled-up process is available.

3.6.8. Reference

As stated above (see section 3.6.6), neither industrial application nor pilot plant implementation of the technology is currently available.

Annex A: References

[EC_05] Integrated Pollution Prevention and Control: Reference Document on Best Available Techniques in the Smitheries and Foundries Industry. European Commission, May 2005; https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/sf_bref_0505_1.pdf (accessed March 1st, 2022).

[EC_22] Best Available Techniques (BAT) Reference Document for the Smitheries and Foundries Industry – Draft 1. European Commission, February 2022; https://eippcb.jrc.ec.europa.eu/sites/default/files/2022-02/SF_BREF_D1_web.pdf (accessed March 1st, 2022)

[Fin22] https://finnrecycling.fi/ (accessed March 14th, 2022).

Annex B: Overview of Binder Systems

Table 22: General description of binder systems compared.

Report Designation	Type
binder 1	fully inorganic, hardening in furnace at approx. 160-200°C
binder 2	fully inorganic, hardening in furnace at approx. 130-180°C
binder 3	fully inorganic
binder 4	hybrid, hardener containing organic compounds (ester-based), self-setting at room temperature
binder 5	hybrid, hardener containing organic compounds (ester-based), self-setting at room temperature
binder 6	fully inorganic
binder 7	fully inorganic
binder 8	hybrid, hardener containing organic compounds (ester-based), self-setting at room temperature
binder 9	hybrid, hardener containing organic compounds (ester-based), self-setting at room temperature

Table 23: Key to binder systems evaluated in the current project.

Report Designation	type	Supplier	Binder Designation	Hardener Designation
binder 1	inorganic	ASK Chemicals	Inotec EP 4703	Inotec Promotor EP 4748
binder 2	inorganic	SATEF Hüttenes Albertus S.P.A.	Cordis 8593	Anorgit 8608
binder 3	inorganic	ASK Chemicals Italia S.R.L.	Inotec hc 2000	Inotec Promotor tc 500
binder 4	hybrid	Peak Deutschland GmbH	Clean Cast S27	Clean Cast K4, K5 and K6
binder 5	hybrid	Sand Team, Czech Republic	Geopol 618	SA 73 and SA 75 hardener
binder 6	inorganic	ASK Chemicals	Inotec	
binder 7	inorganic	ASK Chemicals	Inobake	Inobake LV and Katalysator K5030
binder 8	hybrid	Sand Team, Czech Republic	Geopol W37-20	
binder 9	hybrid	Peak Deutschland GmbH	PEAK W37	