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PHOSPHOROUS REMOVAL BY THE FILTER MATERIALS LIGHT-WEIGHT AGGREGATES AND SHELLSAND – A REVIEW OF PROCESSES AND EXPERIMENTAL SET-UPS FOR IMPROVED DESIGN OF FILTER SYSTEMS FOR WASTEWATER TREATMENT

Fjerning av fosfor i kommunalt avløpsvann ved bruk av filtermaterialene lettklinker og skjellsand – gjennomgang av prosesser og forsøksoppsett for en forbedret utforming av renseanleggene

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Abstract

Constructed wetlands (CWs) and filterbeds are used throughout the world to treat wastewater. For these systems, selection of a suitable filter material for P sorption is essential, as well as design criteria that enables an efficient treatment. Batch experiments have been the main tool for obtaining maximum P sorption capacities for potential filter materials. They have been run in many different ways something that makes comparisons of the materials difficult. A standard method for batch studies is thus proposed, which should be used in order to be able to compare and rank the P sorption capacity of different materials used in CWs and filterbeds. Extraction of total P from filter materials from long-term laboratory studies and on-site treatment systems show that long-term experiments mimic the processes taking place in on-site systems. However, these long-term experiments should have inlet P concentration and hydraulic loads similar to the ones used for on-site treatment systems. Changes regarding inlet-outlet configurations, choice of filter material and ways of calculating the volume of the treatment beds are proposed as means for improving the treatment efficiency of these systems.

Key words – Batch experiments, column studies, constructed wetlands, Filtralite P®, Light-weight aggregate (LWA), on-site studies, optimal design, phosphorus, shellsand, sorption

Sammendrag

Konstruerte våtmarker og filterbedanlegg brukes verden over for å rense kommunalt avløpsvann. I disse systemene er det viktig å velge et filtermateriale med gode fosfor-bindingsegenskaper, i tillegg til en utforming som fører til en effektiv rensing. Batchforsøk har vært det viktigste verktøyet for å finne maksimal bindingskapasitet for potensielle filtermaterialer. Disse forsøkene har vært utført på mange forskjellige måter, noe som gjør at det er vanskelig å sammenligne resultatene fra de ulike forsøkene. En standard metode for batchforsøk blir derfor foreslått i denne artikkelen, for å lettere kunne sammenligne og rangere fosfor-bindingsegenskapene til ulike filtermaterialer brukt i konstruerte våtmarker og filterbedanlegg. Ekstraksjon av total fosfor (P) fra filtermaterialer tatt fra langvarige laboratorieforsøk og fullskalarenseanlegg viser at langtidsforsøk i laboratoriet gir en bra indikasjon på hvilke prosesser som skjer i fullskalarenseanlegg. Det er imidlertid viktig at slike forsøk har innløpskonsentrasjoner og hydraulisk belastning mest mulig lik det som er brukt i fullskalaanlegg. Endringer av posisjonen til innløp/utløp og valg av filtermateriale er foreslått som måter å bedre renseevnen til disse systemene.

Introduction

In rural areas throughout the world, single households and small communities rely heavily on the use of soil infiltration, stabilization ponds and/or constructed wetland (CW) systems for wastewater treatment (Shilton et al., 2005; Westholm, 2006). In Scandinavia, phosphorus (P) in particular, is of major concern, as it is believed to be the major cause for eutrophication and algae bloom. The ideal CW should mimic the key attributes of ponds and natural wetlands in being relatively simple and inexpensive to operate, and requiring no electrical or mechanical equipment, while still being robust and effective in treatment performance (Shilton et al., 2006). On-site wastewater treatment systems can be designed to optimize the removal of P from wastewater through utilization of reactive sorbent materials (Johansson, 1998). To function as an efficient sorbent the substrate must not only possess a high P sorption capacity but also have adequate hydraulic conductivity (Brix, 1994), physico chemical characteristics and recycling potential (Kvarnström et al., 2004) in addition to be locally available at a reasonable cost (Drizo et al., 2006). Jenssen et al. (2005) described the Norwegian concept for small CWs, i.e., the use of a septic tank followed by an aerobic vertical down-flow biofilter succeeded by a anaerobic subsurface horizontal flow CW. The aerobic biofilter is essential for removing organic carbon and achieve nitrification. Most of the systems in Norway use light-weight aggregate (LWA) as a filter substrate besides natural iron rich sand and shellsand.

Small CWs and filterbed systems have been constructed in Norway for about a decade, and despite their good performance with regard to both removal of P and pathogens, problems are occurring. Systems may be clogged due to biofilm growth and compaction of the filter material may lead to reduced flow rates and creation of preferential pathways (Suliman et al., 2005). Use of LWA as filter material has also led to another problem, i.e., leaching of calcium (Ca) from the material and precipitation of $CaCO_3$ in outlet tubes. The Ca loss also reduces the P removal capacity of the material. The challenge of the CW design today, both in Norway and elsewhere, is thus to reduce the size of the treatment systems and at the same time 1) optimize the flow conditions (i.e., avoid clogging, development of preferential flow and Ca loss), 2) keep the removal efficiency high (i.e., avoid eutrophication of receiving water bodies) and 3) improve the nutrient recovery in order to recycle it back to agricultural land.

The design of today's wastewater treatment systems are largely based on results from batch experiments combined with some samples from already existing field scale systems. Batch experiments have been conducted with many different kinds of filter materials to obtain their maximum P sorption capacity; however published data on full-scale application of many of these materials has been limited or is non-existent (Shilton et al., 2006). Today, it is recognized that although batch tests provide a good indication of a material's capacity to retain P, when making a selection of potential filter substrates to be used in CWs and/or filterbeds for P removal; they do not provide the real P removal capacity in on-site systems. It is thus necessary to conduct long-term column or pilot scale experiments in addition (Drizo et al., 2002, 2006; Shilton et al., 2005). The question is then what kind of information is given by these long-term laboratory experiments.

