

## WOOD ASH UTILISATION AS A STABILISER IN ROAD CONSTRUCTION – FIRST RESULTS OF LARGE-SCALE TESTS

Supancic K.<sup>1</sup>, Obernberger I.<sup>1,2,3</sup>

<sup>1</sup>BIOS BIOENERGIESYSTEME GmbH, Inffeldgasse 21b, A-8010 Graz, Austria  
Tel.: +43 (0)316 481300 17, Fax: +43 (0)316 481300 4; E-mail: supancic@bios-bioenergy.at

<sup>2</sup>Institute for Process and Particle Engineering, Inffeldgasse 21b, A-8010 Graz, Austria

<sup>3</sup>BIOENERGY2020+ GmbH, Inffeldgasse 21b, A-8010 Graz, Austria

**ABSTRACT:** In recent years the thermal utilisation of solid biomass for heat and electricity production has increased substantially in Austria and the European Union. This has also led to a strong increase in the amount of combustion residues, i.e. ashes. At present, a large fraction of the biomass ashes produced is disposed of in landfills.

Ash from woody biomass fuels contains a significant amount of CaO. Therefore, the substitution of burnt lime as a binder for silt and clay soil stabilisation by wood ash seems to be a reasonable way of ash utilisation.

The Austrian R&D project focuses on the substitution of burnt lime (CaO) as a binder for stabilisation of silt and clay soils with wood ash. The investigations followed a two-step approach with preliminary laboratory tests (wet chemical analysis and pressure resistance tests) to evaluate the principal suitability of different wood ash fractions from grate and fluidised bed combustion plants as a binder for soils and a large-scale field test, consisting of three road sections stabilised with burnt lime, ash from a bubbling fluidised bed furnace and ash from a grate furnace (with monitoring of the bearing capacity, the chemical composition of the stabilised soil and the leachate quality), in order to evaluate the technical, economical and ecological feasibility of this utilisation technology in comparison to burnt lime.

The results show, that with the proper admixing rate applied, wood ash can substitute burnt lime as a binding material for soil stabilisation. Fly ashes from grate furnaces are not suitable under Austrian conditions since their high contents of volatile heavy metals would lead to concentrations in the stabilised soil which exceed the limiting values (especially for Cd and Zn). A mixture of bottom and coarse fly ash from grate furnaces can be utilised. Fly ashes from fluidised bed furnaces feature comparably lower heavy metal contents due to the dilution with bed material and are therefore suitable for soil stabilisation. The utilisation of wood ashes has the advantage of low raw material costs but due to the higher amount required, the processing time is longer compared to soil stabilisation with burnt lime.

Based on the experience gathered from the field test, a detailed evaluation of the economic feasibility of the utilisation of wood ash as a binding material is currently underway. The ongoing ecological evaluation of soil stabilisation with wood ashes will focus on the analysis of the leachate samples collected regularly. The results of these investigations shall provide the basis for a successful implementation of wood ash utilisation as a binder for soil stabilisation in practice in the future.

Keywords: ashes, biomass, recycling, sustainability, soil stabilisation.

### 1 INTRODUCTION AND OBJECTIVES

In recent years, the promotion of energy production from biomass in Austria and the European Union has led to a strong increase in the amount of combustion residues, i.e. ashes. At present, a large fraction of the wood ashes produced are disposed of in landfills. Finding ways to utilise these ashes in an environmentally and economically efficient manner is thus an important goal throughout Europe.

In December 2009, a 4-year R&D-project was initiated in Austria in cooperation with FHP Austria (an organisation of the Austria forest, wood and paper industry), the University of Natural Resources and Life Sciences, Vienna, BIOS BIOENERGIESYSTEME GmbH, BIOENERGY 2020+ GmbH and a large number of biomass heating and CHP plant operators with the focus on the development of innovative strategies of ash utilisation as well as on the improvement of the technical, logistic and legal framework conditions in order to promote increased ash utilisation. Among other new ash utilisation strategies the project focuses on the utilisation of wood ash as a binding material for soil stabilisation in road construction. The general chemical properties of wood ash (wood ash consists of up to 50%, w/w, d.b., of CaO, and to a minor extend of MgO) as well as their latent hydraulic properties indicate that wood ash can be used as a substitute for burnt lime (CaO), which is used as a binding material for soil stabilisation.

Based on the results of comprehensive analyses as

well as lab-scale and field tests performed within the project, a guideline for the proper use of wood ashes as a binding material for soil stabilisation in road construction shall be developed in order to promote this promising utilisation strategy in the near future. This paper describes the results of the preliminary lab-scale tests performed in spring and summer of 2010 as well first results of the large-scale field test, started in October 2010.

### 2 BACKGROUND

#### 2.1 Soil stabilisation with lime – technical background

The stabilisation of clay and silt soils by mixing burnt lime (if the moisture content of the soil is low, also hydrated lime can be used) with the soil is a proven technology since the 1960's [1]. The mixing rates for lime are usually in a range between 2 and 6 % of the dry mass of the soil (2 to 8 % for hydrated lime), depending on the moisture content and the geotechnical properties of the soil.

The effect of stabilisation by the addition of lime to clay and silt soils is based on several short-term and long-term reactions which alter the properties of the soil permanently (see Table I):

The short-term reactions like the reduction of the moisture content and the formation of larger particles by coagulation lead to an improvement of the compactibility and the ductility properties, an increase of the bearing

capacity and insensibility to water. This way, the processibility of the stabilised soil is increased.

The long-term transformation of clay minerals leads to an improved volume stability, a long-term increase of the resistance, a permanent bearing capacity and frost resistance.

**Table I:** Short-term and long-term reactions during soil stabilisation with lime

Explanations: source: [1]

Short-term reactions	
reduction of the moisture content of the soil/lime mixture due to	chemical reaction of water with lime ( $\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2$ , $\Delta H = -67 \text{ kJ/mol}$ ) the evaporation of water because of heat released from this exothermal reaction chemical reactions in the clay mineral reactions at the boundary surface of the clay mineral
coagulation of clay minerals due to	reduction of their electrokinetic potential caused by the admixture of CaO, which leads to a reduction of the content of silt (0.002 – 0.06 mm) and even smaller particles (< 0.002 mm).
Long-term reactions	
transformation of clay minerals due to	puzzolanic reactions (reactions between $\text{Ca(OH)}_2$ and aluminium silicates of the clay minerals and/or colloidal silica acid).

Since the effect of stabilisation is dependent on the type of soil and its moisture content, preliminary tests with the soil to be stabilised are necessary in order to determine the optimum mixing rate of lime. Therefore, several parameters like the original moisture content of the soil, the optimum moisture content according to the proctor compaction test and the pressure resistance of the soil/lime mixture need to be determined prior to the start of the stabilisation process.

Once the optimum mixing rate is determined, the lime is either applied directly to the soil to be stabilised by a spreader and mixed with the soil (and, if necessary, with water) with a rotary hoe or other suitable machinery (mixed-in-place) or the soil is excavated and mixed with lime (and, if necessary, with water) in a mobile or central mixing station and the soil/lime mixture is then spread to the original site (mixed-in-plant). After this procedure, the soil/lime mixture is compacted by a roller compactor or similar equipment. The construction of the bearing layer can start once the compaction of the base layer is finished.

