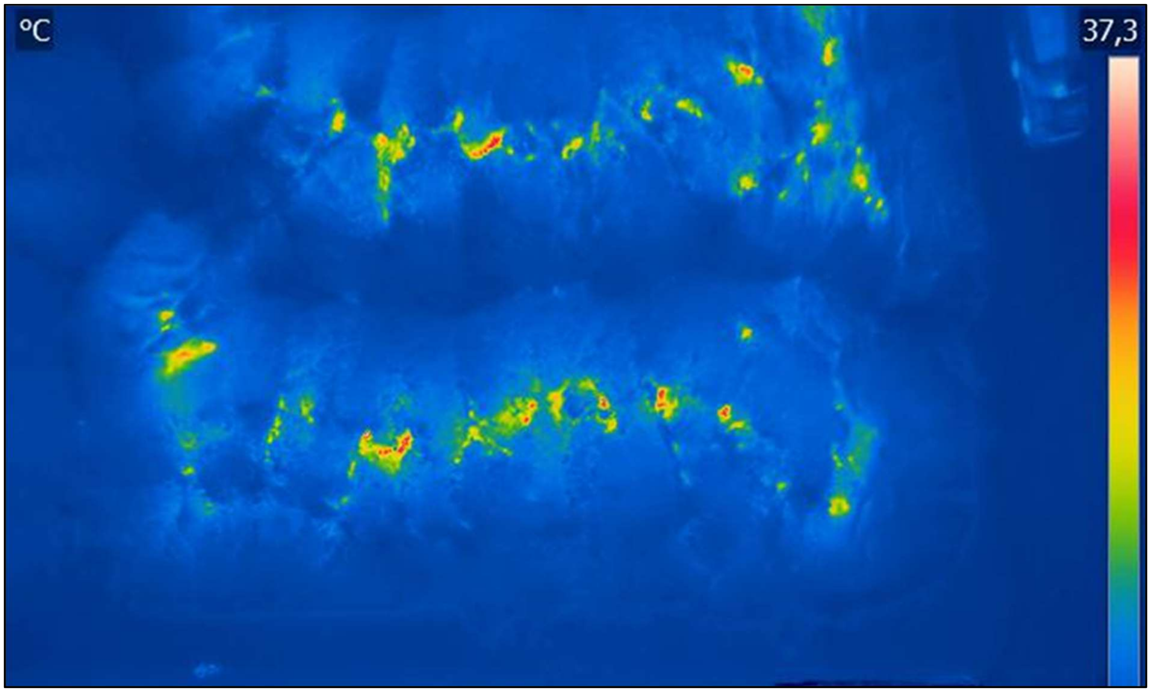
RecAsh –

Recovery of Resources in Bottom Ash

Summary report



Drone thermography showing location of hotspots along ridges of IBA storage piles.

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Introduction

This document is a summary report on the findings in the project RecAsh – Recovery of Resources in Bottom Ash. RecAsh was a Grand Solutions project funded by Innovationsfonden (Journal nr. 5157-00006B). The total budget for the project was 9,69 Mio DKK and it was funded by Innovationsfonden with 5,75 Mio DKK.

The following companies were participating as partners in the project:

- Afatek A/S
- Boes Consulting
- Danish Waste Solutions ApS
- Danish Technological Institute
- DTU

Afatek A/S was administrator of the project and Torben Overgaard from Boes Consulting was project leader.

The project ran from 15. February 2016 to 15. February 2019.

WP1 - Establishment of maturation model

The objective of WP1 was to reach a deeper understanding of the parameters influencing the maturation and drying out of IBA in piles to enable the establishment of a maturation model for IBA.

The initial activity in WP1 was a desk-top study covering the state of the art in the field of carbonation. Some of the most important findings for this project is described in the following.

The weathering of IBA starts immediately after the quenching at the incineration plant and by the time the IBA arrives at the Afatek facility at least a part of the reactive lime (CaO) has reacted into portlandite while releasing heat. Weathering of IBA takes places in at least three different stages which can be defined by the presence of different mineral phases which in turn control the pH and leaching. Only the first two stages are relevant for the weathering in piles as carried out in Denmark (i.e. limited ageing time in the pile). The first stage is the freshly quenched (still unweathered) IBA giving *solution* pH >12 and the second is the quenched IBA undergoing weathering/carbonation giving *solution* pH 10-11.5. The composition and properties of IBA vary in the different particle size fractions. Most importantly the fine fraction (<4 mm) contains a larger amount of lime (CaO) which is the primary reactive compound for the carbonation reaction. The fine fraction also has about twice as large water absorption capacity compared to the coarse fraction; this also means that the fine fraction is drying out slower. The fine fraction of fresh IBA shows higher leaching of contaminants compared to the coarse fraction which may occasionally pass the leaching limit values without ageing. For the natural carbonation IBA a level of 15-20 % moisture content seems optimal. This is also the range of moisture in the quenched IBA coming from the incineration plant. The CO_2 capacity of the IBA is large and the actual supply of CO_2 to the reaction interface seems to be the largest limiting factor in full-scale natural weathering. During weathering, the IBA piles produce a significant amount of heat over long time periods with a maximum temperature of typically around 90 °C, if the surface area versus volume is optimal (i.e. below 0.7). About 40-45 % of the heat is typically allocated to oxidation of metallic iron; the other major fraction of the heat is produced by hydration of lime and carbonation reactions. Reported thermal conductivity of IBA (λ_{IBA}) ranges from 0.23 W/m·K to 1.27 W/m·K for "dry" (<8% MC) and freshly quenched IBA (25-30% MC); these values corresponded to λ_{IBA} determined by TI during this project. The specific heat capacity (Cp) of IBA found in literature ranges between 0.85-1.86 (dry-wet) kJ/kg·K.

Based on the available findings a conceptual maturation model and a laboratory test programme was designed. The test programme included the following measurements/tests: particle size distribution, dry matter content, total content analysis, initial acid neutralisation capacity, laboratory weathering and batch leaching. The results of the tests were evaluated using a weighted matrix with different levels of importance assigned to different performance parameters e.g. final moisture content (which is linked to metal recovery which is in turn linked to treatment costs) and leaching properties had highest importance followed by lower-weighed maturation time (possible cost optimisation) and even less important total carbonation conversion.

The conceptual maturation model was based on three sub-models describing: (1) thermal balance, (2) water balance and (3) the controlling chemistry (se Fig. 1). These sub-models are interlinked and have influence on both the mechanical quality and the chemical/environmental quality of treated IBA.

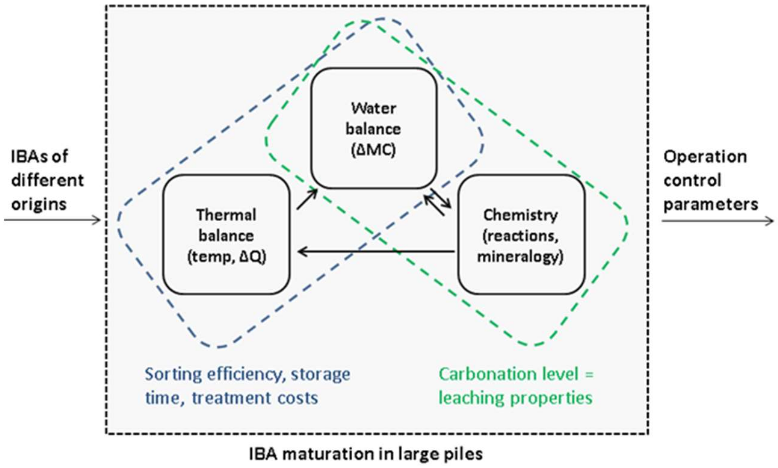


Figure 1. Conceptual maturation model for the IBA in piles.