The objective of this paper is therefore on one hand to review the design of batch as well as long-term column/pilot scale experiments and evaluate the information given by these laboratory tests, and on the other hand utilize previous published results from batch and column experiments as well as data from on-site treatment systems to give suggestions for improvement of the design of on-site treatment system. In addition this paper will also include some new results from batch experiments as well as new data regarding the P content in filter material samples taking from a 13 year old on-site CW. These new results are included in the article in order to elucidate results from previous experiments.

Materials

In this article we are mainly looking at previous experiments where either LWA and/or shellsand has been used as filter material. The new results presented in this article are all from experiments where LWA has been used as filter material. These two types of filter materials will therefore be presented in more details.

Light-weight aggregates (Filtralite P®): Filtralite P® is the last generation of Norwegian LECA, a light weight aggregate (LWA) produced by heating clay to 1200°C where it expands and forms porous particles. Filtralite P® contains about 7 g Mg kg^{-1}, 31 g Ca kg^{-1}, 6 g Fe kg^{-1} and 20 g Al kg^{-1} (Ádám et al., 2007). The main advantages of this substrate are: 1) a good P sorption capacity measured in laboratory tests (Jenssen and Krogstad, 2003; Ádám et al., 2005), 2) the P saturated material has a good fertilizer effect (Kvarnstrøm et al., 2004; Paruch et al., 2005), 3) a good hydrological conductivity (Suliman et al., 2005) and 4) it is highly studied with batch, box, trench, column and full scale studies (Zhu, 1998; Drizo et al., 2002; Jenssen and Krogstad, 2003; Suliman et al., 2005, 2006; Ádám et al., 2005, 2006, 2007). The high pH (above 10) promotes pathogen removal but may hamper the microbial processes nitrification and denitrification, which are responsible for the removal of nitrogen (N) (Mørkved et al., 2005). The main disadvantage of the substrate is the loss of Ca, which leads to clogging of outlet tubes during the first years of operation due to precipitation of $CaCO_3$. In addition the production of the material requires a lot of energy, and it is fairly costly to purchase.

Shellsand: Shellsand is a naturally available material along the coastline all around the world. According to Roseth (2000) 1 million tons are harvested annually only in Norway. There are different types of shellsand, which differ with regard to chemical properties and P sorption capacities. Five different types of shellsand have been studied in Norway by Roseth (2000), Søvik and Kløve (2005) and Ádám et al. (2007). As an example of chemical composition, the shellsand used by Ádám et al (2007) contained 14 g Mg kg^{-1}, 300 g Ca kg^{-1}, 0.6 g Fe kg^{-1} and 0.3 g Al kg^{-1}. The main advantages of shellsand are that: 1) it is naturally available, 2) has a good P sorption capacity measured in laboratory tests (Roseth, 2000; Søvik et al., 2005; Ádám et al. 2007), 3) has good hydraulic conductivity (Roseth, 2000) and 4) it is relatively cheap. The disadvantage is the lack of full-scale experiences. A pH value of about 8 may be too low for pathogen removal, but is on the other hand favorable for removal of N (Mørkved et al., 2005).

Methods

The methods given in this article are only for the experiments, which present some new results, i.e., results that have not previously been published in other papers.

Batch experiments: Hundred millilitres of P solution with 5 different amounts of Filtralite P® was shaken for 24 h using 3 different P concentrations: 2, 10 and 50 mg l^{-1}. The experimental set-up was as follows: 1) a solution of 50 mg P l^{-1} with 0.5, 1, 2 and 3 g of material, 2) a solution of 10 mg P l^{-1} with 0.25, 0.5, 1, and 2 g of material and 3) a solution of 2 mg P l^{-1} with 0.25, 0.5, 0.75 and 1 g of material.

The effect of the shaking time was also investigated. Samples with 1) a solution of 2 mg P l^{-1} and 1 g of Filtralite P®, 2) a solution of 10 mg P l^{-1} and 2 g of Filtralite P® and 3) a solution of 50 mg P l^{-1} and 6 g of Filtralite P® were shaken for 24 and 48 h, respectively. All samples contained 100 ml of P solution.

Samples from a CW: Samples of filter material were collected in May 2006 from an on-site horizontal CW system at Tveter, Norway. The CW had then been in operation for 13 years. The filter material in the CW was the old type of LECA, not Filtralite P®. The system has been described by Zhu (1998) who sampled from the same wetland in May 1995 and 1996, after 2 and 3 years of operation. The samples in this study were taken at 3 locations (1, 6 and 11 m from inlet) and at 3 depths (10–30, 30–50 and 60–80 cm below the surface) in the anaerobic part of the wetland which has horizontal flow. The samples were extracted with the Aqua Regia method (1 g of sample digested with 7 ml of concentrated HCl and 2.33 ml of concentrated HNO_3; ISO 11466) and analysed for total P (TP) according to Murphy and Riley (1962).

Batch experiments with shellsand and Filtralite P®

The purpose with batch experiments is to examine sorption processes and find the sorption capacity for a given material. The sorption capacity of the material is an important parameter for practical applications as it enables designers to estimate the longevity of a system (Ádám et al., 2006 and 2007; Drizo et al., 2006). In batch experiments, a P solution is added to the material, shaken for a certain time and the difference in the P concentration in the solution before and after shaking gives a measure of the amount of P sorbed. Factors that may influence the P sorption are contact time, range of initial P concentrations, temperature, the substrate/solution ratio, ionic strength and cations species of the electrolyte, rate and type of shaking and the type and extend of the substrate/solution separation after shaking (see e.g., Ryden and Syers, 1976; Barrow, 1978; Nair et al., 1984). Sorption isotherms are generally modeled by three classical equations (Langmuir, Freundlich and Temkin), which relate the amount of P left in solution to the amount presumably sorbed to the solid. In most work, the Langmuir equation has been used to model P sorption isotherms (Muljadi et al., 1966; Gunary, 1970; Chen et al., 1973; Kuo and Lotse, 1974; Zhou and Li, 2001; Søvik and Kløve, 2005).

