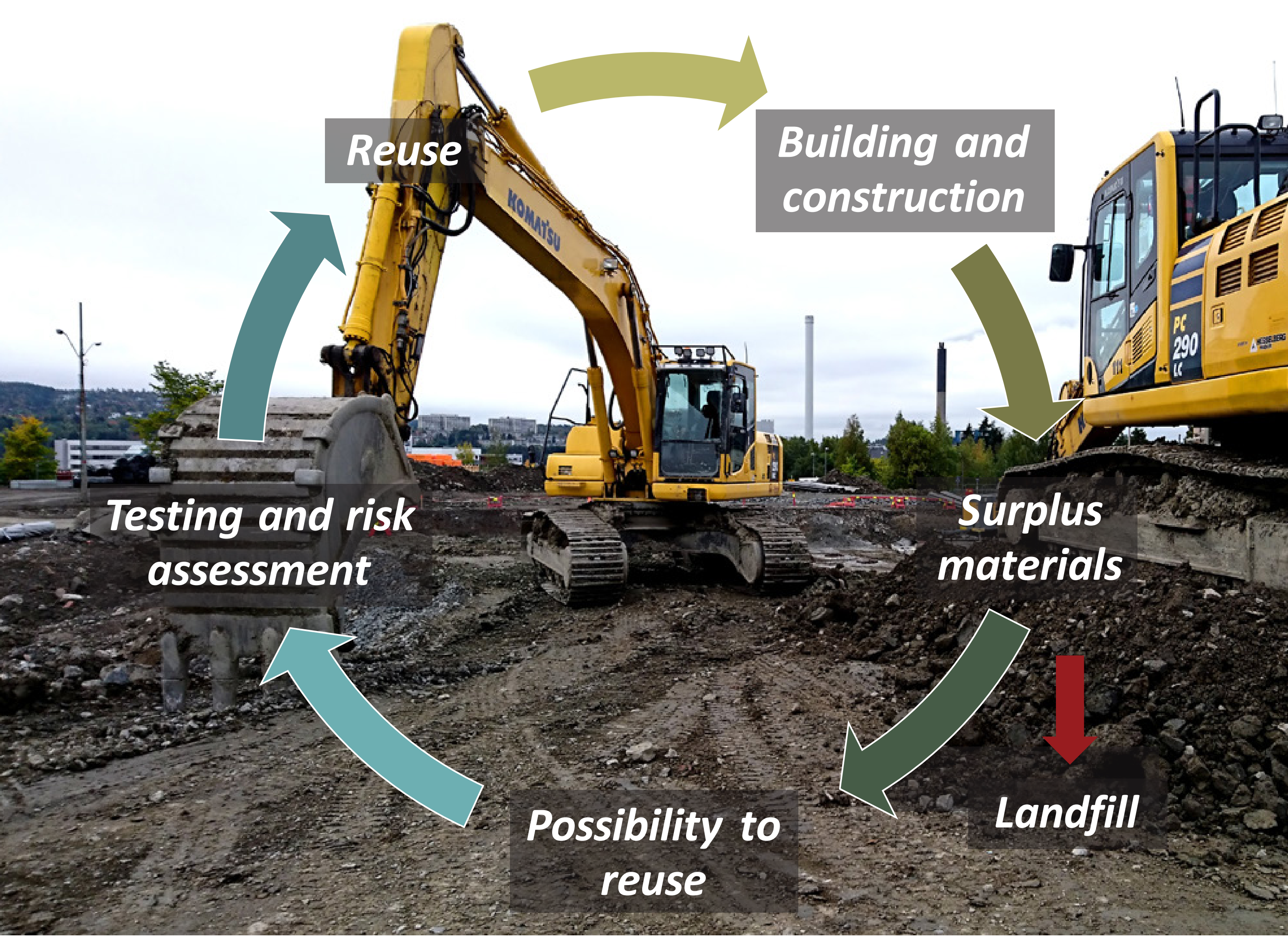
GEOreCIRC

WP2E: Research findings: reuse of lightly contaminated building and construction materials

NGI report 20160794-06-R

GEOreCIRC — GEOressurser i en sirkulær økonomi



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Project

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Abstract

Large scale construction and building projects often result in a surplus of materials, including soil and concrete. One of the goals set out in the Action Plan implemented via the Waste Framework Directive (2008/98/EC) is to achieve a 70 % recovery of construction and demolition waste.

Lightly contaminated soil is one fraction of building and construction waste that has a large potential for reuse, but there are several factors that hinder this:

- Perception: a lack of confidence, or uncertainty related to the quality of the lightly contaminated soil for a reuse purpose
- Definition: lightly contaminated soil is not defined clearly
- Regulation and guidance: there are no guidelines related to the reuse of lightly contaminated soil

In order to address these hinderances WP 2.E of the GEOreCIRC project has the following aim:

***To identify and carry out laboratory test that can be used in order to assess the hazard of pollutant release and dispersion in to the environment from low level contaminated soil*.**

There are several methods that can be used in order to better assess the hazard of soil pollutants. Traditionally total concentrations are used and these are compared to guideline values. The use of shake tests, column tests and passive samplers that allow the determination of leaching potential and bioavailable concentrations are very useful methods. In addition an extended column test that allows the determination of leaching potential and soil hydraulic conductivity simultaneously was developed here.

A method that can be used to reduce the hazard from soil on the environment is stabilization. Within this method, a sorbent material with a high capacity to bind and stabilize pollutants is added to the contaminated soil. This results in the pollutants themselves being locked up and unavailable to the surrounding environment.

Two case studies were focused on: 1) a soil that was contaminated with PAHs at a low concentration and 2) a soil that was contaminated with per- and polyfluoroalkyl substances (PFAS) at a high concentration. In the first case study the test methods above were used in order to assess their suitability from a risk assessment perspective. In the second case study stabilization with activated carbon was carried out.

Results from case study one show that the combined use of a shake test, a column test, passive sampling and an extended column test provides a very solid basis for the assessment of hazard. These methods could be used in order to decide whether lightly contaminated soil can be reused. A site specific risk assessment is also recommended in order to support this decision making process.

Results from case study two show that stabilization is a promising method for the treatment of PFAS contaminated soil as it effectively reduces leaching. When deciding whether stabilization is suitable in the context of reuse of contaminated soil it is important to consider the fact that stabilization effects are soil and sorbent material specific. Adding an infinite amount of sorbent material to a contaminated soil will increase volume and must be considered for a cost-benefit point of view.

A decision tree for the reuse of lightly contaminated soil is presented.

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1 Introduction

Large scale construction and building projects often result in a surplus of materials, including soil and concrete. Based on volume alone, construction and demolition waste is the largest waste stream in the EU (SSB 2019). These materials are often only lightly contaminated, however this can be a problem related to their future use / reuse.

The European Commission's Circular Economy Action Plan includes a legislative proposal on waste and provides long term targets to reduce landfilling and increase recycling and reuse (http://ec.europa.eu/environment/circular-economy/implementation_report.pdf). On the 9th November 2016, the European Commission proposed an industry-wide voluntary protocol on the management of construction and demolition waste. The aim of the protocol is to improve the identification, source separation and collection of waste, as well as logistics, processing, and quality management. The protocol will thus increase trust in the quality of recycled materials and encourage their further use in the construction sector.

One of the goals set out in the Action Plan implemented via the Waste Framework Directive (2008/98/EC) is to achieve a 70 % recovery of construction and demolition waste. Waste and excess material from building and construction projects must therefore be considered a resource that can be used further in its life time. A shift towards a more circular economy and the achievement of this goal will lead to more sustainable solutions to modern environmental problems. If such a paradigm shift can be achieved, then economic and societal gains will be significant.

1.1 The problem with lightly contaminated waste materials

There are several problems that need to be overcome before the target in the Waste Framework Directive can be achieved. Currently all materials that are not recovered are sent to landfill and this is neither sustainable nor cost effective.

The first problem related to the reuse of contaminated waste relates to perceptions, where there is a general lack of confidence, or uncertainty related to the quality of construction and demolition recycled materials. In order to reuse such materials, both geotechnical and chemical properties must be achieved that show the materials are safe to be used both from a construction and pollution point of view. If insufficient documentation exists to provide potential users of these materials with this information, there may be reluctance to use them.

The second large problem relates to the definition of construction and demolition waste. One of the largest fractions of such waste is soil that is contaminated at a low level. However, a working definition of the term "low level contaminated soils" is lacking. The Norwegian Environment Agency currently classifies soil according to the total concentration of organic and inorganic pollutants it contains (SFT, 2009). Five categories are defined according to a sliding concentration scale (classes 1 to 5) and they represent the following soil qualities; very good (class 1), good (class 2), moderate (class 3), bad (class 4) and very bad (class 5). In principle low level contaminated soil could be considered as any soil with concentrations over the values in class 1, but below the values for class 4. However, this definition only takes in to consideration total pollutant concentrations and is therefore subjective.

A third problem is related to current legislation regarding permitted reuse of contaminated soils. Once a soil is dug up and removed from a site it must be treated as waste according to the Waste Framework Directive (2008/98/EC). This means that it must be classified based on total concentrations and also leachability of the pollutants it contains. This classification and definition hinders two things 1) acceptable reuse applications and 2) movement of the soil between sites. The opening for reuse is allowed if the materials do not represent a risk of spreading contaminants to the environment.

In addition, the movement of low level contaminated soils from one site to another is not permitted when considering reuse, unless a special permit has been granted to do so. This can be regardless of the fact that the low level contaminated soil fulfils the designated reuse criteria for the site the material is intended to be moved to. The Norwegian Environment Agency has recognized that this is a common and often very costly problem in large projects. There are no clear guidelines and methods that currently exist in order to assess the risk that such low level contaminated soil poses to the surrounding environment if it is moved from one site to another. As such finding solutions to this problem are severely hampered.