Based on literature and information on the chemistry in the IBA at Afatek the chemical reactions in Fig. 2 are considered relevant for the heat development in the IBA piles. The calculated heat output is around 140-145 MJ/tonne IBA without considering the heat loss caused by evaporation and transport of water outside of the pile. The contribution of different reactions assumed to take place during the relatively short-term weathering in piles. Corrosion of Fe(0) accounts for approximately 42 % of the total heat followed by carbonation of portlandite, hydration of lime and generation of C-S-H (45 % combined). Sulphide oxidation and aluminium oxidation account for 6 % and ~5.5 %, respectively.

Process	**Reaction**	**ΔH (kJ/mol)**
Fe corrosion	a) 2 Fe + 3 H2O + 1.5 O2 → 2 Fe(OH)3	-791
	b) 2 Fe0 + 3/2 O2 + H2O → Fe2O3×H2O	-824
Al corrosion	2Al + 6 H2O → 2 Al(OH)3 + 3H2	-422
CaO hydrolysis	CaO + H2O → Ca(OH)2	-65
Portlandite → Calcite	Ca(OH)2 + H2CO3* → CaCO3 + 2H2O	-111
Portlandite → C-S-H[a)]	*Ca(OH)2 + SiO2 → CaH2SiO4*	-40 to -140
Sulfide oxidation	a) FeS + 2.25O2 + 2.5H2O → Fe(OH)3 + H2SO4	-921
	b) FeS2 + 3.75O2 + 3.5H2O → Fe(OH)3 + 2 H2SO4	-135

Figure 2. Overview of reactions considered relevant for heat development during the full-scale ageing in IBA piles at Afatek.

Evaporation of water consumes 40.7 kJ/mol (or 2257 kJ/kg) and the process should therefore cool the system. However, the exact amount of water (and thus heat) "lost" due to evaporation is unknown as, in order to cause the heat loss, the water vapour needs to leave the system (pile) and not condense (release heat) in other parts of the pile. Consequently, the water balance for the entire pile needs to be established first.

Based on drying of samples at DTU and Afatek (WP2) the free water and water bound to different minerals have been estimated to respectively 82-84 % and 18-16 %. Calculations based on meteorological data and pile dimensions estimate the rain infiltration to be between 2.4 and 1.4 wt.% (WP2). The calculated value is the maximum possible change in dry matter if all precipitation is absorbed by the pile. The worst case is not likely to occur because water may evaporate from the surface and run off the sides of the pile.

The maximum amount of water consumed or released by the different chemical reactions is estimated to 1.6-2 wt.% based on the stoichiometry of the reactions included in the thermal model. From the simplified water balance of the entire system (MCfinal = MCinitial + "rain" - "chemistry" - "evaporation"), it seems that evaporation can at maximum contribute to a ~2.5 % decrease in moisture content. Evaporation of this amount of water (25.1 kg/tonne IBA or 1393 mol/tonne IBA) would result in a heat loss of 56.6 MJ/tonne. Consequently, the thermal output of the pile would decrease from 140-145 MJ/tonne to approximately 83-88 MJ/tonne.

The work performed in WP1 as well as various measurement done in WP2 were used to optimise the processing of the IBA at the Afatek plant. The original processing (reference situation) of IBA in the Afatek plant is depicted in Figure 3. In the reference situation the quenched IBA arrives to Afatek where it is stored in a pile as raw ash for 2-4 weeks followed by a pre-sorting where magnetic ferrous scrap and particles larger than 50 mm is removed. A pile of the remaining IBA is build using front loaders. This pile is stored for 4-12 weeks after which it is sorted for non-Fe minerals. The sampling for declaration tests is done automatically at the end of the metal sorting plant. The remaining minerals are now stored and ready for use as road construction material.

In the optimised processing of IBA at the Afatek plant the main change is that the IBA is stored as raw ash with all iron included longer time before the pre-sorting and sorting for Non-Fe metals are done (see Fig. 4). This reduces the overall time used in the processing as well as leads to faster drying out of the IBA due to a longer period with maximum temperature in the IBA pile. This will be closer described in WP2.

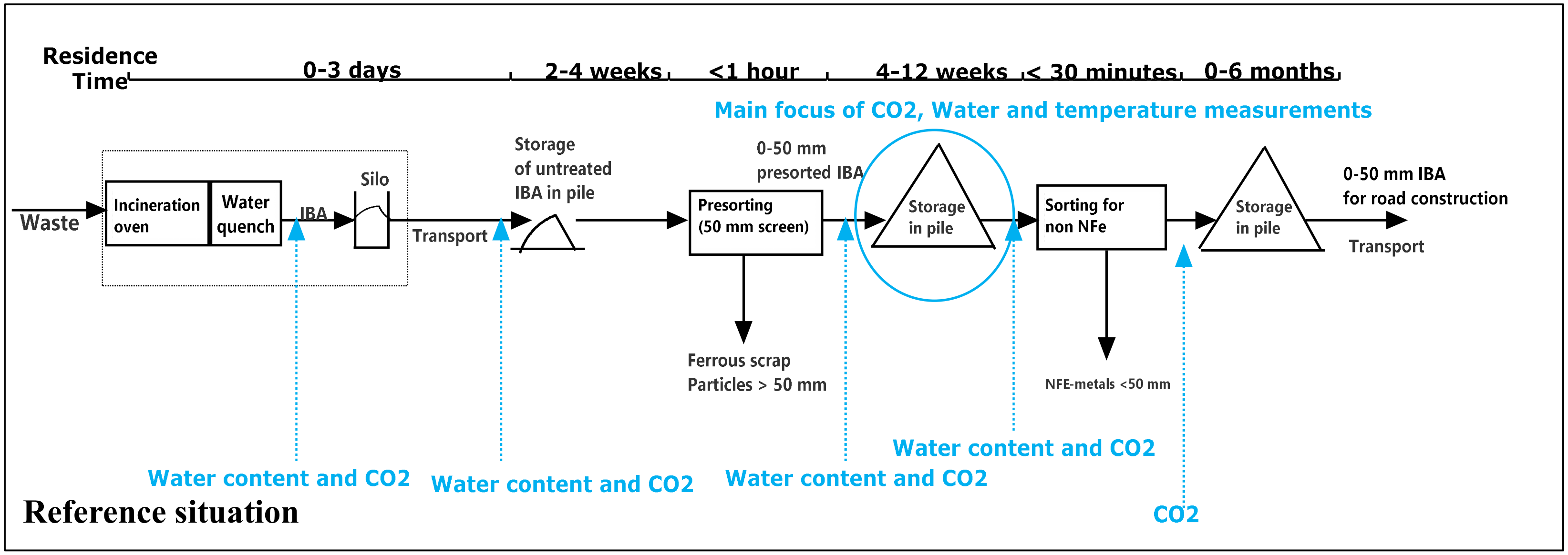


Figure 3. Schematic drawing of the original processing of IBA at the Afatek plant. Points of sampling and measurements in the project are also shown.