Batch experiments – contact time

New results presented in this article show that by increasing the contact time from 24 to 48 h, the Filtralite P® was able to sorb 10, 33 and 50 % more P for the following combinations: 50 mg P l^{-1} – 6 g material, 10 mg P l^{-1} – 2 g material and 2 mg P l^{-1} – 1 g material,

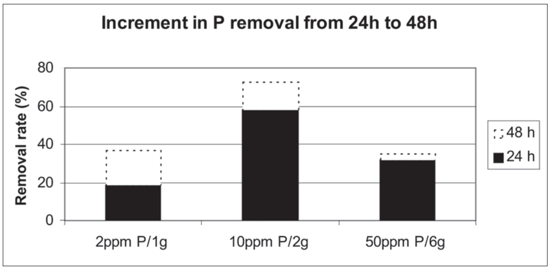

Fig. 1. *New data regarding the P sorption capacity of Filtralite P® after contact times of 24 and 48 h. The data is based on three different concentrations (2, 10 and 50 mg P l^{-1}) and three different substrate-solution ratios (1 g – 100 ml, 2 g – 100 ml and 6 g – 100 ml).*

respectively (Fig. 1). Similar results were obtained by Søvik and Kløve (2005) who found that samples with a substrate/solution ratio of 50 g – 50 ml (1:1 (w/v)) reached equilibrium within 24 hours, while samples with a ratio of 5 g – 75 ml (1:15 (w/v)) did not. The initial concentration for these samples was 25 mg l^{-1}. It is generally agreed from kinetic studies that retention of P in sand involves two reactions, one that proceeds rapidly and one that may continue for weeks and months (Jenssen and Krogstad, 2003).

In the experiments of Søvik and Kløve (2005) the slow process seemed to continue even after 600 hours of shaking for the 5-75 (1:15) samples. It thus seems like batch experiments with a low substrate/solution ratio need longer time to reach equilibrium than experiments with higher substrate/solution ratio. Thus batch experiments with a low substrate/solution ratio and a shaking time of 24 h will not give reliable measurements of the maximum P sorption capacity. A low substrate/solution ratio also differs from the real situation in full-scale filter systems.

Batch experiments – initial concentration of P

In order to find the maximum sorption capacity of a given filter material, a P solution with a high initial concentration is often applied to the material, even concentrations above 1000 mg l^{-1} have been used (Fig. 2). Real wastewater has on the other hand a maximum P concentration of 10–15 mg l^{-1} (Jenssen et al., 2005). These short-term measurements with extreme P concentrations might not give reliable data for the maximum P sorption capacity, as the capacity found by adding a high initial concentration of P is not necessarily equal to the capacity obtained by adding a lower concentration of P several times. For instance precipitation of P seems to be the dominant reaction at high initial concentrations of P, while sorption seems to be the dominating process at lower initial concentrations. This was observed for shellsand with initial concentrations up to 500 mg l^{-1} (Søvik and Kløve, 2005; Ádám et al., 2007). Experiments performed by Søvik and Mæhlum (2005) also showed that at very low initial P concentrations a specific type of shellsand performed much better than Filtralite P®. At high initial P concentrations the opposite was observed, i.e., Filtralite P® sorbed more P than the shellsand. The

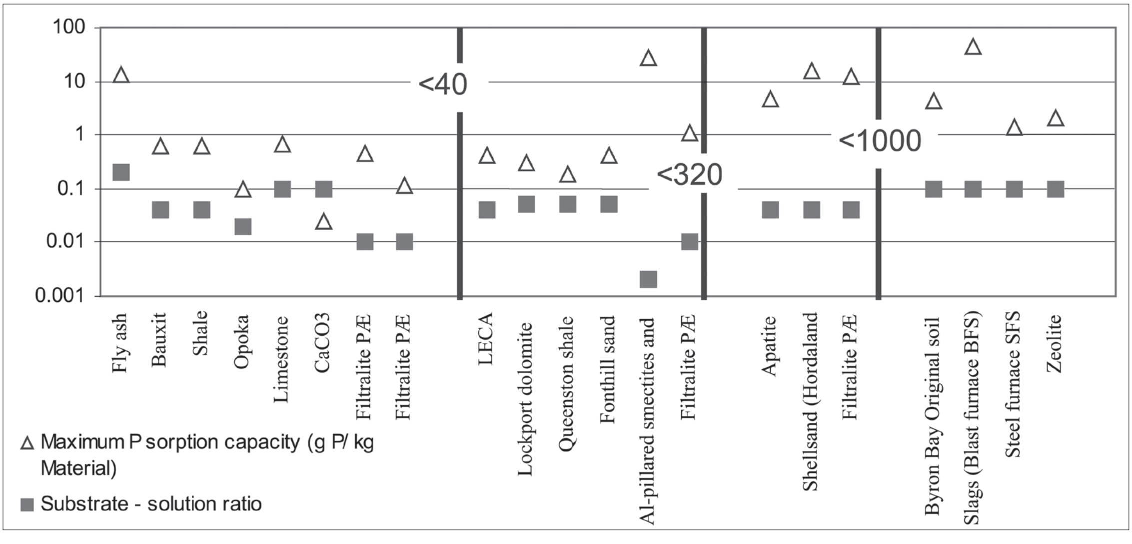

Fig.2. *Literature values for the maximum P sorption capacity of different materials found in batch experiments with varying substrate – solution ratios and initial P solution concentrations. The vertical lines are indicating the initial P concentration, i.e., samples to the left of the first line have initial concentration less than 40 mg l^{-1}. (References are given in the sub-chapter "Substrate/solution ratio".)*

