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FBC2005-78017

**LEACHING OF PHOSPHORUS FROM ASHES OF CO-COMBUSTION OF SEWAGE SLUDGE
AND WOOD**

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Abstract

Municipal sewage sludge has a high concentration of phosphorus, which should be recovered because phosphorus is a limited natural resource. In this work, sewage sludge was co-fired with wood in a FBC boiler. The aim of the investigating was to study the solubility of phosphorus in the ashes, by leaching as an alternative to the phosphorous recovery method of using the ashes directly on farmlands. The fly ashes from the boiler's secondary cyclone and bag filter were leached at various pH-values and the release of phosphorus was measured. Only acidic leaching was applied. The ashes precipitated with $\text{Al}_2(\text{SO}_4)_3$ released nearly all phosphorus at a pH-value of 1, whereas the ashes precipitated with $\text{Fe}_2(\text{SO}_4)_3$ did not release all phosphorus even at the very low pH of 0.5. The concentrations of phosphorous in the leachate must be compared with liquid phosphorus sources such as human urine or liquid animal manure used as fertilisers. This may result in that the leachate has to be processed further. A continuation of the work to investigate to what extent the leachate is contaminated with toxic trace elements is necessary.

Keywords: Phosphorus, ashes, leaching, recover, fertiliser.

Introduction

Sludge from municipal waste-water plants contains organic matter, phosphorus, nitrogen, sulphur and, in many cases, residues from precipitants. Phosphorus is a limited resource and ought to be recycled for use in industry or in agriculture as a fertiliser. Unfortunately, in general sludge is contaminated with trace elements such as arsenic (As), mercury (Hg), cadmium (Cd), lead (Pb), chromium (Cr), copper (Cu), manganese (Mn), cobalt Co, nickel (Ni), antimony (Sb), thallium (Tl), vanadium (V) and zinc (Zn) that contaminate the soil in the long run if the sludge is spread on farmland directly [1].

If the sludge is burned, its components will undergo a number of chemical transformations. It is often beneficial to co-fire the sludge with, for example, wood [2]. In co-combustion the ash-forming species of both fuels will combine, and the low ash content in wood is an advantage when recovering phosphorus. Generally, the phosphorus is

enriched in the fly ashes and so are the trace elements [3]. In a combustion process, the ash flows are collected as bottom ash and fly ash. Due to the environments in the zones where these ash flows leave the boiler, their properties differ. Also, variations in fuel composition and in the combustion process affect the ash properties. Therefore, some of the ashes have high concentration of phosphorus and low concentration of trace elements. Then the ashes can be used as fertilisers without any preparation [3]. If chlorine and sulphur are trapped in the flue gas treatment process they are added to the ash flow.

Some efforts have been made to recover phosphorus from sludge or ashes, e.g. the KREPRO and the BioCon processes [4, 5]. In these cases sludge or ashes are hydrolysed and the chemical demand is high. In contrast, the method tested in the present work includes simple leaching of the ashes collected in the combustion process. This reduces the consumption of chemicals and no external heating is needed. Thus, the costs are decreased as well.

Experimental background

The Boiler

The 12 MW_{th} fluidized bed combustor (FBC), located at Chalmers University of Technology was used for the tests, Figure 1. The boiler delivers heat to the university buildings and has all the features of a commercial unit and is built for research purposes. The combustion chamber (1) has a square cross-section of about 2.25 m² and a height of 13.6 m. Fuel is fed to the bottom of the combustion chamber through a fuel chute (2). The circulating solids are separated in the primary cyclone (9) and transported through the particle return leg (10), the loop seal (11), and, during combustion of pure wood pellets, also through the external heat exchanger (12), back into the combustion chamber. Primary combustion air is supplied to the wind box (3) below the gas distributor, and secondary air is supplied in the combustion chamber (4). The other secondary air ports (5, 6) were not used. After passing the exit duct of the cyclone (8), the flue gases are cooled to 150°C in the convection path and fly ashes are separated from the flue gases in a secondary cyclone (13) and in a bag filter (14).

In contrast to most other commercial CFB boilers this boiler is equipped with a secondary cyclone capturing 80 % of the coarsest size fraction of the fly ash, leaving the remaining fraction of fine particles to the bag filter.

The Fuels

Tables 1 and 2 show the fuel analysis. The base fuel was wood pellets, produced from Swedish domestic trees like pine and birch by “AB Svensk Brikettenergi”. Pellets were chosen for base fuel to get a well defined biofuel with constant properties (the composition of biofuels used commercially tends to vary with time and weather conditions). The additional fuels were two different municipal sewage sludges. In the first set of tests mechanically dewatered sludge from “Ryaverket” was used. This plant is the second largest wastewater treatment plant in Sweden, taking care of wastewater from 775 000 inhabitants of the city of Göteborg and its surroundings. The second set of tests involved dewatered sludge from the wastewater treatment plant Nohlagaverket in Alingsås. This plant treats wastewater from 35 000 inhabitants. Both plants produce digested sludge but employ different precipitation chemicals for phosphorous removal. “Ryaverket” employs $\text{Fe}_2(\text{SO}_4)_3$ (iron sulphate) and the plant in Alingsås $\text{Al}_2(\text{SO}_4)_3$ (aluminium sulphate).

The co-combustion tests were performed with the same boiler load as during mono-combustion operation. This means that the mass flow of the sludge is increased at a higher rate than the flow of wood is decreased. The contents of moisture, combustibles and ash were analysed by a MAC 400 Proximate Analyzer 785-700 system. The main ash components and trace elements of the fuel were analysed by an accredited external laboratory located at the facilities of Kemira Kemi AB in Helsingborg. ICP-MS (inductive coupled plasma with a mass spectrometer as detector) was used for the trace elements and X-ray Fluorescence for the main ash elements. The ultimate analysis of the fuel was performed by another accredited laboratory, SP, Swedish Testing and Research Institute in Borås.

Experimental Procedure

The experimental procedure consists of six combustion test series, each of which consists of three cases. The first run, where the only fuel is wood, is the reference case in every series. In the second series 7% of the total dry mass of the fuel is sludge and in the third 15% is sludge. In this report the tests with 15% sludge have been specially studied. The tests are named after which sludge they origin from, Fe for the sludge precipitated with $\text{Fe}_2(\text{SO}_4)_3$ and Al for the sludge precipitated with $\text{Al}_2(\text{SO}_4)_3$, and an ending relating to which lime addition strategy that was used. In series “Fe+no lime” and “Al+no lime”, no lime was added to the combustion chamber and the emissions of sulphur dioxide (SO_2) and hydrogen chloride (HCl) reached values that reflected the concentrations of sulphur and chlorine in the fuel. In series “Fe+limestone” and “Al+limestone”, limestone (CaCO_3) was added to the bed to capture sulphur as CaSO_4 and in series “Fe+hydr. lime” and “Al+hydr. lime”, hydrated lime ($\text{Ca}(\text{OH})_2$) was injected into the flue gas upstream of the bag filter to investigate its effect on ash chemistry balances and emissions of HCl and SO_2 . Table 3 summarize the variations of the tests.

