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# Utilisation of waste incineration bottom ash in Denmark – a contribution to the circular economy

**Danish Waste Solutions ApS**

**in cooperation with**

**AFATEK A/S**

Danish Waste Solutions
Waste - Resources - Environment

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# Foreword

Danish Waste Association (in Danish: Dansk Affaldsforening, DAF) is an interest organisation for Danish municipalities, waste management companies and the majority of municipal waste incineration plants in Denmark. DAF regards waste as a resource in the circular economy and fully supports maximum utilisation of the resources in the waste: Maximum reuse and recycling of materials and maximum energy utilisation of the materials that cannot be reused or recycled.

Denmark can be considered one of the leading countries in terms of processing and using bottom ash from waste incineration plants with energy utilisation, with a legal framework that protects the environment against unacceptable impacts, and a processing technology and logistics that ensure that the treated bottom ash reaches a quality that allows it to replace raw materials such as natural gravel from gravel pits. As part of the bottom ash processing, significant amounts of metals are also recovered from the bottom ash.

Since 2020, the regulatory basis for the utilisation of bottom ash from Danish waste-to-energy plants has received a renewed focus, partly due to the recent European dialogue on the classification of the mineral residual products, including bottom ash. Unfortunately, the regulatory and operational practice of management of bottom ash, which has been developed over many years in Denmark, has not been adequately described in any recent publications. DAF has therefore requested Danish Waste Solutions ApS with input from the industry (AFATEK A/S) to prepare a paper that describes the experience, conditions and current practice for utilisation of bottom ash from municipal solid waste incineration plants as part of the circular economy. The paper is expected to be used by the waste industry and purchasers of “bottom ash gravel”, but also as general information material for a wider public.

This paper was prepared by Ole Hjelmar and Jiri Hyks (Danish Waste Solutions) with contributions from Jens Kallesøe and Søren Dyhr-Jensen (AFATEK) during the period March – September 2022. The work has been followed and commented on by a steering group consisting of the following:

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The work has been financed by DAFONET, which is a network for the exchange of experience on operating conditions, including bottom ash management, under the Danish Waste Association (DAF) with the participation of all Danish waste incineration plants.

## Content

## Resumé

Through a forward-looking environmental and energy policy combined with good public planning and private development work, Denmark has over a number of years established one of the world's most efficient waste treatment systems. The largest part of the waste (currently approximately 4 million tonnes/year) which cannot be recycled and is suitable for incineration is currently supplied to the 23 modern Danish waste incineration plants that produce district heating and electricity; often, these are referred to as waste-to-energy plants. The thermal treatment of waste suitable for incineration has greatly reduced the need for waste disposal. At the same time, an advanced treatment of 650,000 – 700,000 tonnes of raw bottom ash and subsequent utilisation of 550,000 – 600,000 tonnes of finished “bottom ash gravel” per year for road construction purposes and an annual recovery of 47,000 – 53,000 tonnes of metals (primarily iron, copper and aluminium) make a significant contribution to the circular economy through the replacement of natural raw materials.

While utilisation of the bottom ash contributes positively to the Danish society, it is a prerequisite that the use of the so-called bottom ash gravel takes place in a controlled manner and according to the prescribed environmental regulations. Bottom ash contains small amounts of substances which, if the applicable regulations are not followed, in the long term might potentially cause harm to both humans and the environment. To ensure that this does not happen, the bottom ash must comply with limit values for the content and leaching of a number of undesirable substances, and the rules for where and how the bottom ash may be used must also be followed. These limit values and rules, which aim to protect groundwater and surface water as well as human health against unacceptable impacts, and which are based on risk assessments carried out by the Danish Environmental Protection Agency (EPA), have been described in an almost un-changed form since 2001 in the so-called Statutory Order on Utilisation of Residual Waste (currently BEK no. 1672/2016).

The bottom ash gravel is geotechnically very similar to natural gravel, and after sorting out residual metals and maturing, it has a high bearing capacity. Provided it complies with the environmental legislation's requirements concerning the content and leaching of potentially harmful substances, it can, within certain defined limits, be used in road construction. For more than 20 years, the bottom ash gravel has been used in the subbase of roads, where it replaces natural gravel. As the bearing capacity of “bottom ash gravel” is similar to that of stable gravel (stabilt grus), it can also be used in the base layer of the road to substitute the best (and most expensive) gravel from the Danish gravel pits. It has also been shown that bottom ash gravel can be included in a BSM product (Bitumen Stabilised Material), which is laid just below the asphalt layer (between the base layer and the asphalt wear layer). A certified production of “bottom ash gravel” has been successfully established. A third of the bottom ash in Denmark is also declared in relation to the climate impact through an Environmental Product Declaration (EDP).

From a chemical point of view the bottom ash gravel consists of a number of major elements (primarily silicon, calcium, iron, aluminium, magnesium, sodium, potassium, and oxygen) present in substances or minerals that are also found in roughly the same order of magnitude in the lithosphere, i.e. the upper 100 km of Earth’s crust. In addition, the bottom ash gravel contains a large number of other elements in much smaller quantities. They are all already present in the lithosphere, but some of them are enriched in the bottom ash gravel compared to the lithosphere. These include (in descending order) sulphur, zinc, copper, chloride, lead, barium, strontium, boron, chromium, nickel, tin, antimony, vanadium and others. Some of these elements are undesirable in the bottom ash gravel, as they can be present as substances with negative effects on the environment if they are spread in too high amounts into the surroundings. There is particular focus on the risk of contamination of soil, groundwater and surface water. The processing of the bottom ash into the “bottom ash gravel”, together with the existing limit values for the content and leaching of potentially harmful substances and the established restrictions and conditions for the use of the “bottom ash gravel” aims to minimise potential substance emissions and to ensure that no unacceptable impact can occur on soil, groundwater and surface water in connection with the utilisation of the “bottom ash gravel”.

Despite the high combustion temperatures which destroy almost all organic matter, it cannot be outruled entirely that some specific organic substances, such as PCBs, polychlorinated dioxins (PCDDs) and furans (PCDFs), perfluorinated and polyfluorinated alkyl compounds (PFAS) and brominated flame retardants (BFRs) may be present in the bottom ash, albeit in very small quantities. So far, studies of Danish bottom ash have shown that both the content and leaching of these substances in the bottom ash gravel are very small when the bottom ash is used according to the regulations. It should be mentioned, however, that knowledge of the content and leaching of PFAS and brominated flame retardants is based on a limited number of studies of Danish bottom ash and, therefore, scientific developments in the area are followed closely.

After separation of metals, the quality of bottom ash gravel is controlled in relation to both environmental and geotechnical properties, after which the “bottom ash gravel” is ready for use in road construction. Certified bottom ash gravel complies with Dancert's "Supplementary provisions for certification of production management for waste incineration bottom ash for use in base layers in road construction".

The major part of the bottom ash gravel is used for the construction of roads and sites. Some is also used for the construction of ramps, i.e. substructures for road construction. Bottom ash gravel is used e.g. in the construction of municipal recycling stations where site and road construction are combined. In agricultural projects, bottom ash gravel can be used for levelling, building foundations, sites and connecting roads. The size of the projects can vary substantially from a few thousand tonnes to 140,000 tonnes, with a typical average of approximately 15,000 tonnes. Nevertheless, there are examples of the delivery of more than 300,000 tonnes to a single project, where construction can take place over several years. Efforts are being made to deliver to larger projects, so that the average project size can be increased. Large projects usually have to undergo a specific risk assessment in accordance with the Environmental Protection Act.

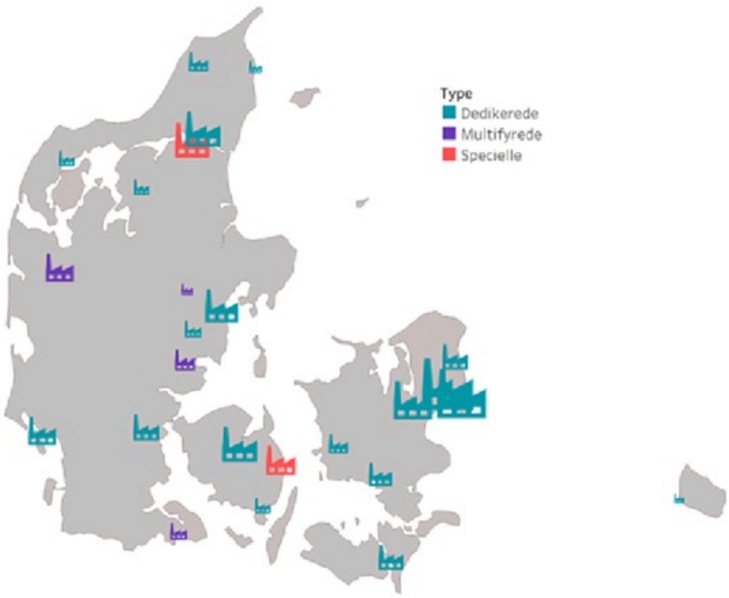
Although we in Denmark have already come a long way with the inclusion of waste incineration bottom ash in the circular economy, there is still room for improvement, and new challenges are still occurring. Currently, the following issues (among others) are under consideration:

- Improved recovery of magnetic and non-magnetic metals and stainless steel
- Reutilisation of previously utilised slag from the past 20 years
- Assessment of the risk to the environment and humans related to new, potentially polluting substances (including PFAS)

It has been typical for Denmark that the industry has responded quickly and constructively to different challenges that have arisen in relation to the utilisation of the bottom ash, i.e. also with regard to the classification of “bottom ash gravel” as non-hazardous or hazardous waste after the introduction of new EU rules for classification in relation to the hazard property “HP14 – Ecotoxic”. This is not the least due to the fact that in Denmark there is a tradition for close cooperation between the waste-to-energy plants and the authorities, with focus on environmental protection and resource utilisation. It can be mentioned that the Danish Environmental Protection Agency recently has initiated a screening of content and leaching of PFAS from Danish waste incineration bottom ash/bottom ash gravel.