cited works thus show that P retention processes in a given material may differ with low and high P concentrations. In addition a specific material, which seems suitable for P sorption purposes when tested with high initial P concentrations, may not be suitable if the P concentration in the actual solution is low. Another interesting observation concerning batch experiments, was made by Ádám et al. (2007). Shellsand and Filtralite P® with initial P concentrations equal to what is found in real wastewater were compared and Filtralite P® was found to have the best sorption capacity of the two materials. However, in batch experiments (initial concentration of 10 mg l^{-1}) with the two materials taken from laboratory columns which had been supplied with P solution for several months, shellsand had a much better sorption capacity then the Filtralite P®. This shows that results from batch experiments receiving one dose of P may give erratic results when the long-term performance of materials is of interest.

Several authors (Sawhney and Hill, 1975; Krogstad, 1986; Arias et al., 2003) have pointed to the inconsistence between laboratory and field experiments regarding P sorption. Arias et al. (2003) reported that a calcite material had a tenfold lower P retention in full-scale systems then previously estimated from laboratory experiments. Whereas several authors have found that the soils below wastewater infiltration systems sorb more P than the adsorption maximum based on batch experiments (Sawhney and Hill, 1975; Krogstad, 1986).

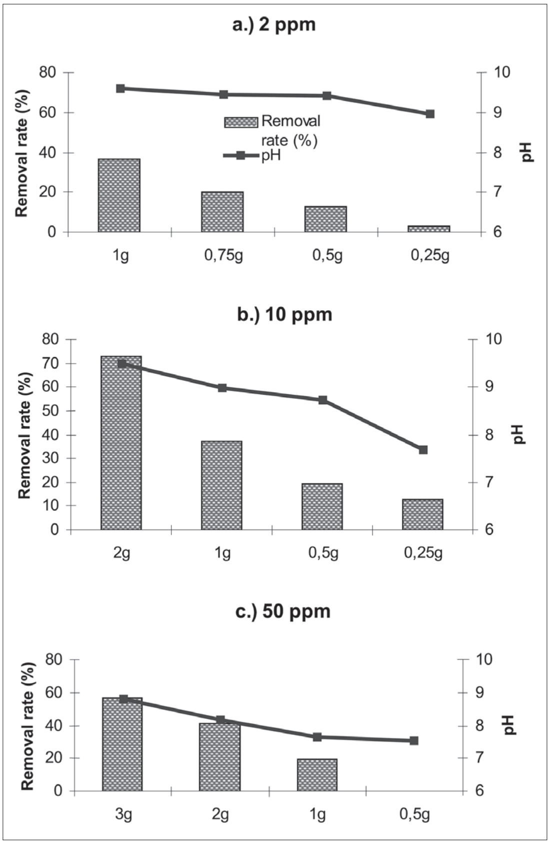

Fig. 3. *New data regarding removal efficiency of Filtralite P® from solutions with a) 2, b) 10 and c) 50 mg P l^{-1} with different amounts of substrate.*

Batch experiments – substrate/solution ratio

New results from batch experiments presented in this article are given in Fig. 3a–c. The pH value of the solutions was 6.67, 6.42 and 6.03 for the 2, 10 and 50 ppm solutions, respectively. The results show that with decreasing substrate/solution ratio the removal rate of P was decreasing. With decreasing amount of material in the system the pH also decreased. There was not enough material to buffer the acidic P solutions. The effect of substrate-solution ratio was also examined by Søvik and Kløve (2005). In a batch experiment with shellsand and substrate/solution ratios of 5 g-75 ml (1:15) and 50 g-50 ml (1:1), the removal rate was highest for samples with 50 g substrate. These results show that the substrate-solution ratio is a critical parameter when performing laboratory batch experiments and have to be taken into consideration when results are used to design full-scale systems.

Many different kinds of materials have been tested worldwide with batch experiments to obtain their maximum P sorption capacity (fly ash (Cheung and Venkitachalan, 2000), bauxite (Drizo et al., 1999), shale (Drizo et al., 1997), opoka (Johansson, 1998), limestone (Zhou and Li, 2001), $CaCO_3$ (Cole et al., 1953; Griffin and Jurinak, 1973; Freeman and Rowell, 1981; Wang and Tzou, 1995), LWA (Johansson, 1998; Zhu, 1998; Drizo et al., 1999), Lockport dolomite (Pant et al., 2001), Queenston shale (Pant et al., 2001), Fonthill sand (Pant et al., 2001), Al-pillared smectites and mica (Kasama et al., 2004), apatite (Molle et al., 2005), Hordaland shellsand (Roseth, 2000; Ádám et al., 2007), Filtralite P® (Ádám et al., 2005, 2006, 2007), Byron Bay Original soil (Sakadevan and Bavor, 1998), blast furnace slag (Johansson, 1998; Sakadevan and Bavor, 1998), steel furnace slag (Johansson, 1998; Sakadevan and Bavor, 1998) and zeolite (Wild et al., 1996; Sakadevan and Bavor, 1998)). As is shown in Fig. 2, there is, however, no universal method for analysis. There is a high variation in the substrate/solution ratio and the initial P concentration used in these studies, which can influence the outcome of the experiments (Fig. 2). In this way it is very difficult to compare potential filter materials for wastewater treatment.

Recommendations for standard P adsorption procedure with filter substrates

One standard method for batch studies should be developed and used internationally to be able to compare and rank different materials used in constructed filterbeds for P sorption. Conducting the analyses in the same way would provide us with a possibility to compare and choose the best material available.