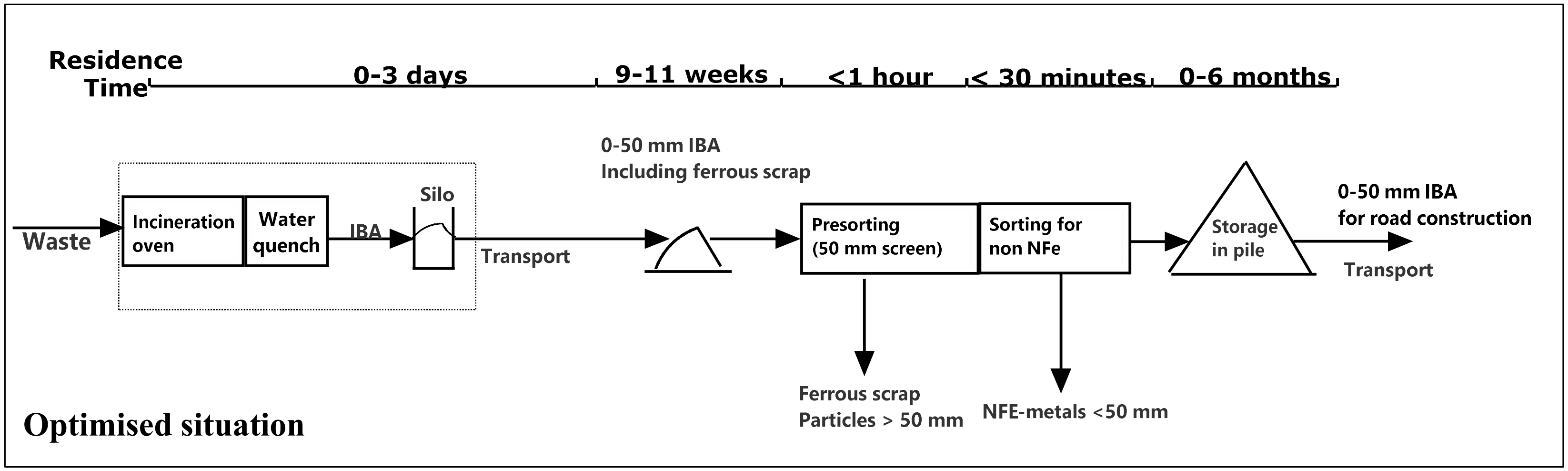


Figure 4. Schematic drawing of the optimised processing of IBA at the Afatek plant.

WP2 – Measurements and optimisation

WP2 deals with the measurements in the IBA piles. The measurements were carried out in two different situations, referred to as “reference situation” and “optimised situation”. The two situations are described in Fig. 3 and Fig. 4 under WP1. The measured parameters in WP2 are temperature inside the pile, CO_2 and water content. To a minor extent also the surface temperatures of the piles as well as oxygen content and pressure inside the piles have been measured.

The measurements were carried out on IBA from Kara/Noveren and Vestforbrænding. Over the course of the project, the waste incineration company Kara/Noveren change its name to Argo. For simplicity the name Kara has been used for all measurements in this work package. Likewise, the piles from Vestforbrænding are referred to as Vest. The results have been obtained in the period from March 2016 to July 2018. Fixed points for measurements of temperature and CO_2 were installed in 17 reference piles and 18 optimised piles.

From the measurements it was found that the core temperatures inside the piles increase to 85-93 °C and that it remains constant over a period of at least 8 weeks after the maximum temperature has been reached (Fig. 5 left). The isothermal core is surrounded by a boundary layer with a steep temperature gradient towards the surface. The temperature gradient close to the surface is ~1 °C/cm and it decreases with the distance to the surface. These observations are valid for both the reference piles and optimised piles. The temperature in the optimised piles is, however, increasing faster than in the reference piles.

Surface temperatures of optimised piles were followed by thermography. It was seen that hot spots, from which escaping vapor is often observed, are present in the optimised piles (Fig 5 right). The drone thermography shows that the hotspots generally occupy in the order or 0 to 3 % of the pile surface area. Following the same piles with drone thermography for 6 weeks, showed that the hotspots remain at the same positions, but that their temperature fluctuate over time. Hotspots were not observed in the reference piles.

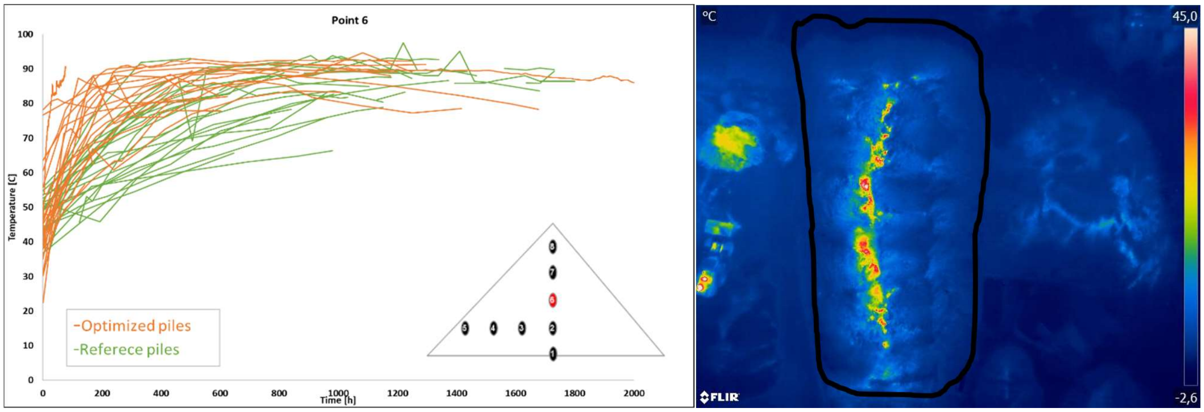


Figure 5. Left: Comparison of measured temperatures at point 6 in the piles over time. The green lines are reference piles and the orange lines are the optimised piles. The red dot in the figure indicates the measuring position. Right: Thermography of Vest 1-2018. The outline of the pile is shown as a black line. The length of the pile is 50 m.

The water content of the IBA in the piles during the storage has been investigated. The measurements showed large variations in the water content when the IBA arrived from the incineration plants (9-23 wt.% water) with an average value of 16.5 wt.%. The surface layer of the piles always contains more water than the central part of the piles. The average drying rate of the reference piles was found to be 0.04 wt.% /day. The average drying rate in the optimized piles was found to be 0.07 wt.%/day i.e. almost twice as fast as in the reference piles. The precipitation in the period of storage does not seem to be of influence on the final water content.

For the carbonation of the IBA it is necessary that CO_2 is available. Inside the piles the CO_2 concentration in the air sucked out from different points were consistently measured below the detection limit of 75 ppm. This value is lower than the atmospheric concentration which is in the range of approximately 400 ppm. This, combined with additional experiments described in the report, shows that that carbonation of IBA is most likely mass transfer limited.

Oxygen is needed for the oxidation of e.g. iron in the piles and a series of test were made to investigate the oxygen content inside the piles. The measurements showed that there was a lower concentration of oxygen in the centre of the piles compared to closer to the surface. This “reduction” in oxygen level could both be due to the oxidation reactions as well as dilution because of generation of other gases and water vapour. The oxygen is not depleted, which indicates a transport of oxygen into the pile.

Some measurement of the differential pressure over time were also made in an optimised pile. A minor overpressure of 0-20 mbar was found inside this pile.

Based on the measurements as well as the information collected in WP1 a model of temperature and drying out of the piles were made. The model consists of an energy balance and a mass balance of water. The components of the model are illustrated below. The methodology of the model can be described by the following steps:

1. The energy production of each pile is determined by the initial heating rate measured inside the pile.
2. The heat loss is calculated from the convective heat loss to the surroundings.
3. The excess energy, which is not used for heating up the pile or lost as heat loss, is used for evaporation of water.
4. The evaporated water condenses on the cold surface.
5. From the surface, the condensed water evaporates to the surroundings.
6. An estimate of the evaporation through the hotspots is made.