# 1 Municipal solid waste incineration (MSWI) bottom ash in view of circular economy

It is common knowledge in Denmark, that waste should be regarded as a resource that should - to the extent possible - be included in the circular economy. In order to utilise the resources in the waste, it must first and foremost be reused or recycled. The largest part of the waste that cannot be recycled and is suitable for incineration (currently approximately 4 million tonnes per year) is today processed in 23 modern waste incineration plants that produce district heating and electricity, and are therefore often referred to as waste-to-energy plants.




*Waste incineration plants in Denmark (BEATE 2018 - 2019)*[1].

Incineration reduces the volume of the waste by approximately 90% and the weight by approximately 70 – 80%. Incineration of 1 tonne of waste generates approximately 200 kg of bottom ash, which after treatment (including maturing and separation of metals), is mainly used as a substitute for natural raw materials in road construction. A large part of the most polluting substances in the incinerated waste is transformed into flue gas and removed from the flue gas before it is discharged and collected as flue gas cleaning residues (30 – 35 kg per tonne of incinerated waste). These flue gas cleaning residues must be further processed in preparation for safe disposal or advanced recovery/raw material extraction.

Through a forward-looking environmental and energy policy combined with good public planning and private development work, Denmark has over a number of years established one of the world's most efficient waste treatment systems. This means that combustible waste, which cannot otherwise be recycled, is used for energy recovery while the largest residual fraction from the energy recovery operation, the bottom ash, is included in the circular economy and replaces natural raw materials under controlled and environmentally sound conditions. After all, Denmark is a small country with limited raw material resources and limited space available for landfilling. The thermal treatment of the combustible waste has strongly reduced the need for waste disposal (Denmark was the first country to impose a ban on the landfilling of combustible waste). At the same time, an advanced treatment of 650,000 – 700,000 tonnes of raw bottom ash and subsequent utilisation of 550,000 – 600,000 tonnes of finished “bottom ash gravel” per year for road construction purposes makes a significant contribution to the circular economy through the replacement of natural raw materials such as gravel from gravel pits. The treatment of the bottom ash also includes the extraction and processing of iron and other metals.

While utilisation of the bottom ash contributes positively to the Danish society, it is a prerequisite that the use of the so-called “bottom ash gravel” takes place in a controlled manner and according to the prescribed environmental regulations. This is necessary, because MSWI bottom ash contains small amounts of substances which, if the applicable regulations are not obeyed, could in the long term potentially cause harm to both humans and the environment. To ensure that this does not happen, the bottom ash must comply with limit values for the content and leaching of a number of undesirable substances, and they must also comply with specific rules for where and how they may be used.

[1] Viegand Maagøe: BEATE 2018 – 2019, Benchmarking af affaldssektoren – Forbrænding. Energistyrelsen.

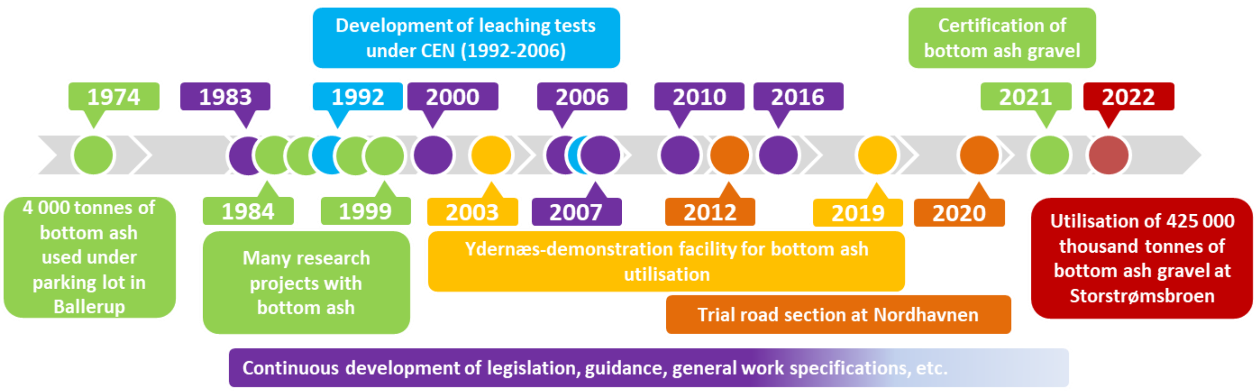
Energnist in Kolding (Dansk Affaldsforening)

ARC in Amager (Rambøll)

ARGO in Roskilde (Rambøll)

Vestforbrænding in Glostrup (Vestforbrænding)

In the following, the history of bottom ash utilisation as part of a circular resource economy in Denmark is told, supplemented with a number of concrete facts about the material's properties, temporal development of utilisation options and rules (see the figure). In addition, further development issues are briefly mentioned.




*Utilisation of MSWI bottom ash in Danmark – a timeline.*

## 2 What is MSWI bottom ash?

Waste incineration bottom ash (hereafter simply bottom ash) is the combustion residue that is removed from the end of the grate at the bottom of the furnace at a waste-to-energy plant (see the figure on the next page).

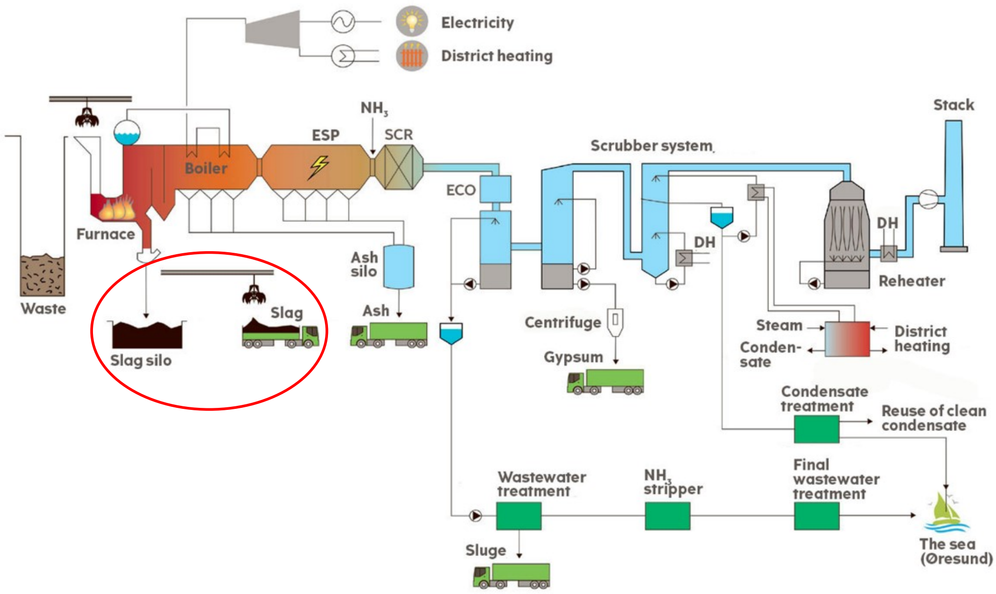



*Figure showing the principle of a modern waste-to-energy facility (ARC in Copenhagen). The bottom ash (slag) removal site at the bottom of the grate is framed in red. It can be seen that the major part of the processes at the facility is aimed at energy recovery and removal of a number of undesired substances from the flue gas before it can be released into the atmosphere*.

During the passage on the grate, which carries the waste through the oven, the waste is incinerated at temperatures of up to approximately 1050 °C. This is sufficient to destroy almost all biological and organic material in the waste during its conversion into raw bottom ash, which is typically cooled by passing through a water bath (quenching). The raw bottom ash (with approximately 20% moisture content) consists of iron scrap (typically 7 – 9%), other metals such as copper, aluminium, stainless steel and zinc (typically 2 – 3% combined) and a mixture of small and large particles of glass, concrete/ceramics, soil and molten or sintered[2] products of mineral composition (typically 85 – 90%).

*An example of raw bottom ash after quenching.*

During outdoor storage of the raw bottom ash in piles, part of the original moisture evaporates and the bottom ash can be subjected to a mechanical metal recovery process.

Iron is removed from the raw bottom ash with the help of magnets and after further purification used for the production of new iron products and steel.

Larger pieces of non-magnetic metals such as aluminium, copper or stainless steel are sorted out by hand sorting, while small pieces/particles of non-magnetic metals (which can also include gold and silver) can be sorted out using so-called eddy current separators or special sensors and subsequently processed into clean metals.

After separation of metals and several weeks of outdoor storage during which the bottom ash is naturally stabilised (matured) through absorption of carbon dioxide (CO2) from the atmosphere ("carbonation"), as well as further processing (e.g. crushing of large particles, screening), the bottom ash becomes so-called bottom ash gravel.

[2] Fused (but not totally melted) due to high temperature.

From a geotechnical point of view, the bottom ash gravel is very similar to natural stable gravel, and provided that it complies with the regulatory environmental requirements concerning content and leaching of potentially harmful substances, it can, within certain specified boundaries which are described in more detail below, be used for road construction applications, where it replaces natural gravel of the best quality from the Danish gravel pits.

# 3 Physical and functional properties of bottom ash gravel

**Suitability for road constructions**
It is well known that bottom ash after removal of metals and maturing has a high bearing capacity and therefor can be used in the construction of roads and similar civil engineering projects. For more than 20 years, "bottom ash gravel" has been used in the subbase of roads, where it replaces natural gravel.

As the bearing capacity of bottom ash gravel is similar to that of stable gravel, it can also be used in the base layer of the road to substitute the best (and most expensive) gravel from the Danish gravel pits.

It has also been shown that bottom ash gravel can be included in a Bitumen Stabilised Material (BSM), which is laid just below the asphalt layer (between the base layer and the asphalt wear layer).

The figure below shows the structure of a typical road, where bottom ash gravel can be included in all three layers of the road. Application in the subbase course has been the standard utilisation of the bottom ash gravel for many years. Application of bottom ash gravel in the base course is hindered by the Road Directorate's current tender regulations, which are, however, undergoing revision and are expected to include this utilisation option within the next year. The application as a BSM product is awaiting the results of an ongoing full-scale test at Lynetteholm in Copenhagen. Bottom ash gravel in BSM has already been mentioned in the road construction rules for BSM.

