



Evaluation of using fine grain size Polonite[®] as sorbent for retaining phosphorus from wastewater.

Carl Nelin

Supervisor – Gunno Renman¹

**Division of Water Resources Engineering
Department of Building and Environmental Technology
Lund Institute of Technology**

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¹Associate Professor, Department of Land and Water Resources Engineering, Royal Institute of Technology, Stockholm

Sammanfattning

Utvärdering av fin fraktionig Polonite[®] som sorptionsmaterial för att återvinna fosfor från avloppsvatten.

För att undvika eutrofikation och stora algbloomingar så är det nödvändigt att reducera fosfor innehåll från avloppsvatten. Avloppreningsystem har idag ofta en bra process för att reducera fosfor, men sällan möjligheten för återanvändning och vidare bruk efter användningen i reningsprocessen, av både material och fosfor.

Polonite[®] är ett reaktivt material som kan binda till sig fosfor och har i flera tidigare undersökningar visat sig väldigt effektivt. I tidigare användningsområden har Polonite[®] storleken varit 2-6mm, i denna rapport utvärderas ett finfraktionigt alternativ där partiklarna är 2mm eller mindre.

I det här examensarbetet testas det om det är möjligt att ta bort fosfor från avloppsvatten med hjälp av finfraktionig Polonite[®] i en nybyggd prototyp som ska återvinna det fosforladdade materialet efter användning. Målet är att kunna ta tillvara fosfor i avloppsvatten från reningsverk och sedan använda den fosforladdade Poloniten[®] som gödningsmedel på åkermark. Om detta visar sig möjligt kommer denna process skapa ett slutet kretslopp för fosfor. Ett kretslopp som vi eftersträvar eftersom det är miljövänligt och bidrar till ett hållbart ekosystem.

Prototypen sattes upp på Skokloster reningsverk i norra Stockholm. Prototypen är utvecklad så att den först skapar rätt förutsättningar för Polonite[®] att komma i kontakt med avloppsvattnet och reducera fosforinnehållet. Sedan behåller den det använda materialet för återanvändning genom att separera materialet från avloppsvattnet med ett trumfilter och en sedimenteringstank.

Avloppsvattnet togs från efter den mekaniska och biologiska reningen eftersom tester i laboratoriet visade på störningar och mindre effektiv process när vattnet innehöll hög BOD och organiskt material.

Som väntat krävdes höga pH-värden för att få bra reduktion av fosfor. När pH var över 10, så var reduktionen av fosfor över 95% på 5 minuter. 4kg Polonite[®]/m³ avloppsvatten användes för att få dessa resultat.

Sorptionskapaciteten för denna mängd Polonite[®] är mer än tillräcklig och med högre pH-värden kan förmodligen lika bra resultat uppnås med mindre Polonite[®]. Förmodligen hämmas den basiska processen av organiska syror och annat organiskt material i avloppsvattnet.

Processen måste göras mer effektiv, för mycket material behövs för riktigt bra fosfor reduktion och gödningspotentialen kan förmodligen inte garanteras med så pass små mängder fosfor bundet till Poloniten[®].

Utgående vattnet undersöktes med avseende på polonitematerial och återvinningen antogs vara över 90%. Ännu bättre återvinning skulle kunna uppnås med en större sedimentationstank och lugnare utsläpp av vattnet.

Aknowledgements

This thesis has been carried out at the Division of Land and Water Resources, at the Royal Institute of Technology (KTH). I am student at Lunds Institute of Technolgy so the thesis must be presented with the LTH logo. Due to the opportunity and appropriate subject I was happy to spend some time in Stockholm to do this work. It could not have been done without the CEO of Biotech AB, Claes Thilander. He gave me the chance to work with this exciting project, which goes hand in hand with my education. He also helped me during the whole project and provided me with the necessary supplies.

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Table of contents

Sammanfattning.....	2
Aknowledgements	3
Table of contents.....	4
Abstract.....	5
1. Introduction	5
1.1 Background.....	5
1.2 Objectives.....	6
1.3 Limitations.....	6
2. Theory.....	7
2.1 Phosphorus and Nitrogen.....	7
2.2 Sorption and sedimentation	7
2.2.1 Sorption	7
2.2.2 Sedimentation	8
2.3 Brief description of kinetics	8
2.3.1 Influence of pH-values in the process	8
2.3.2 Phosphorus sorption capacity	8
2.4 Previously used and tested sorbents	9
2.4.1 Material used at wastewater treatment plants.....	9
2.4.2 Natural materials	9
2.4.3 Commercial products	9
2.4.4 Industrial by-products	9
3. Material and Methods	10
3.1 Opoka – Polonite®	10
3.2 The prototype	10
3.3 Pretesting in the lab.....	11
3.4 Running the prototype.	12
3.5 Analytical method	12
4. Results and Discussion	13
4.1 Results of pre-tests in the lab	13
4.2 Results from running the prototype	14
5. Conclusion.....	18
6. Future studies and investigations	19
7. References	20

Abstract

To avoid eutrofication and excessive algal bloms it is necessary to reduce the phosphorus contents in wastewater. Previous wastewater treatment systems often have a good process for phosphorus reduction but in general not the ability to recycle the material and phosphorus for further utilisation after its use in wastewater treatment.

Polonite® is a material with large content of calciumoxide which makes it very reactive and an effective sorbent of phosphorus. It has also been stated that when loaded with nutrients like phosphorus, Polonite® can be used as fertilizer for plants.

In this thesis a prototype developed by Biotech AB was tested to see if it can remove phosphorus from wastewater with fine grain size Polonite® as sorbent and then retain the phosphorus loaded Polonite® for further use, for example as fertilizer in agriculture. Unlike previous wastewater treatment systems the used material och retained phosphorus would then be recycled. If this can be achieved it would complete the environmental cycle for phosphorus which is important for a sustainable and healthy ecosystem.

The prototype was setup at the wastewater treatment plant in Skokloster, north of Stockholm. The prototype is developed so that it first can create the right circumstances for Polonite® to come in contact with the wastewater and reduce fosfor contents. Then it can retain the used material for further use by separating it from the solution.