In the water balance it is assumed that initially all water is found as free water. As the reactions proceed, the water is consumed in chemical reactions and water is evaporated from the core. As the reactions proceed, the non-bound water starts to evaporate in the isothermal core. When the water vapor passes through the insulating layer it will condensate and afterwards evaporate to the surroundings. The evaporation to the surroundings is dependent on climatic conditions (heat emission, relative humidity, air temperature, wind speed and pressure). The reactions used in the model are from the literature study, performed in the RecAsh WP1.

The energy balance terms used are:

1. $Q_{produced}$ = the energy generated by the chemical reactions.
2. $Q_{accumulated}$ = the accumulated energy (energy used to evaporate water and increase the temperature)
3. Q_{out} = the heat loss to air and ground
4. Q_{in} = energy contribution to pile from outside

Summaries of the water and energy balance in models for the reference piles and the optimised piles can be seen in Figure 6.

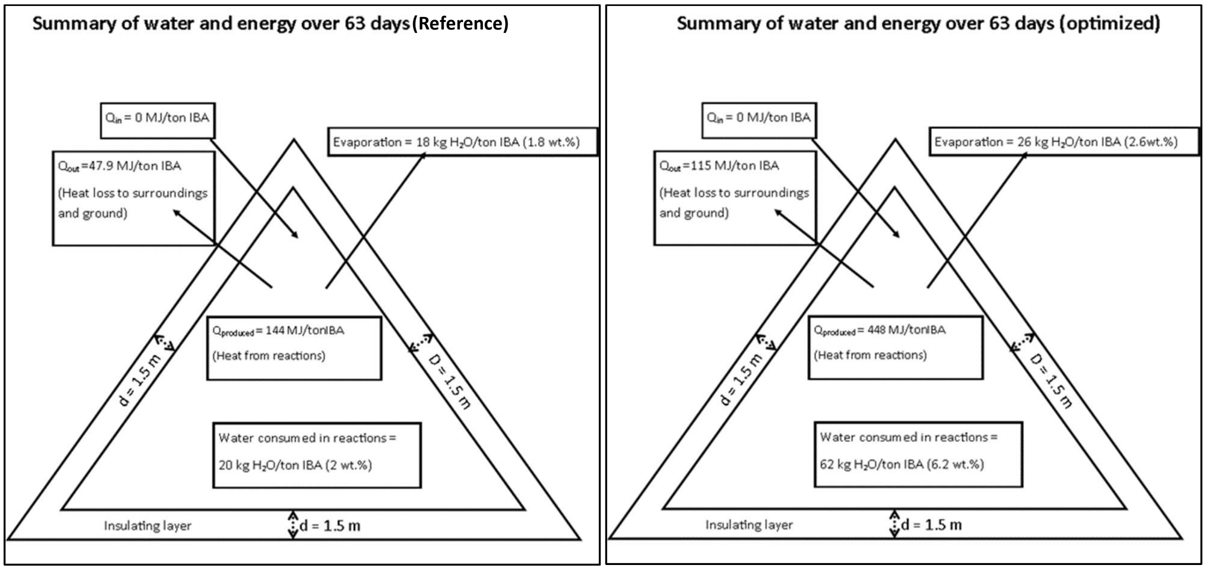


Figure 6. Final model showing energy and water balance, i.e. production, loss and input, in the reference piles and in the optimised piles.

The conclusions from this model work can be summarised as follows:

- The temperature increase during the heating stage can be predicted accurately with the heat of reaction found in the literature (WP1) and the heat loss calculated.
- The energy production was determined from the temperature measurements. The values are 26±15 W/ton for the reference piles and 84±23 W/ton for optimised piles.
- The energy production in reference IBA is in good agreement with the 27 W/ton (144 MJ/ton over 1500 hours) estimated in the literature study. However, the heat generated in the raw ash pile before the pre-sorting of iron is not included.
- The energy production over a 1500-hour period is 448 MJ/ton in the optimised piles.
- During the isothermal stage evaporation needs to be included in the model to explain the constant temperature.
- The evaporation rate in the isothermal stage (85 °C) is 0.014 kgH_2O/ton IBA·h in the reference piles and 0.021 kgH_2O/ton IBA·h in the optimised piles. The rate of chemical water uptake is 0.74 kgH_2O/ton IBA·h (based on literature and adjusted for power output).
- The simulated temperatures and drying are in good agreement with experimental results.
- The pressure build-up rate in the pile shows that the vapor must leave the pile or condense in the outermost layer.
- For the optimised piles the evaporation from surface to air is limiting the rate of drying.
- For the optimised piles a good agreement is found between simulated reduction in water content and measured values.
- For optimised piles the reduction in water content is mainly due to chemical uptake.

WP3 – Metal recovery

The objective of WP3 was to measure and compare the metal recovery in the original IBA processing situation (reference situation) with the optimised situation. In the project samples for metal recovery testing were taken from 17 reference piles and 14 optimised piles. The process to evaluate the metal recovery in the original project description was changed to a much more precise full-scale method.

The method used to evaluate the metal recovery can by described as follows:

1. During the primary metal sorting of each pile of IBA (5000 t) one to two front loader shovels of the sorted IBA are put aside each day. The total amount of the sample is 50-100 ton per pile.
2. The IBA samples are sorted again 3 times using the metal sorting plant. In this way, the loss of metal in the first sorting can be calculated.
3. After each sorting, the amount of NFe 1-4 mm, NFe 4-50 mm and output from the sensor machine is weighed.
4. From each sample of NFe 1-4 mm and NFe 4-50 mm a small sample is collected for further determination of the metal grade. The metal grade of the first sorting is determined from sold metal upgraded at Scan metals.
5. The metal grade of sorting number 2, 3 and 4 is determined by Afatek in a laboratory Eddy Current Separator according to the below procedure.
6. The collected samples are divided in a riffle splitter to contain minimum 1000 particles.
7. The NFe and mineral in the sample is separated in a plexiglass box above the Eddy current separator.
8. The metal and non-metal fractions are weighted.

In addition to the evaluation of the metal grade the test is also used to evaluate the total NFe metal potential as well as the NFe metal loss in the Afatek NFe metal sorting plant.

After resorting of 17 reference piles the following data are found (see Fig. 7):

1. The average sorting efficiency of 1-4 mm NFe is 64±9%.
2. The average sorting efficiency of 4-50 mm is 86±4%
3. The overall sorting efficiency is 78±4%

After resorting of 15 optimized piles, the following sorting efficiencies are found (see Fig. 7):

1. The average sorting efficiency of 1-4 mm NFe is 72±13%. .
2. The average sorting efficiency of 4-50 mm is 90±3% .
3. The overall sorting efficiency is 84±5%.

The sorting is more efficient for the larger particles and less efficient for the smaller and often more humid particles. The increase in NFe metal recovery from the reference piles to the optimised piles are 6 %points, i.e. an increase of 7.7 %. As the total loss is still around 16 %points there is still room for improvement.