An international standard method for P sorption in soils was proposed by four laboratories already in 1984 (Nair et al., 1984). A modification of this method could also be used in ranking filter materials based on their P sorption capacity: 1) weight of substrate: 3 g (1 g as proposed by Nair et al. (1984) might not be a representative sample when the grains are as big as in the case of Filtralite P® or shellsand), 2) substrate/solution ratio: 1:25, 3) time of equilibrium: 48 h (especially in materials with a high Ca and Mg content the equilibration will not be reached after 24 h), 4) electrolyte: 0.005 M $CaCl_2$, 5) initial P concentrations: 0 to 30 mg P l^{-1} (in some countries P based detergents are still in use). With such a procedure, batch experiments may be used for comparing different kinds of materials. However, it is still important to keep in mind that use of batch experiments for comparing materials may give erratic results as pointed out by Ádám et al. (2007). Estimates of the real field scale sorption capacity should be based on long-term laboratory experiments with a P concentration similar to concentrations found in wastewater.

Long-term laboratory experiments

The main questions about long-term laboratory experiments are: 1) how should they be performed and 2) what do the experiments already performed tell us about sorption capacities and sorption processes in on-site treatment systems? The advantages of long-term experiments compared to batch experiments are that they have a more realistic substrate/solution ratio, the water percolates through the material, they may be run over longer time periods and the material is repeatedly exposed to the P solution. Their disadvantages are that they are more time consuming and more expensive to run. In Norway various types of long-term experiments have been performed with Filtralite P® and shellsand during the last decade to learn about the physicochemical properties and the maximum P sorption capacities of these materials (Table 1).

Long-term laboratory experiments – P sorption capacities

The maximum P sorption capacity found in long-term laboratory experiments performed with Filtralite P® and shellsand varies considerably (Table 1). One reason for this could be variations in the experimental set-up such as 1) inlet concentration (higher inlet concentrations yield higher sorbed concentrations but faster saturation), 2) hydraulic load (higher hydraulic load yield higher P sorption (Ádám et al., 2006) and 3) length of the studied system. The results depend as well on whether the system studied was run until saturation (i.e., the inlet P concentrations equals the outlet concentration) or only run until the outlet concentration was equal to 1 mg P l^{-1} (the limit for Norwegian systems). Regarding the long-term experiments in Table 1, the box and column studies were run until saturation, while the outlet concentration of the trenches had not yet reached 1 mg l^{-1}.

The Filtralite P® material in the box did probably have a higher P sorption than in the column as the filter material in the inlet section of the box was exposed to a higher total amount of P than in the column. The high P sorption in the columns with shellsand (Roseth, 2000) was presumably due to the fact that the hydraulic load used was 100 times greater than the expected load for a large-scale system. The long-term experiments with high hydraulic loads had P sorption capacities similar to the results from the batch experiments (Table 1).

The average P sorption capacity in a studied system may be calculated based on mass balance or on extraction of total P from substrate samples. Especially for shellsand the amount of P sorbed based on extractions has been found to be considerably lower than the amount sorbed based on mass calculations. In the work of Ádám et al. (2006) extraction yielded an average of about 140 mg P kg^{-1} (Table 1), while mass calculations yielded 8000 mg P kg^{-1} (results not shown). Similar results have been found by Søvik et al. (2005). One explanation could be that P is precipitated with Ca leached from the material, and this precipitation product accumulates at the bottom of the studied systems, which is not sampled for extraction of P.

These results suggest that in order to predict realistic values for the average as well as the maximum P sorption capacities, long-term laboratory experiments should strive to have inlet P concentration and hydraulic loads which are similar to the ones for on-site treatment systems. Large scale laboratory systems such as the 3 m long trenches should be stopped when the outlet concentrations exceed the effluent limit (1 mg l^{-1}). This makes it possible to find the maximum P sorption capacity under conditions similar to the ones for on-site systems. If the system is run longer, a measure of the

Table 1. *Maximum P sorption capacities of Filtralite P® and shellsand from batch experiments, long-term laboratory experiments and field studies. The data from the long-term laboratory and field experiments are based on extraction of total P from the material (except for Roseth (2000)), and the data has been corrected with the background P concentration. Values in the brackets show the average extracted content of total P. The name of the specific type of shellsand is given below the reference.*

Filtralite P®		Shellsand	
Experiment	P sorption capacity (mg P kg^{-1})	Experiment	P sorption capacity (mg P kg^{-1})
Batch experiment			
Ádám et al. 2005		Roseth (2000)	
Filtralite P®	3300	Einar Øgreid AS	17000
Ádám et al.(2007)		Fosen skjellsand	15000
Filtralite P®	2500	Hordaland tørkeri	16000
		Korall AS	17000
		Brødrene Nilsen AS	16000
		Søvik and Kløve (2005)	
		Korall AS	8000
		Ádám et al. (2007)	
		Hordaland tørkeri	10000
Box experiment[a]			
Ádám et al. (2006)	3900 (1000)		
Trench experiment[b]			
Ádám et al. (2006)	4500 (1048)	Søvik et al.(2005)	
		Korall AS	330 (130)
		Søvik and Kløve (2005)	
		Korall AS	1300 / 420[e] (330)
Column experiment[c]			
Ádám et al. (2007)	950 (635)	Ádám et al. (2007)	
		Hordaland tørkeri	300 (136)
		Roseth (2000) [f]	
		Hordaland tørkeri / Korall AS	3500
Field studies[d]			
Zhu (1998)[g]	800		
Ádám et al. (2006)	250		

[a] Flow experiments in boxes (26x9x7 cm^3) filled with filter material. Inlet at top and outlet at bottom of boxes.

[b] Flow experiments in trenches (3x0.75x0.5 m^3) filled with filter material. Inlet at top and outlet at bottom of trench

[c] Flow experiments in columns (d: 14 cm, length: 1.5 m) filled with filter material. Inlet at bottom of column.