Separation is made with a drumfilter and sedimentationtank. The wastewater was taken from after the mechanical and biological treatment since tests in the laboratory indicated that the process could be interfered and less effective with high BOD and organic matter.

As expected high pH was necessary to get a succesful reduction of phosphorus. When pH is over 10, the reduction of phosphorus is more then 95% after 5 minutes. 4kg Polonite®/m³ had to be added for these results. The sorption capacity for this amount is more than sufficient. The process needs to be more effective, to much material is needed to get good reduction of phosphorus besides the fertilizer potential can probably not be guaranteed with so little phosphorus attached to the Polonite®.

The outgoing water was checked for Polonite® material and the retention was assumed to be over 90%. Even better retention could be achieved with a larger sedimentation tank and smoother outlet of the water stream.

Keywords: Polonite®; Phosphorus reduction; Wastewater treatment; Recycling of sorbent and nutrient.

1. Introduction

It is desirable to reduce phosphorus in municipal wastewater and use the surplus in an efficient and environmentally friendly way by creating a sustainable circulation. By using the phosphorus from wastewater as fertilizer it could be turned into a valuable resource and eliminate pollution problems. (Hylander et al., 2006)

Finite and non-renewable environmental resources must be used and treated in a way that it is sustainable. Phosphorus is one of these finite resources. As an important nutrient and key element in all living forms this substance is vital to investigate for sustainable solutions so that it can be used beneficially while at the same time it can be recycled and used again and again. In this thesis a prototype for phosphorus reduction of municipal wastewater will be tested. Polonite® in small grain sizes will act as a sorbent. When using Polonite® for phosphorus retention a ecological engineering system can be accomplished since it becomes possible to recycle the phosphorus and use it again.

The prototype is expected to solve the problem with detaching the phosphorus-loaded Polonite® from the outgoing water stream. Detachment would be necessary to conclude a circulation where the Polonite® filled with phosphorus could be used again. It has been shown that there are good fertilizer potential in Polonite® loaded with phosphorus, Hylander et al (2006), Cucarella Cabanas (2007) and Renman (2008) has presented work where reactive filter media such as Polonite® saturated with

phosphorus successfully have been used as fertilizer substrate when growing plants.

Polonite® material has in some earlier tests been found to react slower and less effective when interfered by organic substances which occurs in wastewater (Renman G., pers com.). This is interesting to further evaluate because it gives an indication on what kind of treatment that is necessary before applying the prototype.

1.1 Background

When the company Biotech AB construct their circulation well Biop®, used for removal of nutrients and BOD in wastewater, they use a fraction of 2-6mm Polonite® material as a reaction media filter.

Wastewater from households after sewage separation is treated in Polonite® by percolation through the Biop, at a slow rate which gives a high reduction of phosphorus. The smaller fractions under 2mm has shown extremely effective sorption capacity of phosphorus (Cucarella Cabañas, 2000). They are too reactive to be used in a circulation well, the slow percolation would cause clogging from the reactions and the setup would be spoiled.

In this project the smaller fractions are going to be tested in another format which relies on a quicker set of reactions. Also that large amount of wastewater and reasonable amount of material reaches a high enough pH.

A difficulty when using these smaller fractions is that it would be hard to separate the Polonite® from the

water stream once it has removed the pollutions from the wastewater. Removing them is important when creating an effective circulation for phosphorus. The prototype has been created for this purpose and is going to be evaluated in this thesis. The prototype is created in a way so that it can take in wastewater that is mixed with dosed Polonite® by appropriate stirring. When the necessary reactions have taken place and the Polonite® is loaded with nutrients the mixture is taken into a drum filter that is going to separate the Polonite® from the water.

To get a sustainable usage of the phosphorus it needs to be collected from the wastewater and used in other applications such as fertilizer in agriculture. The recovery of the Polonite® and phosphorus should be effective so that the accumulation of otherwise harmful phosphorus in waters and sediments can be avoided.

In Cucarella Cabañas, 2000 it is shown how Polonite® efficiently reduce the phosphorus content and also how the sorption efficiency varies with different particle sizes. Lower grainsizes react faster and require lower amount to accomplish the same phosphorus reduction. Fine grain size substrates have large surface areas and therefore the potential to enhance phosphorus sorption capacity (Xu et al., 2006).

1.2 Objectives

The main purpose for this master thesis is to present results for the fine grain size Polonite® and evaluate its potential to recycle phosphorus from wastewater.

From these results there will be a discussion of whether or not this method has potential to be succesful and if so how the process could be optimized.

Results will discuss the phosphorus sorption ability of fine grain Polonite® with this method and also measures of phosphorus reduction in the wastewater. These two aspects are closely connected to pH values, which will be shown in the results.

Another important and interesting aspect is the separation capacity of the Polonite® from the wastewater mixture after being used in the prototype. How much of the used material can be retained and used for other useful purposes in for example agriculture?

1.3 Limitations

This project does not consider and compare costs in any way. Of course this is a very interesting and important aspect to consider when further investigations about the method are done.

This master thesis highlights the material, fine grain sized Polonite®, and its functions in retaining phosphorus from wastewater.

One simplification that was made was the measurement of phosphorus in the samples. The concentration of phosphates were measured, not the total phosphorus concentrations.

Reason for this is that phosphates are fairly easy and fast to measure while measuring the total phosphorus

is more complicated. However there is a strong connection between the two, effects and indications will be coherent. Orthophosphates is known as the most dominant form in municipal wastewater (Tsalakanidou, 2006).

Another important aspect there was not time for in this thesis but should be further studied is the effects of the phosphorus loaded Polonite® as a fertilizer.