## 2.2 Soil stabilisation with wood ash as substitute for lime

Wood ash consists of up to 50% (w/w, d.b.) of CaO and of up to 8% (w/w, d.b.) of MgO. The addition of ash to clay and silt soils should therefore have similar positive effects to the properties of the soil (see Table I) like the addition of lime.

The substitution of burnt lime with wood ash would lead to the following advantages:

- Reduction of the use of a non-renewable raw material ( $\text{CaCO}_3$ )
- Reduction of negative environmental impacts

of the extraction of  $\text{CaCO}_3$  (dust, loss of top soil, fossil fuel use)

- Reduction of  $\text{CO}_2$ -emissions from the calcination of  $\text{CaCO}_3$  ( $\text{CO}_2$ -emissions amount to 0.79 t per t CaO)
- Preservation of landfill capacities by recycling of wood ash

However, since the CaO content in wood ash is significantly lower compared to lime and also the physical properties (particle size distribution, density) differ from those of lime, a detailed investigation of the application of wood ash as a binder is necessary.

In recent years the utilisation of wood ash as a building material or additive for road construction was investigated in several research projects in Finland [2], Sweden [3, 4] and Germany [5].

Lahtinen [2] investigated the utilisation of different types of fly ashes (from biomass, MSW and coal combustion plants) in admixture with other secondary raw materials like fibre sludge, gypsum and slag as a base material or as a binder in road construction. The results of these investigations show that wood fly ashes are equally suitable or often even more suitable than coal fly ashes for road construction. Wood fly ashes can be used in combination with other secondary raw materials (e.g. fibre sludge, stainless steel slag) as building material for low level roads as well as a binder for the stabilisation of soft soils if they feature specific mechanical, physical (e.g. stability, bearing capacity, frost, mechanical and chemical resistance, permeability) and chemical (pH-value, leaching behaviour) properties. The environmental evaluation of the utilisation of wood, peat or MSW fly ashes showed that there are little or no potential environmental risks arising from the use of fly ashes in road construction as long as the initial content of harmful elements and substances in the ash is rather low.

Research projects within the Swedish/Finnish "Askprogrammet" [3] investigated the utilisation of non-coal ashes (from biomass, MSW and peat) in road construction. Mácsik [6, 7] studied the effects of fly ash stabilisation on the geotechnical properties and the environmental impact of a road. The results indicate that wood ash used as a binder increases the bearing capacity of the road. Regarding the environmental impact of fly ash stabilisation, no significant differences between fly-ash stabilised and reference road sections in the leaching of heavy metals and non-metal substances except for Na, K and  $\text{SO}_4$  which showed higher levels for the fly-ash stabilised sections, could be observed.

Thurdin et al [4] used a mixture of bottom and fly ash from a biomass combustion plant to build a 40 cm road base for a gravel road (the gravel layer above the ash layer features a thickness of approx. 50 cm). The environmental impact of the ash layer was evaluated from soil solutions obtained by centrifugation of soil samples taken over a period of two years. Soil samples were taken from the ash layer, and below the ash layer at two depths in the road and the ditch. The results of the analysis showed that the initial pH-level was rather high (>12) but quickly decreased to a level typical for soils. The soil solutions of the samples taken from the ash layer showed increased concentrations of K,  $\text{SO}_4$ , Zn and Hg while underneath the ash layer an increase of the concentrations of K,  $\text{SO}_4$ , Se, Mo and Cd was observed. However, it is expected that the natural dilution of the leachate leads to a decrease of the concentrations of relevant heavy metals like Cd or Zn below or close to

groundwater median values once the leachate reaches the groundwater layer.

Hottenroth et al [5] evaluated the geotechnical and environmental suitability of ashes from the combustion of woody biomass as well as residues from the paper industry for the stabilisation of soils as a substitute for lime. The results of the geotechnical evaluation indicate that ashes with a higher CaO content show better results in terms of reduction of the moisture content of the soil as well as the bearing capacity. The investigation of the environmental impact of biomass ashes as a binder showed that ashes with higher contents of heavy metals (especially ashes from the combustion of waste wood) are not suitable for the utilisation as a binder, since German guidelines for building materials cannot be met. Bottom ashes from the combustion of untreated wood and residues from paper mills usually meet the requirements.

As a conclusion, the results of the R&D projects already performed indicate that wood ash is technically and environmentally suitable for the utilisation in road construction, if certain technical, physical and chemical requirements are met. Since these properties may change over time (e.g. due to changes in the fuel utilised) regular ash analyses are necessary. Furthermore, depending on the mechanical/physical and chemical properties, a pre-treatment of the ash might be necessary.

The Austrian R&D project focuses on the substitution of burnt lime (CaO) as a binder for the stabilisation of clay and silt soils, with wood ash.

The results discussed above delivered a valuable input for the Austrian research project. However, a comprehensive investigation of this utilisation strategy under Austrian framework conditions is necessary since on the one hand the requirements regarding road construction in Sweden and Finland differ from those in Austria due to the different climatic conditions and the composition of the ashes (co-combustion of woody biomass with peat and other organic material is especially in Finland rather common), and on the other hand large-scale field tests were not performed in the German project. Moreover, the different environmental framework conditions have to be considered.

### 3 METHODOLOGY

#### 3.1 General

The research and development activities of the Austrian R&D project follow a two-step-approach:

1. Performance of preliminary laboratory tests with 6 different wood ash samples (different ash fractions from fixed bed and fluidised bed combustion systems) in order to evaluate the chemical and mechanical suitability of the ash samples as a binder in road construction.
2. Performance of a 3-year field-test to evaluate the ecological impact and the technical and economical suitability of wood ash as a binder in the road base of paved roads. In this test, two road sections built with two different wood ash fractions as a binder are compared with a section stabilised conventionally with burnt lime. For each section, soil, wood ash and lime samples prior to stabilisation as well as samples from the soil stabilised are taken. In addition, leachate will be sampled and analysed in

regular intervals. Additionally, the mechanical properties of the road sections will be measured and the weather conditions will be recorded. The results gained from the measurements and analyses will be used to evaluate the technical and economic feasibility as well as the ecological impact of the utilisation of wood ash as a binding material in road construction.

#### 3.2 Preliminary laboratory tests

The purpose of the preliminary laboratory tests was the chemical and mechanical characterisation of different wood ash fractions from different combustion technologies and the evaluation of their suitability as a binder for soil stabilisation. A total of 6 different ash fractions from a biomass-fired grate furnace (bottom ash, coarse fly ash and filter fly ash) and a biomass-fired bubbling fluidised bed furnace (boiler fly ash, filter fly ash, mixture of boiler and filter fly ash) were analysed.

The following analyses and lab-tests were performed with the wood ashes selected in the first year of the research project:

- Wet chemical analysis and comparison with the chemical properties of burnt lime
- Proctor compaction tests of silt and clay soils
- Laboratory pressure resistance tests of test blocks made of a mixture of ash and soil for the different ash fractions and comparison with test blocks made of burnt lime and soil
- Selection of the most suitable ash fractions based on the results of the laboratory pressure resistance tests and permit obligations for the field test
- Determination of the optimum ash mixing rate for the ash fractions selected for the field test by performing additional pressure resistance tests with different wood ash/soil mixing ratios

##### 3.2.1 Wet chemical analysis

The content of major and minor elements in the selected wood ashes was analysed according to ÖNORM EN 15290 [8] and ÖNORM EN 15297 [9], respectively. The TIC and TOC contents were analysed according to ÖNORM EN 113137 [10]. In addition, the content of free CaO in the ashes according to EN 451-1 [11] was analysed.