[d] Field studies – collection of samples of filter material from an on-site constructed wetland treating wastewater from a group of houses.

[e] The results are for the pre-filter and main filter, respectively

[f] The P sorption capacity is based on mass balance

[g] The field scale system referred to was constructed with light-weight aggregate

sorbed P in the system at the outlet concentration of 1 mg l^{-1} should be available. The average P sorption capacity should be measured both with mass balance and with extraction of total P from several material samples.

Comparing the long-term laboratory studies with results from on-site systems, it is seen that the predicted capacity is far higher than what was found in the field (Table 1 and 2). However, the systems at Tveter (Zhu, 1998) and Haugstein were constructed with LECA, while all the laboratory experiments have been using Filtralite P®, a material with a higher P sorption capacity. Further, the system at Dal (Ádám et al., 2006) and Holt, which have been constructed with Filtralite P®, had only been running for a few years when the samples were taken, and the amount of P sorbed was therefore still low. Only when an on-site system with Filtralite P® has

Table 2. *Amount of sorbed P extracted from different constructed wetland systems in Norway.*

System	Built	Filter material	P sorbed (mg kg^{-1})						Outlet P concentration (mg l^{-1})
			Top (10–30 cm)		Middle (30–50 cm)		Bottom (60–80 cm)		
			In	Out	In	Out	In	Out	
Tveter	1993	LECA							> 2
2004[a]			387	554	427	307	–	–	
2006[a]			420	400	469	272	463	265	
Haugstein	1991	LECA	439	257	298	204	256	220	> 2
Dal	2000	Filtralite P®							
2003[a]			122	163	140	164	138	169	0.084
2004[a]			306	286	182	189	181	187	
Holt	1999	Filtralite P®	480	338	496	305	520	319	NA

[a] year of sampling

been running for several years, will it be possible to draw any conclusions regarding long-term laboratory experiments and prediction of P sorption capacities in on-site treatment systems.

Long-term laboratory experiments – spatial distribution of sorbed P

In trench studies it has been shown by Søvik and Kløve (2005), Søvik et al. (2005), Ádám et al. (2006) and Suliman et al. (2005, 2006) that the filter material in the trenches is successively saturated with P, i.e., there is like a P plume moving from the inlet to the outlet and at the center of the plume the P concentration in the water is equal to the inlet P concentration and the material will here be saturated with P. The same pattern was also seen in a column study by Ádám et al. (2007), i.e., when the effluent reached a concentration of 1 mg P l^{-1}, only a part of the filter material had reached its maximum P sorption capacity.

The same phenomenon has also been found in an on-site treatment plant where the filter material used is light-weight aggregates (LWA). Zhu (1998) reported that in the first two meters of this treatment plant at Tveter, the filter material had P concentrations between 200 and 800 mg P kg^{-1}. In the rest of the system, the P concentration was less than 200 mg kg^{-1} (Zhu, 1998). When comparing our new results from Tveter (i.e., samples collected in 2006) (Fig. 4) with the results of Zhu (1998) (samples collected in 1995–1996) it is obvious that the first 2 m of the bottom layer was already saturated with P in 1996, as no further increase in the P concentration was observed in 2006. In the rest of the wetland, however, the P content of the filter material has increased considerably during the last 10 years. The P concentration of the effluent reached the discharge limit of 1 mg l^{-1} already in 2001; still the amount of sorbed P is far from the adsorption maximum measured in the laboratory by Zhu (1998) (2.21 g P kg^{-1}).

In another on-site treatment systems (the Dal school), the distribution of sorbed P showed no specific pattern. The highest sorbed concentration was even observed close to the outlet. This variable distribution of sorbed P might be due to irregularities in hydraulic parameters such as the hydraulic conductivity, the grain size distribution or the porosity (Suliman el al., 2005). Thus column and trench studies might in some cases predict a probable P distribution pattern within on-site treatment systems. However, as on-site treatment systems are more prone to irregularities regarding hydraulic parameters and establishment of preferential flow paths, predicted sorption patterns will not always be present in the field.

Long-term laboratory experiments – wetting and drying, resting periods

Tofflemire and Chen (1977) showed in a column experiment that a series of wetting and drying periods could extend the lifetime of the media. Ádám et al. (2005) also reported that in a small scale box experiment the introduction of resting periods increased the sorption capacity of the filter material by 22–53 % depending on the hydraulic loading rate. In a column experiment with 14 different medias, resting periods increased the P sorption capacity by 10–40 % depending on the length of the resting periods (Lindbak et al., 1976). However, Arias et al. (2005) showed that wetting and drying periods did not have a great impact on the material's capacity to sorb P. The materials were saturated shortly after the pause and did not remove additional P from the wastewater. In the field, it has also been noted that a drying period may enhance aggregation of Filtralite P®, something that may increase the chances of preferential flow (Køhler, personal communication).

Recommendations for design criteria for on-site treatment systems

Results from examined on-site treatment systems as well as long-term laboratory experiments will be used to propose recommendations for improved design critera. With optimal design (inlet-outlet positioning, size of treatment plant as well as type of filter material) the treatment efficiency of the wetland or filterbed may be increased.

Inlet and outlet positioning – vertical vs. horizontal flow

Good hydraulic performance is important in CWs to obtain adequate retention time and prevent the development of preferential flows and dead zones, all needed in order to increase the P removal. In horizontal flow systems a considerable part of the filter material is not utilized properly (Ádám et al., 2006). In the column and trench studies previously mentioned, only a part of the filter material had reached its P sorption capacity when the effluent P concentration reached the allowed limit (1 mg P l^{-1}). By the use of a two-dimensional flow cell (20x40x1 cm^3), Suliman et al. (2006) found that inlet-outlet configurations that forced the flow through larger portions of the filter bed by injecting into low-conductivity layers and opposing the gravity-driven flow increased the treatment efficiency. The position of the inlet rather than the outlet had a greater effect on the distribution of the flow. When the inlet was positioned at the bottom and the outlet at the top, dead zones only appeared in the upper portion of the flow cell. The average retention time and the effective volume fraction increased and the pore water velocity decreased. In order to verify the results of Suliman et al. (2006), the effect of various inlet / outlet configurations should be tested with long-term laboratory experiments with trenches similar to the ones mentioned previously in this paper.