Polonite® may have better sorption capacity than any other material but the major difference to present wastewater treatment materials could be its potential to, without major treatment, work as a natural fertilizer. Reduction of nitrogen is not tested in this project. All focus is on phosphorus since Polonite® in erlier projects has showed only some reduction, not more than 25% (Renman, 2007). The nitrogen is also usually less harmful since it is usually not the main limiting nutrient. However if the amount of phosphorus becomes very high (unlimited) nitrogen may be limiting for algal and plant growth. In that case nitrogen is going to be a waterpollutant. In wastewater treatment a method for nitrogen reduction is necessary.

2. Theory

2.1 Phosphorus and Nitrogen

Phosphorus and Nitrogen are the key nutrients when discussing removal of nutrients from wastewater, as they cause pollution in the receiving water body. (Kiely, 1996)

Phosphorus is essential for all organisms because it is used in fundamental processes such as storage and transfer of genetic information (DNA and RNA).

Phosphorus is in general the limiting nutrient for the growth of primary producers, such as plants.

If phosphorus exists in a growth limiting environment it is going to be a water pollutant. It stimulates the growth of photosynthetic algae which causes slow moving rivers and eutrophication of lakes. (Kiely, 1996)

Due to human impact over the last 50 years, a lot of lakes close to urban areas have shown considerably higher amounts of phosphorus than undisturbed lakes, making them classified as eutrophic. If accumulated in sediments or deposited in landfills (that only postpones the environmental problems) it loses its nutrient potential and unwanted eutrophication will occur, causing severe reductions in water quality and in fish populations. Eutrophic lakes have high primary productivity causing excessive algal blooms, resulting in poor water quality. Oxygen deficiency is commonly existing in these lakes causing for example lack of some fish species. (Brönmark and Hansson, 2005) Phosphorus also reaches water bodies and soil from surface runoff after being released in the environment by the weathering of rocks.

The phosphorus in soil is usually difficult for plants to obtain. Additions of phosphorus in form of fertilizers are necessary in most agricultural systems to get good productivity. Agriculture accounts for a major part of phosphorus usage in the world (80%), but it is also used in detergents (12%) and animal feeds (5%). (Cucarella et al., 2006)

In solutions, such as water, phosphorus occurs in particles or detritus or in the bodies of micro-organisms as Orthophosphates (PO_4^{3-} , HPO_4^{2-} , H_2PO_4), Polyphosphate (P_2O_7) and Organically bound phosphorus.

Conventionally activated sludge converts most phosphorus to the orthophosphate forms. (Kiely, 1996) These are then removed by chemical precipitation.

When using calcium, reactions are going to be such as:



Nitrogen occurs in amino acids and proteins of organisms. Nitrogen is usually not the main limiting nutrient. However, if the amount of phosphorus becomes very high (unlimited for the utilizers), the nitrogen may be limiting for algal and plant growth. (Brönmark and Hansson, 2005)

Just like phosphorus, nitrogen is going to be a water pollutant if existing in a growth limiting environment causing similar environmental problems when present in surplus.

The total amount of nitrogen in wastewater can be approximated by organic and ammonia nitrogen. However, in the wastewater treatment process these two substances are oxidized, which means they will take the state of nitrite and nitrate. Nitrite is unstable and oxidizes easily to nitrate. When the nitrogen then is in the state of nitrate it can, by the processes of nitrification and denitrification, be turned into nitrogen gas (N_2) which is desirable in the treatment process.

Nitrification is an aerobic process where the conversion of ammonia to nitrite takes place, while denitrification takes place in an anoxic environment where nitrate is transformed into nitrogen gas. (Kiely, 1996)

2.2 Sorption and sedimentation

These two concepts are fundamental for this project and also in general for wastewater treatment.

2.2.1 Sorption

Sorption could occur through three different occurrences: adsorption, ion-exchange and surface precipitation. While adsorption and surface precipitation takes place at the solid surface, the solute species in a ion-exchange are incorporated to the solid structure. These types of sorption depend on several factors such as particle size, structure and the chemical composition of the sorbent. Temperature, what kind of other ions present in the solution and the concentration of them also plays an important role. (Tsalakanidou, 2006)

Adsorption occurs by the complexation mechanism between donor and acceptor where atoms of the surface functional group donate electrons to the sorbent molecules.

When designing industrial absorbers it is essential to provide some description of the rate of adsorption, the time elapsed before a given concentration of pollutant is removed from solution. (McKay, 1996) Cations and anions adsorb with pH dependance, each modified by ionic strength, complex formations, hydrolysis and the ratio of present adsorbate to total sorbent surface area. In general, sorption of cations is weak at low pH and stronger at high pH. Opposite applies for anions.

Ions near the solid-water interface attaches to the mineral surface by electrostatic forces or by the formation of complexes. This surface complex could be inner or outer-sphere. Outer-sphere are just loosely attached to the solid surface by electrostatic bonding. This is because water molecules intervene between the adsorbed species and the solid surface and the adsorbed species never come close enough. However, inner-sphere complex has no intervening water molecules. Ionic and covalent bonding can therefore form between adsorbed species and specific functional groups on the solid surface.

Surface Precipitation occurs when the solubility product of a solid phase has been exceeded. It occurs on that solid phase when there is a supersaturation which is required. The surface precipitation is a threedimensional molecular arrangement with a structure and composition that depends on the host. In general, precipitation reactions are much slower than adsorption reactions. (Tsalakanidou, 2006)

Ion-exchange involves replacement of ions on a solid compound by another ionic species taken from an aqueous solution in contact with the solid. Every ion that is removed from the water to the charged solid surface by electrostatic attraction is replaced by the same amount of similar charged ions from the solid. (Tsalakanidou, 2006) In the wastewater treatment process it is necessary to use material that is able take up pollution-ions and release less harmful ions. Ion-exchange is not the major process in sorption of phosphorus. (Eveborn, 2003)

2.2.2 Sedimentation

Sedimentation describes the motion of molecules in solution in response to an external force such as gravity, centrifugal force or electric force. This phenomena is fundamental in the wastewater treatment process due to its simple ability to separate unwanted substances that have a different density than water from the wastewater. In this case, this simple phenomena will be avoided at the start of the process when Polonite® is mixed with the wastewater. The mix should be kept turbulent to get good contact between the adsorbent and its reactant. The process would not be effective if Polonite® settled as sediment on the bottom. Although, the sedimentation phenomena will be helpful after the adsorption process when separating the Polonite® used for phosphorus removal from the less phosphorus polluted water.