Currently the Norwegian Environment Agency has published guidelines related to the storage and final disposal of soil and stones that are not contaminated (Miljødirektoratet, 2018). This guidance document does not contain any reference to lightly contaminated materials. However the guidance document formalizes the requirements for the reuse of soil and rocks which are considered waste fractions. Further the guidance states that is it necessary to assess risk and apply for a permit if there is any chance that the reuse application might result in spreading of contaminants.

2 Problematic physico-chemical parameters of waste

The vast majority of waste fractions (including lightly contaminated soil) contain levels of pollution that warrant assessment in order to determine whether they pose a threat to the surrounding environment or human health. One method that can be used in order to obtain an answer to this question is to quantify the level of leaching of pollutants from the waste fraction. Threshold levels do exist for acceptable leaching from waste fractions in cases where they will be sent to inert and ordinary landfills and in cases where hazardous waste will be stabilized and then disposed of at an ordinary landfill (Avfallsforskriften 2004). Leaching from waste materials is determined in the laboratory following standard method EN 12457-2, a batch shake test and CEN/TS 14405 a column test. Following this, a comparison of leached concentrations with limit values is carried out in order to determine to which type of landfill the waste should be sent. The leaching threshold values are based on back calculation from a threshold level that is protective of groundwater that are derived using a simplified hydrogeological model where a certain protective barrier around the waste is included.

Currently there are no guideline threshold levels that can be used in order to assess whether leachate concentrations are "safe" or "unsafe" for the surrounding environment and human health in cases where reuse of the waste fraction is desirable. However, one must assume that the waste to be reused contains lower leachable concentrations that those for disposal of at an inert landfill, in cases where it is desirable to reuse the waste.

3 The aims of WP 2.E

WP 2.E has the main overall aim of ***identifying and carrying out laboratory test that can be used in order to assess the hazard of pollutant release and dispersion in to the environment from low level contaminated soil***.

This will be achieved by identifying case study sites which have a surplus of low level contaminated soil (organic or inorganic pollutants), in which it would be desirable to increase the reuse of the soils. A laboratory program will be designed to test the most promising methods that allow one to identify the hazard a pollutant release presents and could ultimately be used in order to assess whether low level contaminated soil can be designated as a promising reuse material.

In addition WP2.E will investigate whether chemical stabilization can be used a method to reduce the risk of pollutant release from the soils. One case study site will be selected and several amendment materials will be added to the contaminated soil and then level of pollutant release monitored.

4 Tests that can be used to assess hazard

In order to ascertain whether lightly contaminated soil poses a hazard to the surrounding environment and human health, several methods can be used. Only when both the hazard and the likelihood of exposure are considered together, can risk be determined, as risk is a function of hazard and exposure.

4.1 Total concentrations

Currently the assessment of hazard is most often determined by measuring the total pollutant concentration of a material and comparing the values with guidelines that have been set in order to protect the environment and human health. As outlined earlier there are no guideline values that can be compared to in order to determine whether lightly contaminated soil can be reused.

4.2 Bioavailable concentrations

It is widely accepted that the concentration of pollutants that actually has the potential to cause harm to the environment and human health is the bioavailable concentration (Reichenberg and Mayer 2006, Ehlers et al., 2003). This concentration is a measure of the concentration of pollutants that can be accumulated by organisms in the surrounding environment.

There are several methods that can be used in order to determine bioavailable concentrations of organic and inorganic pollutants including the use of passive samplers, extraction methods for soil which are less harsh than those use to determine total concentrations and the application of physicochemical models that rely on an understanding of the partitioning of the pollutants between environmental compartments. Further information can be found in NGI report 20160794-02-R (NGI 2019a)

Currently using bioavailable concentrations in order to assess hazard is not included in any Norwegian or European legislation, despite a scientific consensus that a determination of bioavailability provides a better picture of hazard. The water framework directive (Directive 2000/60/EC) opens up for the possibility of the use of methods that determine bioavailable concentrations as it states that monitoring should be carried out using the "best available techniques", but it does not provide any guideline values to be compared to that are based on bioavailable concentrations.

4.3 Leaching potential

The Norwegian Waste Regulations name two specific methods as well as providing concentration limits values, that can be used in order to determine the hazard a waste material, with the intention of being sent to landfill, could pose to the surrounding environment and human health. The concentration threshold levels are set at a level at which leaching to the surrounding environment is assumed to be acceptable. The two methods that are named are batch shake tests and column tests. The batch shake tests represent a worst case scenario, while the column tests are more representative of real field conditions.

4.3.1 Batch shake tests

The batch shake test is carried out according to NS-EN 12457/1-3 and simulates a worst case scenario with respect to leaching of pollutants from a material. In brief, this test encompasses the following: Sieving the soil to 4 mm before use and determining the water content. Following this, soil (175 ± 5g) is added to a 500 ml plastic (for inorganic tests) or glass (for organic tests) bottle along with deionised water at a volume corresponding to an L/S ratio of 2. The bottle is closed and placed on an end over end shaker for 24 hours. Following this time period the bottle is removed from the shaking table and left to settle for 15 minutes before being filtered through a 0.45 μm filter paper using a high pressure filter set up. The collected eluate is sent to an accredited laboratory for chemical analysis. The pH and conductivity of the water is measured following filtration.

4.3.2 Column tests

The column test is carried out according to European standard NS-EN 14405:2017 and it is carried out to estimate short and middle term leaching of pollutants from various materials. The column is prepared by placing a polypropylene cork and a 0.45 μm membrane filter in the bottom of a column with a diameter of 5 cm. The sample is added to the column to a height of 30 cm ± 5 cm in five stages. First, approximately 6 cm of sample is added to the column and then the material is compacted using a specially designed piece of equipment with a weight (125 or 500 g depending on the column size) at the top of a rod which is dropped on to the sample three times. The process is repeated until the full 30 cm is added to the column. The column is topped with another 0.45 μm filter and a polypropylene top. The column is weighed and then a Teflon tube is connected to the bottom before it is placed in a stand and connected to a peristaltic pump. The test is carried out at room temperature.

Before the test begins the column is wetted from the bottom until water starts to come out of the top. The column is allowed to stand for three days to reach equilibrium before the test then begins. At this point the pump is started and water is pumped with a linear speed that corresponds to 15 ± 2 cm/day through an empty column, which is a flow rate of 12.3 ml/hour for a column with a 5 cm diameter and 49.0 ml/hour for a column with a 10 cm diameter.

Water is pumped through the column until L/S 0.1 and L/S 10 which correspond to 0.1 and 10 times the dry weight of the sample that was added to the column. The pH is measured in the eluate.

5 Methods that can be used to reduce hazard

5.1 Stabilisation

In order to reduce the hazard of a soil, one method that could be used is stabilisation. Within this method a small amount of a strongly sorbing material is added to a contaminated soil in order to bind and essentially lock up the pollutants in order that the leaching to the surrounding environment is reduced. When the strongly sorbing material is added to the soil then there is a mass transfer of the soil pollutants to the sorbent material. There are many scientific publications that show this method can be used for soils contaminated with polycyclic aromatic hydrocarbons (Hale et al., 2012), pesticides (Hilber et al, 2009), polychlorinated biphenyls (Vasilyeva et al., 2010) and per- and polyfluoroalkyl substances (Hale et al., 2017).

6 Case study 1: Large building and construction project

6.1 Site description

The redevelopment company OBOS (member in the project reference group) is currently building a large number of housing and service complexes throughout the Oslo area. In connection with the project being carried out at Brobekkveien 62B at Vollebekk in Oslo, soil that was designated to be removed from the site and sent to landfill was used as case study 1 for WP2.E. Figure 1 below shows the site which has gnr. 123, bnr. 7, and gnr./bnr. 122/425. The total area of the site is approximately 37 000m^2.