The operating conditions of the tests are presented in Table 4. The arrangements of the research boiler allows to keep the operating conditions similar in all tests, only changing the amount of sludge added, type of sludge and lime addition strategy. The operating conditions were chosen to represent a typical CFB boiler with a bottom bed temperature of 850 °C, an excess air ratio of 1.2, and split of air supply into primary and secondary air, inlet of secondary air at 2.2 meter and a load corresponding to a fluidising velocity of 5 m/s at the top of the combustion chamber.

The research boiler is equipped with a control system that makes it possible to maintain a very stable operating condition. The system maintains the air flows constant once the boiler load is set. The fuel flows are then controlled by the constant oxygen concentration in the stack. All tests were run for 12 hours before the solids samples for analysis were taken. The time range was set to establish steady-state concentrations of trace elements. In each test the following samples were taken (for locations see Figure 1); wood pellets (20), sludge (21), bottom bed

(H2), cyclone leg (10), secondary cyclone (13) and bag filter (14).

Analyses of ashes

The ash samples were analysed on main components and trace elements, by the same methods and laboratory as used for the fuel analysis. In this leaching study only the ashes from the secondary cyclone (13) and the bag filter (14) were utilized. The ashes from the furnace and the cyclone leg mainly consist of bed material (silica sand, and in the tests involving lime addition to the bed, also of CaO and CaSO₄) and the phosphorus content is low [3]. In Figure 2 the flows of phosphorus in the ashes are shown. The phosphorus is found in the fly ashes and particularly in the coarser fraction separated in the secondary cyclone. Therefore, recovery of phosphorus should be made with the fly ashes as the starting material.

Leaching of ashes

The ashes were leached in room temperature by water and sulphuric acid by a 718 pH-STAT Titration unit (Metrohm Ltd.) keeping a constant pH-value by continually measuring the pH-value and compensating with acid. After leaching, the samples were separated into a solid part and a leachate by a membrane filter. This filter has a pore size of 45µm. The ashes were leached for 90 minutes. This time was chosen, based on earlier experience of leaching and considering real processes, where flow problems will occur if the processing time is longer.

Analyses of leachate

The content of PO₄⁻³ ions in the leachate was determined by a colorimetric method with a molybdenum reagent and an Ion Chromatographic (IC) method. The total phosphorus content was analysed with inductively coupled plasma with optical emission spectrometry (ICP-AES) by an accredited laboratory (AnalyCen in Lidköping). The main components and trace elements in the leachate were analysed by inductively coupled plasma with mass spectrometry (ICP-MS) or inductively coupled plasma with optical emission spectrometry (ICP-AES) and Hg by atomic fluorescence (AFS) after cold vaporisation by AnalyCen in Lidköping.

Results

Ash balance and distribution of ash

The accuracy of the measurements is estimated by the mass balance over the combustion unit. The total mass balance of solid material over a fluidised bed combustor under steady-state operating conditions is expressed as [3]:

The mass flow of fuel ash, lime and silica sand fed = exiting mass flows of bottom ash and fly ash

In the present study the release of volatiles from the ashes is neglected, but the conversion of lime and unburned char in the exit flows is taken into account. The results of the total mass balances, shown in Figure 3, verify that the closure is good. The distribution of ash between bottom and fly ash is seen in Figure 4. The bottom ash flow is higher for the tests combusting sludges precipitated with aluminium sulphate compared to the similar tests with sludges precipitated with iron sulphate. The dominant ash flow in all tests is that of the secondary cyclone ashes, except for the test "Al+no lime" in which the bottom ash flow is only slightly dominant. This case also has the lowest bag-filter ash flow, not counting the reference case with wood only. The addition of hydrated lime to the bag filter is clearly seen in the bag-filter ash flows in cases "Fe+hydr. lime" and "Al+hydr. lime". Judging from the ash flows, the most interesting ashes for utilisation studies is the secondary cyclone ashes and the bag filter ashes with hydrated lime addition, se Figure 4.

Phosphorus concentrations

The original form of phosphorus in the sludge prior the digestion is FePO₄ or AlPO₄, depending on which precipitation agent the waste-water plant employs. According to chemical equilibrium calculations using FactSage [6] does the burning of the sludges lead to that the Fe ends up as Fe₂O₃(s), while Al is found in a number of silicates but also in AlPO₄. The phosphorous combine with calcium to Ca₃(PO₄)₂ depending on the availability of Ca. Lack of enough Ca leads to the formation AlPO₄ [6]. Then the phosphorus will probably combine with other species like calcium. After combustion, the phosphorus is found in the ashes, in concentrations between 1.1 to 6.6% P on dry basis, Figure 5. The

low phosphorus concentration in the bottom ash is due to the dilution by the bed material. The low phosphorus concentration in the bag filter ash in series E and F can be explained as a dilution by the added hydrated lime. The average phosphorus concentration in 47 waste water treatment plants in Sweden has been shown to be 2.7% [1]. In the two sludges investigated here the average phosphorus concentrations were 2.8% for both sludges, Table 2. It is evident that these sludges well represent typical Swedish sludges with respect to the content of phosphorus. This confirms that the concentrations are high enough for direct agricultural utilization of the sludge as fertilisers. The factors determining if it is possible or not to use the ashes as fertilisers are related to the form phosphorus have after combustion and the degree of contamination of the ashes by trace elements.