2.3 Brief description of kinetics

When interacting solution phosphate with calcite a rapid decrease in phosphate during 10 min followed by a slow decrease could be expected. Higher temperatures increase the reaction rate while the lower temperatures decrease the approach towards equilibrium. The rate of adsorption is regulated by the solution concentration of phosphate and the number of empty surface sites. The calcium phosphate compound which is nucleated on the surface (usually hydroxylapatite) depends on the initial phosphorus concentration, i.e., the Ca/P ratio. (Griffin and Jurinak, 1974)

2.3.1 Influence of pH-values in the process

Polonites sorption effect of phosphorus is very related to the pH value in the surrounding liquid, as is sorption of most inorganic compounds. This has to do with the electrostatic attractions involved in this kind of reactions. Large parts of the particle charge in these ions are variable which makes these attractions different depending on pH-values.

Soluble monocalcium phosphate reacts with calcium carbonate to form first dicalcium phosphate and then the tricalcium phosphate, TCP. Those compounds are quite insoluble, but there are possibilities to form even more insoluble compounds, such as hydroxyl-, oxy-, carbonate- and fluoroapatite compounds. (Bertrand, 2008)

In alkaline conditions soluble phosphate ions reacts with calcium which is a major component in Polonite®, as is seen in Table 1.

The precipitation that forms from this, is apart from pH also dependent on temperature, phosphate concentration and supersaturation index.

The precipitation of calcium carbonate/phosphate minerals are described as different sequences. These sequences consists of amorphous tricalcium phosphates (TCP), dicalcium phosphate dihydrate (DCPD) and octacalcium phosphate (OCP) which form as precursor phases that transform to hydroxyapatite (HAP) depending on the circumstances. At pH values 7-9 the TCP phase converts to OCP as a precursor state to HAP. The conversion from the amorphous solids to OCP and HAP depends on the temperature and pH of the solution. At increased alkaline conditions, pH~9.3 and higher, the hydrolysis of OCP to HAP is very rapid and makes it difficult to detect the precursor OCP state. So at higher pH values, the conversion from TCP to HAP appears direct without intermediates. (House, 1999) This could be one explanation for the results later presented.

2.3.2 Phosphorus sorption capacity

The phosphorus sorption capacity is measured and expressed as the phosphorus sorbed per unit substrate. The substrate unit is usually mass. The capacity for a phosphorus sorbent can range from a few grams per kilo up to over 100g P/kg substrate which is the case for Polonite®. The sorption capacity can vary with particle size of a material and also with the type of experiment that is applied to estimate the capacity. The capacity can be determined by batch and column experiments.

In chapter 2.4 there is a selection of materials that has been used and tested for phosphorus removal. The sorption capacity mentioned with each material should only be compared as a hint. The materials are used in unlike ways and may not require a very high capacity. For example when investigating substrates used for construction of wetlands the focus lies on availability and cheap restproducts are often considered.

The numbers for the sorption capacity should not be considered as absolute. The experiments for each material does not have the same setup. Even with the same type of experiment the results can be very varying. For example varying amounts of phosphate and different times for batch experiments may be misleading.

Another important aspect when considering the appropriate substrate for phosphorus removal is the percentage of phosphorus uptake.

2.4 Previously used and tested sorbents

Many materials has been tested and evaluated for reduction of phosphorus. Here follows a description of some selected substrates.

2.4.1 Material used at wastewater treatment plants

Ecoflock is a chemical that is commonly used at wastewater treatment plants in Sweden for precipitation of among other things phosphorus. It consists of polyaluminahydroxide.

Ekoflock is used at for example Skokloster, Fagerhult and Sanda wastewater treatment plant. In 2006 Fagerhult used 45g *Ekoflock*/m³ wastewater (5800kg/127563m³) (Pettersson 2007). Sanda used 195g/m³ during the first half year of 2007 and then changed precipitation chemical to *Pluspac1465* (poly aluminahydroxide solution) which is used in approximately the same amounts (Strand 2007). At Hidingsta wastewater treatment plant it was used 197g/m³ *Pluspac1465* 2007 (Örebro 2007).

2.4.2 Natural materials

Bauxite is a natural existing mineral rich in Al- and Fe-oxides that can be used to adsorb phosphorus. It has an estimated sorptioncapacity of 0.35-0.61g P/kg from batch and column experiments (Eveborn 2003).

Zeolite is a aluminasilicatemineral that is in some cases used for industrial purposes due to its well known adsorption capacity. In batch experiments the sorptioncapacity for *Zeolite* has been estimated up to 0.215g P/kg (Eveborn 2003). *Zeolites* has been succesfully used for nitrogen removal. (Hedström 2006)

Limestone consist of calciumcarbonates were calcite and dolomite is the major constituents. Its sorptioncapacity has in batch experiments been estimated to 0.68g P/kg (Eveborn 2003).