Within a foreseeable future, it will in all probability be possible to use bottom ash gravel in most parts of a road profile and hence contribute to saving natural material from gravel pits both for the subbase and the base layers.

The good results are the consequence of many years of development work at laboratory-scale as well as full-scale tests, followed by full certification of the bottom ash gravel processing and monitoring of the bottom ash gravel quality. Certification has so far been completed for part of the annually produced bottom ash in Denmark, but data indicate that all bottom ash can be certified and that approximately 90% will meet the quality requirements for utilisation in base course, while the remaining 10 % can still be used in the subbase course.

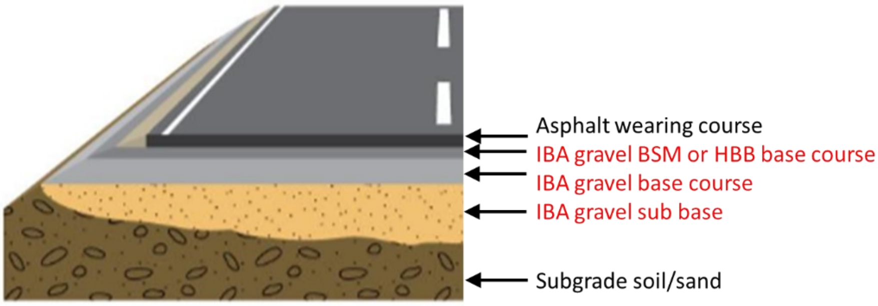



*Illustration showing the use of bottom ash gravel in the different layers of a road (AFATEK).*

**Laboratory tests**
As part of the project "RecAsh", which was a 3-year innovation project supported by the Danish Innovation Fund, a series of tests were carried out on the bottom ash gravel showing that the load-bearing capacity (the so-called E-modulus) was comparable with natural "stable gravel" (https://afatek.dk/projekter/recash-recovery-of-resources-in-bottom-ash).

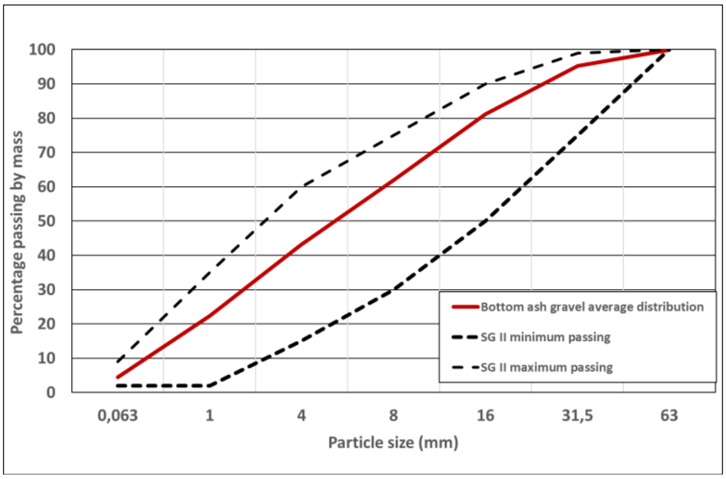
**Full-scale testing**
In a test section of Nordsøvej in Copenhagen, the load-bearing capacity of the bottom ash gravel has been tested for more than 10 years since 2012 (see the figure on the next page). The total traffic load over the years corresponds to a so-called traffic road class T5. The Road Directorate continues the monitoring in the

expectation that the bottom ash gravel will not only hold up to a T5 load, but also to the highest traffic road class T7 (i.e. highways), after which the utilisation of bottom ash gravel may be allowed in both subbase course and base course in all types of roads (https://www.vejdirektoratet.dk/sites/default/files/publications/forsgs-strkning_p_nordhavnen.pdf).

*Test of bottom ash gravel at Nordsøvej in Copenhagen from 2012 to (so far) 2022 (AFATEK).*

**Certification**
A company is provisionally certified for the production of bottom ash gravel when the quality control of the processing of the bottom ash gravel from the raw bottom ash includes entry and exit controls as well as sampling for the environmental compliance testing and testing of technical properties. When both the environmental and technical test reports meet the criteria, a declaration is issued that accompanies the bottom ash gravel until it reaches the end-user at the intended road construction site. As the quality of the product is documented, both in relation to the environmental and the construction technical properties, all actors, such as consulting engineers, environmental officers and construction officers at municipalities and private companies can thus be sure of the quality of the bottom ash gravel.

The test report of the technical properties must show compliance with a number of parameters including the grain size distribution curve, purity (i.e. the proportion of floatable particles), the degree of burnout, brittleness of the individual grains (Los Angeles test) and others – all in accordance with the standard DS/EN 13285 (https://afatek.dk/sites/afatek.dk/files/media/document/Certifikat%20Slaggegrus%2023.12.2020.pdf). Of the parameters mentioned above, the grain size distribution is the single most important property responsible for the high load-bearing capacity of the bottom ash gravel. As shown in the figure below, the grain size distribution curve of bottom ash gravel will in the vast majority of cases (approximately 90%) lie within the upper and lower limits for stable gravel.




*Graph showing average particle size distribution curve for bottom ash gravel 0/31.5 mm and distribution curve limits for stable gravel quality II according to the Danish Road Directorate's rules for application of stable gravel.*

**EPD – Environmental Product Declaration**
In 2021, bottom ash gravel has also obtained a climate-related declaration. Currently, about one third of the Danish bottom ash is declared by EPD Danmark. Based on a life cycle analysis, Afatek's production of bottom ash gravel corresponds to a Global Warming Potential (GWP) of up to -10 kg $CO_2$ per ton of bottom ash gravel. The negative result (i.e. net savings in $CO_2$ emission) is caused by the fact that during the maturation (carbonation) of the bottom ash, atmospheric $CO_2$ is absorbed by the material. If natural gravel is used instead, the GWP is estimated at 2 – 5 kg of CO2 per ton of gravel. The utilisation of bottom ash gravel instead of natural gravel thus has a positive impact on the GWP.

# 4 The chemical and environmental properties of bottom ash gravel

**Composition of bottom ash gravel and BAT requirements**
While utilisation of the bottom ash contributes positively to the Danish society, it is a prerequisite that the use of the bottom ash gravel takes place in a controlled manner and according to the prescribed environmental regulations. It is because bottom ash contains small amounts of substances which, if the applicable regulations are not met, in the longer term could cause harm to both humans and the environment.

The composition of waste incineration bottom ash depends on the composition of the incinerated waste as well as the type of incineration plant and its operating conditions. The modern Danish waste-to-energy plants are subject to a number of EU regulations, including the directive on industrial emissions (IED), which sets a number of so-called BAT requirements (i.e. requirements for the application of Best Available Techniques) in the area of environmental protection. The BAT requirements ensure, among other things, that the degree of combustion is sufficiently effective (measured as residual organic carbon (TOC) in the bottom ash, which must not exceed 3% by weight). It can be mentioned that Danish bottom ash today has an average TOC of 0.77% by weight. The Danish EPA approves waste incineration plants and supervises their operation, including compliance with BAT requirements. Requirements are also placed on the temperatures in the combustion chamber, which on the one hand must ensure the destruction of harmful organic substances in the waste and on the other hand must prevent the formation of new harmful substances during combustion and flue gas cleaning. In addition, there is a requirement that bottom ash must be collected separately from other residual products (fly ash, flue gas cleaning products, etc.).

**Main composition**
Chemically, the bottom ash gravel consists of a number of main components, which are substances or minerals that we also find in roughly the same order of magnitude in the lithosphere, i.e. the upper 100 km of Earth’s crust. The table here shows the content of main components in 11 samples of bottom ash gravel from Danish incineration plants in 2020 and 2021, expressed as minimum and maximum contents of the substances in oxide form. For comparison, the average content in the lithosphere of the same oxides can be seen. It is the content of these substances or minerals that gives the “bottom ash gravel” the physical properties that enable its use for entrepreneurial purposes.

| | | Bottom ash gravel | | Lithosphere |
|---|---|---|---|---|
| **Element** | **As oxide** | **Min** | **Max** | **Average** |
| | | Mass-% | Mass-% | Mass-% |
| Silicium (Si) | SiO2 | 39,4 | 54,2 | 59 |
| Calcium (Ca) | CaO | 11,8 | 17,9 | 5,0 |
| Iron (Fe) | Fe2O3 | 4,7 | 12,0 | 7,3 |
| Aluminium (Al) | Al2O3 | 4,6 | 8,4 | 15 |
| Magnesium (Mg) | MgO | 1,1 | 1,8 | 3,5 |
| Sodium (Na) | Na2O | 0,90 | 1,4 | 3,8 |
| Potassium (K) | K2O | 0,45 | 0,62 | 3,1 |
| Titanium (Ti) | TiO2 | 0,36 | 0,54 | 1,0 |
| Manganese (Mn) | MnO | 0,081 | 0,23 | 0,12 |
| Phosphorus (P) | P2O5 | 0,051 | 1,2 | 0,27 |

**Inorganic trace elements**
In addition to the main components, the bottom ash gravel contains a large number of other elements in much smaller quantities. They are also present in the lithosphere, but some of them are enriched in the bottom ash gravel as compared to the lithosphere. Some of these elements are undesirable in the bottom ash gravel, as they can be present in substances with negative effects on the environment if they are spread in excessive concentrations into the surroundings. There is particular focus on the risk of contamination of soil, groundwater

and surface water. The processing of the bottom ash into the bottom ash gravel, together with the existing limit values for the content and leaching of potentially harmful substances and the established restrictions and conditions on the use of the bottom ash gravel aims to minimise potential substance emissions and ensure that no unacceptable impact can occur on soil, groundwater and surface water in connection with the utilisation of the bottom ash gravel.