Phosphorus yield in leachate

In pre-tests, leaching at pH 4 showed that the pH has to be decreased to make an acid environment or increased to make an alkaline environment. In the main study, an acid environment was investigated. When the ashes were leached at pH 2.5 only 22-30% of the phosphorus in the secondary cyclone ashes were solved (Figure 6) and 35-60% of the phosphorus in the bag filter ashes. By decreasing the pH-value to 1 the phosphorus yield in the leachate from the secondary cyclone ash, precipitated with aluminium sulphate, increased to 74-95%, whereas the secondary cyclone ashes, precipitated with iron sulphate, only increased to 49-65%. The phosphorus in the Al-rich ashes was easier to extract than the phosphorus in the Fe-rich ashes, where approximately 30% less phosphorus was solved. Also, in the leachate from the bag filter ashes the solubility increased by the decreased pH-value. The solubility was higher for the ashes precipitated with aluminium sulphate, even if the differences were not as great as with the secondary cyclone ashes. In order to investigate whether the phosphorus would be solved further for the ashes precipitated with iron sulphate, additional leaching tests were performed where the pH-value was decreased to 0.5, Figure 6. The only ash where the yield increased when lowering the pH was the bag filter ash, produced when hydrated lime was added for capture of

chlorine and sulphur (Fe+hydr. lime, Figure 6), where the phosphorus yield increased from 68% to 85%. In test "Fe+no lime", secondary cyclone ash, and test "Al+no lime", secondary cyclone- and bag filter ash, the results were the opposite, and the phosphorus was less solved at pH 0.5 than at pH 1. This supports other studies [7] where efforts were made to use Fe as a stabilizer in sludge to prevent phosphorus leakage from the produced ashes after their disposal on dump sites or when the ashes is used as construction material. How the Fe stabilizes the phosphorous is unclear and not reported in ref. [7]. According to [6] the Fe reacts with oxygen to form $Fe_2O_3(s)$ and Fe does not react with phosphorous. The addition of lime seems to be of minor importance. There are no clear tendencies in the solubility of phosphorus that can be related to the supply of limestone to the bed or to hydrated lime added to the bag filter. For limestone supplied to the bed, both fly ashes produced in tests "Fe+limestone" and "Al+limestone" can be compared to the fly ashes from the similar tests with no lime added to the bed (tests "Fe+no lime" and "Al+no lime") For the tests with addition of hydrated lime ("Fe+hydr. lime" and "Al+hydr. lime") only the bag filter ashes changes as a result of the hydrated lime and the secondary cyclone ashes for these two tests are similar compared to the tests with no lime addition.

Release of precipitation agent to the leachate

The Fe-concentration in the leachate is low. It is obvious that Fe remains in the solid phase after leaching in the form of different compounds, for example, iron oxide, Figure 7. The Fe present in the ashes of the sludge precipitated by an Fe-salt is just solved with 2-3% at pH 1, while 9-19% of the Fe is solved in the ashes of the sludge precipitated by an Al-salt. The extracted amounts of Al are shown in Figure 8. The Al-concentrations in the ashes of the sludge precipitated by an Al-salt are approximately twice as high as in the ashes of the sludge precipitated by a Fe-salt, Figure 9. This means that the aluminium species present in the Al-rich ashes from the secondary cyclone are easier to extract than the Al in the Fe-rich ashes, see Figure 8. For the bag filter ashes the solubility of Al is the same regardless which of the bag filter ashes that was used and the Al yield is not related to the Al concentration in the ash.

Between 20-40% of the Al was found in the leachate at pH 1 but most of the calcium (Figure 10). This means that the extracted phosphorus probably was present as $\text{Ca}_3(\text{PO}_4)_2$ in the ash. The sludges contained nearly enough Ca to match the amount of phosphorus (The molar ratio was $3\text{Ca}/2\text{P}=0.91$ in test "Fe+no lime" and $3\text{Ca}/2\text{P}=0.82$ in test "Al+no lime"). Lime addition increases the amount of $\text{Ca}_3(\text{PO}_4)_2$ in the ash according to [6].

Leachate as fertiliser

Phosphorus can be extracted by leaching. A simple low cost method can therefore be used in the future to recover phosphorus.

The phosphorus concentration in the leachate has to be compared with liquid phosphorus sources used as fertilisers (e. g. human urine or liquid animal manure) in order to judge if further processing of the leachate can be necessary. By using the leachate instead of artificial fertilisers natural resources can be saved in the future and the leakage of phosphorus to the environment will then be reduced. Future work will elaborate if this will be possible.

Trace elements release in the leachate

The value of leachate containing phosphorus for the purpose of fertilisation depends on the content of trace elements in the leachate. The question is if the trace elements showed in Table 2 follow the phosphorus or not. This will be the subject of a continuation of this work.

Conclusions

The following conclusions can be drawn:

- On the average 60% of the inert material leaving the boiler is fly ash. The special arrangement in the boiler used is even more favourable for recovery of phosphorus, since 80% of this ash is secondary cyclone ash having a high concentration of phosphorus. Some of the bag filter ashes can also be useful for this purpose. The bottom ash is too diluted with bed material and is not suitable.
- Phosphorus can be extracted by leaching. This means that a simple low cost method can be used in the future to recover phosphorus.

- The phosphorus in the ash is easier to extract if the precipitation agent used in the water treatment plant is aluminium sulphate instead of iron sulphate. The phosphorus release is suppressed by the presence of iron. Approximately 30% of the phosphorus in the ash is retained but the chemistry behind this is still unclear.
- The pH-value has to be low (about 1) in order to achieve a phosphorus yield above 50% in the leachate from ashes of sludge precipitated by Fe in short-time leaching, suitable for an industrial process. A pH of 1 gives a phosphorus yield of 75-95% from ash originating from Al-precipitated sludge.
- Leachates of fly ashes from co-combustion of sewage sludge and wood contain most of the phosphorus available in the ashes. The concentrations must be compared with liquid phosphorus sources used as fertilisers. This may result in that the leachate has to be processed further.
- A continuation of the work to investigate to what extent the leachate is contaminated with toxic trace elements is necessary.

Acknowledgments

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TABLES

Table 1: Properties of the municipal sewage sludge and wood pellets.

	Sewage sludge ¹	Sewage sludge ²	Wood pellets
Precipitation agent	Fe ₂ (SO ₄) ₃	Al ₂ (SO ₄) ₃	—
Proximate analysis			
Water (wt-%, raw)	72.1	77.5	7.7
Ash (wt-%, dry)	12.7	9.5	0.34
Combustibles(wt-%, raw)	15.1	13.0	92.0
Volatiles (wt-%, daf)	94.5	85.3	81.7
Ultimate analysis (wt-%, daf)			
C	52.3	50.1	50.2
H	7.2	7.3	6.1
N	5.4	5.1	1.5
S	1.8	1.3	0.2
Cl	0.12	0.07	0.13
O	33.2	36.2	43.5
Lower heating value (MJ/kg)			
Hu, daf	20.50	19.40	18.80
Hu, raw	2.78	2.24	17.20
Ash analysis (g/kg dry ash)			
K	17.7	10.3	82.0
Na	9.8	6.7	6.7
Al	97.6	189	12.2
Si	174	115	79.7
Fe	205	42.3	20.9
Ca	51.3	37.7	164
Mg	12.5	5.3	26.4
P	72.8	61.3	12.7
Ti	5.6	9.7	0.7

(1)= Ryaverket; (2)= Alingsås.

daf= dry and ash free, raw= as received

Table 2: Trace elements and main inorganic components calculated on dry fuel. Comparison of the sludges in this study (Rya and Alingsås) and average Swedish sludge.