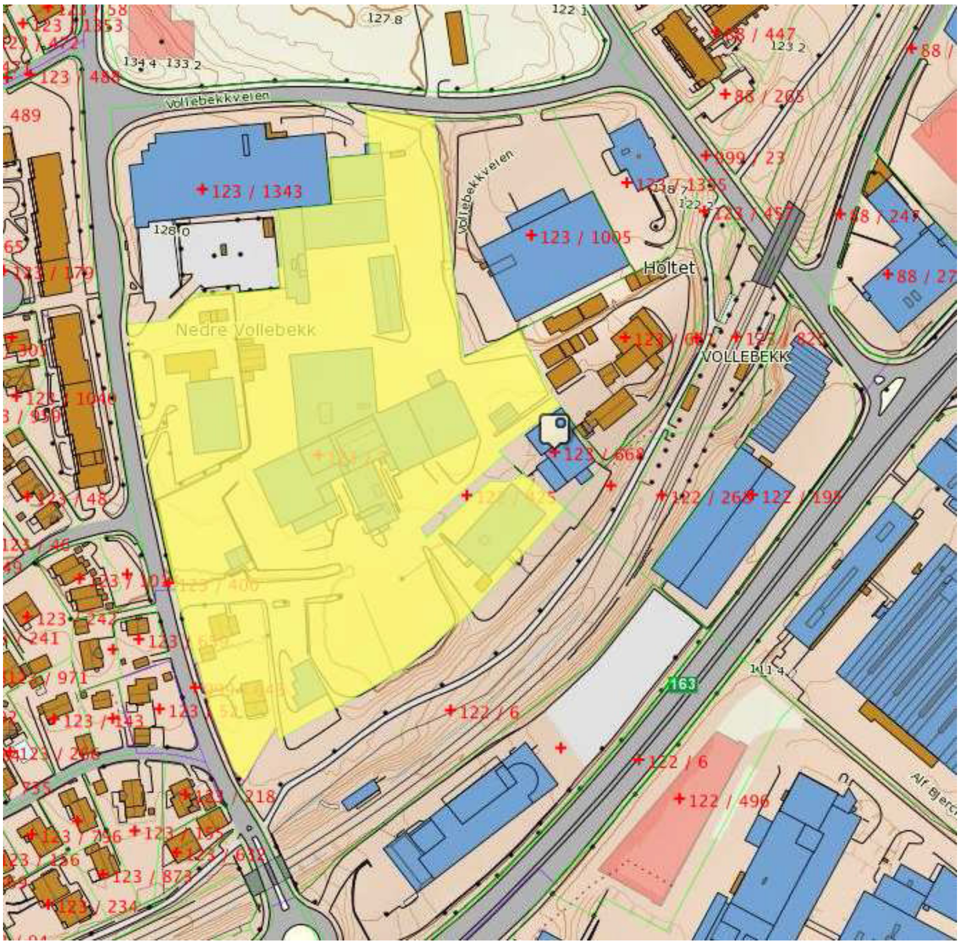

Figure 1: location of the site for case study 1

6.2 Methods

6.2.1 Previous site assessments

OBOS had undertaken several site assessments in order to classify the soil from the site according to the Norwegian Environment Agency's helsebaserte tilstandssklasser (SFT 2007). This information was used, along with site logistics (when certain areas of the site were going to be excavated), when deciding where to obtain the soil to use in this case study. Figure 2 shows the results of a previous site assessment and the corresponding classification of the level of pollution in the soil (Multiconsult 2017).

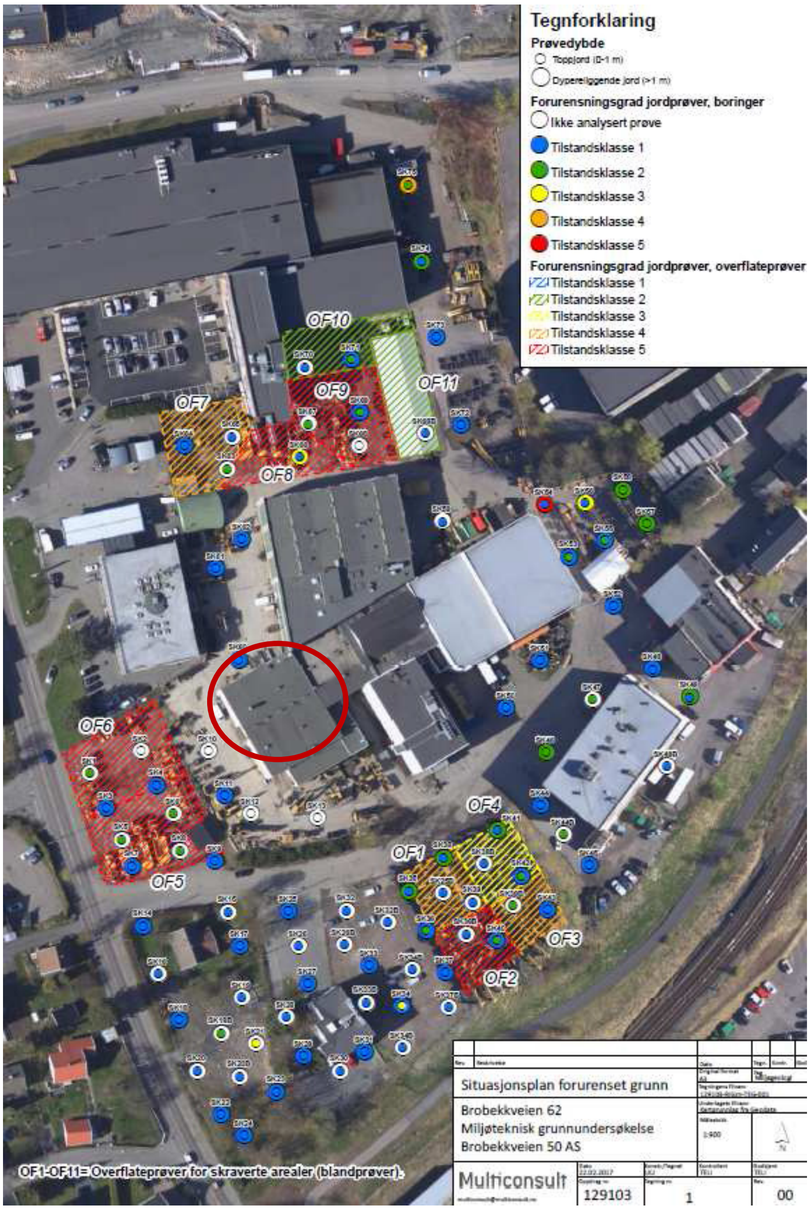

Figure 2: results from a previous site assessment and the corresponding classification of soil according to the Norwegian Environment Agency's helsebaserte tilstandssklasser.

6.2.2 Soil sampling

Soil samples were taken from four different locations in the red circle shown in figure 2 and are referred to as Vollbekk 1, 2, 3 and 4 throughout. Samples 1, 3 and 4 were taken as a mixed sample from the top soil (1 m depth) and sample 2 was taken from a depth of 2 m, while the area was being excavated and the soil was being taken to a landfill. Vollbekk 1 contained a lot of stones and clay, smelt of oil and was earlier classified as contaminant class 3-4 (Multiconsult 2017). Vollbekk 2 consisted of a lot of clay and very little surplus material (including concrete, bricks and previously excavated soil), often used to add volume in such cases. Vollebekk 3 contained stones, gravel and sand and the amount of smaller particles that could be taken during sampling was limited. Vollebekk 4 consisted of surplus materials, stones, gravel, sand and some pieces of wood and asphalt. Figure 3 shows photographs of the 4 samples.

	
Vollebekk 1	Vollebekk 2
	
Vollebekk 3	Vollebekk 4

Figure 3: Photographs of soil samples Vollebekk 1, 2, 3 and 4

6.2.3 Laboratory tests

A laboratory program was designed in order to investigate the following questions:

- Can total concentrations be used as to represent the risk a contaminated soil presents?
- Is there a better method that can be used in order to more accurately assess risk?
- Do passive samples have a role to play in this assessment?

Table 1 shows the laboratory program that was carried out on sample Vollebekk 4. As discussed below, all samples, except Vollebekk 4 were classified as clean (according to the Norwegian Environment Agency's classification scheme), and inert (according to the Norwegian Waste Regulations), despite previous site investigations indicating this may not be the case. Vollebekk 4 was the only sample that contained any pollutants above the "clean" concentration limits and was therefore used in all tests.

Table 1: Laboratory program

Test 1	*Test*	*Total concentration*
	Variables	Standard laboratory extraction
	Analysis	Organic and inorganic analysis
Tests 2 and 3	*Test*	*Batch shake test*
	Variables	Standard test without polyethylene (PE) passive sampler, and modified test with PE passive sampler
	Analysis	Organic and inorganic analysis for the water (test 2) and organic analysis for the water and the PE (test 3)
Test 4	*Test*	*Batch shake test*
	Variables	Standard test followed by the exposure of PE to the water phase
	Analysis	Organic analysis for the water and the PE
Test 5	*Test*	*Column test*
	Variables	Standard test collecting eluate at L/S 0,1 and 10
	Analysis	Organic and inorganic analysis for the water
Test 6	*Test*	*Column test*
	Variables	Use the samples from test 5, expose PE to eluate from L/S 10 (worst case)
	Analysis	Organic analysis for the PE

The laboratory program consisted of the determination of both total and bioavailable pollutant concentrations using a combination of leachability tests (batch shake test and column test).

Passive samplers were chosen as the method to be used in order to assess bioavailable concentrations. Passive samplers can be used in order to determine bioavailable concentrations of organic pollutants and metals depending on the sampler chosen. In this work a polyethylene passive sampler was used to monitor organic pollutant concentrations based on previous experience with this type of sampler (Adams et al 2007). Passive samplers passively accumulate pollutants when they are exposed to a contaminated soil, sediment or water until an equilibrium is established. Using predetermined partitioning coefficients for the pollutants of interest that are available in the scientific literature, bioavailable porewater (in the case of soil or sediment) and water concentrations can be determined. The polyethylene passive sampler used here is able to determine bioavailable concentrations of organic pollutants only. Bioavailable concentrations of inorganic pollutants can be determined using different sampler types (for example a diffusive gradient thin film, DGT, sampler) (Morin et al 2015).

6.2.4 Test descriptions

Test 1: Total concentrations

All soil samples were sent to accredited laboratory ALS Laboratories for analysis of organic and inorganic pollutants. The following pollutants and methods were used; heavy metals with method DS259, PCB-7 with method EN ISO 15308 and EPA 35550C, PAH with method REFLAB 4:2008, BTEX with method REFLAB 1:2010 and the determination of aliphatics using a GCMS method.

Tests 2, 3 and 4: Shake tests

Tests 2, 3 and 4 were carried out according to EN 12457-2. This method is a standard shake test which is used to quantify the amount of leaching from a material. Test 2 was carried out without modification. Test 3 was carried out using a modified method in which a polyethylene passive sampler was included in the batch test itself and that analysis of organic pollutants was carried out for the passive sampler only. Test 4 was carried out in stages. In the first stage a standard shake test was carried out, and following this, a PE passive sampler was exposed to the water leachate. Analysis was carried out only for the PE passive sampler.

All three tests provide additional and complimentary information to each other with regards to the risk that the organic pollutants contained in the soil pose to the environment and human health. Test 2 provides a worst case scenario in which the harshest conditions were used in order to maximize leaching of pollutants of organic pollutants. Test 3 provides more realistic conditions as the passive sampler measures bioavailable and not total water concentrations of organic pollutants. It is well known and accepted that the risk organic pollutants pose to the environment and human health is better correlated with bioavailable, and not total, water concentrations. Test 4 was carried out in order to ascertain whether there were any differences between the inclusion of a passive sampler in the original shake test itself and a batch containing only contaminated water.