| | Bottom ash gravel | | Lithosphere | | Bottom ash gravel | | Lithosphere |
|---|---|---|---|---|---|---|---|
| Element | Min | Max | Average | Element | Min | Max | Average |
| | Mass-% | Mass-% | Mass-% | | Mass-% | Mass-% | Mass-% |
| Sulphur, S | 0,48 | 1,1 | 0,06 | Lithium, Li | 0,0020 | 0,0039 | 0,0065 |
| Zinc, Zn | 0,30 | 0,55 | 0,008 | Cobalt, Co | 0,0013 | 0,0037 | 0,0040 |
| Copper, Cu | 0,15 | 4,2 | 0,007 | Arsenic, As | 0,0010 | 0,0025 | 0,0005 |
| Chlorine, Cl | 0,067 | 0,40 | 0,05 | Molybdenum, Mo | 0,00052 | 0,0019 | 0,00023 |
| Lead, Pb | 0,043 | 0,12 | 0,0016 | Selenium, Se | 0,00020 | 0,0010 | 0,000009 |
| Barium, Ba | 0,021 | 0,063 | 0,043 | Cadmium, Cd | 0,00019 | 0,00070 | 0,00002 |
| Strontium, Sr | 0,019 | 0,031 | 0,015 | Silver, Ag | 0,00019 | 0,00080 | 0,0000007 |
| Boron, B | 0,015 | 0,026 | 0,001 | Bismuth, Bi | 0,00010 | 0,00050 | - |
| Chromium, Cr total | 0,014 | 0,05 | 0,02 | Thallium, Tl | 0,000050 | 0,00025 | - |
| Nickel, Ni | 0,010 | 0,028 | 0,01 | Chromium 6, Cr(VI) | 0,000038 | 0,00018 | - |
| Tin, Sn | 0,006 | 0,17 | 0,04 | Beryllium Be | 0,000021 | 0,000039 | 0,00028 |
| Antimony, Sb | 0,0025 | 0,019 | - | Mercury, Hg | 0,000020 | 0,00010 | 0,00001 |
| Vanadium, V | 0,0023 | 0,0038 | 0,015 | | | | |

**Organic substances**
Despite the high combustion temperatures, which destroy almost all organic matter, it cannot be outruled entirely that some specific organic substances, such as PCBs, polychlorinated dioxins and furans, perfluorinated and polyfluorinated alkyl compounds (PFAS) and brominated flame retardants may be present in the bottom ash, albeit in very small quantities. In a recently published study carried out for the Danish EPA, samples of bottom ash gravel from Danish waste incineration plants were analysed for some of these substances (https://www2.mst.dk/Udgiv/publikationer/2022/05/978-87-7038-420-9.pdf). Only one of the 11 samples had a (very limited) content of polycyclic aromatic hydrocarbons, PAH (US EPA 16), above the detection limit of 0.1 mg/kg. No samples showed a content of PCB7 above the detection limit of 0.01 mg/kg, and none of the 11 samples had a content of volatile benzene-like substances (BTEX) above the detection limit. The content of polychlorinated dioxins and furans was analysed in two samples and neither of them exceeded 0.009 µg TEQ/kg TS. The same two samples were also analysed for the content of PFAS. For one sample, no PFAS above the detection limit of 0.0005 mg/kg TS was measured, while in the other a total of 0.0045 mg/kg (sum of 3 PFAS) was measured. This is lower than the Danish EPA's soil quality requirements (requirement for clean soil). Investigations of “new” substances or groups of substances (most recently PFAS), which could conceivably have an impact on the conditions for handling and use of the slags, are carried out regularly. It can be mentioned that the Danish Environmental Protection Agency recently has initiated a screening of content and leaching of PFAS from Danish waste incineration bottom ash/bottom ash gravel.

**Protection of groundwater**
In Denmark, the drinking water supply consists almost entirely of groundwater, and securing the groundwater quality against pollution, also from bottom ash gravel, is therefore a high priority. Groundwater protection has thus always been an important part of the regulations surrounding the use of bottom ash gravel.

The aforementioned solid content analyses of the bottom ash gravel cannot be used to assess whether a given application could pose a risk of groundwater contamination. Here one has to use so-called leaching tests, where one examines the extent to which the various substances in the bottom ash gravel can be dissolved in percolating (rain) water, i.e. mobilised, and subsequently transported through the soil to the groundwater, which thereby – depending on the types and quantities of substances – can possibly be influenced so that the groundwater quality criteria may be exceeded. As mentioned below, considerable knowledge has been accumulated in Denmark over the past 20 – 30 years about substance leaching from both untreated bottom ash and bottom ash gravel and the associated potential environmental risks.

**Risk assessments and research and demonstration projects**
On the basis of risk assessments, where a correlation has been created between the result of a leaching test on bottom ash gravel and the impact on the ground water in the vicinity of a bottom ash gravel application, limit values for the leaching of a number of selected substances that will ensure that groundwater quality criteria will not be exceeded, have been determined. These limit values must be complied with if one wants to use

bottom ash gravel for road construction or similar purposes (see section 6). Over the past 22 years, all batches of “bottom ash gravel” that have been utilised, have first been tested for composition and substance leaching. Since a maximum size of a bottom ash gravel batch for testing is 5,000 tonnes, several thousand datasets with test results are currently available, which has provided in-depth knowledge of the composition and leaching properties of the bottom ash gravel and their development over time. In addition, a number of research and development projects have been carried out to elucidate various aspects of risk assessment and environmental protection in connection with the utilisation of bottom ash gravel.

Below are photos from a large demonstration project, which was carried out in the period 2002 – 2019, where leachate (permeating precipitation) was collected from 5 test fields with bottom ash gravel laid out as 50 cm thick subbase course in 4 x 100 m2 and 1 x 200 m2 fields with different surface covers (pearl stone, tiles and asphalt). The project, which was financed by DAFONET, has provided valuable information about the leaching of “bottom ash gravel” over a longer period of time and about the correlation between the substance leaching on a laboratory scale and on a full scale. Even on a worldwide scale, the demonstration project is quite unique, especially because the laboratory leaching tests were carried out according to the then brand-new CEN standards and because it has been carried out over such a long period of time (17 years) where, typically, only few large-scale studies have lasted more than 3 – 5 years.


Photos from the demonstration site for utilisation of bottom ash gravel at Ydernæs in 2002 - 2019 (DanWS).

In connection with the project mentioned above and the previously mentioned recent investigation of 11 representative samples of bottom ash gravel carried out for the Danish EPA, a number of leaching tests have been carried out in the laboratory in addition to the several thousand sets of results of the routine leaching tests on samples of bottom ash gravel” that have been collected over the last 20 years. This has provided an in-depth knowledge of the substances leaching from bottom ash gravel under different conditions that enables descriptions of the leaching process over shorter and longer periods of time and under different environmental and climatic conditions. Among other things, the results are used as realistic input to mathematical models, which are used both for risk assessment in specific situations and for calculating limit values for substance leaching from bottom ash gravel, which protects the groundwater (and surface water) against unacceptable impacts from utilisation of bottom ash gravel in road construction and similar applications.

**Substances leached from bottom ash gravel**
Salts (chlorides and sulphates of Na, Ca and K) are the substances leached from bottom ash gravel in the greatest quantities. Although they are not generally considered hazardous, they can have a negative effect on groundwater if they are present in excessive amounts (they are already present in the groundwater, but at low concentration levels). This must be taken into consideration in connection with utilisation of bottom ash gravel. However, there is usually a greater focus on trace elements and heavy metals (e.g. As, Cd. Cr, Cu, Hg, Mo, Ni, Pb, Sb and Zn). These substances may under various conditions be leached in quantities that require compliance with the regulatory conditions for handling and utilisation of the bottom ash gravel. Otherwise, or if used incorrectly, they may pose a risk to the quality of local groundwater or surface water, even though most of them are present as background concentrations albeit in very small quantities. The earlier mentioned recent testing of 11 representative samples of bottom ash gravel showed that the leaching of organic substances such as BTEX, hydrocarbons, PAH and PCB is so small that often it cannot be measured.

# 5 Environmental protection measures and legislation

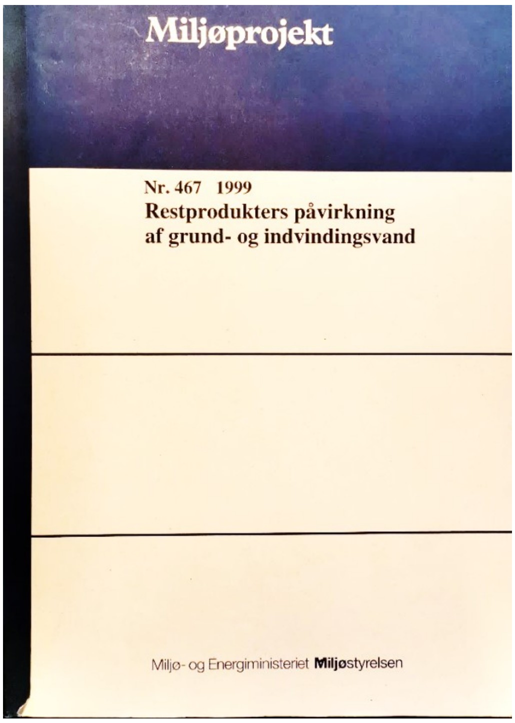
**Historical Statutory Order on the utilisation of bottom ash**
The first version of the Danish Environmental Protection Act entered into force in 1973, but did not address utilisation of bottom ash (or bottom ash gravel). There were thus no actual Danish regulations for the use of bottom ash gravel for subbase course under roads and car parking spaces in 1974, when 4000 tonnes of

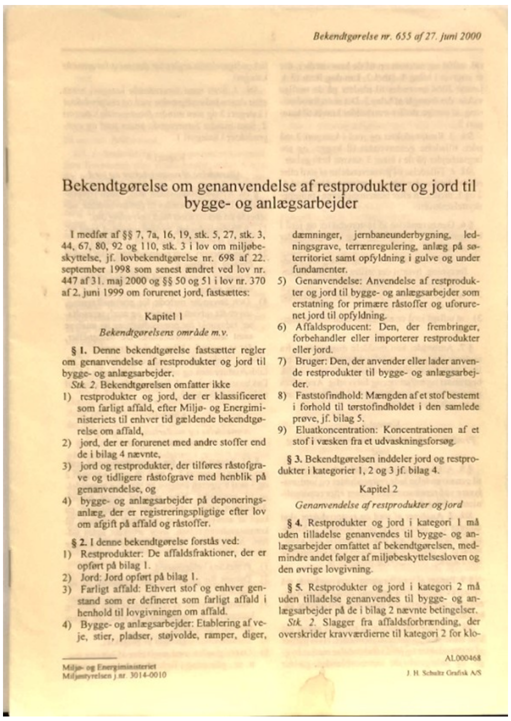
bottom ash from Vestforbrænding under the car parking space at Ballerup Town Hall became the first major bottom ash application in Denmark. Samples of the percolating water (leachate) and surface runoff water were collected, and the leaching of salts and a few metals was subsequently followed for more than 20 years. The metal content was generally very low, and often the surface run-off water contained more metal than the leachate (this was especially true for lead, which was found in petrol at the time).