##### 3.2.2 Proctor compaction test

The optimum moisture content of the soil used in the preliminary pressure resistance tests was determined with the proctor compaction test according to ÖNORM B 4418 [12] and EN 13286-2 [13].

##### 3.2.3 Laboratory pressure resistance tests

For the pressure resistance test a set of test blocks of a mixture of lime and soil as well as of the individual ash fractions and soil was prepared. Each test block featured a diameter of approx. 10 cm and a height of approx. 12 cm. The pressure resistance tests were performed 7, 21 and 28 days after the test blocks were prepared. At every measuring date, 3 test blocks of each mixture were tested, so every set of test blocks consisted of 9 pieces.

During the test each test block is exposed to increasing axial compression load. The pressure resistance of each test block is based on the compression load at the moment the block bursts.

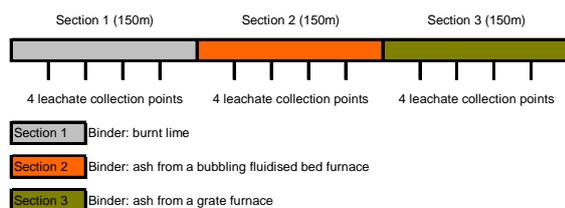
Based on the results of these tests and considering the

permit obligations of the local authorities (limiting values for the content of heavy metals and other harmful components in the solid matter and the leachate of the ash/soil mixture, see chapter 4) the most suitable ash fraction from each furnace type was selected for application in a large scale-field test. The optimum mixing rates for the two selected ashes as well as for burnt lime were determined by performing additional pressure resistance tests with three different ash/soil mixtures, using soil from the road construction site selected for the field test. The optimum mixing rates were then applied in the field test.

### 3.3 Large-scale field test

The purpose of the large-scale field test is the application of wood ashes as a binding material under practical conditions in order to evaluate the technical and economic feasibility as well as the ecological impact of this application in comparison with burnt lime.

The test layout of the field test features 3 sections with a length of 150 m. The road base in section 1 was stabilised using burnt lime as a binding material. Section 2 and section 3 were stabilised using wood ash from a bubbling fluidised bed furnace and wood ash from grate furnaces, respectively (see Figure 1).



**Figure 1:** Layout of the field test

The following steps were performed during and after the construction of the test sections:

- Installation of 12 leachate collection points (4 collection points per section)
- Collection of soil samples for each section
- Measurement of the bearing capacity of the road base before stabilisation using a light falling weight deflectometer
- Application of the binding material by a spreader (burnt lime and fly ashes from a bubbling fluidised bed furnace) or a shovel excavator (mixture of bottom and coarse fly ash from a grate furnace)
- Sampling of the burnt lime and the two ash fractions applied
- Mixing of the binding material with the soil of the road base with a rotary hoe
- Sampling of the ash/soil mixture and burnt lime/soil mixture
- Compaction with a roller compactor
- Measurement of the bearing capacity of the road base before stabilisation and compaction as well as 7 and 28 days after stabilisation/compaction
- Wet chemical analysis of the soil, ash, burnt lime as well as ash/soil and burnt lime/soil mixtures and comparison of the results with limiting values according to permit obligations (limiting values similar for recycled excavated soil)
- After the road base was finished, further steps

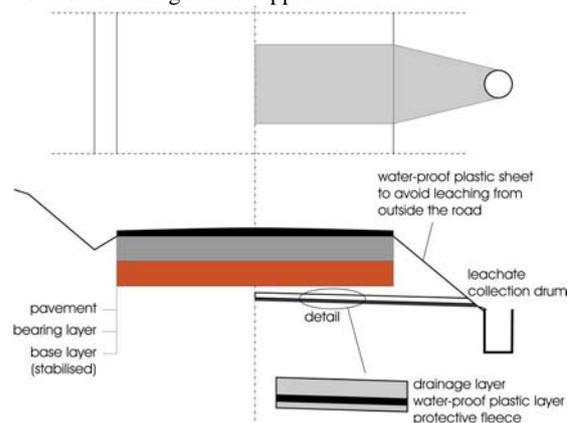
to construct the bearing layer were performed. Due to the cold weather conditions, the final pavement layer (wearing surface) will not be constructed before end of spring 2011.

- Sampling and analysis of the leachate collected in regular intervals for a period of 3 years (until autumn 2013)

#### 3.3.1 Installation of leachate collection points

In order to evaluate the ecological impact of the utilisation of wood ash as a binder leachate collected underneath the stabilised base layer will be regularly sampled and analysed during the 3 year test period. The leachate is collected at a total of 12 leachate collection points (4 collections points for each section).

For the installation of each collection point a ditch about 60 cm deep and 2 x 2 m wide was excavated. First, a protective fleece followed by a water-proof plastic sheet was inserted. On top of the water-proof plastic sheet a drainage layer was applied and the ditch refilled with soil (see also Figure 2). The waterproof plastic sheet extends into a drum situated next to each collection point where the leachate is collected. Each collection point covers a leaching area of approx. 4 m<sup>2</sup>.



**Figure 2:** Schematic illustration of the leachate collection points

#### 3.3.2 Measurement of the bearing capacity of the road base

The bearing capacity of the road base was measured using a light falling weight deflectometer (see Figure 3).

Measurements were performed in all sections on top of the base layer before as well as 7 and 28 days after stabilisation. Additional measurements on top of the bearing layer were performed after the freezing period in spring 2011.



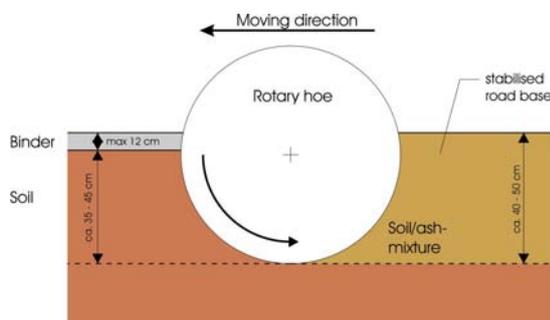
**Figure 3:** Light falling deflectometer

Explanations: source: Terramix Bodenstabilisierung GmbH, Austria

### 3.3.3 Application and mixing of the binding materials and compaction of the stabilised base layer

The equipment used for the application of the binding material is dependent on the particle size of the binder. Burnt lime and fly ashes from a bubbling fluidised bed furnace which both feature particle sizes below 1 mm are applied with a spreader. The mixture of bottom and coarse fly ash from a grate furnace features significantly greater particle sizes and is therefore applied by a shovel excavator (see chapter 4.2 for pictures).