Wallastonite is a calcium metasilicate with a reported phosphorus sorption capacity. Its mineral composition is similar to *Polonite*[®]. (Cucarella Cabañas, 2007)

Shellsand exists in different types and differ slightly in chemical properties. It contains around 30% Ca and low amounts of Mg and Fe. *Shellsand* is naturally available along the coastline. It has good phosphorus sorption capacity and hydraulic conductivity in labatory tests. There is a lack of full-scale experiences but shellsand has the right properties. The phosphorus sorption capacity has been estimated to 8-17g P/kg in different batch experiments. (Adam et al., 2007)

2.4.3 Commercial products

Filtra P consist of lime, iron compounds and gypsum. It is a commercial product developed by the finnish company Nordkalk. *Filtra P* has high phosphorus removal efficiency due to its high pH and major Ca content. The removal percentage of phosphorus from

wastewater has been as high as 95% with *Filtra P*. (Cucarella Cabañas, 2007)

Filtralite P is a light weight aggregate (LWA) produced by heating clay to 1200°C. It has a some phosphorus sorption ability, measured in laboratory tests. Its capacity has been measured to 2.5-4.5g P/kg in batch and column experiments. *Filtralite P* also has a reported good fertilizer effect. (Adam et al., 2007)

2.4.4 Industrial by-products

Blast furnace slag is the most investigated industrial by-product for phosphorus sorption. It is derived during iron production from slag forming minerals, mainly limestone. (Hedström 2006)

Red mud is a by-product from alumina production. It contains among other things iron- and aluminahydroxides. Batch experimants has estimated the sorption capacity to 27g P/kg. (Eveborn 2003)

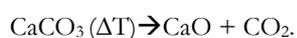
3. Material and Methods

3.1 Opoka – Polonite®

Opoka is a bedrock of calcium rich sediment deposit formed from the remains of minute marine organisms. It occurs in south-eastern Europe and Russia and consists mainly of SiO₂ and CaCO₃. Depending on the ratio between these two they are called light-weight, if more SiO₂ or heavy-weight if CaCO₃ is major. Its contents and properties suggest a high sorption of PO₃-P and therefore it is a promising sorbent in municipal wastewater treatment.

The chemical composition of Opoka/Polonite® (silica-calcium) is friendly to the environment and not dangerous for agriculture and soil. The heavy metal content is similar to what is normally found in most agricultural. (Brogowski and Renman, 2004)

Polonite® is a product of opoka processing. By heating opoka at high temperatures most of the calcium carbonate is transformed into calcium oxide.



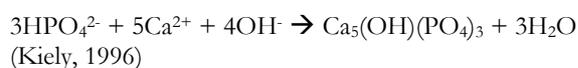
This gives a higher solubility product that is more reactive in aqueous solutions.

Polonite® is a material that has been developed with the intention of creating a good reactant for fixating phosphorus. Tested sorption capacity shows very high results, up to 119g P/kg. One of the active developers is the supervisor of this thesis, Gunno Renman. The product name is owned by Biotech AB.

The P-sorption capacity of Polonite® is high. Its P-sorption efficiency depends strongly on the particle size and retention time. Tests has showed that Polonite® can fixate phosphorus up to 12% of its own weight. Its high pH also makes it successful in reducing bacteria from wastewater.

Polonite® has in earlier investigation appeared to be a very promising sorbent and appropriate for fixating phosphorus, reducing it from wastewater.

Chemical precipitation to remove ortho-phosphate forms:



Tabel 1. The chemical composition of Opoka and Polonite® (Brogowsky and Renman, 2004).

Compound (% dry weight)	Opoka	Polonite®
SiO ₂	52,10	52,50
CaO	19,30	32,30
Al ₂ O ₃	5,75	5,67
Other	~23	~9

Good fertilizer potential in Polonite® has been presented, which is very beneficial for environmental purposes. The fertilizer potential is possible because the bonds between the nutrients and the Polonite® are not too strong for plants to overcome. Cucarella et al., 2006 has among others stated that when saturated with phosphorus, Polonite® can be used as fertilizer substrate in agriculture.

When considered as fertilizer Polonites® ability to trap heavy metals needs to be considered (Brogowski and Renman, 2004). Studies has shown that Polonite® can reduce many sorts of metals from wastewater hence there are metals attached to the eventual fertilizer.

However, some studies has shown that the concentration of metals are much lower than the limits for spreading sludge on arable land. (Renman 2008)

3.2 The prototype

The prototype (fig 1) has been developed and built at Biotech AB's sister company, Hallstaviks Mekaniska Maskinmontage AB in Hallstavik, 70km north of Stockholm. It has been constructed for this purpose only and is thought to be further developed if promising results can be achieved.

The effect of Polonite® reducing phosphorus in wastewater is already known to be succesfull, but it has not been tested in this format before. The fraction tested in this case 0.1mm-2mm is also more difficult to handle in the recycle part of the project. After mixing it with the wastewater and reducing phosphorus concentrations it needs to be extracted so it can be used again. Possibly as a natural fertilizer.

This prototype, makes the extraction after usage possible.



Fig. 1 CEO of Biotech, Claes Thilander and the prototype.

Wastewater is pumped in to a mixing jar (fig. 2-4). The jar can take about 500L wastewater and is equipped with two different types of propellers stirring the mixture. This is where the Polonite® is dosed into the turbulent wastewater creating the right circumstances. When the wastewater mixture has got high enough pH and phosphorus levels in the water hopefully are reduced and minimized the mixture is released off to the next step which is a filter drum where the purpose

is to recycle the Polonite® which now should be loaded with phosphorus.

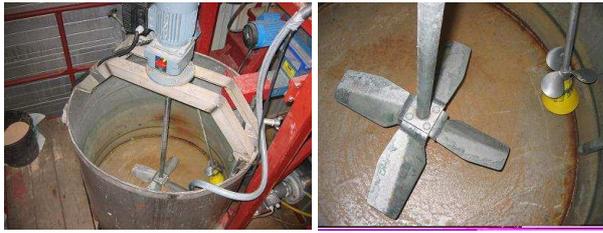


Fig.2-4 Setup of the mixing jar. A turbulent mixture is needed to keep the Polonite® powder active in the whole jar. High pH is desirable to attach phosphorus to the reactive Polonite and thereby remove it from the wastewater.



This drum filter separates particles from incoming water in small pockets due to centrifugal forces. These small pockets eventually reach a water jet that flushes down the Polonite® in a separation compartment. The water that is used in this jets was in this case additional water from external force, but it could easily be arranged so that water from the process is partly used again after being treated, creating a process which is less dependent on other sources. This added water makes measurements of phosphorus concentrations limited to the mixingjar before the solution is diluted. Therefore were all samples taken from the surface of the solution in the mixing jar.