The first Danish Statutory Order specifically dealing with bottom ash gravel was the Statutory Order No. 568 of 6 December 1983 on the use of bottom ash and fly ash, which laid down rules for the extent to which bottom ash and fly ash from the incineration of waste (and coal) could be used in connection with building and construction works without a permit according to the Environmental Protection Act. This Statutory Order did not distinguish between bottom ash and fly ash, the limit values were set for only the content of cadmium, mercury and lead. Among the requirements set for utilisation of these materials were: low permeable cover (e.g. asphalt, concrete or other non-permeable layer), minimum distance to drinking water boreholes of 20 m, placement above the highest groundwater table, and maximum average layer thickness of 1 m. The same rules formally applied to both bottom ash and fly ash, but while bottom ash could normally comply with the limit values, the fly ash could not. Consequently, already at this early stage there has been an incentive to collect and handle bottom ash and fly ash separately. This became a common practice during the second half of the 1980s and 1990s, and today it is one of the absolute BAT requirements in the EU Directive on Industrial Emissions (IED).

**Development of a new approach to environmental protection when using bottom ash gravel**
The Statutory Order No. 568/1983 remained in force during the period 1984 – 2000. But already at the end of the 1980s there was a growing general recognition that the risk of groundwater pollution associated with the utilisation of bottom ash gravel for construction purposes was linked to the material's leaching properties rather than the total content of potentially polluting substances in the material. This later led to the inclusion of requirements for leaching tests in the rules for bottom ash gravel utilisation. In the research community, the development of methods for testing of substance leaching had already begun in the 1970s, and in 1992 pan-European standards for leaching tests began to be developed under the patronage of CEN.

During the 1990s, a number of projects were carried out regarding the chemical and leaching characterisation of bottom ash and bottom ash gravel. More specifically, limit values for a number of substances found in the bottom ash gravel were generated for both the content and leaching. Assessments focused on the risk of groundwater pollution under different forms of use (scenarios) of bottom ash gravel and identifying which measures could reduce this risk. Furthermore, it was investigated which types of leaching tests would be relevant and how the results should be interpreted in relation to the risk of groundwater pollution. Many of these studies were carried out on behalf of the Danish EPA to ensure that the use of bottom ash gravel would not cause any harm to the environment or human





*Bekendtgørelse nr. 655 af 27. juni 2000*

Bekendtgørelse om genanvendelse af restprodukter og jord til bygge- og anlægsarbejder

I medfør af §§ 7, 7a, 16, 19, stk. 5, 27, stk. 3, 44, 67, 80, 92 og 110, stk. 3 i lov om miljøbeskyttelse, jf. lovbekendtgørelse nr. 698 af 22. september 1998 som senest ændret ved lov nr. 447 af 31. maj 2000 og §§ 50 og 51 i lov nr. 370 af 2. juni 1999 om forurenet jord, fastsættes:

Kapitel 1

*Bekendtgørelsens område m.v.*

**§ 1.** Denne bekendtgørelse fastsætter regler om genanvendelse af restprodukter og jord til bygge- og anlægsarbejder.

*Stk. 2.* Bekendtgørelsen omfatter ikke
1) restprodukter og jord, der er klassificeret som farligt affald, efter Miljø- og Energiministeriets til enhver tid gældende bekendtgørelse om affald,
2) jord, der er forurenet med andre stoffer end de i bilag 4 nævnte,
3) jord og restprodukter, der tilføres råstofgrave og tidligere råstofgrave med henblik på genanvendelse, og
4) bygge- og anlægsarbejder på deponeringsanlæg, der er registreringspligtige efter lov om afgift på affald og råstoffer.

**§ 2.** I denne bekendtgørelse forstås ved:
1) Restprodukter: De affaldsfraktioner, der er opført på bilag 1.
2) Jord: Jord opført på bilag 1.
3) Farligt affald: Ethvert stof og enhver genstand som er defineret som farligt affald i henhold til lovgivningen om affald.
4) Bygge- og anlægsarbejder: Etablering af veje, stier, pladser, støjvolde, ramper, diger, dæmninger, jernbaneunderbygning, ledningsgrave, terrænregulering, anlæg på søterritoriet samt opfyldning i gulve og under fundamenter.
5) Genanvendelse: Anvendelse af restprodukter og jord til bygge- og anlægsarbejder som erstatning for primære råstoffer og uforurenet jord til opfyldning.
6) Affaldsproducent: Den, der frembringer, forbehandler eller importerer restprodukter eller jord.
7) Bruger: Den, der anvender eller lader anvende restprodukter til bygge- og anlægsarbejder.
8) Faststofindhold: Mængden af et stof bestemt i forhold til tørstofindholdet i den samlede prøve, jf. bilag 5.
9) Eluatkoncentration: Koncentrationen af et stof i væsken fra et udvaskningsforsøg.

**§ 3.** Bekendtgørelsen inddeler jord og restprodukter i kategorier 1, 2 og 3 jf. bilag 4.

Kapitel 2

*Genanvendelse af restprodukter og jord*

**§ 4.** Restprodukter og jord i kategori 1 må uden tilladelse genanvendes til bygge- og anlægsarbejder omfattet af bekendtgørelsen, medmindre andet følger af miljøbeskyttelsesloven og den øvrige lovgivning.

**§ 5.** Restprodukter og jord i kategori 2 må uden tilladelse genanvendes til bygge- og anlægsarbejder på de i bilag 2 nævnte betingelser.

*Stk. 2.* Slagger fra affaldsforbrænding, der overskrider kravværdierne til kategori 2 for klo-

Miljø- og Energiministeriet
Miljøstyrelsen j.nr. 3014-0010

AL000468
J. H. Schultz Grafisk A/S

*Part of the documentation (left) of the work preceding the Statutory Order no. 655/2000 (right).*

Following extensive preparatory work including performance of a number of model-based risk assessments to test the efficiency of implementing various preventive environmental protection measures as well as hearings and expert discussions, the Danish EPA issued the Statutory Order No. 655 of 27 June 2000 on the recycling of residual products and soil for construction works to replace the Statutory Order No. 568/1983 from 1 January 2001.

**Current environmental protection legislation on the use of bottom ash gravel**

The Statutory Order from 2000 represented a significant step forward in terms of protecting not only groundwater quality, but also human health in connection with the use of bottom ash gravel. The order specified limit values for the polluting substances (metals and salts) which are washed out when residual products are used for building and construction works. The leaching limit values were derived to ensure that there would be no unacceptable pollution of the groundwater. At the same time, specific conditions were defined for how and where the bottom ash gravel may be used.

Criteria for solid content were set on the basis of the soil quality criteria, which ensure that one can move around the areas freely without health risks (Category 1). If these criteria cannot be met, precautions must be taken in the conditions of use to protect people and animals from contact with the "bottom ash gravel" (Category 2 and Category 3). This will be the case for bottom ash gravel.

There are two levels of the leaching criteria: (i) if it can be determined whether the amount of substances that are leached corresponds to the leaching from clean soil and the residual product can be used freely (Category 1 - if the requirements for substance content for this category are also complied with) or with certain precautions and restrictions (Category 2), and (ii) if it can be determined whether the leached substance quantities are acceptable when additional precautions are taken and additional restrictions apply (Category 3).

**Statutory Order no. 1672/2016: Limit values and conditions of application of bottom ash gravel for backfilling and road construction purposes**
**Only bottom ash classified as non-hazardous waste is included in the scope of this statutory order**

**Category 1:** Can be used freely for the purposes below

**Category 2 and 3:**
Minimum distance to drinking water extraction wells: 30 m
Placement above highest groundwater level

**Category 2 can be used for:**
**Roads** - Solid cover, H max = 1 m
**Paths** - Solid cover, H max = 0.3 m
**Squares** - Solid cover, H max = 1 m
**Cable/pipe conduits and trenches** - Solid cover
**Ramps** - Solid cover, H max = 4 m, min. slope = 15 0/00
**Noice barriers** - Solid cover, H max = 5 m, max width of crest = 2 m, gradient of sides = 2:1 or steeper, erosion protection when solid cover is soil
**Foundations and floors** - H max = 1 m under buildings

**Category 3 can be used for:**
**Roads** - Tight surface cover, collection of surface run-off, H max = 1 m
**Paths** - Solid cover, H max = 0.3 m
**Cable/pipe conduits and trenches** - Solid cover
**Foundations and floors** - H max = 1 m under buildings

**H max:** Maximum height of bottom ash gravel layer

**Tight surface cover:** Asphalt, concrete etc., which reduces the amount of precipitation that will infiltrate through the top cover. Together with collection of surface run-off this is is expected to ensure that no more than 10 % of the precipitation will percolate through the IBA layer.