After the binding materials have been applied they are mixed with the soil using a rotary hoe (mixed-in-place). The principle of mixing with a rotary hoe is shown in Figure 4). The depth of the mixed layer is dependent on the characteristics of the soil and the amount of binder applied. Usually the thickness of the binder layer is limited to some 12 cm, since a thicker binder layer leads to problems with binder displacement beyond the processing width of the rotary hoe. Thus, if more than 12 cm binder are applied, two or even three mixing steps are necessary.



**Figure 4:** Schematic illustration of the mixing process by a rotary hoe

Finally, the lime/soil and the ash/soil mixtures are compacted by a roller compactor or similar compacting equipment.

### 3.3.4 Sampling and wet chemical analysis of soil, binders and soil/binder mixtures

Each binder (burnt lime, mixture of bottom and coarse fly ash from a grate furnace, mixture of boiler and filter fly ash from a BFB furnace) as well as the soil from each section were sampled before the mixing procedure. In addition, the lime/soil as well as the two ash/soil mixtures were sampled after mixing with the rotary hoe.

The same analysis methods as described in chapter 3.2.1 were used for the analysis of the content of major and minor elements as well as the TIC and TOC contents. Furthermore, the content of various organic parameters in the solid matter as well as the content of selected heavy metals and organic parameters in the leachate of the samples was analysed. The leaching was performed based on ÖNORM EN 12457-4 [14]. A complete list of the parameters analysed and the standards applied is shown in Table II.

The results of the wet chemical analysis were compared with limiting values for specific parameters determined by the authority during the permit application process for the field test.

### 3.3.5 Sampling and analysis of the leachate collected

The leachate collected at the 12 collection points will be sampled regularly over a 3 year period (until autumn 2011). The parameters analysed are similar to these

shown in Table II. The analysis of the first samples is scheduled to summer 2011).

**Table II:** Parameters analysed in the samples taken from the field test

Parameters in solid matter	Comments
Total inorganic carbon (TIC) total organic carbon (TOC)	All samples, according to ÖNORM EN 13137 [10]
Al, Ba, Ca, Fe, K, Mg, Mn, Na, P, S, Si	All samples, according to ÖNORM EN 15290 [8]
As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, V, Zn	All samples, according to ÖNORM EN 15297 [9]
Cl	All samples, according to ÖNORM EN ISO 10304-1 [15]
hydrocarbon index (HC-index)	All samples, according to ÖNORM EN ISO 9377-2 [16]
PAK (sum of 16 EPA-congeneres), Benz[a]pyren	All samples, according to ÖNORM L 1200 [17]
Sum of benzene, toluene, ethylbenzene, and xylenes (BTEX)	All samples, according to DIN 38407-9 [18]
PCB (sum of 6 selected single compounds)	All samples, according to ÖNORM EN 15308 [19]
PCDD/F	Ash/soil and lime/soil mixtures only, according to ÖNORM EN 1948 [20]
Parameters in the leachates	
As, Cd, Co, Cr total, Cu, Ni, Pb, Zn	All samples, according to ÖNORM EN 16192 [21]
Hg, TOC, absorbable organic bound halogens (AOX) as chlorine	All samples, according to ÖNORM EN 13370 [22]

## 4 RESULTS

### 4.1 Preliminary Laboratory Tests

#### 4.1.1 Ash fractions analysed

For the preliminary laboratory tests different ash fractions from two different biomass combustion plants, a grate furnace and a bubbling fluidized bed (BFB) furnace were selected. These plants represent two of the most common combustion technologies used for biomass in Austria.

The ash fractions selected from the grate furnace are bottom ash, coarse fly ash (a mixture of cyclone, air pre-heater and economiser fly ash) and filter fly ash from an electrostatic precipitator. The ash fractions selected from the BFB furnace are boiler fly ash, filter fly ash from a baghouse filter and a mixture of boiler and filter fly ash. Since the bottom ash of a BFB furnace consists mainly of inert bed material ( $\text{SiO}_2$ ), this fraction was considered not suitable for the purpose of this project and was therefore not evaluated. The mixture of boiler and filter fly ash was selected since boiler and filter fly ash are often collected and stored as a mixture at BFB plants.

For details regarding ash fractions selected and technical data of the combustion plants the samples were taken from, see Table III.

**Table III:** Ash fractions selected for the preliminary laboratory tests and technical data of the biomass combustion plants

Source	Biomass-fired CHP-plant with a grate furnace
Ash fractions selected	bottom ash, coarse fly ash (mixture of cyclone, air pre-heater and economiser fly ash), filter fly ash
Fuel power input	20 MW
Fuels used	bark and wood chips
Flue gas cleaning system	Multi-cyclone and electrostatic precipitator
Source	Biomass-fired CHP-plant with a bubbling fluidised bed furnace
Ash fractions selected	boiler fly ash, filter fly ash, mixture of boiler and filter fly ash
Fuel power input	43 MW
Fuels used	wood chips
Bed material	quartz sand (SiO <sub>2</sub> )
Flue gas cleaning system	baghouse filter

#### 4.1.2 Wet chemical analysis

Prior to the laboratory pressure resistance tests the chemical composition and the content of free CaO of all ash samples were determined. The results of the analysis of the Ca and CaO contents are shown in Table IV. The ash fractions from the grate furnace feature higher Ca contents compared to the ash fractions from the BFB furnace which was expected since the ash fractions from a BFB furnace are usually diluted by the bed material (usually SiO<sub>2</sub>).

A comparison of the Ca content and the content of free CaO shows that both the free CaO content and the share of Ca bound as free CaO are higher for the ash fractions from the grate furnace. This can be attributed to the fact that CaO is preferably formed at temperatures above 900°C, which are usually present in grate furnaces (combustion temperatures between 900 and 1050°C). The combustion temperature in a BFB furnace, however, is usually between 800 and 900°C.

**Table IV:** Ca and free CaO content of the ash fractions selected for the preliminary laboratory tests

Explanations: GF ... grate furnace; BFBF ... bubbling fluidised bed furnace; d.b. ... dry basis

Sample	Ca [mg/kg] d.b.	free CaO [mg/kg] d.b.	Ca as CaO [wt. %] d.b.
GF bottom ash	278.000	359.000	92%
GF coarse fly ash	351.000	381.000	78%
GF filter fly ash	313.000	261.000	60%
BFBF boiler fly ash	226.000	160.000	51%
BFBF filter fly ash	259.000	125.000	34%
BFBF mixture of boiler and filter fly ash	252.000	111.000	31%

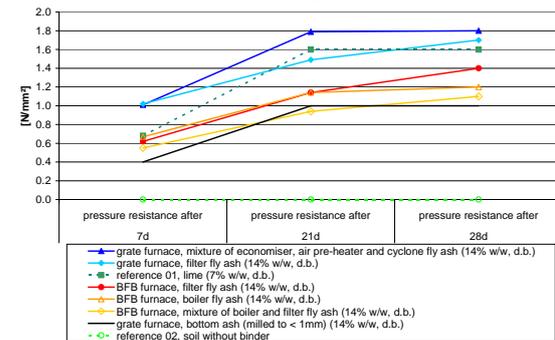
#### 4.1.3 Proctor compaction test

A clay and silt soil, which is a soil type usually stabilised with lime, was used for the pressure resistance test. The soil featured an initial moisture content of 26.2

% (w/w, w.b.). The optimum moisture content based on the proctor compaction test was 21.2 % (w/w, w.b.).