Concentrations determined in the water in µg/L were used to calculate the leachable concentrations in mg/kg and a comparison to the threshold levels in the Norwegian waste regulations was carried out.

Concentrations in the PE passive samplers were converted to bioavailable concentrations using literature PE-water partitioning coefficients ($K_{PE\text{-}w}$ L/kg) (ref), according to the following equation

$K_{PE\text{-}w} = C_{PE} / C_W$

Tests 5 and 6: column tests

Tests 5 was carried out in accordance with the European standard NS-EN 14405:2017 (see section 4.3.2 for more description). This is a standard method used to determine the leaching behaviour of pollutants from granular waste. The sample is subjected to upward flow percolation where water moves slowly up through the sample. The amount of water percolated is calculated using specified liquid to solid ratios. It is a once through column leaching test that demonstrates the difference between release patterns of pollutants.

Test 5 was carried out without modification, collecting eluates at L/S 0.1 and 10. Water from the eluates was then analysed for organic and inorganic pollutants. In test 6, a PE passive sampler was exposed to water from eluate L/S = 10 (worst case scenario). The PE passive sampler was then analysed for organic pollutants.

6.3 Results

6.3.1 Test 1: Total concentrations

Table 2 shows the measured total concentrations of organic and inorganic pollutants contained in Vollebekk 1, 2, 3 and 4 samples. In addition, the measured concentrations are compared to the threshold levels for inert waste according to the Norwegian waste regulations (Avfallsforskriften). All four samples were classified as inert waste as none of the threshold levels were exceeded. The total concentrations were also compared to the threshold levels for contaminated soil that are used by the Norwegian Environment Agency in order to determine the degree of pollution in a soil. All samples, except Vollebekk 4 were classified as class 1 which corresponds to clean soil. Vollebekk 4 was classified as class 2 which corresponds to lightly contaminated soil based on the concentration of benzo(a)pyrene and sum PAH-16. None of the concentrations are over the threshold levels for disposal at an inert landfill.

Table 2: Total concentrations (mg/kg) of organic and inorganic pollutants contained in Vollebekk 1, 2, 3 and 4. The table also shows a comparison with the Norwegian waste regulations for inert waste (Avfallsforskriften)

	Vollebekk 1	Vollebekk 2	Vollebekk 3	Vollebekk 4	Concentration threshold levels for inert waste
As (Arsenic)	2	3.8	<0.5	4	
Cd (Cadmium)	0.26	0.43	0.11	0.29	
Cr (Chromium)	42	37	30	28	
Cu (Copper)	42	28	20	23	
Hg (Mercury)	0.03	0.02	0.02	0.03	
Ni (Nickle)	46	37	22	29	
Pb (Lead)	16	16	4	14	
Zn (Zinc)	89	95	43	66	
PCB 28	<0.0010	<0.0010	<0.0010	<0.0010	

	Vollebekk 1	Vollebekk 2	Vollebekk 3	Vollebekk 4	Concentration threshold levels for inert waste
PCB 52	<0.0010	<0.0010	<0.0010	<0.0010	
PCB 101	<0.0010	<0.0010	<0.0010	0.001	
PCB 118	<0.0010	<0.0010	<0.0010	<0.0010	
PCB 138	<0.0010	<0.0010	<0.0010	0.0022	
PCB 153	<0.0010	<0.0010	<0.0010	0.0032	
PCB 180	<0.0010	<0.0010	<0.0010	<0.0010	
Sum PCB-7	n.d.	n.d.	n.d.	0.0064	1
Naphthalene	<0.010	<0.010	<0.010	0.016	
Acenaphtylene	<0.010	<0.010	<0.010	0.35	
Acenaphtene	<0.010	<0.010	<0.010	0.028	
Fluorene	<0.010	<0.010	<0.010	0.021	
Phenanthrene	<0.010	<0.010	<0.010	0.59	
Anthracene	<0.010	<0.010	<0.010	0.33	
Fluoranthene	0.011	<0.010	<0.010	1.2	
Pyrene	<0.010	<0.010	<0.010	1.1	
Benzo(a)anthracene	<0.010	<0.010	<0.010	0.42	
Chrysene	<0.010	<0.010	<0.010	0.36	
Benzo(b+j)fluoranthene	<0.010	<0.010	<0.010	0.46	
Benzo(k)fluoranthene	<0.010	<0.010	<0.010	0.17	
Benzo(a)pyrene	<0.010	<0.010	<0.010	0.38	2
Dibenzo(ah)anthracene	<0.010	<0.010	<0.010	0.082	
Benzo(ghi)perylene	<0.010	<0.010	<0.010	0.2	
Indeno(123cd)pyrene^	<0.010	<0.010	<0.010	0.18	
Sum PAH-16	0.011	n.d.	n.d.	5.89	20
Benzene	<0.010	<0.010	<0.010	<0.010	
Toluene	<0.040	<0.040	<0.040	<0.040	
Ethylbenzene	<0.040	<0.040	<0.040	<0.040	
Xylene	<0.040	<0.040	<0.040	<0.040	
Sum BTEX	n.d.	n.d.	n.d.	n.d.	6
Aliphatic >C5-C6	<2.5	<2.5	<2.5	<2.5	
Aliphatic >C6-C8	<2.0	<2.0	<2.0	<2.0	
Aliphatic >C8-C10	<2.0	<2.0	<2.0	<2.0	
Aliphatic >C10-C12	<5.0	<5.0	<5.0	<5.0	
Aliphatic >C12-C16	<5.0	<5.0	<5.0	<5.0	
Aliphatic >C16-C35	<10	<10	<10	44	
Sum Aliphatic >C12-C35	n.d.	n.d.	n.d.	44	
Sum Aliphatic >C5-C35	n.d.	n.d.	n.d.	44	500

n.d – not detected

6.3.2 Test 2: Standard shake test

Table 3 shows the concentration of inorganic pollutants in the leachate water from test 2 along with a comparison to limit concentrations given in the Norwegian waste regulations for inert, ordinary and hazardous waste (Avfallsforskriften). Threshold levels are currently only available for inorganic pollutants. The soil sample leaches very low concentrations of inorganic pollutants and is classified as inert waste.

Table 4 shows the concentration of organic pollutants contained in the water for shake test 2. In the majority of cases, the concentrations detected in the leachate water are below the limit of analytical detection. This supports the notion that the sample is only contaminated to a very low degree and that the leaching of organic pollutants to the surrounding environment and subsequent risk to human health is minimal.

Table 3: Concentration of inorganic pollutants contained in the water (µg/L), leachable contents mg/kg) and limit concentrations given in the Norwegian waste regulations (mg/kg) for standard shake test 2

			Comparison with waste regulations mg/kg		
	Water concentration	Leachable content	Inert waste	Ordinary waste	Hazardous waste
Pollutant	µg/L	mg/kg			
As (Arsenic)	3.35	0.0335	0.5	2	25
Cd (Cadmium)	0.0191	0.000191	0.04	1	5
Cr (Chromium)	4.26	0.0426	0.5	10	70
Cu (Copper)	8.68	0.0868	2	50	100
Hg (Mercury)	0.01125	0.0001125	0.01	0.2	2
Ni (Nickel)	1.76	0.0176	0.4	10	40
Pb (Lead)	0.9095	0.009095	0.5	10	50
Zn (zinc)	4.985	0.04985	4	50	50

Table 4: Concentration of organic pollutants contained in the water (µg/L and mg/kg)

	Water concentration	Solid concentration
Pollutant	µg/L	mg/kg
PCB 28	<0.00880	<0.0000880
PCB 52	<0.00880	<0.0000880
PCB 101	<0.00600	<0.0000600
PCB 118	<0.00880	<0.0000880
PCB 138	<0.00960	<0.000096
PCB 153	<0.00880	<0.0000880
PCB 180	<0.00760	<0.0000760
Sum PCB-7	n.d.	n.d.
Naphthalene	<0.030	<0.000300
Acenaphtylene	<0.010	<0.000100
Acenaphtene	0.0345	0.000345
Fluorene	0.023	0.00023
Phenanthrene	0.027	0.00027
Anthracene	0.0245	0.000245
Fluoranthene	0.2645	0.002645
Pyrene	0.2205	0.002205
Benzo(a)anthracene	0.025	0.00025
Chrysene	0.023	0.00023
Benzo(b+j)fluoranthene	0.0235	0.000235
Benszo(k)fluoranthene	0.012	0.00012
Benzo(a)pyrene	0.0185	0.000185
Dibenzo(ah)anthracene	<0.010	<0.000100
Benzo(ghi)perylene	<0.010	<0.000100
Indeno(123cd)pyrene	<0.010	<0.000100
Sum PAH-16	0.665	0.00665
Benzene	<0.20	<0.00200
Toluene	<0.50	<0.00500
Ethylbenzene	<0.10	<0.00100
Xylene	<0.10	<0.00100
Sum BTEX	<0.20	<0.00200
Aliphatic >C5-C6	n.d.	n.d.
Aliphatic >C6-C8	<5.0	<0.0500
Aliphatic >C8-C10	<5.0	<0.0500
Aliphatic >C10-C12	<5.0	<0.0500
Aliphatic >C12-C16	<5	<0.0500
Aliphatic >C16-C35	<5	<0.0500
Sum Aliphatic >C12-C35	<30	<0.300
Sum Aliphatic >C5-C35	n.d.	n.d.