Previous studies also show that with the use of vertical up-flow systems the Ca loss from the Filtralite P® material decreased. In an experiment with horizontal flow in small boxes (26x12x7 cm^3) the material lost 1/3rd of its Ca content in 150 days, while in the columns with a vertical up-flow, only 3 % of Ca was lost after about 300 days (Ádám et al., 2005, 2007). Again these results need to be verified with trench experiments where e.g., the last part of the filter system consists of a vertical up-flow section, and the Ca loss is monitored and compared to systems without such a vertical flow section.

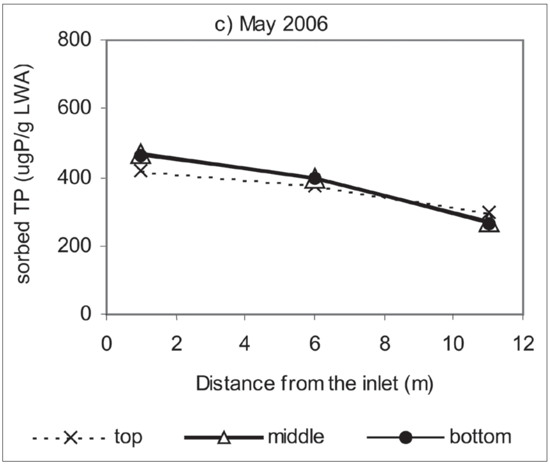

Fig. 4. *New data regarding the concentration of P in the filter material (LWA) of the on-site treatment system at Tveter, Norway, measured in 2006.*

Filter material

In most filterbed and constructed wetland systems in Norway, LWA (and recently Filtralite P®) has been used as filter material. However, in recent years, the use of shellsand has gained popularity. Different types of shellsand have been used in the experiments referred to in this article. Some types of shellsand seem to have a better P sorption capacities than Filtralite P® (Ádám et al., 2007) while other types seem to sorb less P than Filtralite P® (Søvik et al., 2005). Whether Filtralite P® or shellsand has the highest retention capacity for P is also dependant on the concentration of the P solution added to the material (Søvik and Mæhlum, 2005; Ádám et al., 2007). Thus the quality of shellsands vary a lot, and the P sorption capacity found for one type of shellsand may not automatically be transferred to another type of shellsand.

The loss of Ca from the Filtralite P® and the subsequent precipitation of $CaCO_3$ tends to clog outlet tubes during the first years of operation of a treatment plant. The very high pH of the porewater during the first years may also hamper the microbial processes responsible for the removal of N (Mørkved et al., 2005). Thus if N removal is required shellsand is probably a more suitable filter material than Filtralite P®. Alternatively a combination of the two types of material may be used; shellsand in the first part of the horizontal bed promoting N and P removal, while use of Filtralite P® in the last part of the bed ensures removal of pathogens and further removal of P. Such combinations of filter materials should be examined in long-term trench studies.

Calculation of lifetime of filterbed /CW

According to Norwegian guidelines a household of five persons will for a period of 15 years need 40 m^3 of filter material in order to have an effluent concentration that does not exceed 1 mg P l^{-1}. This means that there will be about 8 m^3 person^{-1} for 15 years.

Normally the lifetime of a CW is calculated by multiplying the maximum P sorption capacity with the total mass of filter material (Jenssen and Krogstad, 2003). Jenssen and Krogstad (2003) estimated the field sorption capacity to be 6 g P kg^{-1} (or 3.3 kg P m^{-3}), assuming that it is about 50 % of the P sorption capacity measured with batch experiments. With this data, about 2.5 m^3 of Filtralite P® material is needed for one person over 15 years, assuming that one person produces about 1.5 g P a day (547.5 g a year) (Holtan et al., 1988).

The trench study was stopped before the outlet concentration reached 1.0 mg P l^{-1} (Ádám et al., 2006). At the end of the experiment, the depth average concentration at 0.9 m from the inlet was at about 1.0 mg P l^{-1}, still only the parts of the material within the first 90 cm had attained the maximum sorption capacity. The same was observed for the box experiment, even though the boxes were run until saturation (Ádám et al., 2006). This shows that an average sorption concentration has to be considered when the life time of a CW system is calculated. In order to estimate the m^3 of filter material needed for one person over 15 years based on the trench experiment, we consider the first 0.9 m of the container as a separate system. Assuming that half of this volume sorbed about 4500 mg P kg^{-1} (2.5 kg P m^{-3}), while the remaining half sorbed about 1700 mg P kg^{-1} (equal to 0.94 kg P m^{-3}), the average sorption capacity would be 1.7 kg P m^{-3}. With this number, about 4.8 m^3 of filter material would be needed for 1 person over 15 years. This amount is the double of the calculated amount based on the data of Jenssen and Krogstad (2003), but still well within the limits of the Norwegian guidelines. Estimates of such an average sorption concentration should be based on samples of filter material collected from several on-site CWs when their outlet concentration reaches 1 mg P l^{-1}.

Size reduction

The constructed wetland systems used today in Norway are rather large, occupying considerable space (about 40 m^3 per household) and thus the investment costs are rather high. In remote areas the space is not a question but by introducing decentralized systems in more densely populated areas, the owner might not be willing to use a large part of his garden for a treatment system. To make these systems more popular and competitive the reduction of size is essential. Norway adapted the EU guidelines concerning P removal with some modifications. The national regulations about the expected effluent quality and a potential recipient are mainly influencing the design of the system.