#### 4.1.4 Laboratory pressure resistance tests

Based on the results of the proctor compaction test a mixing rate for burnt lime of 7 % based on the dry weight of the soil was selected. Considering the lower CaO content of the ash samples a mixing rate of 14 % was selected. Prior to the test, the bottom ash was milled to a particle size < 1 mm. The results of the pressure resistance tests are shown in Figure 5.



**Figure 5:** Results of the preliminary pressure resistance test with lime and selected ash fractions

Explanations: BFB ... bubbling fluidised bed; mixing rate for lime: 7 % (w/w, based on dry weight of the soil); mixing rate for wood ash: 14 %; list in order of pressure resistance after 28 days.

The results indicate that wood ash can be used as a binding material for soil stabilisation. The binding properties, however, are dependent on the particle size as well as on the content of CaO in the ash, whereas the particle size (a smaller particle size leads to better results) has a bigger influence than the CaO content (a higher CaO content leads to better results). Thus, fly ashes feature better results than bottom ashes and fly ashes with a higher CaO content (coarse and filter fly ash from a grate furnace) feature better results than fly ashes with a lower CaO content (boiler and filter fly ash from a BFB furnace). So based on the binding properties, fly ashes are favoured over bottom ashes. The results also show that due to the smaller CaO content of the wood ashes compared to burnt lime, a higher amount of wood ash (about two to three times compared to burnt lime) needs to be mixed with the soil in order to achieve the same pressure resistance as soil stabilised with burnt lime.

#### 4.1.4 Selection of the most suitable ash fractions

Based on the results of the laboratory pressure resistance test, the coarse and fine fly ash fractions from a grate furnace as well as filter fly ash from a BFB furnace seem to be the most suitable ash fractions for the stabilisation of silt and clay soils.

However, apart from the mechanical properties the permit obligations of the local authorities for the application of wood ashes in the field test had to be considered in the selection of the most suitable ash fractions.

There are no specific legal regulations regarding the utilisation of wood ashes as a binder in Austria, so the limiting values focus on the ecological impact of the stabilised soil. The limiting values for the field test as shown in Table V represent the limiting values for the recycling of excavated soil for backfilling in the course of landscaping, as stated in the Austrian Federal Waste Management Plan [23].

**Table V:** Limiting values for the stabilised soil after stabilisation according to the permit obligations for the field test

Explanations: limiting values according to [23], chapter 5.2.14.1, Table 3 and Table 4; n.r. ... not relevant; I-TEQ ... International Toxic Equivalents for dioxins and furans; for abbreviations see Table II

Parameter	unit	limiting values	
		total content	content in the leachate
As	mg/kg d.b.	30	0.30
Cd	mg/kg d.b.	1.1	0.03
Cr total	mg/kg d.b.	90	0.30
Cu	mg/kg d.b.	90	0.60
Hg	mg/kg d.b.	0.7	0.01
Ni	mg/kg d.b.	55	0.60
Pb	mg/kg d.b.	100	0.30
Zn	mg/kg d.b.	450	18.00
Hydrocarbon-Index	mg/kg d.b.	200	n.r.
PAK (16 EPA-congeners)	mg/kg d.b.	2.0	n.r.
Benz[a]pyren	mg/kg d.b.	0.2	n.r.
BTEX	mg/kg d.b.	1.0	n.r.
PCB	mg/kg d.b.	0.1	n.r.
AOX as chlorine	mg/kg d.b.	n.r.	0.3
TOC	mg/kg d.b.	5,000	n.r.
PCDD/F	ng/kg I-TEQ d.b.	5.0	n.r.

Since typical soils usually feature contents below the limiting values, the quality of the ash determines whether the limiting values for the ash/soil mixture can be met or not.

Compared to bottom ash, coarse and filter fly ashes from grate furnaces feature high contents of volatile heavy metals such as As, Cd, Pb and Zn, with the highest contents in the filter fly ashes [24]. The contents of relevant volatile heavy metals of the ash fractions analysed in comparison with average values for Austrian soils is shown in Table VI.

**Table VI:** Contents of relevant volatile heavy metals in the wood ash fractions analysed and average values for Austrian soils vs. limiting values for the ash/soil mixture

Explanations: GF ... grate furnace; BFBF ... bubbling fluidised bed furnace; d.b. ... dry basis; source for average values Austrian soils: [25]; the As-contents of all ashes analysed were below the limiting value for the ash/soil mixture

Sample	Cd [mg/kg] d.b.	Pb [mg/kg] d.b.	Zn [mg/kg] d.b.
GF bottom ash	0.5	5.7	59
GF coarse fly ash	15.8	36.3	2,280
GF filter fly ash	27.0	105.5	5,360
BFBF boiler fly ash	4.7	18.5	240
BFBF filter fly ash	8.3	26.3	387
BFBF mixture of boiler and filter fly ash	6.9	26.3	331
Average values Austrian soils	0.3	30.0	140.0
Limiting values ash/soil mixture	1.1	100.0	450.0

Since the limiting values for Cd and Zn in the solid matter are rather low, ash/soil mixtures with coarse fly ash and filter fly ash fractions from grate furnaces usually exceed the limiting values. Therefore, only a mixture of

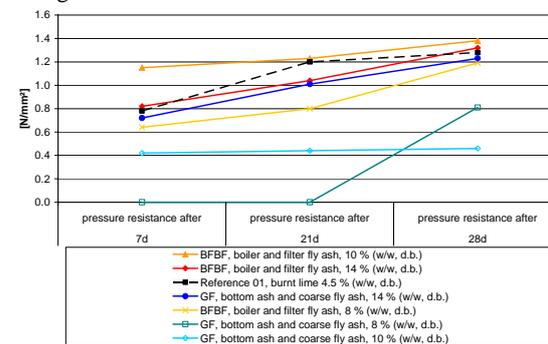
bottom and coarse fly ash from grate furnaces could be used in the field test. Fly ashes from fluidised bed furnaces usually feature lower contents of volatile heavy metals, since the ash is diluted with bed material (usually SiO<sub>2</sub>), which generally reduces the content of other elements in the ash. So the application fly ash fractions from a bubbling fluidised bed furnace in the field test was possible. The mixture of boiler and filter fly ash was selected for practical reasons, since these fractions are usually collected and stored together in BFB plants.

#### 4.1.5 Determination of the optimum mixing rates

The optimum mixing rates for the two selected ash fractions were determined by performing additional pressure resistance tests with three different mixing rates. The mixture of bottom ash and coarse fly ash from a grate furnace was used as produced, since a milling of the whole amount of ash needed for the field test (about 66 t) was too expensive.

This time, soil (silt and clay) from the road construction site selected for the field test was used in the test. The initial moisture content of the soil was 24.8 % (w/w, w.b.), the optimum water content according to the proctor compaction test was determined at 22.0 % (w/w, w.b.). Mixing rates of 8, 10 and 14 % wood ash (w/w, based on the dry mass of the soil) were investigated. Additionally, also the optimum mixing rate for lime was determined.

The results of pressure resistance tests are displayed in Figure 6.



**Figure 6:** Results of the pressure resistance test with different mixing rates for the two most suitable wood ash fractions in comparison to burnt lime

Explanations: GF ... grate furnace; BFBF ... bubbling fluidised bed furnace; list in order of pressure resistance after 28 days.