6.3.3 Test 3: Shake test with PE passive sampler

In test 3, a PE passive sampler was added to the shake test batch in order to quantify the bioavailable pollutant concentration. Table 5 shows the results of the test for both the water concentrations and the bioavailable concentrations. As mentioned earlier, the PE sampler is only able to measure the concentration of organic pollutants. Owing to the concentration of PCBs, BTEX and aliphatics being below the analytical limit of detection in the water, these compounds were not analyzed in the PE. Thus, the focus of the PE analysis was on PAHs.

Table 5: Average water (µg/L) and bioavailable concentrations (ng/L) for test 3.

	Water concentration	Bioavailable concentration
Pollutant	µg/L	ng/L
As (Arsenic)	4.475	
Cd (Cadmium)	0.0753	
Cr (Chromium)	5.86	
Cu (Copper)	10.25	
Hg (Mercury)	0.00758	
Ni (Nickel)	3.01	
Pb (Lead)	1.69	
Zn (Zink)	12.45	
PCB 28	<0.00110	
PCB 52	<0.00110	
PCB 101	<0.000750	
PCB 118	<0.00110	
PCB 138	<0.00120	
PCB 153	<0.00110	
PCB 180	<0.000950	
Sum PCB-7	n.d.	
Naphthalene	<0.030	
Acenaphtylene	<0.010	1.12
Acenaphtene	<0.010	
Fluorene	<0.010	
Phenanthrene	0.024	
Anthracene	0.011	
Fluoranthene	0.026	2.60
Pyrene	0.066	1.76
Benzo(a)anthracene	<0.010	0.43
Chrysene	<0.010	0.22
Benzo(b+j)fluoranthene	<0.010	0.15

	Water concentration	Bioavailable concentration
Pollutant	µg/L	ng/L
Benszo(k)fluoranthene	<0.010	0.073
Benzo(a)pyrene	<0.010	0.18
Dibenzo(ah)anthracene	<0.010	0.00047
Benzo(ghi)perylene	<0.010	0.0028
Indeno(123cd)pyrene	<0.010	0.0049
Sum PAH-16	0.11	
Benzene	<0.20	
Toluene	<0.50	
Ethylbenzene	<0.10	
Xylene	<0.10	
Sum BTEX	<0.20	
Aliphatic >C5-C6	n.d.	
Aliphatic >C6-C8	<5.0	
Aliphatic >C8-C10	<5.0	
Aliphatic >C10-C12	<5.0	
Aliphatic >C12-C16	<5.0	
Aliphatic >C16-C35	<5.0	
Sum Aliphatic >C12-C35	<30.0	
Sum Aliphatic >C5-C35	n.d.	

In cases where values are not given, the concentration in the PE was below the LOD

From the results in table 5 it is clear that the bioavailable concentrations are extremely low when compared to the water concentrations, and that the risk posed by this soil is very low. Interesting to note is the fact that although the water concentrations are in some cases below the analytical LOD, the bioavailable concentration is above the LOD. This highlights the greater sensitivity of using such a method.

6.3.4 Test 4: Shake test followed by exposure of PE to water phase

Test 4 was carried out by first running a standard shake test (as for test 2) and then exposing a PE passive sampler to the water in order to determine bioavailable concentrations. Table 6 shows the results of the test for the water concentrations and then the subsequently determined bioavailable concentrations.

Table 6: Average water (µg/L) and bioavailable concentrations (ng/L) for test 4

Pollutant	Water concentration	Bioavailable concentrations
	µg/L	ng/L
As (Arsenic)	4.47	
Cd (Cadmium)	0.0978	
Cr (Chromium)	6.765	
Cu (Copper)	9.33	
Hg (Mercury)	0.01341	
Ni (Nickel)	2.68	
Pb (Lead)	1.435	
Zn (Zink)	8.36	
PCB 28	<0.00110	
PCB 52	<0.00110	
PCB 101	<0.000750	
PCB 118	<0.00110	
PCB 138	<0.00120	
PCB 153	<0.00110	
PCB 180	<0.000950	
Sum PCB-7	n.d.	
Naphthalene	<0.030	
Acenaphtylene	<0.010	
Acenaphtene	<0.010	
Fluorene	<0.010	
Phenanthrene	0.035	
Anthracene	0.012	
Fluoranthene	0.0445	0,378
Pyrene	0.068	0,870
Benzo(a)anthracene	<0.010	
Chrysene	<0.010	
Benzo(b+j)fluoranthene	<0.010	0,0027
Benzo(k)fluoranthene	<0.010	0,0020
Benzo(a)pyrene	<0.010	0,0032
Dibenzo(ah)anthracene	<0.010	
Benzo(ghi)perylene	<0.010	
Indeno(123cd)pyrene	<0.010	
Sum PAH-16	0.1355	
Benzene	<0.20	
Toluene	<0.50	
Ethylbenzene	<0.10	
Xylene	<0.10	
Sum BTEX	<0.20	

Pollutant	Water concentration	Bioavailable concentrations
Aliphatic >C5-C6	n.d.	
Aliphatic >C6-C8	<5.0	
Aliphatic >C8-C10	<5.0	
Aliphatic >C10-C12	<5.0	
Aliphatic >C12-C16	<5.0	
Aliphatic >C16-C35	<5.0	
Sum Aliphatic >C12-C35	<30.0	
Sum Aliphatic >C5-C35	n.d.	

In cases where values are not given, the concentration in the PE was below the LOD

As expected, the concentrations in the water for tests 3 and 4 are extremely similar (mostly below 20 % difference). Bioavailable concentrations are lower in test 4 compared to test 3 and this suggests that exposure to water following a shake test provides a more conservative estimate of the hazard posed.

6.3.5 Test 5: Standard column test

Test 5 was carried out as a standard column test where the eluate was collected at L/S 0.1 and 10. Table 7 shows the concentrations in the eluate compared to the threshold levels given in the hazardous waste regulations. Only concentrations of pollutants above the analytical limit of detection are shown.

Table 7: Concentration of inorganic pollutants contained in the eluate from column test 5 for the eluate collected at L/S 0.1 and L/S 10 as well as the threshold levels for the Norwegian waste regulations (µg/L) for the L/S 0.1 eluate

	L/S 0.1 column eluate (µg/L)	L/S 10 column eluate (µg/L)	Inert waste (µg/L)	Ordinary waste (µg/L)	Stabilized hazardous waste sent to ordinary landfill (µg/L)
As (Arsenic)	5.39	13.4	60	300	3000
Cd (Cadmium)	0.246	0.0696	20	300	1700
Cr (Chromium)	1.5	10.7	100	2500	15000
Cu (Copper)	48.4	27	600	30000	60000
Hg (Mercury)	0.0691	0.0437	2	30	300
Ni (Nickle)	11.9	7.76	120	3000	12000
Pb (Lead)	0.788	5.22	150	3000	15000
Zn (Zinc)	18.1	31.8	4000	15000	60000

The volume of leachate collected for the test with L/S 0.1 was only sufficient to determine the concentration of inorganic pollutants, however the volume collected from the L/S 10 test was also sufficient for the quantification of organic pollutants. Table 8 shows these results. There are currently no threshold levels for organic pollutants with respect to disposal at different category landfill sites. The results from the concentration of inorganic pollutants in the leachate show that they are lower, in all cases, than the threshold levels for an inert landfill.

Table 8: Concentration of organic pollutants contained in the eluate from column test 5 for the eluate collected at L/S 10

Pollutant	**L/S 10 column eluate (µg/L)**	**Pollutant**	**L/S 10 column eluate (µg/L)**
PCB 28	<0.00110	Benzo(k)fluoranthene	<0.010
PCB 52	<0.00110	Benzo(a)pyrene	0.01
PCB 101	<0.000750	Dibenzo(ah)anthracene	<0.010
PCB 118	<0.00110	Benzo(ghi)perylene	<0.010
PCB 138	<0.00120	Indeno(123cd)pyrene	<0.010
PCB 153	<0.00110	Sum PAH-16	0.12
PCB 180	<0.000950	Benzene	<0.20
Sum PCB-7	n.d.	Toluene	<0.50
Naphthalene	<0.030	Ethylbenzene	<0.10
Acenaphtylene	<0.010	Xylene	<0.10
Acenaphtene	<0.010	Sum BTEX	<0.20
Fluorene	<0.010	Aliphatic >C5-C6	n.d.
Phenanthrene	<0.020	Aliphatic >C6-C8	<5.0
Anthracene	<0.010	Aliphatic >C8-C10	<5.0
Fluoranthene	<0.010	Aliphatic >C10-C12	<5.0
Pyrene	0.094	Aliphatic >C12-C16	<5.0
Benzo(a)anthracene	<0.010	Aliphatic >C16-C35	<5.0
Chrysene	<0.010	Sum Aliphatic >C12-C35	<30.0
Benzo(b)fluoranthene	0.011	Sum Aliphatic >C5-C35	n.d.

The concentrations in table 8 are all very low and there are only 4 chemicals detected. These results confirm the fact that the shake test represents the worst case scenario, whilst the column tests is more representative of what would happen in the field, representing middle (L/S 10) term leaching.

6.3.6 Test 6: Exposure of PE to eluate from L/S 10 standard column test

Test 6 involved exposing PE to the leachate from the standard column test (test 5) and results are shown in table 9.

Table 9: Bioavailable concentrations following exposure of PE to eluate from column tests 5

Pollutant	Bioavailable concentrations
	ng/L
Naphthalene	11.02
Acenaphtylene	
Acenaphtene	
Fluorene	
Phenanthrene	0.70
Anthracene	
Fluoranthene	0.11
Pyrene	0.13
Benzo(a)anthracene	
Chrysene	
Benzo(b+j)fluoranthene	
Benzo(k)fluoranthene	
Benzo(a)pyrene	
Dibenzo(ah)anthracene	
Benzo(ghi)perylene	
Indeno(123cd)pyrene	

In cases where values are not given, the concentration in the PE was below the LOD

The relatively high concentration of naphthalene is likely due to an artefact. In concurrence with the results for the shake test in which PE was exposed, the bioavailable pollutant concentrations in this soil are extremely low. Based on the use of the more representative test for real world hazard, it can be concluded that this sample poses a very minimal hazard to the environment.