	Sewage sludge ¹ Fe ₂ (SO ₄) ₃	Sewage sludge ² Al ₂ (SO ₄) ₃	Wood pellets —	Sewage Sludge ³ average	Sewage Sludge ⁴ average
Trace elements (mg/kg dry fuel)					
Hg	1.2	0.78	0.02	1.1	1.2
Cd	0.86	0.53	0.11	1.2	1.4
Pb	38	17	0.35	33	42
Cr	31	43	0.64	33	39
Cu	400	270	2.6	390	430
Mn	300	300	120	280	280
Co	6.9	2.8	0.04	6.2	8.3
Ni	22	13	0.20	20	22
As	5.9	5.2	0.12	4.7	5.5
Sb	14	15	0.06	2.4	3.4
V	23	23	0.06	18	18
Tl	10	10	0.06	0.15	0.16
Zn	650	390	15	550	680
Se	14	15	n.a.	1.3	1.6
Main elements g/kg dry fuel					
K	6.6	4.9	0.04	n.r	n.r
Na	3.6	3.1	0.04	n.r	n.r
Al	35	88	0.07	n.r	n.r
Si	62	52	0.49	n.r	n.r
Fe	77	19	0.13	n.r	n.r
Ca	19	17	1.01	n.r	n.r
Mg	4.8	2.4	0.16	n.r	n.r
P	28	28	0.08	27	33
Ti	2.1	4.3	0.004	1.8	1.8

Trace elements and inorganic components calculated on dry fuel. N.a.: not analysed, n.r.: not reported.

(1)= Ryaverket; (2)= Alingsås.

(3)= Average of analysis of sludge from 48 different waste water treatment plants in Sweden [1].

(4)= Weighted average of trace elements in sludge with respect to amount of sludge produced at each waste water treatment plant and average of sludge produced in Sweden [1].

Table 3: Test matrix.

Test names	Precipitation agent	No Lime	Lime to bed	Hydrated lime to bag filter
Fe+no lime	Fe ₂ (SO ₄) ₃	X		
Al+no lime	Al ₂ (SO ₄) ₃	X		
Fe+limestone	Fe ₂ (SO ₄) ₃		X	
Al+limestone	Al ₂ (SO ₄) ₃		X	
Fe+hydr. lime	Fe ₂ (SO ₄) ₃			X
Al+hydr. lime	Al ₂ (SO ₄) ₃			X

Table 4: Operating conditions.

	Wood/Sludge ¹	Wood/Sludge ²	Wood/Sludge ¹	Wood/Sludge ²	Wood/Sludge ¹	Wood/Sludge ²
	Fe+no lime	Al+no lime	Fe+limestone	Al+limestone	Fe+hydr. lime	Al+hydr. lime
Load, MW _{th}	6.1	6.0	6.0	6.4	6.0	6.0
Bed temp., °C (bottom)	848	843	852	850	850	848
Bed temp., °C (top)	866	880	852	856	882	870
Exit temp. of after burning chamber, °C	849	855	865	861	828	834
Total riser pressure drop, kPa	6.4	6.4	6.5	6.3	6.6	6.3
Calcium addition molar ratio Ca/S	0.0	0.0	1.7	2.7	4.6	5.0
Ca/S with Ca in fuel included	1.9	1.9	3.7	4.7	6.3	7.2
Excess air ratio	1.2	1.2	1.2	1.2	1.2	1.3
Primary air flow/total air flow, %	57	50	59	59	57	57
Superficial flue gas velocity at top of riser U _{top} , m/s	5.3	5.2	5.2	5.4	4.9	5.0

(1)= Ryaverket; (2)= Alingsås.