The mixture of boiler and filter fly ash from a BFB furnace shows an interesting behaviour. In contrast to the mixture of bottom and coarse fly ash from a grate furnace, which featured the highest pressure resistance with the highest mixing rate, the fly ash mixture from the BFB furnace shows the best result with a mixing rate of 10 % (w/w, d.b.), while the results for a smaller and higher mixing rate show a lower pressure resistance.

Based on the results of this test, a mixing rate of 10 % of a mixture of boiler and filter fly ash from a BFB furnace and 14 % of a mixture of bottom and coarse fly ash from a grate furnace, respectively, feature the best results. The optimum mixing rate for lime was determined at about 4 %. The mixing rates determined were then applied in the field test.

## 4.2 Large-scale field test

### 4.2.1 Location

The large-scale field test was performed during the construction of an access road to a farm. The road is about 710 m long and 4 m wide and is situated in Zerlach, some 25 km southeast of Graz, the capital of Styria, one of Austria's nine provinces. The old road was removed completely before construction.

### 4.2.2 Processability of wood ash

As already discussed in chapter 3.3, the road base of three 150 m long sections was stabilised with lime (about 15 t), a mixture of boiler and filter fly ash from a BFB furnace (about 44 t) and a mixture of bottom and coarse fly ash from a grate furnace (about 65 t), respectively.

The transport logistics used were according to present framework conditions in Austrian biomass combustion plants. Fly ashes from fluidised bed furnaces are usually collected and stored in silos whereas the bottom and coarse fly ashes are usually collected not in silos but in containers. Therefore, the fly ash mixture from the BFB furnace was delivered in silo wagons, while the mixture of bottom and coarse fly ash from a grate furnace was delivered in container trucks. As already mentioned above, the bottom ash was not milled before application, since a milling to a particle size below 1 mm was too expensive for a batch of about 60 t.

The experience gathered during the construction of the test sections showed that the mixture of fly ash from a BFB furnace can be applied with the same standard equipment that is used for burnt lime (delivery: silo wagon, application: spreader), since the transport logistics are similar and the fly ash mixture features a particle size distribution which is suitable for automatic spreaders (maximum particle size below 1 mm).

The coarser mixture of bottom ash and coarse fly ash from a grate furnace, however, cannot be applied by spreaders due to the significantly larger particle sizes ( $>> 1$  mm). The mixture of bottom ash and coarse fly ash was therefore delivered in container trucks. On site, the ash had to be dumped from the container and then applied with a shovel excavator, leading to a significant dust formation (see Figure 7).

After the binders had been applied, they were mixed with the soil by a rotary hoe and compacted afterwards by a roller compactor (see Figure 8). The application of the pavement layer will be performed in late May/early June 2011.

Regarding the time required for spreading and mixing the individual binders, the experience gathered from the field test showed that due to the higher amount of ash required (admixing rate for lime 4%, for fly ash mixture 10% and for mixture of bottom and coarse fly ash 14%, w/w, d.b.) longer processing times for spreading and mixing of the ash compared to the application of burnt lime are required.

Besides the different admixing rates, the differences in the bulk density between burnt lime and the ash fractions utilised have to be considered. Burnt lime features a bulk density of about  $900 \text{ kg/m}^3$ , which is within the typical range of the bulk density of mixtures of bottom ash and coarse fly ash ( $800$  to  $1,000 \text{ kg/m}^3$ ). However, the mixture of boiler and filter fly ash from the BFB furnace has a considerably lower bulk density (approx. between  $500$  and  $600 \text{ kg/m}^3$ ). This fact increases the volume to be processed compared to burnt lime even

more and thus also adds to the processing time for the application of the fly ash mixture from a BFB furnace.



**Figure 7:** Application of the individual binders used in the field test

Explanations: top: application of burnt lime with a spreader; middle: application of a mixture of boiler and filter fly ash from a bubbling fluidised bed furnace with a spreader; bottom: application of a mixture of bottom and coarse fly ash from a grate furnace with a shovel excavator

Due to these facts the spreading of the fly ash mixture from a BFB furnace took about 2.5 times longer compared to the application of burnt lime and the mixing with the rotary hoe took twice as long, since the thickness of the ash applied exceeded 12 cm. The spreading of the mixture of bottom ash and coarse fly ash from a grate furnace took about twice as long compared to the spreading of burnt lime. The mixing was possible in one step so no additional time compared to burnt lime was required for mixing.

The impact of the additional time required for the application of wood ash will be evaluated in a detailed economic evaluation, which is currently underway.



**Figure 8:** Mixing of the binder with a rotary hoe and subsequent compacting with a roller compactor

**Explanations:** top: mixing of a mixture of boiler and filter fly ash from a BFB furnace; bottom: compaction of the stabilised road base with a roller compactor

#### 4.2.3 Effects of the application of wood ash on the bearing capacity of the soil stabilised

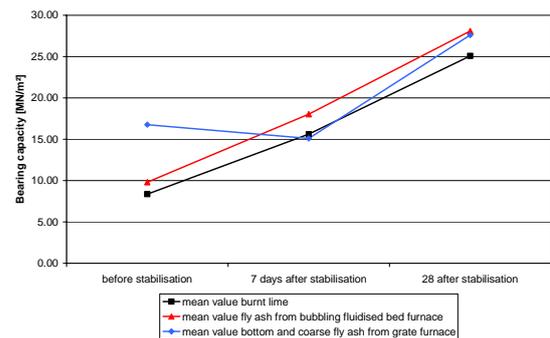
The results of the measurements of the bearing capacity of the base layer as described in chapter 3.3.2 are shown in Figure 9.

The decrease of the bearing capacity of the base layer stabilised with a mixture of bottom and coarse fly ash after 7 days is caused by the fact that due to heavy rainfall during the measurements the surface of the road base was soaked with water, which significantly decreased the values measured with the light falling deflectometer.

However, a comparison of the bearing capacity of the base layer of the three individual sections 28 days after stabilisation shows that the bearing capacity achieved is similar for all sections. These results were also confirmed by a measurement of the bearing capacity of the bearing layer after the frost period early spring 2011, which showed no significant differences between the individual sections.

#### 4.2.3 Ecological impact of soil stabilisation with wood ash

In the course of the permit application process for the field test, the authorities determined limiting values for specific parameters for the content in the solid matter as well as in the leachate of the soil/ash and soil/lime mixture, respectively (see Table V). The results of the wet chemical analysis of the ash/soil and burnt lime/soil mixtures, respectively, are shown in Table VII.