6.4 Conclusions: use of passive samplers as a tool for risk assessment of lightly contaminated soil

The soil chosen to carry out the experiments above was from a site under redevelopment by OBOS (a member of the project reference group). The soil itself was only lightly contaminated, and based on total concentrations was class 2 soil. Results of the leachability tests (shake and column tests) showed that the leaching of pollutants was minimal.

In order to assess this further, PE passive samplers were used to determine bioavailable concentrations both in the shake and column tests. Bioavailable concentrations were extremely low (ng/L) range and the hazard the soil poses can be concluded as very low to negligible. The values are lower than Environmental Quality Standards (EQS) for water, as well as PNEC values for water.

Passive samplers have therefore proven to provide a better assessment of the real world hazard a soil can pose. They are a useful additional tool for regulators in order to determine realistic measures of environmental damage and thus could be included in the decision making process surrounding the reuse of lightly contaminated soil. Bioavailable concentrations are very relevant in the context of uptake from soil to organisms, plants and soil ingested by humans. However, these concentrations are less relevant in cases where transport occurs via particle erosion and leaching to groundwater. This is especially true for PAHs, PCBs and heavy metals which can be colloidal or dissolved organic carbon (DOC) bound and hence have a high transport pathway and potential for environmental spreading. This can be despite bioavailable concentrations are low. In addition, there may be cases where soil concentrations are low, but the amount of lightly contaminated soil for reuse is large, and the recipient water body is small. These three factors will lead to an increased risk.

Therefore it is important that a site specific assessment of leaching is carried out that takes in to consideration the total amount of pollutants that will spread and how this will affect local groundwater and surface water. Such an assessment can be done by using a relatively simple box model, based on basic hydrogeological principles and pollutant partitioning between soil and porewater. A detailed description of this approach can be found in NGI report (2019b).

7 Case study 2: The stabilisation of per- and polyfluoroalkyl substances (PFAS) contaminated soil

7.1 PFAS in soil

PFAS comprise more than 4700 manmade substances and are of high global concern due to poorly defined risks to the environment and human health. More than 3000 PFAS are suspected to have been / are available on the global market and have been produced since the 1950s. They are used for a variety of industrial and consumer applications including cosmetics, household products, medical devices, oil production, mining, pesticides, aqueous film forming foams (AFFF), as protective coatings for textiles and food contact paper and packaging (Lindstrom 2011).

PFAS have a hydrophobic, alkylated, fluorine-saturated carbon-chain of variable length with a hydrophilic head attached at a terminal end. PFAS are characterised by a high environmental persistence (Arp 2006) and ubiquitous environmental presence (Zareitalabad, 2013). Unique chemical properties including; hydrophobicity, oleophobicity, resistance to chemical, biological and physical degradation processes, high potential for bioaccumulation and biomagnification and toxicity to organisms at environmentally relevant concentrations has given rise to environmental concern.

One of the problematic properties of PFAS is their very large leaching capacity from soils. This means that there is a need to reduce the leaching of PFAS from soil in order to reduce hazard. One possible option for this is stabilisation as discussed above and as is the focus of this case study.

7.2 Site description

Case study two focused on the use of different sorbent amendment materials to stabilise per- and polyfluoroalkyl substances (PFAS) in a soil contaminated by the use of aqueous film forming foam (AFFF) in firefighting training activities. The firefighting training facility site is located at the west of the Oslo airport site, Gardermoen, Norway (60°12'10"N, 11°5'2"E). This facility was established in 1989 and has been used for firefighting training activities even before this time. AFFF has been used extensively at the site. In 2007, the use of AFFF containing PFOS was banned at the facility and a complete ban on the use of organofluorine AFFF was enforced in 2011. In 2001 the site owner ceased using AFFF containing PFOS. It is known that different types of AFFF, with different levels of PFAS have been used at the site over time. The soil is known to be contaminated with a range of perfluorinated compounds resulting from this historical contaminant input.

7.3 Methods

7.3.1 Soil

Soil was sampled from 6 different sampling points around the firefighting training facility by digging holes with a small excavator and using a spade to take a representative sample from the 0-1 m, 1-2 m, 2-3 m and 3 to groundwater table level (which was in all cases above 4 m) (referred to by the following location numbers: 4, 5, 6, 10, 17 and 21). The metal spade was rinsed with methanol before sampling at each point and the soil was transferred in to nylon-11 sampling bags before being taken back to the laboratory. In total 21 samples were taken from the site and soil was stored at 4 °C prior to use. All soil samples were classified as medium sand.

7.3.2 Sorbents

Three sorbent materials were chosen based on material availability for a full scale remediation project: activated carbon (AC), montmorillonite and compost soil. Powdered aquasorb BP2 bituminous coal based AC was obtained from Jacobi Carbon (Kalmar, Sweden). The BP2 AC has a surface area of 726 m^2/g and a pH of 8-11. Montmorillonite K 10, was purchased from Sigma Aldrich as a powder (Norway). The montmorillonite had a surface area of 220-270 m^2/g. Compost soil was purchased from a Norwegian garden shop (http://www.plantasjen.no/kompostjord-40l-200017081-no) and had a high content of nitrogen, phosphate and potassium. All materials were used as received.

7.3.3 Sorption studies

In order to quantify the leaching of PFAS from the soil with and without sorbent amendment, a standard one step batch leach test was carried out according to method EN 12457-2 with a few modifications before and after sorbent amendment. Briefly soil (90 g taken from a homogenised subsample of soil) was shaken with water for 8 days at a liquid to solid ratio of 10 and then filtered (through 0.7 μm polyethersulfone membrane) before analysis. For sorbent amended samples, 3 % of each sorbent material was homogenously mixed with soil and the procedure repeated. Leachate water was stored at 4 °C prior to analysis. The concentration of each individual PFAS in the filtered water at the end of the experiment (C_{water}, μg L-1) was measured, and the concentration leached per dry weight of soil, $C_{leached}$ (μg kg-1) was calculated as follows:

$$C_{leached} = C_{water} V_{water} / M_{solid,dw}$$

Where V_{water} (L) is the volume of water in the batch system, and $M_{solid,dw}$ is the solid (soil or soil+sorbent) dry weight (kg).

Based on the batch leach tests for soils, three soil samples with low PFOS concentrations were further selected for the batch leach tests following sorbent amendment. Currently excavation is not feasible for large amounts of soil contaminated with high PFAS concentrations based on the large cost encured. However, if sorbent amendment was carried out and resulted in an immobilisation of PFAS then excavation and landfilling may become a more viable solution.

7.3.4 PFAS analysis

The PFAS investigated in this case study were: perfluorobutanoic sulfonate (PFBS, C4), perfluorobutanoic acid (PFBA, C4), perfluoropentanoic acid (PFPeA, C5), perfluorohexanoic sulfonate (PFHxS, C6), perfluorohexanoic acid (PFHxA, C6), perfluoroheptanoic acid (PFHpA, C7), 6:2 fluorotelomer sulfonate (FTS, C8) (H4PFOS), perfluorooctanoic sulfonate (PFOS, linear C8), perfluorooctanoic acid (PFOA, C8), perfluorononanoate (PFNA, C9), 8:2 fluorotelomer sulfonate (FTS, C10) and perfluorodecanoic acid (PFDeA, C10). All analyses were carried out at the accredited laboratory Eurofins GfA Lab Service GmbH (in Germany). For soil, PFAS was quantified using method DIN 38414-S14 based on a methanol or acetonitrile ultrasonic extraction with a multi-step solvent clean up using SPE, followed by analysis using liquid chromatography coupled with mass spectrometry (LC/MS-MS). Leachate was analysed for PFAS following method DIN 38407-F42 and quantification using LC/MS-MS.

7.3.5 Additional soil and leachate water chemical characterisation

The content of iron (Fe), calcium (Ca), chloride (Cl), manganese (Mn), sulfate (SO4), total organic carbon (TOC) and pH were quantified in soil samples at accredited Eurofins laboratories. Fe, Ca and Mn were analysed according to EN ISO 11885, Cl and SO_4 were analysed following method EN ISO 10304-1, pH was measured according to method EN 12176 and TOC was measured according to method AM 374.02. Leachate water samples were analysed for the same properties apart from TOC, which was substituted for the determination of content of dissolved organic carbon (DOC). Fe and Mn were analysed according to EN ISO 17294-2 after digestion, Cl was analysed following method EPA Method 325.2, pH was measured according to method EN ISO 10523 and DOC was measured according to EN 1484. Ca and SO4 were analysed sulphate was analysed according to the methods above.

7.3.6 Data Analysis

The reduction in leachate concentrations of PFAS following sorbent amendment was determined by comparing the C_{water} before and after sorbent amendment (reduction = $C_{water\ after\ amendment}/C_{water\ before\ amendment}$).

In addition, the fraction of PFAS leached, $f_{leached}$, was also calculated as follows

$f_{leached} = C_{leached}$ (µg kg-1)/$C_{soil,0}$ (µg kg-1)

Where $C_{soil,0}$ is the initial soil concentration of PFAS in soil before the batch leach test.

Soil-water partitioning coefficients K_D (L/kg) were estimated using mass balances for soils with sorbent amendments when possible according to:

K_D (L/kg) = ($C_{soil,0}$ – $C_{leached}$ (µg/kg))/C_{water} (µg/L)

For the AC amendment batches there were several replicates where C_{water} was below the analytical method limit of detection (LOD). In such cases, half of the analytical LOD was used as the measured concentration to calculate K_D as a conservative assumption.