**Solid cover:** Asphalt, concrete, flagstones, minimum 1 m of clean soil, etc. that will prevent and protect against contact

| **Solid content** | **Unit** | **Category 1** | **Category 2** | **Category 3** |
|---|---|---|---|---|
| Total organic carborn, TOC | Mass % (DM) | 3 | 3 | 3 |
| Arsenic, As | mg/kg DM | 20 | | |
| Cadmium, Cd | mg/kg DM | 0,5 | | |
| Chromium-total, Cr | mg/kg DM | 500 | | |
| Chromium 6, Cr(VI) | mg/kg DM | 20 | | |
| Copper, Cu | mg/kg DM | 500 | | |
| Mercury, Hg | mg/kg DM | 1 | | |
| Nickel, Ni | mg/kg DM | 30 | | |
| Lead, Pb | mg/kg DM | 40 | | |
| Zinc, Zn | mg/kg DM | 500 | | |

| **Leached amount** | **Unit** | **Category 1** | **Category 2** | **Category 3** |
|---|---|---|---|---|
| Chloride | mg/kg DM | 300 | 300 | 6000 |
| Sulphate | mg/kg DM | 500 | 500 | 8000 |
| Sodium, Na | mg/kg DM | 200 | 200 | 3000 |
| Arsenic, As | mg/kg DM | 0,016 | 0,016 | 0,1 |
| Barium, Ba | mg/kg DM | 0,6 | 0,6 | 8 |
| Cadmium, Cd | mg/kg DM | 0,004 | 0,004 | 0,08 |
| Chromium-total, Cr | mg/kg DM | 0,02 | 0,02 | 1 |
| Copper, Cu | mg/kg DM | 0,090 | 0,090 | 4 |
| Mercury, Hg | mg/kg DM | 0,0002 | 0,0002 | 0,002 |
| Nickel, Ni | mg/kg DM | 0,020 | 0,020 | 0,14 |
| Lead, Pb | mg/kg DM | 0,020 | 0,020 | 0,2 |
| Selenium, Se | mg/kg DM | 0,020 | 0,020 | 0,06 |
| Zinc, Zn | mg/kg DM | 0,200 | 0,200 | 3 |

**DM** = dry matter
**Solid content of TOC** to be determined according to EN 15936
**Solid content of metals** to be determined after digestion according to DS 259 (digestion with 7 M $HNO_3$ at 200 kPa/120 °C for 30 minutes).
**Leached amount** determined at L/S = 2 l/kg according to EN 12457-1

Applications which does not meet the criteria for Category 1, 2 or 3, or which do not meet the above described conditions of use, may possibly obtain permission according to § 19 or approval according to § 33 of the Environmental Protection Act. This will generally require a specific risk assessment.

The box on the previous page presents a condensed overview of the limit values for solid content and leaching for the various categories of bottom ash gravel and the associated restrictions on its use. Since 2001, the Statutory Order has been updated 5 times, but the criteria for the use of bottom ash gravel have not been changed in relation to the Statutory Order No. 655/2000, with the exception of the addition of leaching criteria for selenium (Se) in 2010. The description in the box corresponds to the current Statutory Order No. 1672/2016.

The preconditions upon which the risk assessments used by Danish EPA were based when calculating the leaching limit values were relatively conservative (i.e. strict) to ensure environmental protection (and possibly overestimating the potential impact). Consequently, the resulting leaching limit values (shown in the box) are quite restrictive. This means, among other things, that bottom ash gravel will never comply with the requirements for free use (Category 1) and, normally, neither with the requirements for Category 2. On the other hand, almost all Danish bottom ash gravel complies with the quality requirements for Category 3. This opens up the possibility for utilisation of bottom ash gravel in general road-building projects. For major construction projects, such as the examples shown in section 6, specific risk assessments must be carried out describing environmental protection measures and the resulting environmental impacts in order to obtain permission according to §19 or approval according to § 33 of the Environmental Protection Act.

**Classification of MSW incineration bottom ash**
As shown in the box, the Statutory Order No. 1672/2016 on the use of residual products etc. applies only to bottom ash classified as non-hazardous waste. As in most other European countries, waste incineration bottom ash (and bottom ash gravel) has been and most likely will continue to be regarded as non-hazardous waste and, in turn, is covered by Statutory Order No. 1672/2016.

The EU rules for the classification of waste are described in the Statutory Order No. 2512/2021 on waste, and for the most recently completed part in Council Regulation (EU) 2017/997 on the decision on whether waste must be classified as hazardous waste with regards to the hazardous property HP 14 "Ecotoxic". The council regulation states the principles for classification in relation to HP14, but provides virtually no guidance on how the classification should be carried out in practice. The result is that the rules for waste classification according to HP14 vary from country to country. In Denmark, there is currently no official guidance on how an HP14 classification should be carried out in practice, and the responsibility for classifying waste as hazardous or non-hazardous is currently left to the individual municipalities.

At one point, this situation created some uncertainty about the classification of bottom ash gravel in relation to HP14. However, a proposal on how bottom ash from waste incineration could be classified with regard to HP14 in Denmark has been developed. The method[3], which is based on an assessment of the bioavailability of potentially hazardous substances, was applied to 12 Danish and 12 European waste incineration bottom ashes, all of whom were classified as non-hazardous waste. A Finnish/Swedish development project[4] has developed and tested another method (the so-called T/D protocol) on 9 Nordic samples of waste incineration bottom ash, all of which were also classified as non-hazardous waste. There are thus significant indications that waste incineration bottom ash can normally be classified as non-hazardous waste with regard to HP14 (this also applies with regard to the other hazardous properties included in the overall classification).

It can also be noted that the limit values and conditions specified in the Statutory Order No. 1672/2016 are precisely aimed at protecting the aquatic environment against the ecotoxic effects that HP14 is an expression of. Thus, it would actually be fully justifiable if the scope of the Statutory Order No. 1672/2016 was extended to also include waste incineration bottom ash classified as hazardous waste only with regard to HP14.

**Health and safety protection**
Safety data sheets (SDSs) have been prepared that accompany deliveries of bottom ash gravel to the end user. The SDSs contain relevant information on the material's properties, classification, toxicity, potential risks associated with handling and use, etc. Information is also provided on how to avoid or minimise fugitive dust formation by keeping the bottom ash gravel moist as well as on the need for and use of personal protective equipment in connection with handling and placement of the bottom ash gravel.

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[3] Danish Waste Solutions (2020): Consolidation of a method for classification of waste incineration bottom ash with respect to HP14. Project carried out for AFATEK, ARC, Reno-Nord, Energnist, Fjernvarme Fyns Affaldsenergi A/S og Kredsløb.

[4] Wahlström, M., Tiberg, C., Fedje, K.K., Mäkelä, T., Kikuchi, J., Mohammadi, A.S (2022): Ecotoxic properties of ashes in hazardous waste classification. Adaptation of the transformation/dissolution (T/D) protocol for assessment of ecotoxic properties of waste ashes. TemaNord 2022-525, Nordic Council of Ministers.

# 6 Processing and application of bottom ash gravel in practice

**Maturation (carbonation)**
When the fresh bottom ash from the incineration plant arrives at the bottom ash processing site, it is placed in heaps. Within the heaps, the temperature rises spontaneously which causes both maturation and drying out of the bottom ash. During the maturation, which usually takes 2 to 3 months, the geotechnical and environmental properties are stabilised so that the bottom ash gravel can be used for e.g. road construction.

*Maturation of the bottom ash gravel for 2 – 3 months dries the ash to a moisture content of 10 – 12 % which is sufficient to allow effective removal of metals. The bottom ash gravel also takes up $CO_2$ during maturation.*

**Sorting and recovery of metals**
Although metals such as iron, stainless steel, copper, zinc and aluminium only make up a minor part of the bottom ash, they represent a significant value. After maturing in heaps, the bottom ash is dry enough to go through advanced separation of metals. The first sorting is done using a band magnet, which can remove larger objects consisting of magnetic iron. After cleaning, 5-6% of the raw bottom ash can be sold as iron for recycling.

Separation of non-magnetic metals takes place in an advanced sorting plant where the incoming bottom ash is sieved into 5 grain size fractions down to less than 1 mm. The non-magnetic metals (i.e. copper, aluminium, zinc, brass, stainless steel and even precious metals such as silver and gold) are sorted out by various methods. With this sorting, close to 90% of all metals are removed from the slag in sizes down to less than 1 mm. Experience shows that non-magnetic metals and stainless steel make up approximately 2% of the incoming amount of raw bottom ash. This amount is divided between approximately 1.8% from metal sorting facilities and approximately 0.2% from hand sorting. The 1.8% of non-magnetic metals from metal sorting facilities contains approximately 70% aluminium and approximately 30% of a mixture of Cu, Zn and a very small proportion of stainless steel.

The sorted non-magnetic metals are remelted and reused thereby replacing part of metals from primary production. Each year, around 12,000-13,000 tonnes of non-magnetic metals (primarily aluminium and copper) and 35,000-40,000 tonnes of iron are recovered in Denmark from the approximately 650,000-700,000 tonnes of raw waste incineration bottom ash.

It can be mentioned that the production of primary aluminium is very energy-intensive, and its "$CO_2$ footprint" therefore varies between less than 4 tons of $CO_2$ equivalents per ton of aluminium in hydropower-based regions to more than 20 tons of $CO_2$ equivalents per ton of aluminium in coal-based regions. The recycling process of aluminium requires a significantly smaller amount of energy resulting in lower $CO_2$ emissions: approximately 0.5 tonnes of $CO_2$ equivalents per tonne of aluminium[5].