**Figure 9:** Results of the measurement of the bearing capacity of the base layer for the individual sections of the test site

**Explanations:** each of the values shown represents the mean value of 4 individual measurements

**Table VII:** Results of the wet chemical analysis of the wood ash/soil and burnt lime/soil mixture

**Explanations:** BFBF ... bubbling fluidised bed furnace; GF ... grate furnace; d.b. ... dry basis; n.d. ... not detectible; I-TEQ ... International Toxic Equivalents for dioxins and furans; for abbreviations of the parameters see Table II

Parameter	Total content		
	burned lime mg/kg d.b.	boiler and filter fly ash from a BFBF mg/kg d.b.	bottom and coarse fly ash from a GF mg/kg d.b.
As	9.82	11.35	19.12
Cd	0.05	0.58	0.32
Cr total	50.40	53.70	64.50
Cu	12.20	17.70	22.40
Hg	< 0.25	< 0.25	< 0,25
Ni	22.60	27.90	33.50
Pb	6.15	8.79	7.02
Zn	44.00	65.00	91.40
HC-Index	< 20	< 20	< 20
PAK	< 0.40	< 0.40	< 0.40
Benz[a]pyren	< 0.10	< 0.10	< 0.10
BTEX	< 0.50	< 0.50	< 0.50
PCB	n.d.	n.d.	n.d.
TOC	2,200	4,600	4,800
	ng/kg I-TEQ d.b.	ng/kg I-TEQ d.b.	ng/kg I-TEQ d.b.
PCDD/F	< 1	< 1	< 1
	Content in the leachate		
	mg/kg d.b.	mg/kg d.b.	mg/kg d.b.
As	< 0,10	< 0,10	< 0,10
Cd	< 0.03	< 0.03	< 0.03
Cr total	< 0.50	< 0.50	< 0.50
Cu	< 0,10	0.26	0.22
Hg	0.19	0.24	0.21
Ni	<0.01	<0.01	<0.01
Pb	0.30	0.60	< 0.50
Zn	< 0.30	< 0.30	< 0.30
AOX	< 0.20	< 0.20	< 0.20

The results of the wet chemical analysis shown in Table VII indicate that the limiting values given in Table V were met by samples from all three sections. As expected, the lime/soil mixture features the lowest contents of heavy metals in the solid matter but also the soil mixtures with the mixture of bottom and coarse fly ash from a grate furnace and the mixture of boiler and filter fly ash from BFB furnace feature concentrations

well below the limiting values. Only the contents in the leachate of Cr and Ni of the ash/soil mixtures are close to the limiting values. Due to the natural leaching of the base layer it is expected that the concentrations in the leachate will further decrease over time.

Apart from the analysis of the stabilised soil the leachates collected at the leachate collection points will also be analysed and evaluated. To date (early May 2011), 3 samples have been taken from each sampling point. The sampling will continue until autumn 2013. The analysis of the first batch of samples is scheduled for June 2011.

## 5 CONCLUSIONS AND OUTLOOK

### 5.1 Conclusions from the preliminary laboratory tests

The results of the wet chemical analysis showed that wood ashes feature a significant amount of free CaO, which is the relevant reacting component in the soil stabilisation process with lime or wood ashes. However, the concentration varies between the different ash fractions and different combustion technologies. Ashes from grate furnaces feature higher CaO contents (from 26 to 38 %, w/w, d.b.) than ashes from fluidized bed furnaces (from 11 to 16 %), since the combustion temperature is usually higher in grate furnaces (CaO is mainly formed at temperatures above 900°C). Another reason for the usually lower CaO content in ashes from fluidized bed furnaces is the dilution with bed material (usually SiO<sub>2</sub>).

The results of the pressure resistance tests indicate that wood ash can be used as a binding material for soil stabilisation. The binding properties, however, are dependent on the particle size as well as on the content of CaO in the ash, whereas the particle size (a smaller particle size leads to better results) has a bigger influence than the CaO content (a higher CaO content leads to better results). The results also show that due to the smaller CaO content of the wood ashes compared to burnt lime, a higher amount of wood ash (about two to three times compared to burnt lime) is required for stabilisation in order to achieve the same pressure resistance as soil stabilised with burnt lime.

Apart from the mechanical properties the permit obligations of the Austrian authorities for the application of wood ashes in the field test had to be considered in the selection of the most suitable ash fractions. Since fly ash fractions from grate furnaces feature higher concentrations for volatile heavy metals such as As, Cd, Pb and Zn and especially the limiting values for Cd and Zn in the stabilised soil are rather low, pure coarse fly ash or filter fly ash from grate furnaces would usually lead to an exceeding of the limiting values. Ashes from fluidised bed furnaces usually feature lower heavy metal contents due to the dilution with bed material (usually SiO<sub>2</sub>), so the utilisation of fly ashes from fluidised bed furnaces is possible.

Based on the findings of the preliminary laboratory tests as well as on the Austrian permit obligations the application of a mixture of bottom ash and coarse fly ash from grate furnaces and a mixture of boiler and filter fly ash from fluidised bed furnaces is recommended as a binder for soil stabilisation.

### 5.2 Conclusions from the field test

Based on the experience gathered from the field test,

the application of different wood ash fractions is possible and leads to results comparable to burnt lime.

Considering the results available so far and the current Austrian framework conditions regarding ash logistics (fly ashes from fluidised bed furnaces are usually collected and stored in silos while bottom ashes and coarse fly ashes from grate furnaces are typically collected and stored in containers) the following pro's and con's for the utilisation of wood ashes as a binder for soil stabilisation have been identified:

Pro's:

- With the proper admixing rate applied, soil stabilised with wood ash reaches a bearing capacity similar to soil stabilised with burnt lime.
- If ash fractions with rather low heavy metal contents are selected (fly ashes from fluidised bed furnaces as well as a mixture of bottom and coarse fly ash from grate furnaces), the Austrian limiting values for the recycling of excavated soil for backfilling can be met.
- Lower raw material costs compared to burnt lime.
- Reduction of the use of a non-renewable raw material (CaCO<sub>3</sub>) and the negative environmental impacts of its extraction (dust, loss of top soil, fossil fuel use)
- Reduction of CO<sub>2</sub>-emissions from the calcination of CaCO<sub>3</sub>
- Preservation of landfill capacities by recycling of wood ash
- Fly ashes from fluidised bed furnaces can be delivered and applied with standard equipment (silo wagon, spreader and rotary hoe) also used for burnt lime.

Con's:

- The application of a mixture of bottom ash and coarse fly ash from grate furnaces cannot be performed with a spreader due to its particle size well above 1 mm. A road grader or a shovel excavator must be used instead. This leads to a significant dust formation during dumping and spreading, so an application in residential areas is currently not possible.
- The time required to stabilise a particular area with wood ash is more than two times longer compared to the stabilisation with lime (due to the higher admixing rate more wood ash needs to be applied and mixed).

The milling of the bottom ash to a particle size < 1 mm and its collection and storage together with coarse fly ash in a silo would enable the application with a spreader and reduce dust formation, but would also increase the costs.

The additional processing time needed as well as milling costs for bottom ash need to be considered in an economic evaluation.

### 5.3 Outlook

Based on the experience gathered from the field test, a detailed evaluation of the economic feasibility of the utilisation of wood ash as a binding material is currently underway. The aim of this evaluation is the determination of framework conditions for an economically feasible utilisation of wood ashes as a binder in soil stabilisation.

The ecological evaluation of soil stabilisation with

wood ashes will focus on the analysis of the leachate samples collected regularly.

The results of these investigations shall provide the basis for a successful implementation of wood ash utilisation as a binder for soil stabilisation in practice in the future.