Fig 5-6 Description of the drumfilter that separates used Polonite from the wastewater mix. Cylinder goes around and catches particles in its small pockets, while water is released to the next step. Fig. 6 (to the right) shows the separation compartment where parts of the material is retained.

The drumfilter can be run both manually and automatically. Manually in this case means that it runs constantly with no stopping when its turned on. When it runs automatically it means that the water level inside the drum decides when to turn on the power. A sensor starts the drum when the waterlevel is at a certain height.

For this test run the Polonite® separated in the drumfilter was lead down to the same tank as the rest of the mixture. In further testing of this prototype it should be arranged so that separated material from the drumfilter is retained in another storage tank. As it was now, it was hard to estimate how much of the used material that was retained in the drumfilter.

After going through the drumfilter, the wastewater moves on down to the last step of the prototype which is a sedimentation tank (fig 7) for the remaining

Polonite® material to settle and be retained as much as possible.

This tank is constructed with a blocking section in the outgoing end so that water running out has to go over an edge (fig 8-9). This way, only the top water at the surface will move out of the tank. Which means that particles with a density higher than water will stay in the tank if the water is calm enough.



Fig. 7-9 Final step of the prototype. Sedimentation tank where remaining used material is retained by letting it settle to the bottom.

Table 2. Facts of the prototype tested in this project.

Quick facts

Size:

- Length: 5m
- Width: 1.9m

Parts:

- Mixingjar: diameter 900mm , height 820mm. Approx: 520dm³ (L)
- Drum filter and sedimentation tank used for retention of the polonitematerial.

Necessary assets:

- Waterconnection
- Electricity

3.3 Pretesting in the lab.

Before starting up the prototype out in Skokloster wastewater treatment plant some tests were done in the lab. Mainly to get an idea of how much reaction media material that is needed for removing nutrients from the water. To get an effective process pH-values of the mixture must be high as stated earlier. To get an idea of what pH to expect with different concentrations a test with a miniature flockulater was setup. Normal tap water was used and three different kinds of Opoka material tested. One of the materials was used as a reference since it has been tested for high sorption capacity and used successfully for phosphate reduction before, in this case called Opoka1000 (fine grain Opoka burned in 1000°C). Opoka testburn was calcinated in Poland in conditions not tested before.

Last material was untreated Opoka burned in 900°C in the lab just days before this test.

The different materials were carefully weighted and added while stirring the solution. The solutions were measured for pH with time and compared.

Another test with the same miniature flocculator was done to test the phosphate and ammonium uptake. A synthetic wastewater was constructed and compared with real wastewater which contained approximately the same amount of phosphorus and nitrogen. Synthetic wastewater was made from solving K_2PO_4 resp. NH_4Cl into distilled water.

This comparison between synthetic wastewater containing salts only and wastewater from treatment plant with all organic additives is interesting because it would give an indication of where in the wastewater treatment process the prototype would be most effective. It will show the interference that may occur from high BOD content in the process.

Three parallel tests were done adding 0.5, 1.0 and 2.0g/L Polonite® (Opoka1000). Samples from the three mixtures were taken after 5, 10, 20 and 30min of stirring. Measurements of pH were done before the addition of Polonite® and after the test was over.

The Polonite® material used is a powder with fractions of 0.5mm and less. Samples were taken after certain times with a syringe, filtered and put in a fridge. Few days later the tests were examined for ortho-Phosphates in a Aquatec-tecator auto analyzer. Further described later in Analytical method (3.5). Tests for ammonium were not conducted. Phosphorus was decided to be far more interesting and earlier investigations with Polonite® for ammonium uptake have not been successful (Renman G., pers com.).

3.4 Running the prototype.

The prototype was setup at Skokloster wastewater treatment plant. Wastewater was brought to the prototype with a pump. Water pumped from after the BOD treatment step, but before the addition of ecoflock (precipitation chemical, present phosphorus reductant).

The amount of water pumped in to the prototype was measured by timing how long the pump was running. The pump was estimated to pump 0.4L/s.

From earlier tests at Skokloster the phosphorus concentrations have been as low as 0.2-2.0mg/L. So to be sure of getting results that shows not only reduction but also the extent of the reduction, a solution of K_2HPO_4 in distilled water was added to the wastewater in the mixing jar.

After pumping in the required amount of wastewater to the mixing jar a first sample was taken for starting concentrations.

The Polonite® was added while stirring. Samples were taken from the surface with a syringe, 20ml of every sample which was immediately filtered. They were then kept in 20ml bottles and put into a freezer. All samples were taken from the mixing jar because of the

fact that water is added later in the prototype process (when used Polonite® is regained) and the starting concentrations would not be comparable with the concentrations of the treated water.

3.5 Analytical method

All the samples taken for this experiment were tested for concentrations by using an ortho-Phosphate measuring electronic instrument, Aquatec-tecator auto analyzer.

The Aquatec uses a Molybdate method for determination of Orthophosphate concentration in the water samples. Orthophosphates in the sample reacts with Ammonium Molybdate (Mo), $(NH_4)_6Mo_7O_{24} \cdot 4H_2O$ to form heteropoly Molybdophosphoric acid.

The acid is reduced in a second step to Phosphomolybdenum blue by Stannous Chloride $SnCl_2 \cdot 2H_2O$ in a Sulphuric acid medium. This strong blue colour from the heteropoly compound is then measured at 690 nm.

The artificial Phosphorus solution used for the determination method was prepared by dissolving solid di-potassium hydrogen Phosphate ($K_2HPO_4 \cdot 4H_2O$) in distilled water.

The original solution was of 100 mgP/L. From the original solution the reference solutions for the Aquatec was prepared and diluted to 5, 10, 25 and 50 mgP/L.

The original solution was prepared by dissolving 0.4393 g of Potassium dihydrogen Phosphate in distilled water which was diluted to 1000 ml.