FIGURES

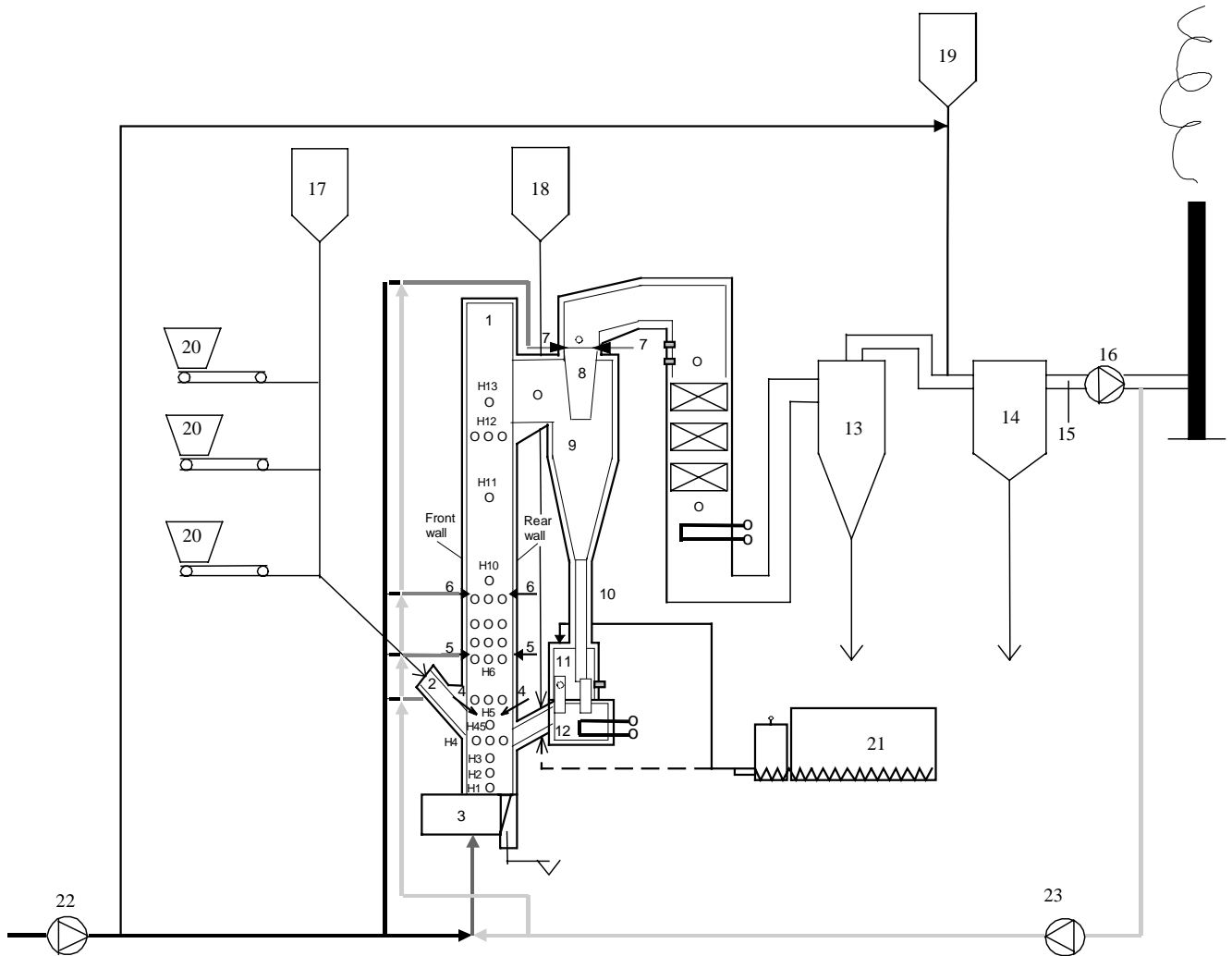


Figure 1: The 12-MW_{th} FBC boiler at Chalmers University of Technology. (1) combustion chamber, (2) fuel feed chute, (3) wind box, (4) secondary air inlet at 2.1m, (5) secondary air inlet at 3.7 m, (6) secondary air inlet at 5.4 m, (7) secondary air inlet into cyclone exit duct, (8) cyclone exit duct, (9) hot primary cyclone, (10) particle return leg, (11) particle seal, (12) heat exchanger, (13) cold secondary cyclone, (14) bag filter, (15) gas-extraction probe for emission monitoring, (16) flue gas fan, (17) sand bin, (18) lime bin, (19) hydrated lime bin, (20) fuel bunkers, (21) sludge pump (22) air fan, (23) flue gas recirculation fan.

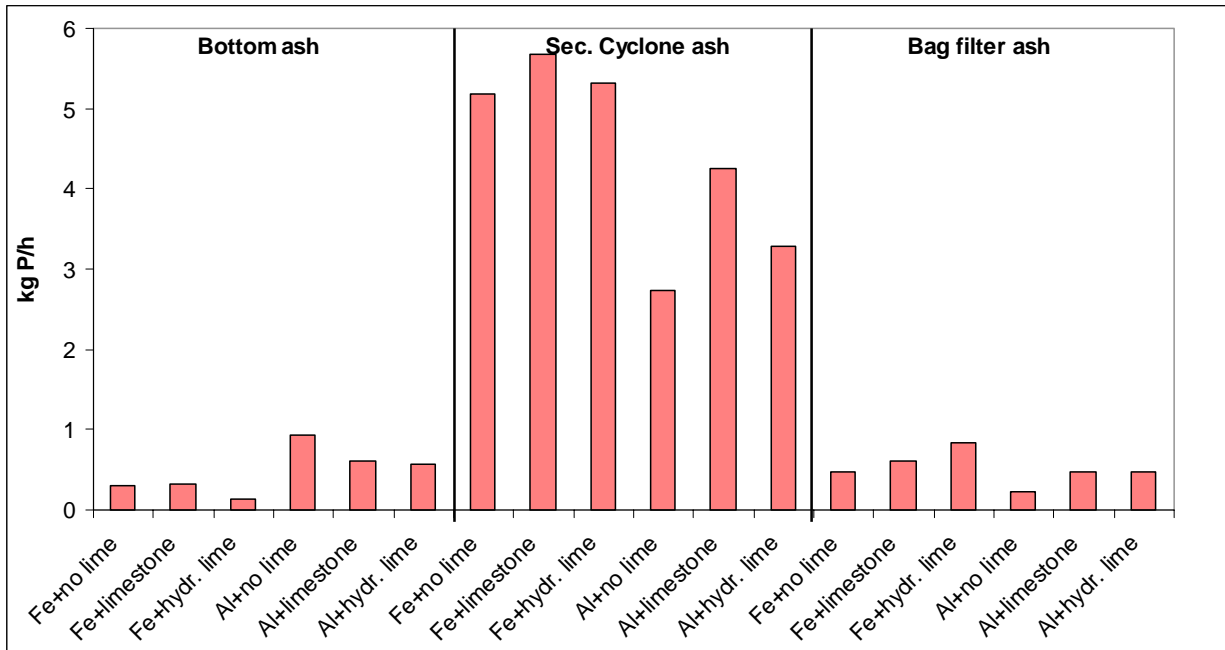


Figure 2: Phosphorus flows in the different ashes as kg/h for the different tests in Table 3.

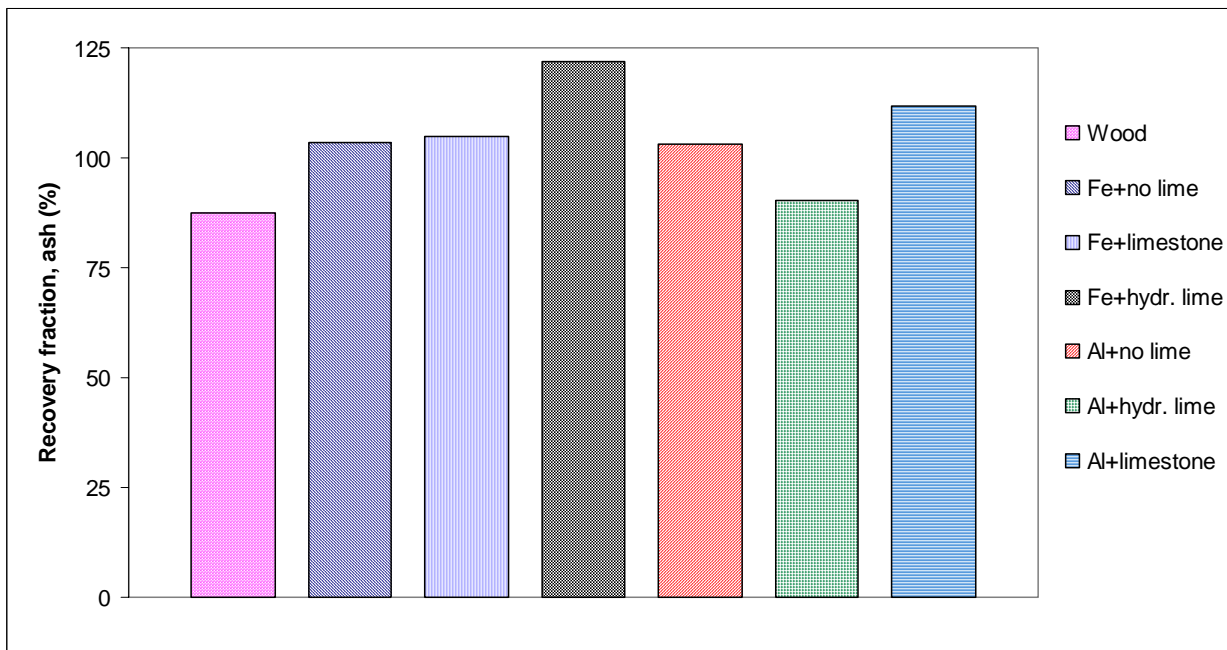


Figure 3: Ash recovery fraction ($100 \cdot \text{out/in}$) in the reference case with wood pellets and in the tests with 15% sludge as co-fuel and wood pellets as base fuel.