## 6 REFERENCES

- [1] Bundesverband der Deutschen Kalkindustrie e.V. (ed.): Bodenverbesserung, Bodenverfestigung mit Kalk (2004), Köln, Germany
- [2] P. Lahtinen. Fly Ash Mixtures as Flexible Structural Materials for Low-Volume Roads. (2001). Finnish Road Administration, Helsinki, Finland, ISBN 951-726-826-2
- [3] H. Bjurström, R. Herbert: The Swedish Ash Programme 2002-2008 – Biomass, waste, peat – any fuel but coal (2009). Värmeforsk Service AB, Stockholm, Sweden
- [4] R.T. Thurdin, P.A.W. van Hees, D. Bylund, U.S. Lundström: Bio fuel ash in a road construction: impact on soil solution chemistry. Waste Management 26 (2006) pp. 593-613
- [5] S. Hottenroth, B. Hartleitner, W. Rommel, S. Kögl, J. Steinemann. Verwertung von Aschen aus der Biomasseverbrennung – Bioasche als Kalkersatz? (2003). Bayrisches Institut für Angewandte Umweltforschung und Technik GmbH, Augsburg, Germany
- [6] J. Mácsik, B. Svedberg: "Skogsbilvägsrenovering av Ehnsjövägen, Hallstavik" ("Gravel road stabilisation of Ehnsjövägen, Hallstavik") (in Swedish), (2006). Värmeforsk, report 968, Sweden
- [7] J. Mácsik: "Flygaska som förstärkningslager i grusväg", ("Fly ash stabilisation of gravel roads") (in Swedish), (2006). Värmeforsk, report 949, Stockholm, Sweden
- [8] Austrian Standards Plus GmbH (ed.): ÖNORM EN 15290, Feste Biobrennstoffe - Bestimmung von Hauptelementen - Al, Ca, Fe, Mg, P, K, Si, Na und Ti (2011)
- [9] Austrian Standards Plus GmbH (ed.): ÖNORM EN 15297, Feste Biobrennstoffe - Bestimmung von Spurenelementen - As, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, V und Zn (2011)
- [10] Austrian Standards Plus GmbH (ed.): ÖNORM EN 13137, Charakterisierung von Abfall - Bestimmung des gesamten organischen Kohlenstoffs (TOC) in Abfall, Schlämmen und Sedimenten (2001)
- [11] Austrian Standards Plus GmbH (ed.): ÖNORM EN 451-1, Prüfverfahren für Flugasche - Teil 1: Bestimmung des freien Calciumoxidgehalts (2009)
- [12] Austrian Standards Plus GmbH (ed.): ÖNORM B 4418, Geotechnik - Durchführung von Proctorversuchen im Erdbau (2007)
- [13] Austrian Standards Plus GmbH (ed.): ÖNORM EN 13286-2, Ungebundene und hydraulisch gebundene Gemische - Teil 2: Laborprüfverfahren für die Trockendichte und den Wassergehalt – Proctorversuch (2004)
- [14] Austrian Standards Plus GmbH (ed.): ÖNORM EN 12457-4, Charakterisierung von Abfällen - Auslaugung - Übereinstimmungsuntersuchung für die Auslaugung von körnigen Abfällen und Schlämmen - Teil 4: Einstufiges Schüttelverfahren mit einem Flüssigkeits-/Feststoffverhältnis von 10 l/kg für Materialien mit einer Korngröße unter 10 mm (ohne oder mit Korngrößenreduzierung) (2003)
- [15] Austrian Standards Plus GmbH (ed.): ÖNORM EN ISO 10304-1, Wasserbeschaffenheit - Bestimmung von gelösten Anionen mittels Flüssigkeits-Ionenchromatographie - Teil 1: Bestimmung von Bromid, Chlorid, Fluorid, Nitrat, Nitrit, Phosphat und Sulfat (2009)
- [16] Austrian Standards Plus GmbH (ed.): ÖNORM EN ISO 9377-2, Wasserbeschaffenheit - Bestimmung des Kohlenwasserstoff-Index - Teil 2: Verfahren nach Lösemittelextraktion und Gaschromatographie (2001)
- [17] Austrian Standards Plus GmbH (ed.): ÖNORM L 1200, Bestimmung von polyzyklischen aromatischen Kohlenwasserstoffen (PAK) in Böden, Klärschlämmen und Komposten (2003)
- [18] Deutsches Institut für Normung e.V. (ed.): DIN 38407-9, Deutsche Einheitsverfahren zur Wasser-, Abwasser- und Schlammuntersuchung; Gemeinsam erfassbare Stoffgruppen (Gruppe F); Bestimmung von Benzol und einigen Derivaten mittels Gaschromatographie (F 9) (1991)
- [19] Austrian Standards Plus GmbH (ed.): ÖNORM EN 15308, Charakterisierung von Abfällen - Bestimmung ausgewählter polychlorierter Biphenyle (PCB) in festem Abfall unter Anwendung der Kapillar-Gaschromatographie mit Elektroneneinfang-Detektion oder massenspektrometrischer Detektion (2008)
- [20] Austrian Standards Plus GmbH (ed.): ÖNORM EN 1948, Emissionen aus stationären Quellen - Bestimmung der Massenkonzentration von PCDD/PCDF und dioxin-ähnlichen PCB - Teil 3: Identifizierung und Quantifizierung von PCDD/PCDF (2006)
- [21] Austrian Standards Plus GmbH (ed.): ÖNORM EN 16192, Charakterisierung von Abfällen - Analyse von Eluaten (2010)
- [22] Austrian Standards Plus GmbH (ed.): ÖNORM EN 13370, Charakterisierung von Abfällen - Chemische Analyse von Eluaten - Bestimmung von Ammonium, AOX, Leitfähigkeit, Hg, Phenolindex, TOC, leicht freisetzbarem CN-, F- (2003)
- [23] Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (ed.): Bundesabfallwirtschaftsplan 2006 (2006), Vienna, Austria, ISBN 3-902 010-70-3
- [24] I. Obernberger, K. Supancic: Possibilities of ash utilisation from biomass combustion plants (2009), Proceedings of the 17<sup>th</sup> European Biomass Conference and Exhibition, pp. 2373-2384, Hamburg, Germany, ISBN 978-88-89407-57-3
- [25] W. Krainer: Bodenschutzbericht 2000 (2000) Landwirtschaftliches Versuchszentrum Steiermark, Graz, Austria

## 7 ACKNOWLEDGEMENTS

- The Authors are grateful to the FFG (Österreichische Forschungsförderungsgesellschaft) for funding and the FHP, namely Rainer Handl, for funding and supporting this project.
- The Authors are grateful to Alex Dellantonio,

Manuel Gösseringer, Helmut Govedic, Rudolf Kaufmann, Norbert Kienzl, Alois Kohler and Armin Schlachter for the good cooperation and their support regarding the performance of the laboratory and field tests.

8 LOGO SPACE



**BIOENERGIESYSTEME GmbH**

Research, Development and  
Design of Plants for Heat and  
Power Production from Biomass

Inffeldgasse 21b  
A-8010 Graz  
Tel.: +43 (0)316 481300-0  
Fax: +43 (0)316 481300-4



Email: [office@bios-bioenergy.at](mailto:office@bios-bioenergy.at)  
Homepage: [www.bios-bioenergy.at](http://www.bios-bioenergy.at)

bioenergy2020+