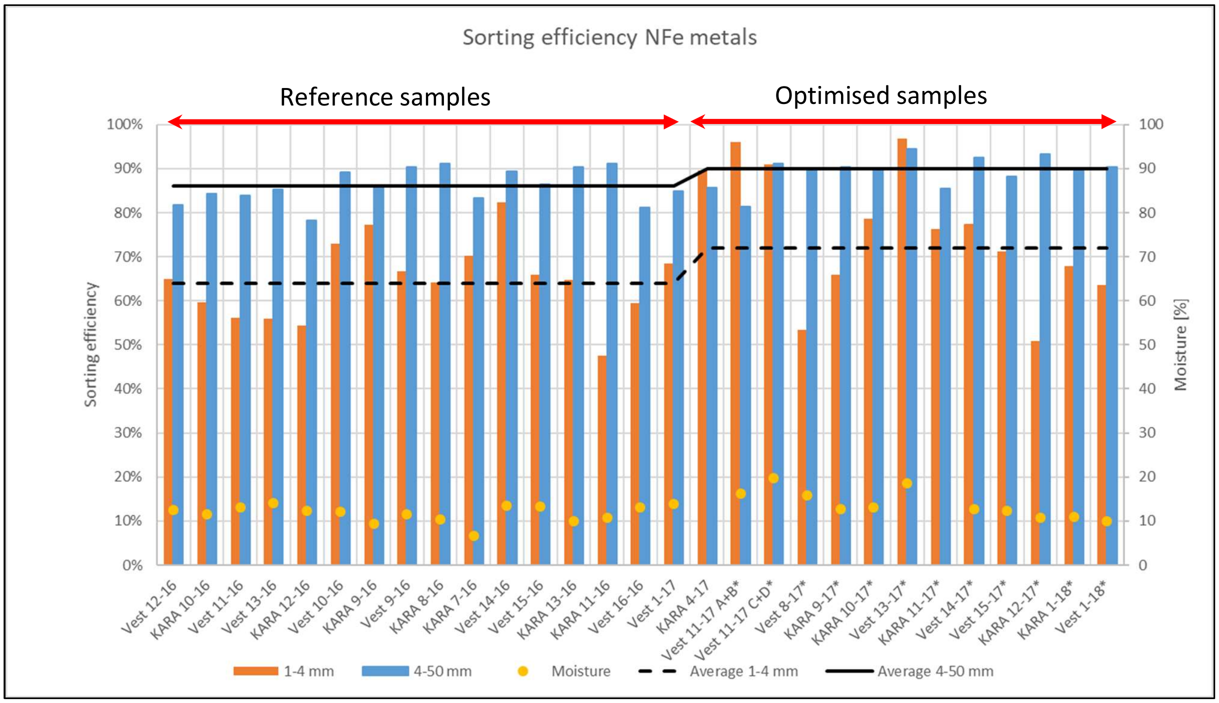
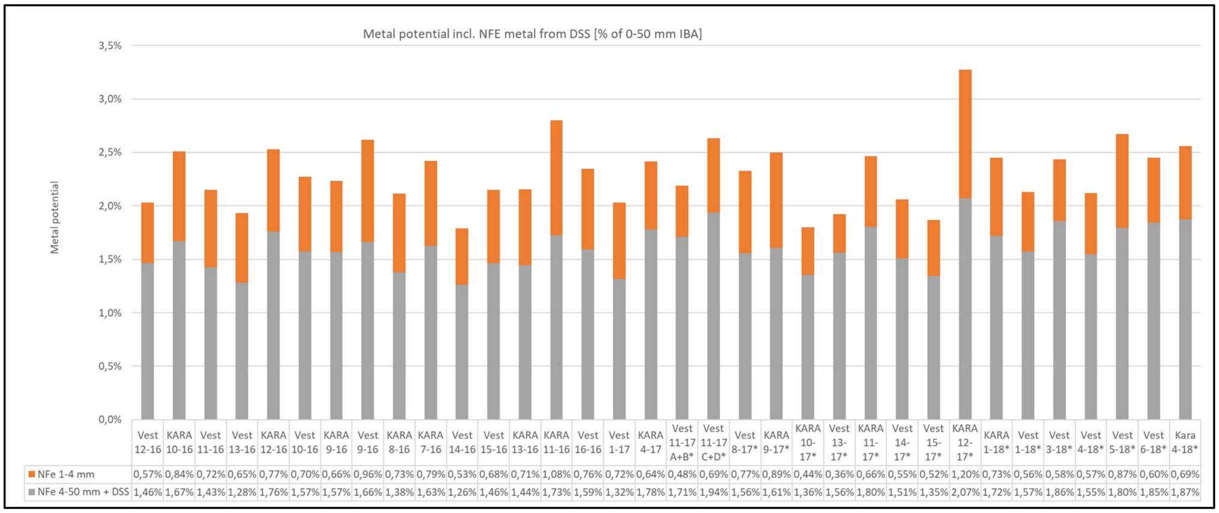


Figure 7. Sorting efficiency from reference samples compared to optimised samples.

A comparison of the recovery grade as function of moisture does not show a clear correlation for the 4-50 mm fraction. For the 1-4 mm fraction an increasing recovery grade is found with decreasing moisture content. However, the data indicates that moisture cannot be used exclusively to describe the recovery grade.



	Vest 12-16	KARA 10-16	Vest 11-16	Vest 13-16	KARA 12-16	Vest 10-16	KARA 9-16	Vest 9-16	KARA 8-16	KARA 7-16	Vest 14-16	Vest 15-16	KARA 13-16	KARA 11-16	Vest 16-16	Vest 1-17	KARA 4-17	Vest 11-17 A+B*	Vest 11-17 C+D*	Vest 8-17*	KARA 9-17*	KARA 10-17*	Vest 13-17*	KARA 11-17*	Vest 14-17*	Vest 15-17*	KARA 12-17*	KARA 1-18*	Vest 1-18*	Vest 3-18*	Vest 4-18*	Vest 5-18*	Vest 6-18*	Kara 4-18*
■ NFe 1-4 mm	0,57%	0,84%	0,72%	0,65%	0,77%	0,70%	0,66%	0,96%	0,73%	0,79%	0,53%	0,68%	0,71%	1,08%	0,76%	0,72%	0,64%	0,48%	0,69%	0,77%	0,89%	0,44%	0,36%	0,66%	0,55%	0,52%	1,20%	0,73%	0,56%	0,58%	0,57%	0,87%	0,60%	0,69%
■ NFe 4-50 mm + DSS	1,46%	1,67%	1,43%	1,28%	1,76%	1,57%	1,57%	1,66%	1,38%	1,63%	1,26%	1,46%	1,44%	1,73%	1,59%	1,32%	1,78%	1,71%	1,94%	1,56%	1,61%	1,36%	1,56%	1,80%	1,51%	1,35%	2,07%	1,72%	1,57%	1,86%	1,55%	1,80%	1,85%	1,87%

Figure 8. NFe metal potential in reference and optimised piles.

In Figure 8 the NFe metal potential is seen to vary from 1.8 to 2.8 % of 0-50 mm IBA (excluding outliers). Based on raw ash the potential would vary between 1.6 and 2.5 % of the raw ash.