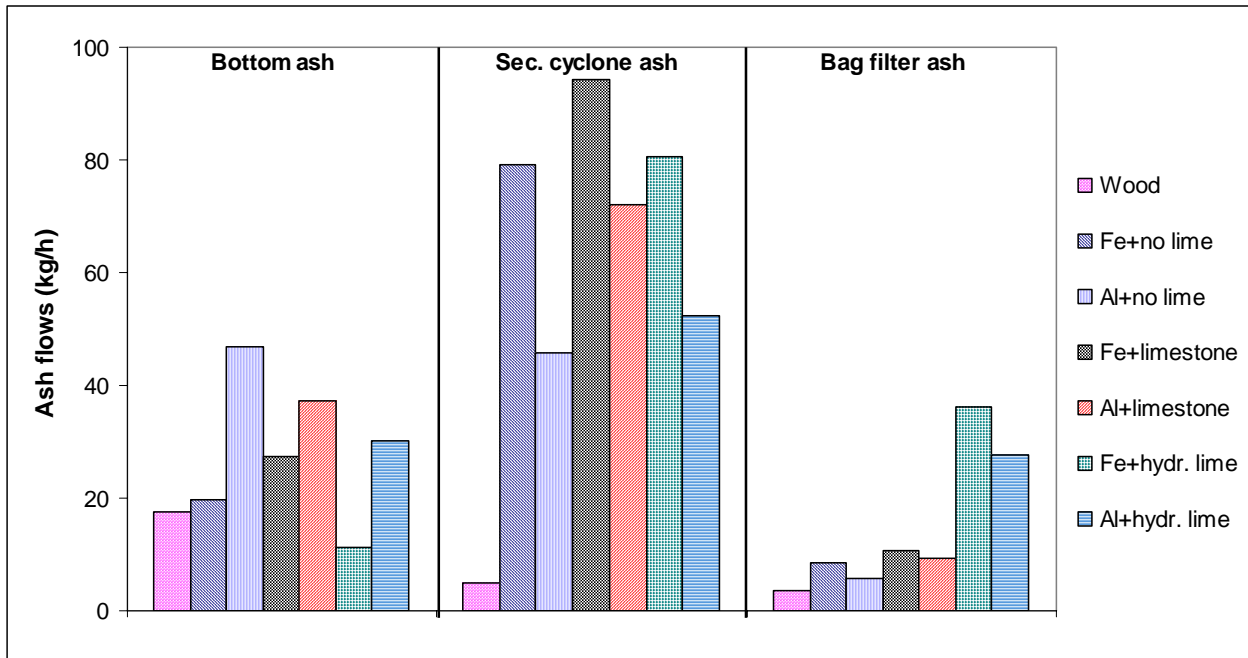


Figure 4: The flows of solids through the boiler in the reference case with wood pellets and the tests with 15% sludge as co-fuel and wood pellets as base fuel.

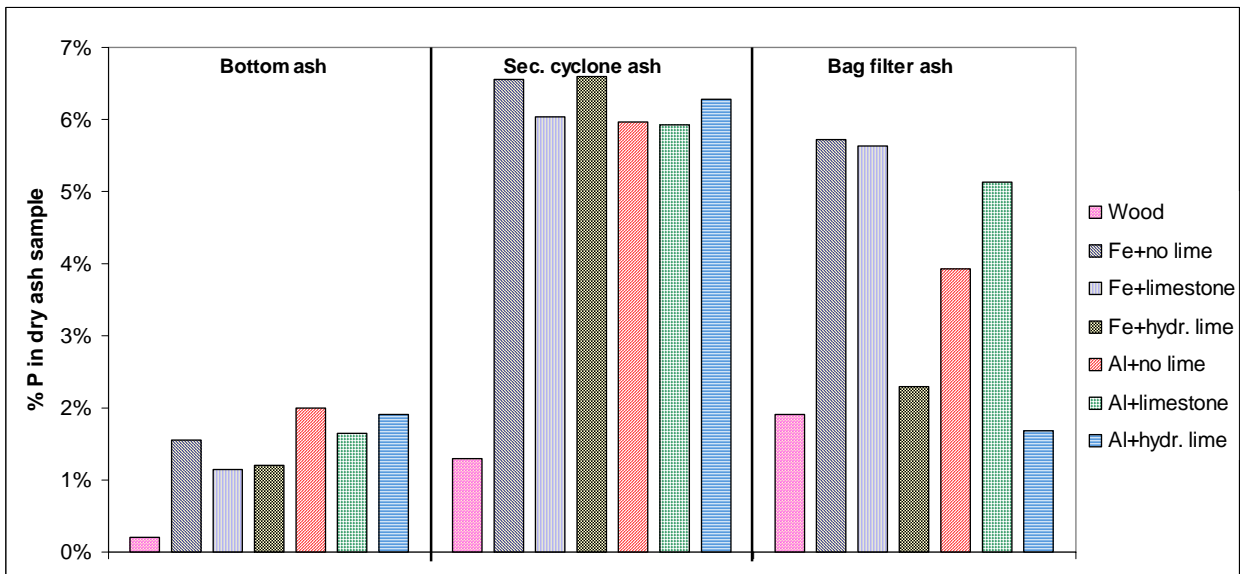


Figure 5: Phosphorus concentrations in the different ashes from the reference case with wood pellets and the tests with 15% sludge as co-fuel and wood pellets as base fuel.