7.4 Results

7.4.1 Concentration of PFAS in soil

PFOS was the most dominate PFAS detected in all soil samples and for this reason PFOS data are presented most prominently here (Figure 4). The PFOS concentration ranged from 6.4 to 2400 µg/kg (samples 21, 2-3 m and 17, 1-2 m). The highest concentrations were typically found in soil samples taken at 1-2 m depth (except for location 4 at 2-3 m depth and location 21 at 0-1 m depth), and not at 0-1 m depth, suggesting a downwards migration of PFOS in the soil profile over time. Differences in the fingerprint of PFAS in soil samples from different locations could suggest a different pattern of use for the various AFFFs used over time. There were four PFAS that were not observed in any of the soil samples: PFBS, PFBA, PFHxA and PFHpA. The compounds that were detected in the soil samples included PFPeA (one sample at 2.8 µg/kg), PFHxS (36 % of samples, range 3.0 to 25.3 µg/kg), 6:2 FTS (12 % of samples, range 13 to 92.4 µg/kg), PFOA (19 % of samples, range 3.0 to 13 µg/kg), PFNA (40 % of samples, range 2.8 to 41.3 µg/kg), 8:2 FTS (7 % of samples, range 3.8 to116 µg/kg) and PFDeA (26 % of samples, range 2.6 to 72.1 µg/kg).

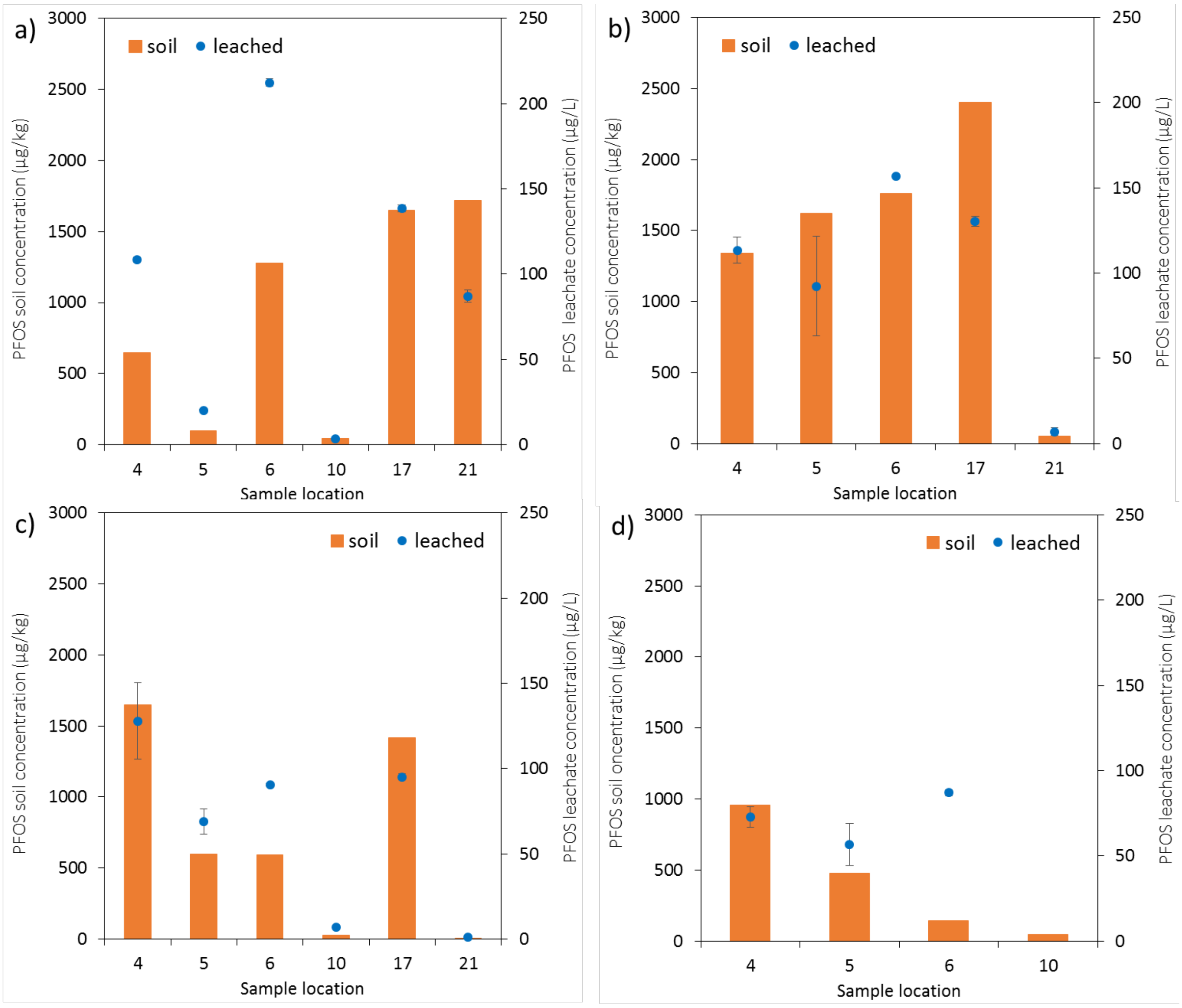

Figure 4: PFOS soil concentration (µg/kg) and PFOS leachate concentration (µg/L) for a) 0-1 m samples, b) 1-2 m samples, c) 2-3 m samples and d) 3 m to groundwater level samples. Standard deviations represent triplicate measurements.

There was no correlation between any of the additionally measured soil parameter (Fe (mg/kg), Cl (mg/kg), Ca (mg/kg), Mn (mg/kg), SO_4 (mg/kg), pH (-) and TOC (%)).

7.4.2 Leaching of PFAS from soil before sorbent amendment

The concentration of PFOS in the leachate (both in µg/kg and µg/L) along with the percentage of total PFOS leached from the soil is given in Figure 4. The percentage of total PFOS leached from the soil was calculated by comparison of the concentration in the soil in µg/kg before and after leaching. Leachate concentrations of PFOS varied from 1.2 µg/L (location 21 2-3 m) to 212 µg/L (location 6 0-1 m) and the percentage of PFOS leached from the soil itself varied between 23 and 601 %.

The additional physicochemical parameters that were measured for the leachate following the batch test (Fe mg/L, Ca mg/L, Cl mg/L, Mn mg/L, SO_4 mg/L, pH (-) and DOC mg/L) were not correlated with PFOS concentrations. Following the batch leaching tests more individual PFAS were detected in the leachate water than in the soil itself following the solvent extraction, again supporting the notion that water extraction provides a more representative extraction method for these soils and compounds reducing the interference from other AFFF components. PFBS was the only PFAS not to be detected in any leachate water samples; therefore, being the only analysed PFAS not found in any leachate or soil samples. PFBA, PFHxA and PFHeA were detected in some leachate samples while they were below the LOD in the corresponding soil sample, likely due to the higher LOD in soil. The percentage of samples with detections and concentration ranges for other compounds were as follows: PFBA - 20 %, range 0.01 to 0.02 µg/L, PFPeA - 43 %, range 0.01 to 0.78 µg/L, PFHxS - 100 %, range 0.02 to 9.03 µg/L, PFHxA - 81 % of samples, range 0.01 to 0.49 µg/L, PFHpA – 25 % of samples, range 0.02 to 0.10 µg/L, 6:2 FTS - 38 %, range 0.10 to 5.97 µg/L, PFOA – 60 % of samples, range 0.06 to 3.13 µg/L, PFNA - 71 % range 0.02 to 16.93 µg/L, 8:2 FTS - 10 % range 0.13 to 1.23 µg/L and PFDeA - 48 %, range 0.01 to 2.20 µg/L (Figure S5). The concentration profiles varied with depth and with sample location and were not systematically affected by the chain length of the PFAS or whether the acid or sulfonate was present. This again, as for the soil could be due to different use patterns at different parts of the site.

7.4.3 Leaching of PFAS from soil following sorbent amendment

The soil samples chosen for the sorbent amendment test contained 6.4 µg/kg to 54.5 µg/kg PFOS. The concentration of PFOS in the leachate water following sorbent amendment are given in Table 10, and the reduction in leaching following amendment is given in Figure 5. Leaching of PFOS was reduced between 28 and 34 % following the amendment of compost soil, between 28 and 40 % for the montmorillonite amendment and between 94 and 99.9 % for AC. There were very few other PFAS where it was possible to quantify the change in leachate concentration following sorbent amendment as concentrations were below the LOD either before, after or both before and after sorbent amendment. For those compounds where it was possible to quantify changes, mixed results, independent of sorbent (including AC) and compound were observed. In some cases, there was a reduction in concentration following amendment as expected, but in others an increase was observed. This increase may have been related to working close to the analytical LOD (from 0.31 µg/L down to 0.01 µg/L).

Despite this, the exceptionally strong remediation efficacy of AC for PFOS demonstrated here agrees with a previous study (Kupryianchyk et al., 2016) in which AC was amended to three Norwegian soils (with high levels of organic carbon). Kupryianchyk et al., (2016) observed an almost complete removal of PFAS from soil porewater following AC amendment (over 99 %). Das et al., (2013) investigated the remediation efficiency of a modified clay material (MatCARE, a palygorskite based material modified with oleyamine) and an AC in a PFOS impacted soil. MatCARE was observed to have a higher sorption capacity for PFOS (0.093 mmol/g) than a commercially available AC.