[5] https://www.climateaction.org/news/carbon-footprint-of-recycled-aluminium

*Bottom ash with a moisture content of 10 – 12 % allows for recovery of metals down to 1 mm particle size and for a high recovery rate of non-magnetic metals such as copper, brass, zinc, aluminium and precious metals like gold and silver. In some cases, also stainless steel is recovered.*

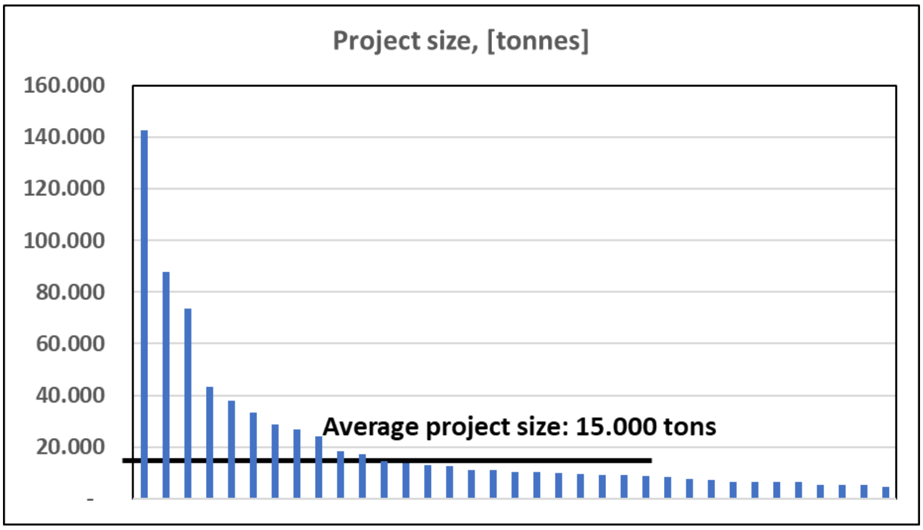
**Bottom ash gravel**
After the recovery of metals, the quality of the product is checked with respect to both environmental and technical properties, and the bottom ash gravel is ready for use in road construction.

*Processed bottoms – certified bottom ash gravel, ready for use (AFATEK).*

Certified bottom ash gravel complies with Dancert's "Supplementary provisions for certification of production management for waste incineration slag for use in base layers in road construction". (https://afatek.dk/sites/afatek.dk/files/media/document/Certifikat%20Slaggegrus%2023.12.2020.pdf)

**Scale of the bottom ash gravel utilisation projects**
As can be seen from the figure on the next page, bottom ash gravel is supplied for projects of very different sizes, where, however, the very smallest projects must be disregarded, because they may often constitute a subsequent delivery within the framework of a larger project. The scale of the largest projects (here in the size of 140,000 tonnes) can vary quite a lot. There are examples of delivery of more than 300,000 tonnes for a single project taking place over several years.

Efforts are being made to deliver bottom ash gravel to larger projects, thereby increasing the average project size. This can, among other things, be achieved by the fact that certified bottom ash gravel can now be supplied to a larger part of a road construction site – for both subbase course and base course. A new product, bitumen stabilised material (BSM), may, as previously mentioned, enable an even larger part of the road to consist of bottom ash gravel.




*Size of projects with bottom ash gravel - over a 5-year period.*

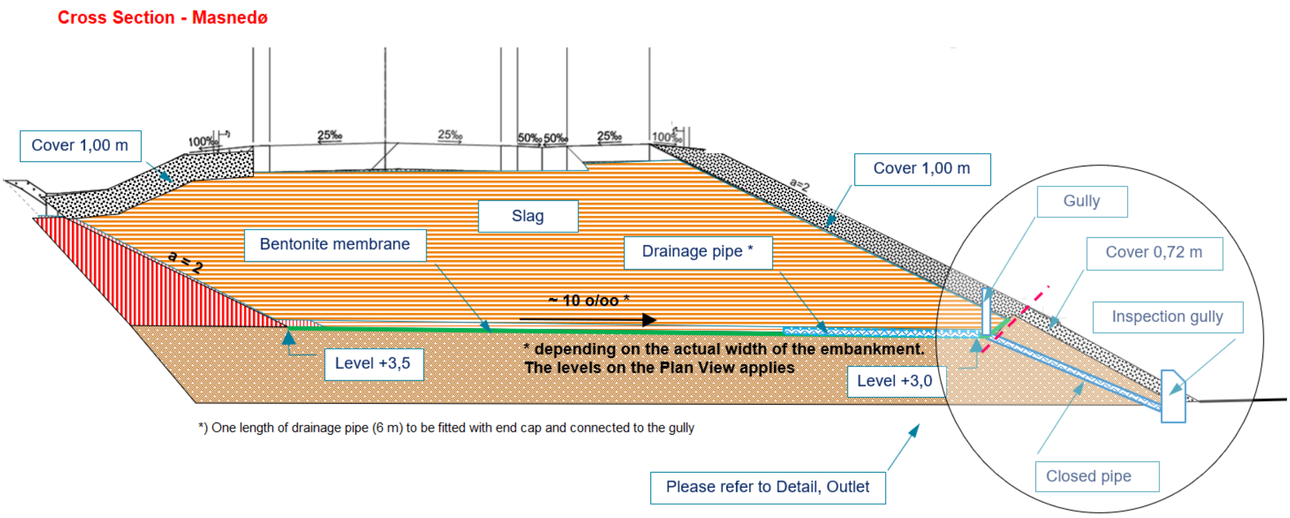
**Types of projects**
The major part of the bottom ash gravel is used for the construction of roads and sites. Some are also used for the construction of ramps, i.e. substructures for road construction. Bottom ash gravel is used e.g. at constructing municipal recycling stations where site and road construction are combined. In agricultural projects, bottom ash gravel can be used for levelling of landscape, building foundations, sites and connecting roads.

***Example of a large project - Storstrømsbroen***
In the construction of the new Storstrømsbro, approximately 250,000 tonnes of bottom ash gravel were used in ramps that connect the roads to the bridge. At the highest point of the ramp, the bottom ash gravel has now been built in to a height of 11 metres.

An environmental approval has been granted according to § 33 of the Environmental Protection Act, because the project has a large filling height (exceeding the height allowed by the Statutory Order No. 1672/2016, and because in this case the environmental authority has wanted an environmental assessment of both the construction and operational phases (operational phase: total lifetime of 100 years). The environmental permit has made it possible for an area to be set up prior to construction, where bottom ash gravel can be continuously supplied and placed in temporary storage for fast incorporation into the ramps.

*Construction site at Storstrømsbro with bottom ash gravel in stock ready for use in connecting roads to the new bridge.*

As shown in the figure below, the Road Directorate has established an extensive monitoring system with the aim to expand the knowledge related to full-scale utilisation of bottom ash gravel. Among other things, a bentonite membrane and drains/collection wells were established under the bottom ash gravel allowing for collection and analysis of rainwater that may percolate through the bottom ash gravel. However, no significant percolation of water through the bottom ash gravel is expected during the operational phase. The bottom ash gravel has a large capacity to hold and retain water, which is an advantage, as the material must be supplied with a significant amount of water during installation in order for maximum compaction to be achieved.




*Cross section showing how the bottom ash gravel is applied in the ramps.*

**Example of a typical road construction project**
The figure below shows a road where bottom ash gravel is built into the subbase course. According to the Road Directorate's tender regulations, the “bottom ash gravel” is laid out in layers of 20 cm and compacted. The bottom ash gravel must be well moisturised (to optimum water content) so that the sharp-edged grains can slide together and form a strong layer.

*Example of bottom ash gravel used as subbase in roads.*

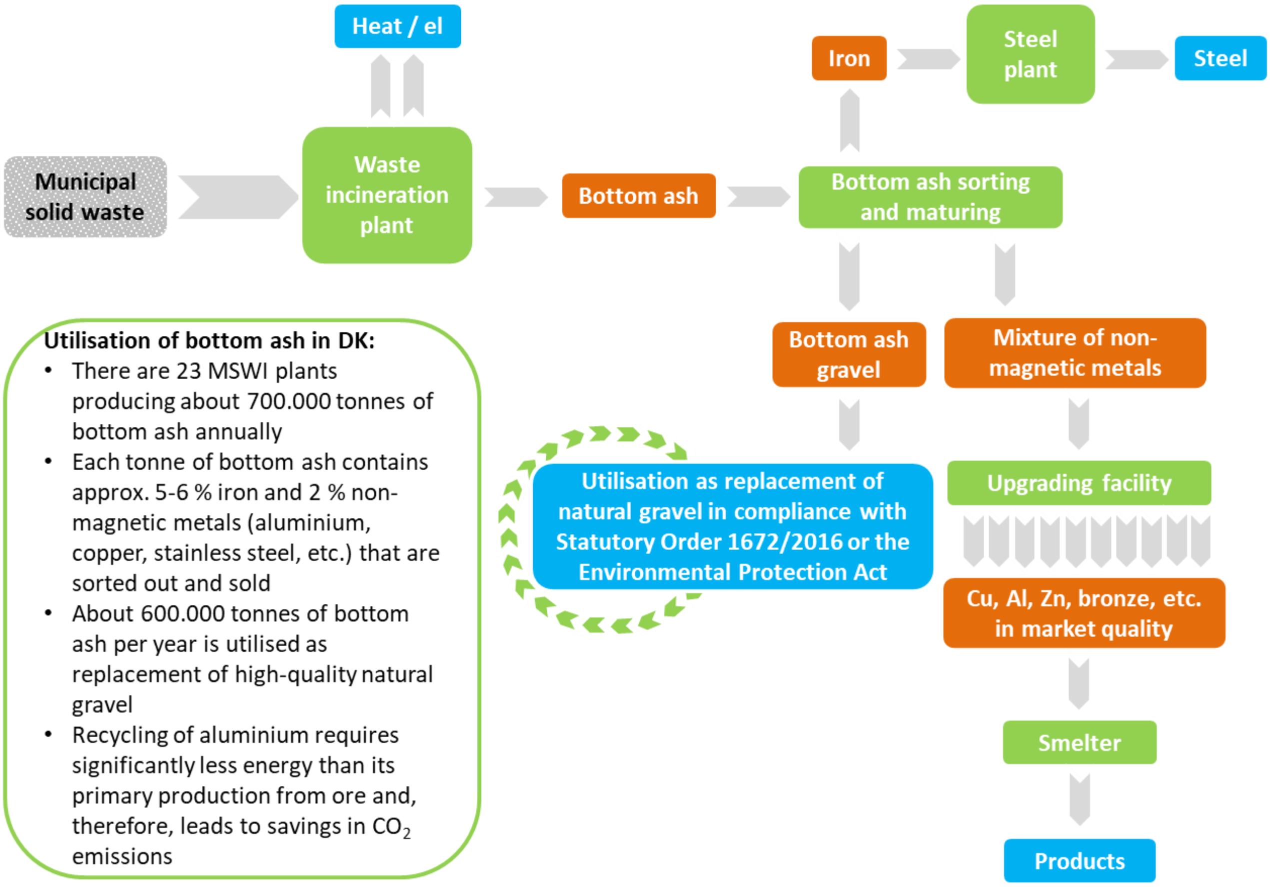
***Example of a bike path***
The figure on the next page shows an example of bottom ash gravel utilisation in a bike path. As this bike path is located in an urban area, it is relatively narrow. In other locations, bike paths resemble bike roads that must be able to take a significant amount of traffic. With a national policy for a strong expansion of the bike path network, supported by a governmental development scheme, municipalities are expected to need large quantities of bottom ash gravel for bike path construction in the coming years.