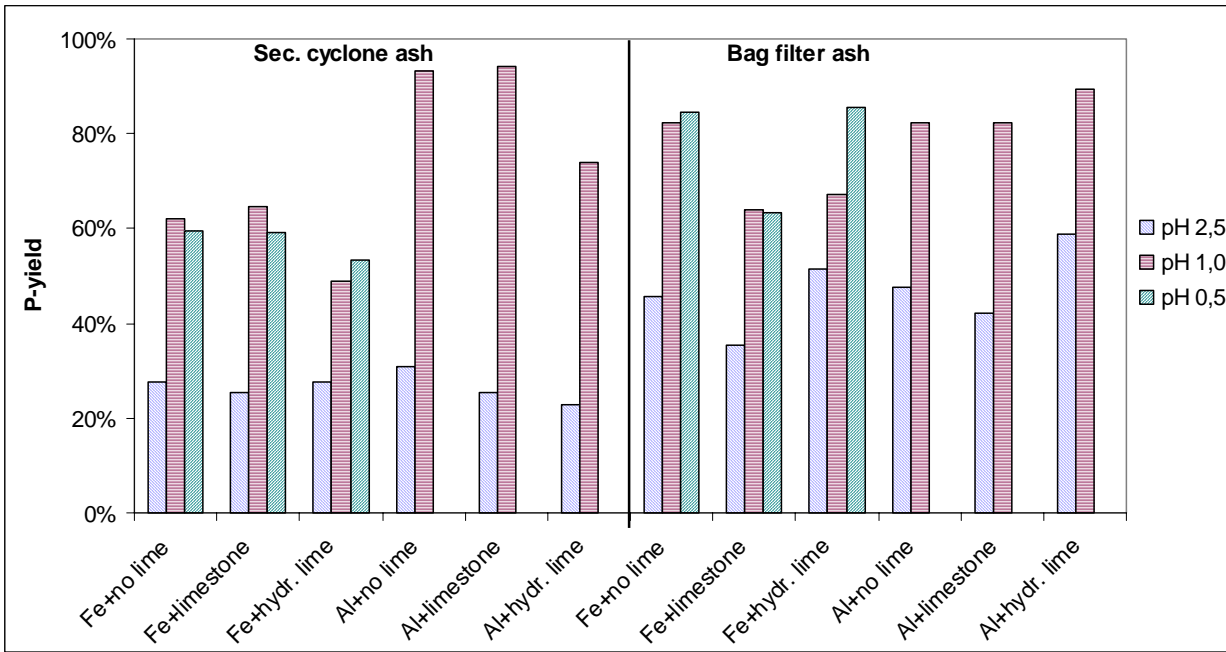


Figure 6: P-yield in leachate from secondary cyclone and bag filter ashes, leached with different pH.

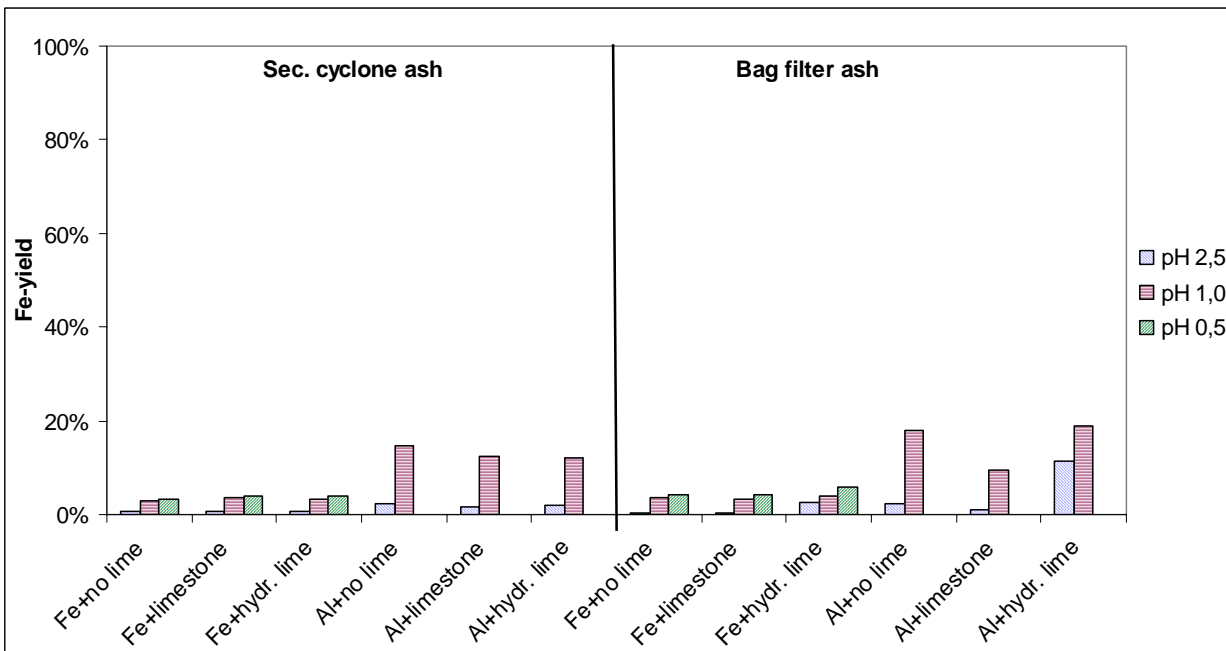


Figure 7: Fe-yield in leachate from secondary cyclone and bag filter ashes leached with different pH.