4. Results and Discussion

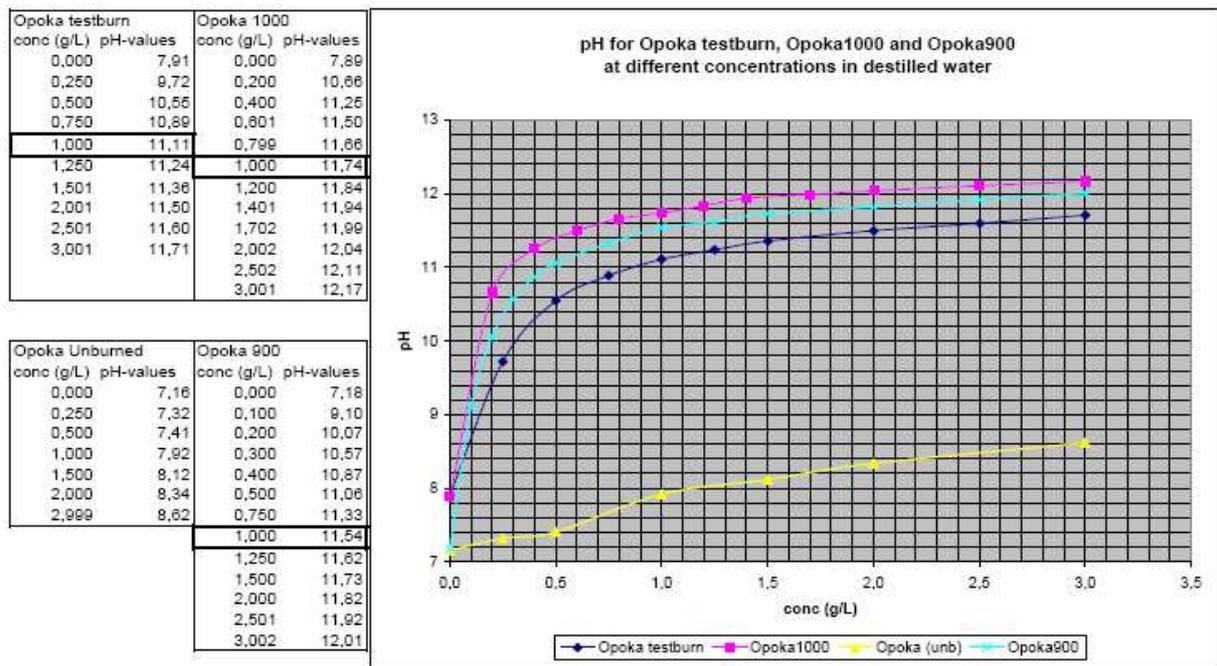


Fig. 10 Shows pH measurements of three types of burned Opoka materials in distilled water. This could give a good indication of amounts of Polonite needed for phosphorus reduction. Axes shows pH for varying concentrations of material added. For a successful absorption of phosphorus, pH of the solution needs to be close to 11 or higher.

4.1 Results of pre-tests in the lab

Results in figure 10 is from pre-tests in the laboratory where pH values were tested for some different Polonite® materials. Opoka1000 was used as a reference. From earlier tests it is known that if pH reaches 10~11 in a solution, phosphorus will be successfully removed (Renman G., pers. com.). Observe that the names are just to separate the materials. They are all materials produced from burning Opoka. The number used in the name indicates the temperature the Opoka was burned in.

The reference had clearly the highest pH. Opoka testburn was produced and burned in a way not tested before showed remarkably low values. Opoka900 was burned two days before the tests in the lab in a small

scale production and is slightly coarser than the reference material. Some unburned Opoka was also tested just to show the huge difference in alkalinity when the material has been oxidized.

Testing pH in Polonite®/water solutions is a good and fairly easy way to test the quality of the material. With high pH in a water solution, a high sorption rate of phosphorus could be expected. It seems that coarser material gives slightly lower pH. This could depend on larger available surface and better spreading in the solution.

The same pH values can not be expected in a wastewater solution due to different composition with organic acids and BOD contents.

Therefore another similar test with wastewater was

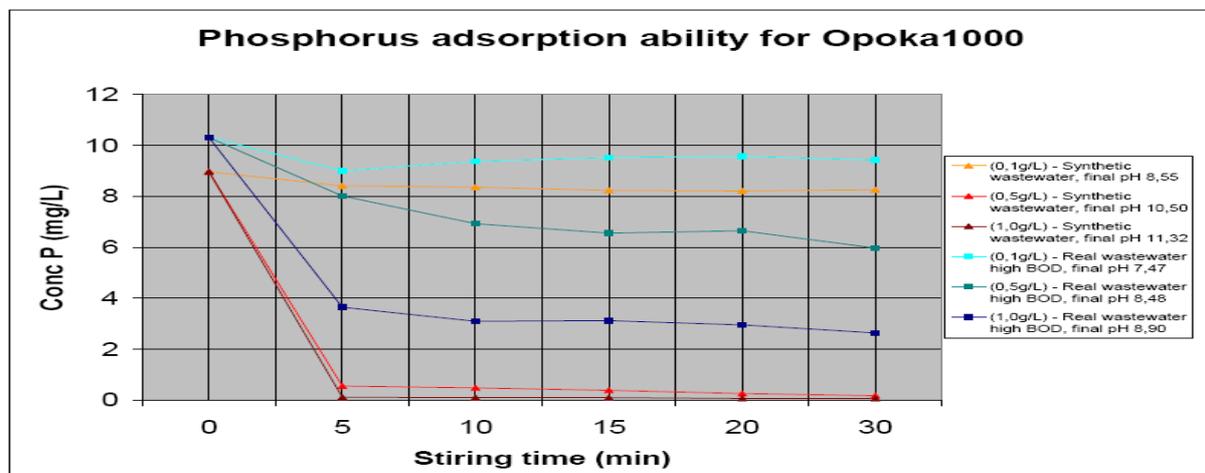


Fig. 11 Phosphorus reduction in synthetic resp. real wastewater (high BOD). Axes shows phosphorus concentration and stirring time with Opoka1000 in the solution. Lines show that reduction is much less effective with untreated wastewater.

done with the reference material. It was done with real wastewater and synthetic wastewater (fig 11). The reduction capacity was tested in two kinds of solutions. One with synthetic wastewater containing approximately 9 mg/L phosphorus and 30 mg/L nitrogen. Another one with real wastewater with similar contents of phosphorus (slightly higher) and nitrogen, but also high BOD content, organic acids and all other ingredients of disposal. This was done to see how the BOD and other contents could effect the pH values and thereby the reduction process of phosphorus.