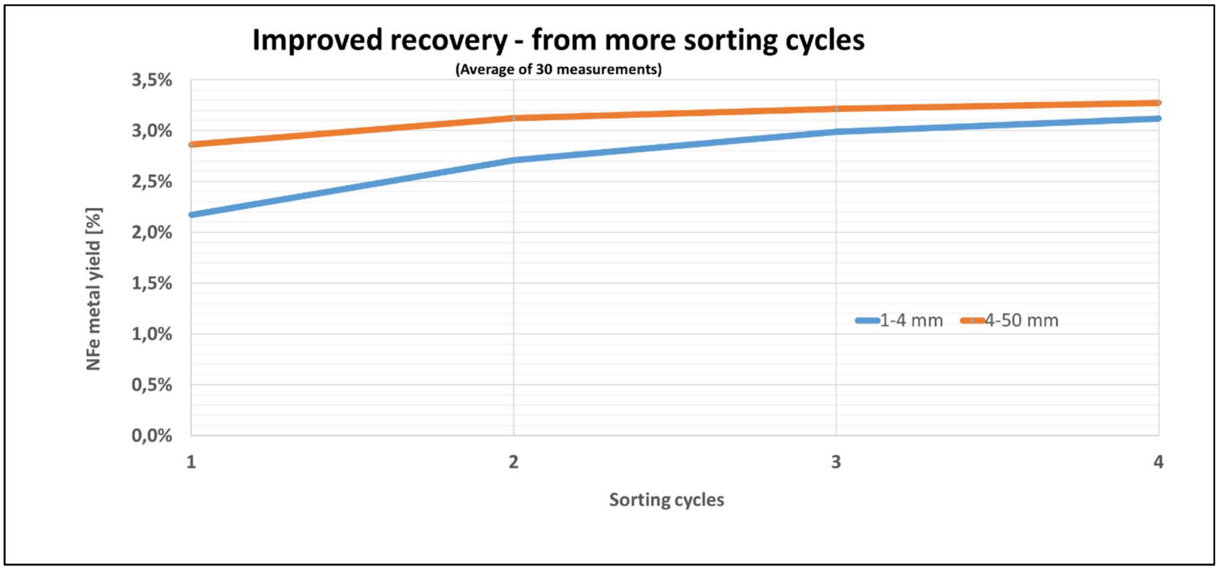


Figure 9. Improved recovery from sorting cycles.

In the sorting tests there is some improvement in the recovery in the 2nd and 3rd sorting (Fig. 9). However, in the 4th sorting there is almost no increase in the yield. Based on the above average yields from 30 measurements is could possibly be a good idea to add a second and possibly also a third sorting to the Afatek NFe sorting plant.

In the future, the method developed in this work package can be used to investigate the effect of other changes of the IBA sorting process on the recovery grade. The method can as well be used to monitor the performance of the metal sorting plant.

WP4 – Geotechnical testing on IBA

The change in processing of the IBA to optimise the metal recovery could also change the geotechnical properties of the mineral part of the IBA. An optimisation of the maturation could lead to a higher quality material but the intended shorter storage time of the IBA could on the other hand also lead to a poorer quality of the IBA in terms of its use as road construction material. It is therefore crucial that these issues are investigated to secure the mineral quality of the IBA.

The purpose of the geotechnical investigations in WP4 can be summarised as follows:

1. Investigate the geotechnical quality of the IBA before optimisation of the process to establish a reference level.
2. Investigate the geotechnical quality of the IBA from the optimised process in order to secure its present use as subbase material in road constructions.
3. Establish new knowledge on the geotechnical parameters of the IBA to possibly enable its future use as base course material in road construction.

Municipal waste incineration bottom ash also often just referred to as incineration bottom ash (IBA) is defined as a residual product and can therefore only be used as a construction material when analysed and declared according to a Ministerial Order. The use of IBA as subbase material for road construction requires an additional declaration according to the Danish Road Directorates. In this declaration, called General Working Specification, it is required to fulfil the specification on the following properties: grading, total organic content and cleanness. Apart from the above several other parameters are normally also declared or analysed for in the IBA. These include a petrographic description, pH, maximum dry density and water content at maximum dry density. Comparative tests between reference IBA and optimised IBA were performed to evaluate whether the quality of the IBA were the same. For the parameters where it was reasonable a comparison with SG II were also done. The tests and analyses showed that there is no difference in the measured parameters when comparing reference IBA samples with optimised IBA samples. The grading of the tested IBA samples fulfil the requirements for SG II except for one sample. The observed difference in dry density and optimum water content between the IBA samples and the SG II sample is as expected as the IBA is a much more porous material than sand and gravel.

If IBA is used as a base course material in roads it will be exposed to freezing and it is therefore important to know if the material is frost heave susceptible. The frost heave susceptibility of soils and similar materials is primarily depending on the capillarity and the permeability of the soil as well as the distance from the freezing zone to the water table. Materials with high capillarity as well as high permeability will be highly frost susceptible. SG II is the standard material used in base course layers in road construction and this material is not considered to be frost heave susceptible. As IBA has a similar grain size distribution and in the tests shows similarly low value of capillary rise and permeability coefficient as SG II, it can be concluded that IBA is not frost heave susceptible as well. Laboratory frost-heave trials on Swedish IBA, which is quite like Danish IBA, also show no tendency for frost-heave (Arm, 2000).

During the carbonation and oxidation of the IBA several mineral transformations as well as oxidation of metals can lead to expansion of the material. Former studies (Larsen, 2011) showed that storage of the IBA for 3 months in weather exposed piles will reduce the expansion potential to a minimum. As the RecAsh project intends to reduce the storage time of the IBA it is important to follow up on the expansion potential of the optimised IBA compared to the reference IBA. The expansion potential is studied using steel cylinders packed with IBA. The surcharge on the cylinder top plate corresponds to approximately 10 centimetre of asphalt cover. The expansion tests on the two reference IBA both show very little and negligible expansion (<0.2 %) after one year of testing. The expansion tests on the optimised IBA samples also show very little expansion <0.1 % for three samples and around 0.5 % for one sample all after close to one year of testing (see Fig.10). The small heave observed could possibly be due to growth of alteration minerals as well as oxidation of small amounts of iron and other metals left in the IBA. Formation of e.g. ettringite is well known during ageing of IBA. The small expansion observed in the tests are comparable to the levels found for IBA matured in 3 months in the investigation by Larsen (2011). The observed potential expansion of the IBA is of no importance for its use as a road building material.