In Norway the effluent limit regarding onsite treatment systems is about 1 mg P l^{-1} in the municipalities. At this effluent concentration, the filter material has to be changed. The Norwegian systems have proven to maintain their good (below 1 mg P l^{-1}, see Fig. 5.) removal capacity for a long period of time. Comparing onsite CW systems with e.g., conventional mini treat-

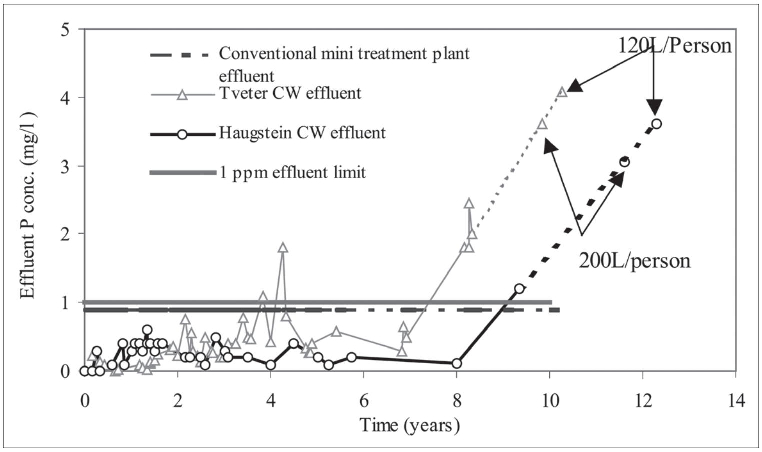

Fig. 5. *Comparison of long-term effluent quality between CW systems and conventional mini treatment plants. (The effluent data for Tveter and Haugstein CW was collected by Holte and Nybråten, (2001).)*

ment plants (CMTP) we can see that the long-term effluent quality differs significantly in the first 3–5 years in favour of the onsite systems. The onsite CW systems have a very low initial effluent P concentration (about 0.01 mg l^{-1}) for the first 3–5 years and then the concentration gradually increases by time reaching the 1 mg P l^{-1} effluent limit. On the other hand CMTPs have a more constant effluent concentration throughout their lifetime keeping the effluent P concentration just below 1 mg P l^{-1}. Ádám et al. (2006) showed that the Dal CW in Norway operating with Filtralite P® had an average effluent P quality of 0.084 mg P l^{-1} after 3 years of operation. Jenssen et al. (2005) studied 13 CW systems in Norway with Filtralite P® as filter media. Most of the systems were 5 years old or younger, and had effluent concentrations <0.5 mg P l^{-1}, thus consistent with the results for Tveter and Haugstein. The question is then whether an average effluent concentration of 1 mg P l^{-1} throughout the lifetime of a system could be used? Due to the low effluent concentrations during the first years, concentrations higher than 1 mg P l^{-1} could be tolerated for the last years, and thus increasing the lifetime of the system. According to the current Norwegian guidelines regarding design of decentralized treatment systems 1 person produces 200 litres of wastewater per day and 1.6 g P d^{-1} and one household has an average of 5 persons. However, in a recent study by Vestjord (2005) including 111 households, the water consumption was on the average 120 litres person^{-1} d^{-1} and the average PE per household was 3.4, thus large deviations from the guidelines. As mentioned above CW systems can maintain low (below 1 mg l^{-1}) effluent P concentration in the first 3–5 years of operation. Calculating the difference in TP removed over a period of 8.3 and 9.3 years for Tveter and Haugstein CW systems respectively (with 1000 l household^{-1} day^{-1}) we can conclude that they discharged 1.03 (Tveter) and 2.1 kg (Haugstein) less TP than an average CMTP would have discharged. Performing the calculations with the data obtained by Vestjord (2005), Tveter and Haugstein CW systems would have discharged 1.72 and 3.55 kg less TP than CMTPs. Assuming that these CWs could discharge the same amount of TP as CMTPs for 8.3 and 9.3 years they would be able to continue operation for another 1.5 and 2.3 years with 1000 l household^{-1} day^{-1} and 2 and 3 years for 600 l household^{-1} day^{-1} for Tveter and Haugstein, respectively, assuming that the effluent quality follows the increasing trend (Fig. 5). Constructed wetland systems using Filtralite P® as media are able to remove even larger amounts of TP than the LWA systems. Considering the factors mentioned above and the potential use of source separation or changing the filter materials more often, systems might be able to become more compact and desirable for the costumers.

Conclusions

Results from batch experiments are strongly influenced by contact time, initial P concentrations and substrate-solution ratio. Thus an internationally accepted standard method for batch studies is proposed in this article, which would make it possible for scientist to compare and rank filter materials used in CWs. As batch studies do not give reliable P sorption capacities, they should only be used to compare different filter materials. Long-term laboratory experiments mimic processes in on-site treatment systems better than batch studies, however, in order to predict realistic values for the average as well as the maximum P sorption capacities, these long-term experiments should have inlet P concentration and hydraulic loads similar to the ones used for on-site treatment systems.

With optimal design (inlet-outlet positioning, size and type of material) the treatment efficiency of on-site CWs or filterbeds may be increased. Experiments in a flow cell suggest that with the inlet positioned at the bottom and the outlet at the top of a CW, water will flow through a larger portions of the filter material. A filter material with a high P sorption is essential for efficient treatment of wastewater. Some types of shell-sand have been found to sorb more P than Filtralite P®, others less. The sorption of P in CWs has been found to be spatial heterogeneous, thus calculations giving the volume of wetland beds should be based on average sorption capacities instead of the maximum sorption capacity.

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