*Bottom ash gravel used in a bike path.*

# 7 Continued need for development

**The current situation**

The figure below presents an overall description of how we in Denmark seek to utilise the material and energy resources in the waste that is fed to the waste incineration plants, because it cannot immediately be recycled or utilised in itself. The figure focuses on the treatment of the bottom ash and does not address the management of the smaller residual product streams (boiler ash, fly ash, flue gas cleaning products), which still have to be treated and/or landfilled to a significant extent. These waste streams are subject to development activities aimed at resource optimisation and inclusion in the circular economy, with due consideration of the environment and human health.




*Overall description of the recovery of resources from bottom ash from incineration of waste in Denmark.*

Although in this country, we have already come a long way with the inclusion of waste incineration bottom ash in the circular economy, there is still room for improvement, and new challenges are still occurring. Among these are:

- Improved recovery of iron and non-magnetic metals and stainless steel
- Recycling of previously utilised bottom ash gravel from the past 20 years
- Assessment of risk to the environment and humans posed by new, potentially polluting substances

**Improved recovery of iron and non-magnetic metals**
Although the metal recovery efficiencies achieved by the metal sorting facilities in Denmark are generally high, there is still potential for improvement, especially in the sorting of copper and precious metals in the fraction less than 1 mm. Foreign experience indicates that this fraction can contain not only significant amounts of copper, but also gold (0.2 – 1 mg/kg), silver (5 – 20 mg/kg) and platinum group metals (in smaller amounts). The Danish bottom ash processing industry is closely following the latest developments in the field and continuously assesses whether new measures should be implemented.

**Recovery of stainless steel**
As indicated, iron and non-magnetic metals in bottom ash are generally recovered with a high recovery rate. In contrast, stainless steel is currently recovered only from a smaller part of the produced bottom ash. Stainless steel cannot be sorted with conventional techniques consisting of different types of magnets. It requires the use of special techniques such as sensor machines that, among other things, uses air pressure to separate stainless steel particles from the bottom ash. Other techniques focused on sorting of e.g. stainless steel rods are also being developed.

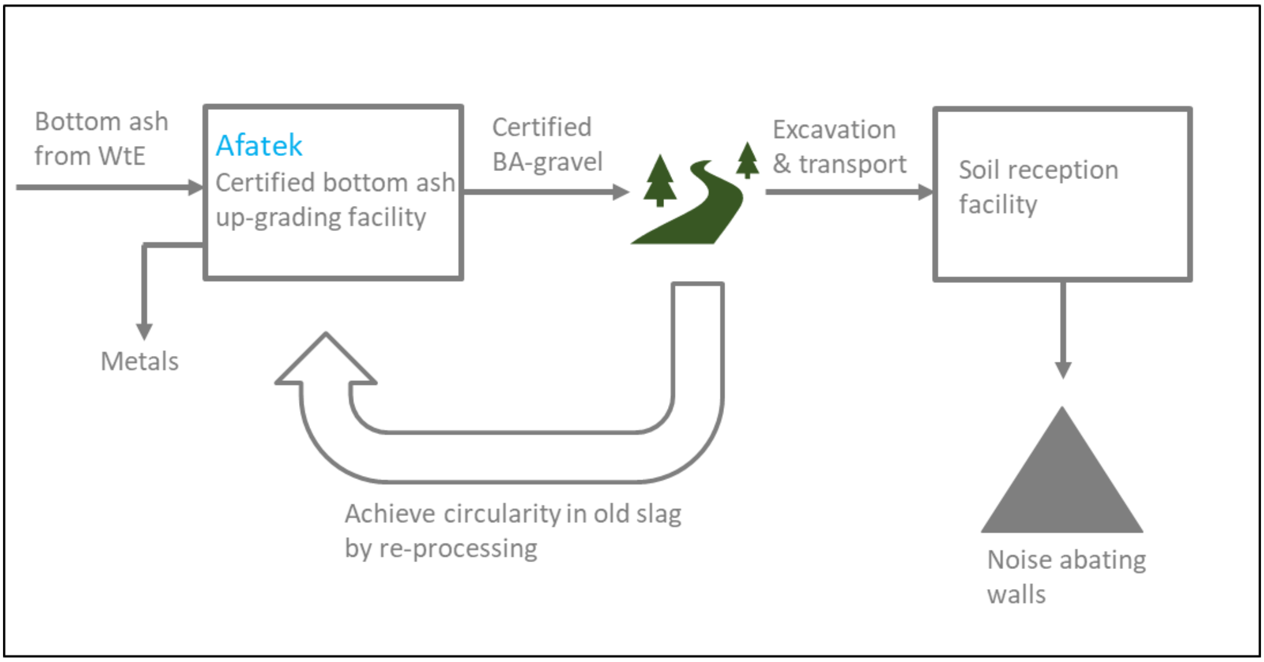
Increased recovery of stainless steel is important for the total recovery rate of metals. In addition, the purity of the bottom ash gravel will increase further. This has particular significance for the latest development, where bottom ash gravel can be used in the upper layers of the road construction – in the base course as well as in the surface layer (in the form of BSM), where the demand on the quality of the material is the highest (see above).

**Improved circularity of the old bottom ash**
Over the past 50 years, approximately 30 million tonnes of bottom ash gravel were utilised in Denmark. During the early years of bottom ash utilisation, the bottom ash could be used with only a few restrictions and often in relatively small projects (see section 5). After the introduction of the more restrictive quality requirements and conditions of application in 2001, the bottom ash gravel has been used in significantly larger projects, and the locations have been registered. Consequently, there is a good track of where the bottom ash gravel applications (approximately 12 million tonnes of bottom ash gravel since 2001) is located and who produced the material.

When a road is to be demolished, it is common practice today (according to the rules in the Statutory Order No. 1452/2015 on notification and documentation in connection with the transfer of soil) that the building materials are excavated in a mixed form and taken to an approved reception facility. After analysis, the materials are used in e.g. a noise barriers or equivalent, that is, in applications where they replace low quality materials such as soil.

Together with the municipalities of Copenhagen and Vordingborg, The Region of Zealand and the Danish EPA, Afatek has taken the initiative to implement a project where the closure of a road will be followed by separating the materials into individual fractions (i.e. asphalt, natural gravel, bottom ash gravel, soil). The bottom ash gravel is returned to a bottom ash processing facility and subjected to the modern metal sorting processes. After passing environmental testing, it becomes certified bottom ash gravel ready for use in the construction of new roads and, in turn, can once again replace the best quality natural gravel.

Overall, bottom ash gravel that has already been used once (or more) can be brought back into circulation at a higher level in the waste/material hierarchy. In addition, this solution addresses the needs of different municipalities and other users of bottom ash gravel by answering their questions about how to get rid of the bottom ash gravel when you no longer need it. Finally, in view of the expected shortage of natural materials, better recovery of both old bottom ash and the bottom ash gravel we use today is necessary. In this way, good control of a contaminated residual product is maintained - which was also the intention when the Statutory Order on the use of residual products etc. required registration of the end use of the bottom ash.




*Circularity of old bottom ash which is recirculated and processed to certified bottom ash gravel rather than being downcycled for use in e.g noise barriers.*

**New potential pollutants**

Despite extensive knowledge of the many potentially polluting substances present in the bottom ash and their leaching properties, new groups of pollutants are identified from time to time, which could potentially be problematic in relation to the utilisation of bottom ash gravel. For example, various brominated organic compounds, including brominated flame retardants, which are chemicals added to plastic, foam and furniture textiles to prevent fire. These have recently been identified in South Korean bottom ash samples as a result of co-incineration of municipal solid waste with relatively large amounts of brominated plastics. Although co-incineration of large amounts of brominated plastic is not a common practice in Denmark, measurements of these compounds in a number of representative samples of "bottom ash gravel" could be carried out by accredited laboratories to enable a correct assessment of potential risks. In addition, PFAS, which for a long time have been used in many daily products and in packaging, have been seen to have spread to all parts of environment. Although the abovementioned analyses of a few samples of bottom ash gravel for the content of PFAS showed very low values, a wider study of the content and leaching of PFAS from bottom ash gravel which has been initiated by the Danish Environmental Protection Agency is expected to provide more information on the situation and – if necessary to provide a basis for decisions on how a potential risk of spreading such substances in connection with use of the bottom ash gravel should be assessed and minimised.

**Concluding remarks**

The latest product development with certified bottom ash gravel and BSM (as well as a number of ongoing development projects) is often driven by the end users of the product (construction contractors, consulting engineers and authorities). It has been typical for Denmark that the bottom ash processing industry has responded quickly and constructively to challenges connected to utilisation of bottom ash gravel; e.g. also with regard to the classification of waste as non-hazardous or hazardous following the introduction of new rules for classification in relation to HP14 – Ecotoxic (discussed earlier). A contributing factor may be that in Denmark there has always been a close cooperation between the different waste-to-energy plants and between them and the authorities with focus on environmental protection and resource recovery.