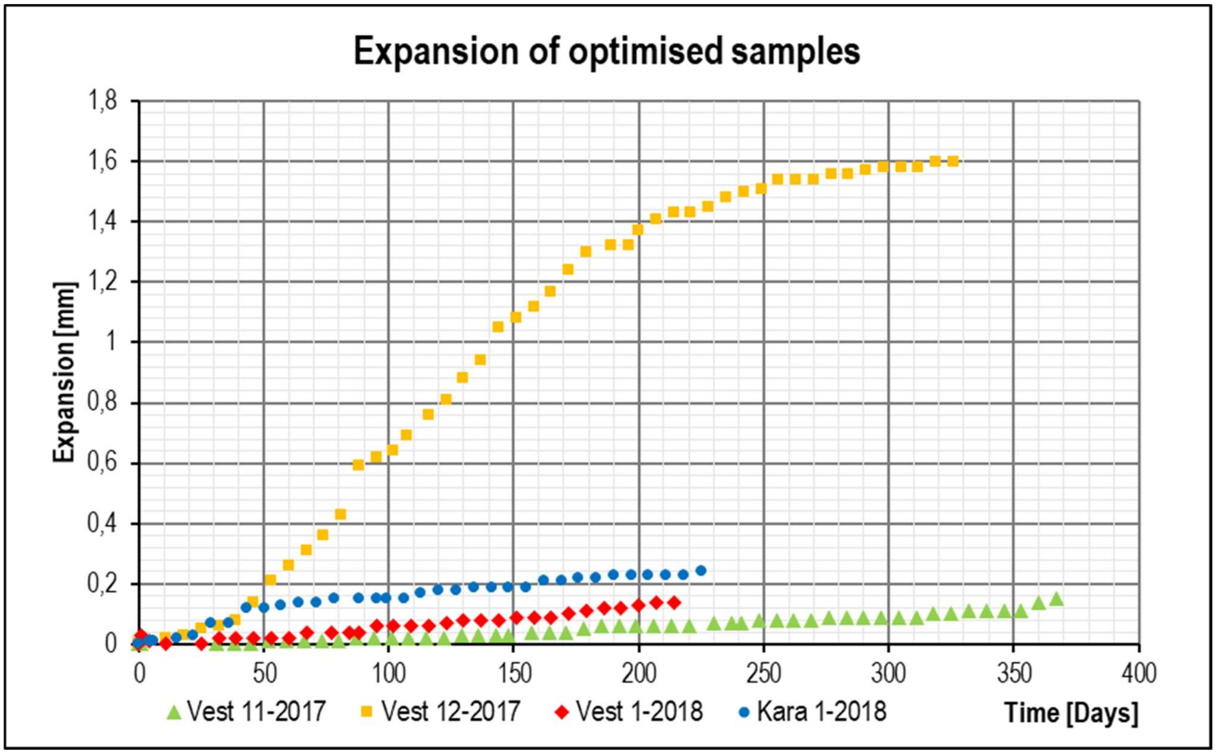


Figure 10. Expansion on compacted IBA in cylinders 300 by 300 mm. The expansion is from <0.1 % to 0.5 % of sample height.

The particle strength is an important parameter of a materials suitability for use as a base course layer in road construction. In this project two different tests have been carried out to investigate the particle strength of IBA compared to SG II. One is a crushing and abrasion resistance test measured in the Los Angeles (LA) test machine the other is a crushing strength test, which measures crushing during compaction in the vibration table. The results of the LA tests clearly show that the particles in SG II is stronger towards abrasion than the IBA particles. This is obvious when considering the porous nature of the IBA particles compared to the more massive SG II particles. However, the data indicates that the present IBA particles are much stronger compared to samples investigated previously. This is in line with the change in treatment of the IBA, with an additional non-Fe metal sorting process. The LA values of the reference IBA samples and the optimised IBA samples are at the same level. The average LA value of the analysed IBA samples are 40 ±2 i.e. very close to the present requirement of LA ≤40 for crushed concrete used as base course material (Vejdirektoratet, 2011).

The deformation of unbound granular materials in road subbase layers and base course layers under the cyclic loading from the traffic consists of resilient or recoverable deformation (RD) and plastic or permanent deformation (PD). The RD is characterised using the resilient modulus (stiffness) M_R which is associated with the fatigue cracking of the overlaying asphalt layers. A material's resilient modulus is an estimate of its modulus of elasticity (E-modulus). The PD accumulates with load repetitions and may lead to rutting of the structure. These mechanical properties of unbound granular materials used for the structural design of flexible pavements are mainly based on empirical data in Denmark. However, in recent years work have begun to evaluate these materials in the laboratory using Repeated Triaxial Loading (RTL) tests (Gudmundsson & Rohde 2014, Rahman 2015). The RTL test applies cyclic loading on prepared cylindrical specimen and the corresponding deformations are recorded. The RD and PD properties can then be evaluated by analysing the data. Materials with high resilient modulus and low permanent deformation are preferred for base course layers in road constructions.

To evaluate the deformation of IBA comparative RTL tests with SG II were performed by VTI in Sweden in accordance with EN 13286-7 (CEN 2004b) using the PD test with multistage loading at constant confining pressure and at low stress level. A graph showing the average resilient modulus of the investigated materials can be seen in Figure 11. The resilient modulus of the optimised IBA is higher than for the reference IBA and the resilient modulus of 6-months matured IBA is close to but slightly lower than the one found in SG II Løng samples. However, the resilient modulus of the 6-months matured IBA is within the range of resilient modulus in SG II found in other investigations.

The permanent deformation is lower in the optimised IBA compared to the reference IBA. Already after 2-months of ageing the optimised IBA will have permanent deformation at the same low level as SG II, i.e. the durability of matured IBA and SG II should be comparable.

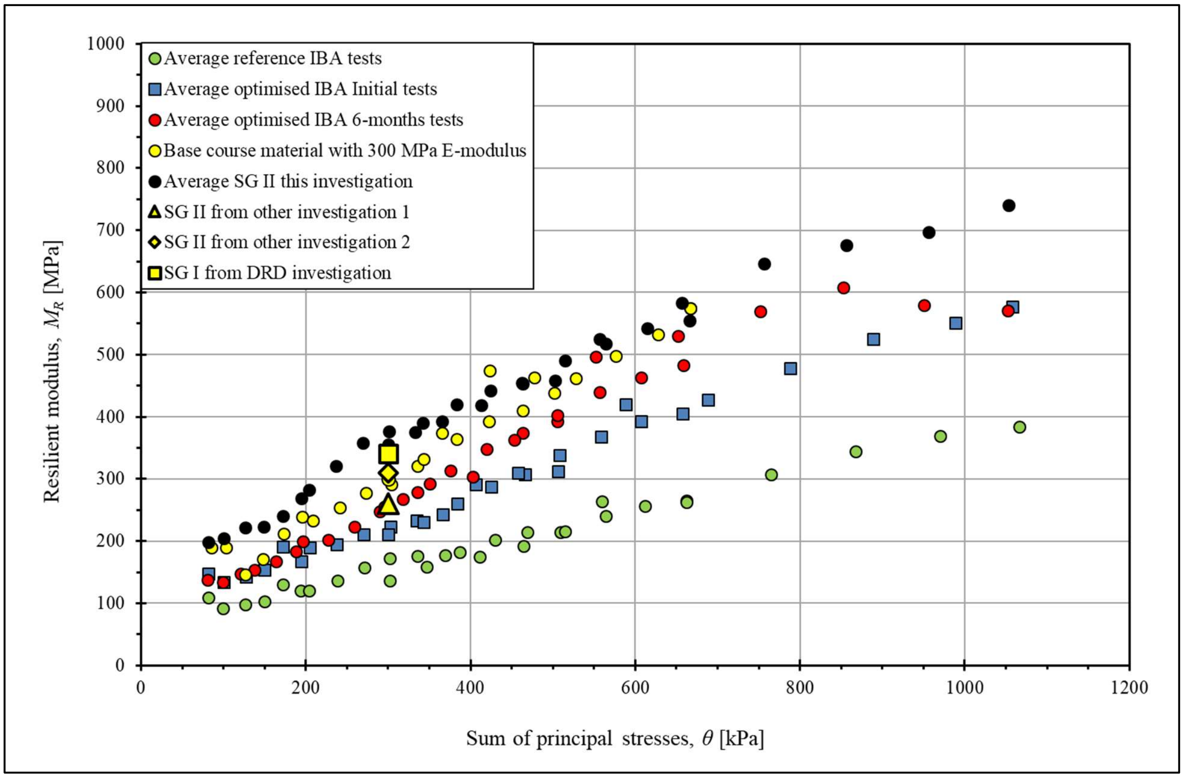


Figure 11. Average results of RTL testing on reference ad optimised IBA and SG II. The graph shows resilient modulus as a function of principal stresses. The resilient modulus of the materials is read at 300 kPa bulk stress.

A test program with a combination of XRF and XRD/EDX analyses were performed to investigate the reasons for the cohesion observed in IBA layers in road constructions. Analyses of "fresh" and matured IBA samples shows that abundant cementing alteration minerals are formed on the surfaces of the IBA particles during the ageing of the IBA. The newly formed minerals like calcite, ettringite and different calcium aluminate hydrates are the most probable causes for the hardening of the IBA which may occur during its weathering. Apart from the weak cementing between the IBA particles from the newly formed minerals the porous nature of the particles will allow them to form an interlocking texture when the material is compacted and thereby ad to the cohesion as well as the general strength of the material.