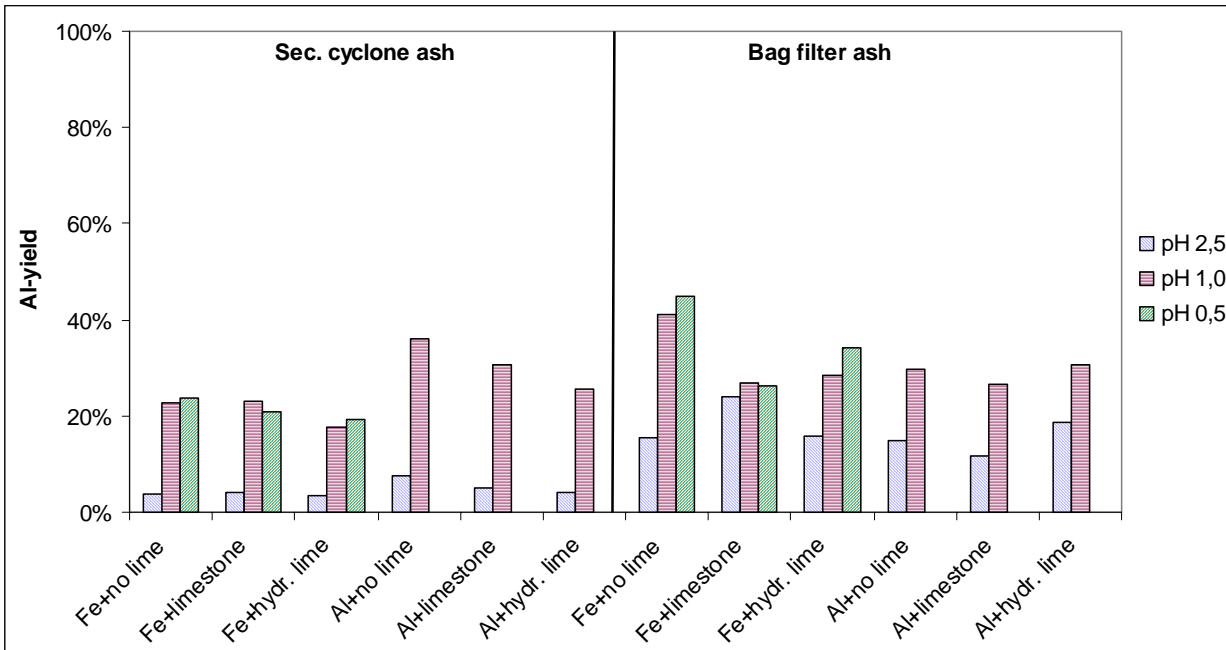


Figure 8: Al-yield in leachate from secondary cyclone and bag filter ashes leached with different pH.

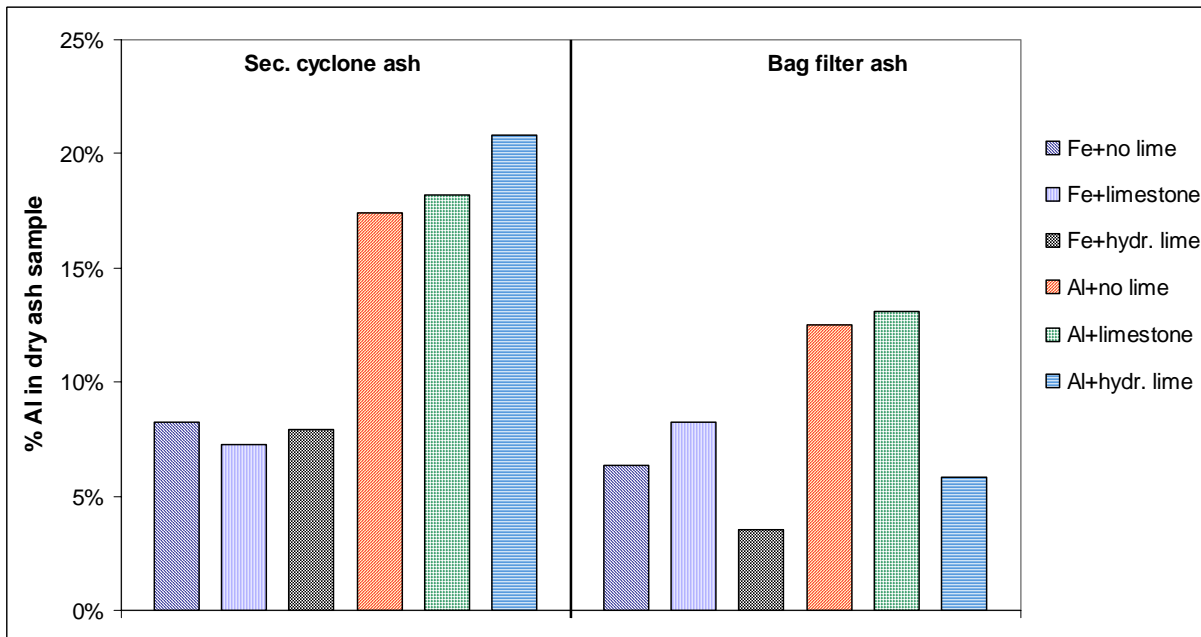


Figure 9: Aluminium concentrations in the different ashes from the reference case with wood pellets and the tests with 15% sludge as co-fuel and wood as base fuel.

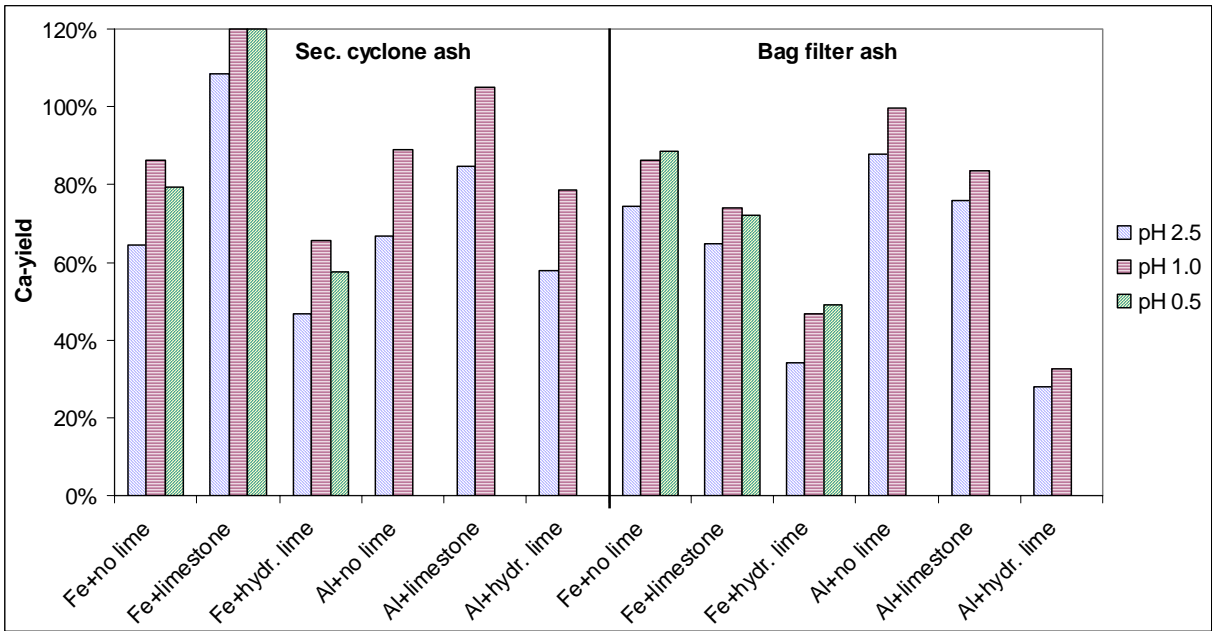


Figure 10: Ca-yield in leachate from secondary cyclone and bag filter ashes leached with different pH.