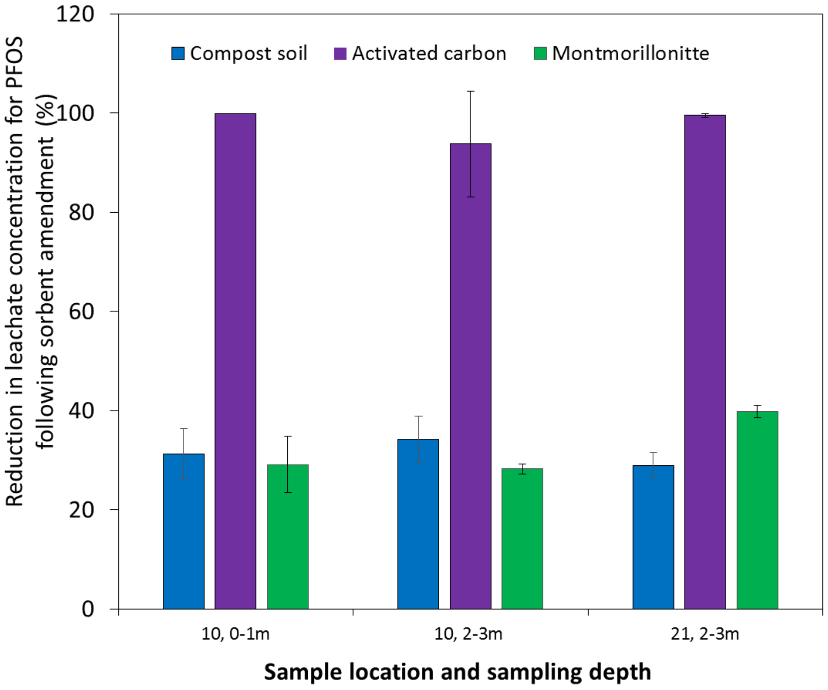

Figure 5: Relative reduction in PFOS leachate concentration after sorbent amendment. Standard deviations represent triplicate measurements.

Table 10: PFOS leachate water concentrations after sorbent amendment (µg/L), the reduction in leaching following sorbent amendment (as compared to the respective unamended sample) and partitioning coefficients (K_D, L/kg) for soil amended with compost soil, AC and montmorillonite.

Sample location	**Depth of sampling**	**Sorbent material**	**PFOS concentration in leachate water after amendment**	**Reduction in leaching following sorbent amendment**	**Partitioning coefficient (K_D)**
	M		µg/L	**%**	**(L/kg)**
10	0-1	Compost soil	2.26 ± 0.17	31.2 ± 6.7	8.8 ± 1.4
	0-1	AC	0.003 ± 0	99.9 ± 0.002	16940 ± 0
	0-1	Montmorillonite	2.33 ± 0.19	29.1 ± 5.9	8.2 ± 1.4
	2-3	Compost soil	4.54 ± 0.32	34.2 ± 2.8	*
	2-3	AC	0.43 ± 0.74	93.9 ± 10.5	> 7287 ± 6287 **
	2-3	Montmorillonite	4.95 ± 0.07	28.0 ± 5.5	*
21	2-3	Compost soil	0.82 ± 0.03	28.2 ± 10.7	*
	2-3	AC	0.01 ± 0.005	99.6 ± 0.4	> 1889 ± 1126 **
	2-3	Montmorillonite	0.70 ± 0.01	39.5 ± 5.4	*

* values are not given as $C_{leached}$ (µg/kg) was higher than $C_{soil,0}$ (µg/kg).

** The leachate water concentration was below LOD, therefore values of half of the LOD were used as a conservative assumption, resulting in large standard deviations.

7.4.4 Determination of partitioning coefficients following sorbent amendment (K_D)

It was possible to determine partitioning coefficients for soil samples with sorbent amendment (K_D (L/kg)) in some cases (Table 10), as sufficiently less PFOS was extracted in the batch leach test following sorbent amendment. One value of 8.8 L/kg could be calculated for the compost soil, one value of 8.2 L/kg could be calculated for the montmorillonite and values from 1889 ± 1126 to 16940 ± 0.00 L/kg were calculated for AC. Soil+AC/water partitioning coefficients reported for three other Norwegian soils varied between 5888 L/kg and 37154 L/kg, overlapping with the values measured here (Kupryianchyk et al., 2016).

7.5 Conclusion: can stabilisation be used to reduce the hazard of PFAS contaminated soil

Based on the results of this case study, it is clear that stabilisation of PFAS contaminated soil can be used in order to reduce leaching and therefore environmental hazard the soil poses. Stabilization could therefore be considered as a possible method for PFAS soils in the context of reuse. However it is important to note that while stabilization reduces the leaching of pollutants it does not reduce the absolute concentrations, and as mentioned earlier it is these concentrations that many regulations are based on.

The effect of stabilization is very case specific as it depends on the soil and also on the sorbent material. Those materials that have a high sorption capacity need to be added in lower doses than those with a lower sorption capacity. A cut off point in needed when considering reuse, as the addition of a sorbent increases volume and it will be impractical to add an infinite amount of sorbent material in order to reduce PFAS concentrations to levels where reuse may be possible.

Stabilization has also been used successfully for other organic pollutants, as well as heavy metals. Therefore, when considering the reuse of lightly contaminated soil, stabilisation could be considered as a method that could be used to reduce the leaching of organic pollutants.

8 Recommendations: the reuse of lightly contaminated soil

8.1 Practice

Following field sampling, an analysis of total concentrations should be made in order to determine if the soil is lightly contaminated. Following this, a shake test with and without a passive sampler should be carried out. Based on results, the soil can be classified in accordance with the type of landfill that it should be disposed at. For soils that leach concentrations corresponding to hazardous waste, reuse will not be possible. For soils that are considered to the ordinary, a consideration of the suitability of pollutant stabilisation can be carried out and the analysis repeated. For soils that are classified as inert (or have leachate concentrations below the guideline values for inert waste), a column test should be carried out and a passive sampler exposed to the eluate. The same principle applies for those results and their comparison to concentrations to determine landfill type. In cases where an inert classification is confirmed, a site specific risk assessment should be carried out. This assessment will include the bioavailable concentrations as well as a site specific assessment of leaching that takes in to consideration the total amount of pollutants that will spread and how this will affect local groundwater and surface water. This is summarized in Figure 6.

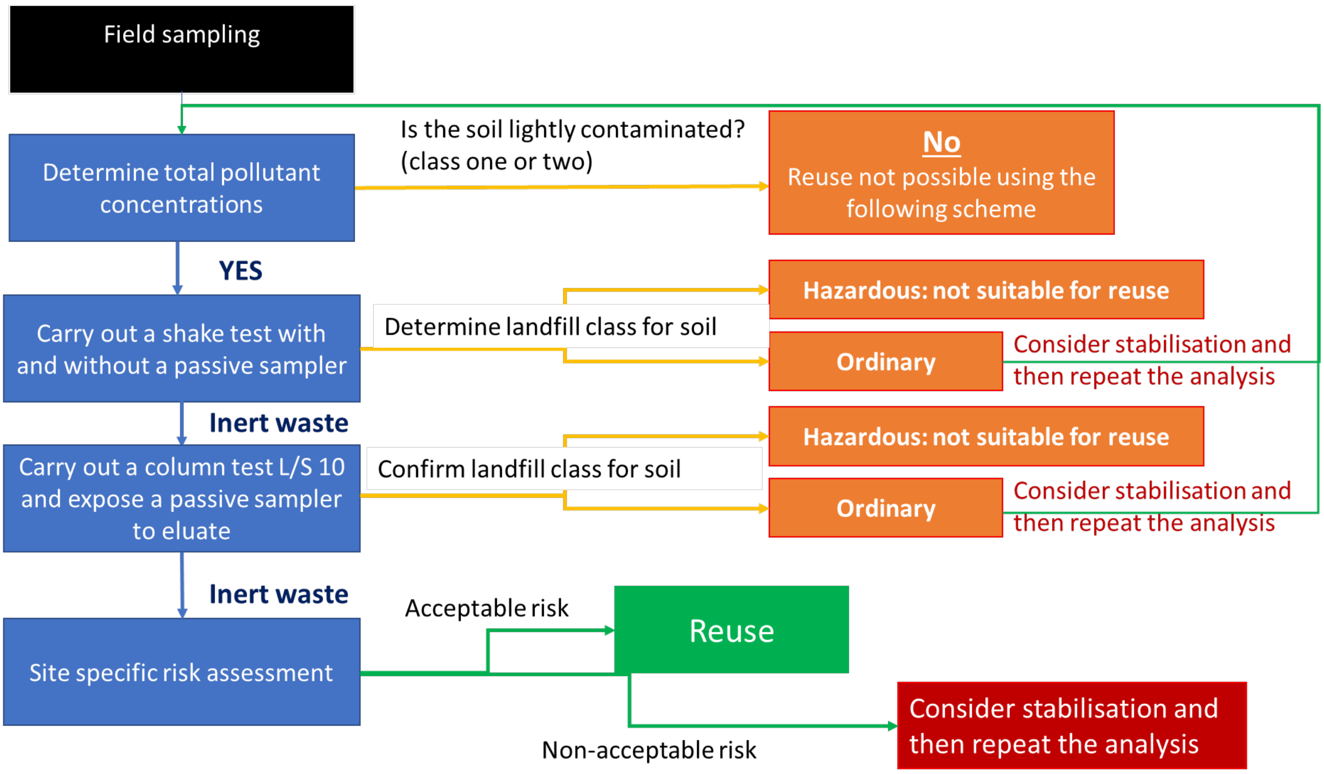

Figure 6: decision tree for the reuse of lightly contaminated soil

As well as assessing the environmental aspects of the reuse of lightly contaminated soil, a cost benefit analysis should also be carried out in order to ascertain whether reuse is beneficial from a wider perspective. There are endless categories that could be considered in such an assessment, including: release of green house gases, transport, damage to the wider ecosystem. In order to compare options it is important that the categories remain the same for the different options.

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