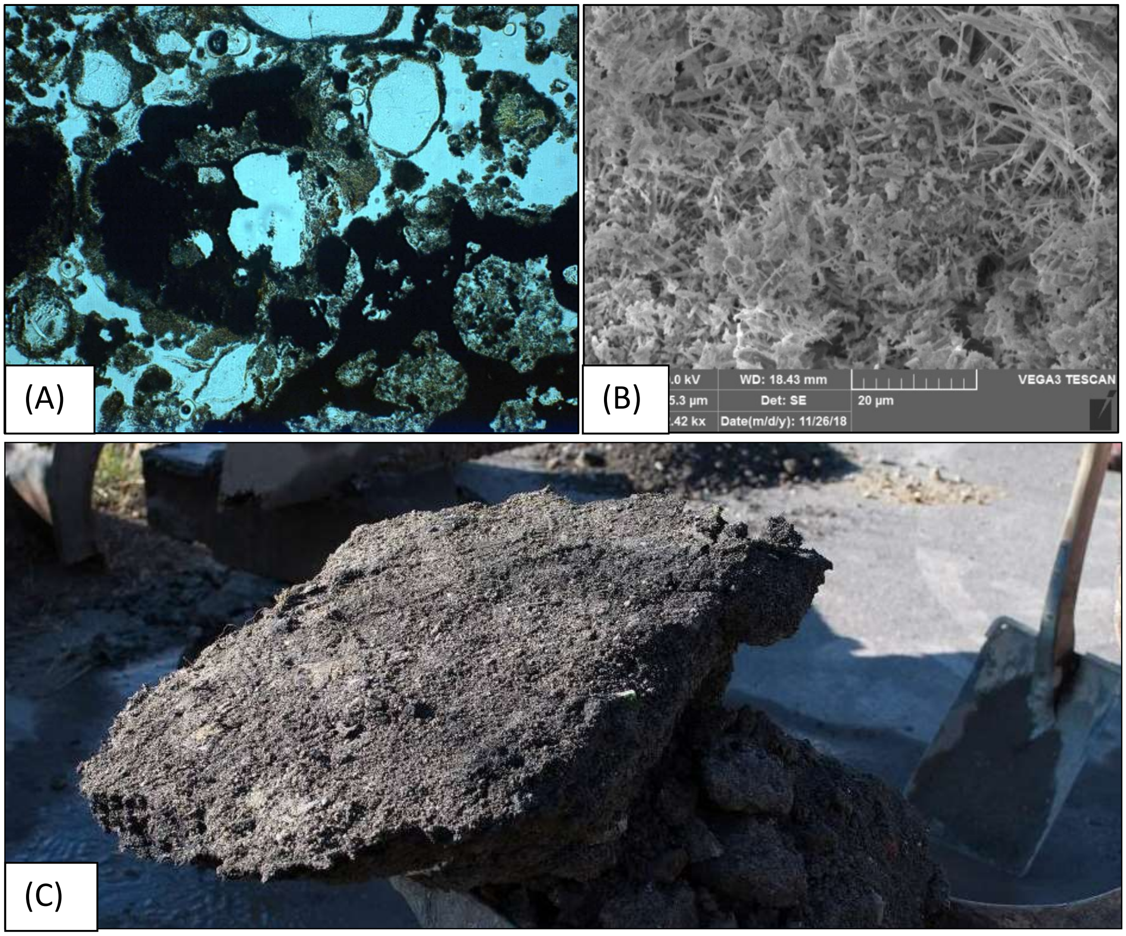


Figure 12. (A) Picture of interlocking grains in compacted IBA (0.75 mm high and 1.0 mm wide). (B) Surface of compacted IBA covered by alteration phases. (C) Coherent block of IBA from subbase layer.

The conclusions on the geotechnical investigations in WP4 can be summarised as follows:

1. A reference level of the geotechnical quality of the IBA before optimisation has been established.
2. The geotechnical quality of the optimised IBA has been investigated and is found comparable to and for some parameter's even superior to the reference IBA, i.e. the continued use of IBA as subbase material in road constructions is secured.
3. New knowledge on several geotechnical parameters, e.g. the resilient modulus and permanent deformation, of IBA has been established. The results indicate that the optimised IBA could be a possible future candidate for use as base course material in road construction.

WP5 – Dissemination

Presentations:

Recovery of Resources in Bottom Ash – Semi Dry Concept. By Søren Dyhr-Jensen made at Expert Forum "Removal, Treatment and utilisation of waste incineration bottom ash", Vienna Austria, October 3, 2018.

Papers:

Recovery of Resources in Bottom Ash – Semi Dry Concept. Kallesøe, J. & Dyhr-Jensen, S. in "Removal, Treatment and Utilisation of Waste Incineration Bottom Ash" by Holm, O.; Thomé-Kozmiensky, E. ISBN 978-3-944310-44-2. 2018.

Optimizing the large-scale ageing of municipal solid waste incinerator bottom ash prior to the advanced metal recovery: Phase I: Monitoring of temperature, moisture content, and CO_2 level. Nørgaard, K.P., Hyks, J., Mulvad, J.K., Frederiksen, J.O., Hjelmar, O. Accepted for print in Waste Management 85 (2019) 95–105.

More papers are planned to follow up on the paper accepted in Waste Management.

A paper on the results of the geotechnical investigations on IBA is also planned.

Fulfilment of success criteria

The success criteria for the project was to:

1. Reach a deeper understanding of the parameters influencing the maturation and drying out of IBA in piles.
2. Reduce stockpiling time for maturation of IBA from an average of 3-4 months to 1-2 months.
3. Increase the amount of matured and dry IBA enabling metals separation to smaller grain sizes (between 0.5-4 mm) without decreasing the environmental and geotechnical quality. Thereby increasing the total non-ferrous metal recovery from IBA with approx. 25 %.
4. Maintain the utilisation of IBA (mineral part) as subbase material for road construction.
5. Establish data for development of a road standard on use of IBA (mineral part) for base course material in road construction.

The following fulfilment has been achieved:

1. An understanding of the parameters governing the maturation and drying out of IBA in full scale scenarios has been established leading to an optimisation of the processing of IBA at the plant. In the optimised process the IBA is stored as raw ash including the ferrous scrap using a telestacker leading to faster maturation and drying out of the IBA.
2. Average stockpiling time for the maturation of IBA has been reduced from 88 days for the reference IBA to 68 days for the optimised IBA.
3. Already before the start-up of the RecAsh project the drying out of the IBA was improved to an extend where some piles of IBA could be screened down to 1 mm. During the optimisation even, larger parts of the IBA can be screened down to 1 mm and some trial with screening to 0.5 mm has also been performed. As some improvement was done before the start-up the increase in total non-ferrous metals recovery could only reach 7.7 %.
4. The geotechnical quality of the reference IBA and the optimised IBA has been thoroughly investigated and compared to the standard base course material, SG II. The geotechnical quality of the IBA is improved by the optimisation process compared to the reference situation and the utilisation of IBA (mineral part) as subbase material for road construction is hereby maintained.
5. New knowledge on several geotechnical parameters, e.g. the resilient modulus and permanent deformation, of IBA has been established. The results indicate that the optimised IBA could be a possible future candidate for use as base course material in road construction. The collected data can be used in the development of a new road standard on use of IBA (mineral part) for base course material in road construction.

It can be concluded that all the success criteria have been fulfilled to a very large degree.