As can be seen, there was a significant interruption in this case. It should be mentioned that the wastewater used in this case was untreated and from visual estimation (dark and not transparent) had very high BOD and organic matter.

From these results it was decided that the prototype was going to treat wastewater taken from after the BOD treatment step in the treatment plant to avoid

unnecessary interruption in the phosphorus reduction process.

It is also clear that 1g/L of Polonite® is enough if there is no substances that are interfering. However, in wastewater there will be some contents that will keep pH down. To keep pH of the solution high enough it will be necessary with more material.

4.2 Results from running the prototype

The prototype was setup at Skokloster treatment plant north of Stockholm in the municipality of Håbo.

The average daily intake to this treatment plant is 500-600m³ from approximately 2000 people, depending on season. The limits for outgoing concentrations have been set to 0.3mg/L for phosphorus and 10mg/L BOD. (Håbo kommun, 2007)

The prototype was tested with different amounts of water in the mixing jar and Polonite® added in varying concentrations. (fig. 12-14)

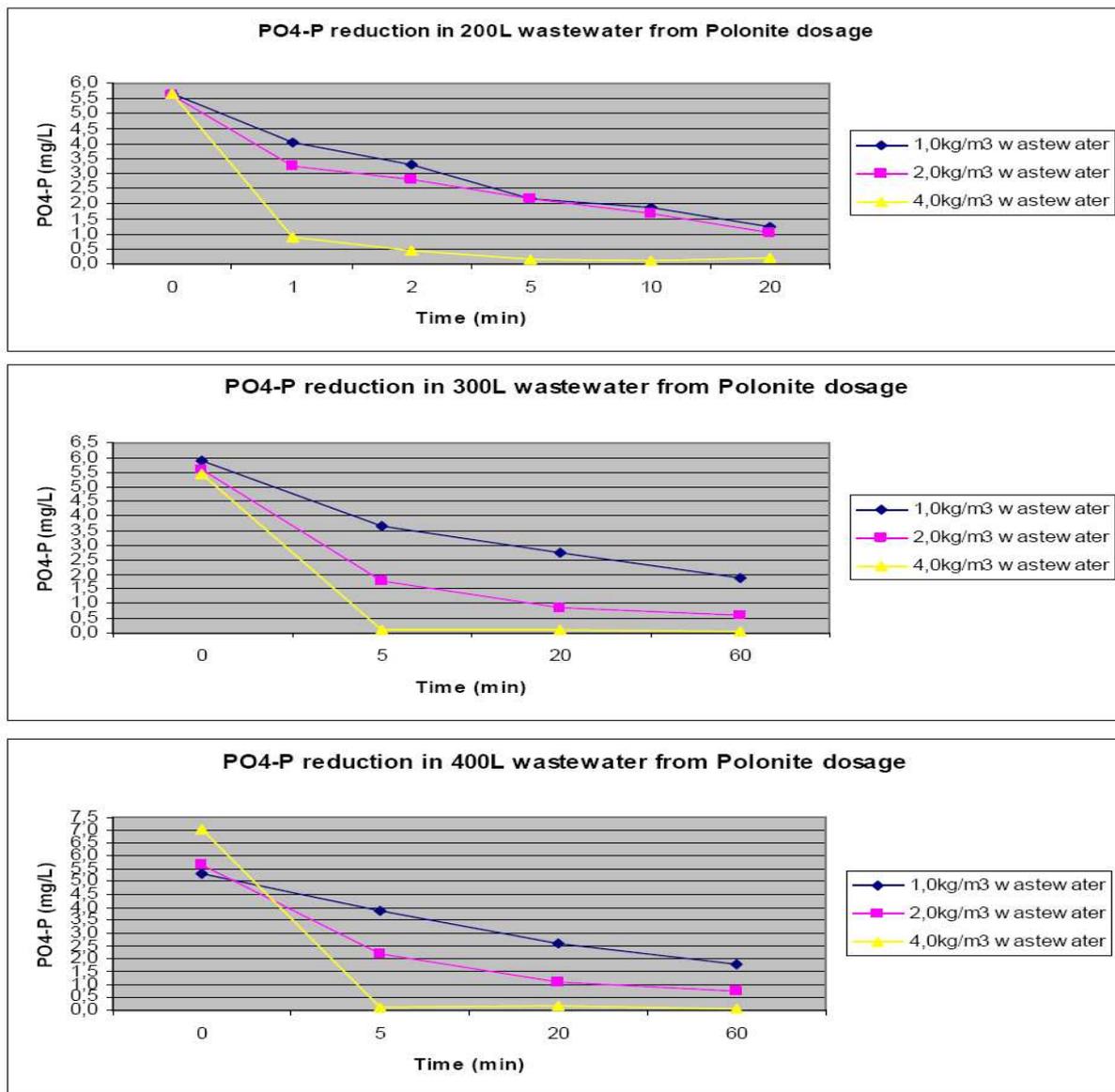


Fig. 12-14. Phosphorus concentration in the solution decreasing over time after Polonite® dosement.

Tests with same concentrations were done because more water in the mixingjar was assumed to be less turbulent which would give less contact between the phosphorus and Polonite® and weaker reduction of phosphorus. Results showed no such indication. Most starting concentrations of phosphorus were 5-6 mg/L (measured in ortophosphates). The wastewater that was used was taken from after the mechanical and BOD treatment step. 1 kg/m³ was not enough to reduce the phosphorus amounts under Skokloster treatment plants approved outlet limits (0.3mg/L). At double amounts of Polonite® the limits are close to be reached but phosphorus concentrations are still over 0.5 mg/L. The national recommendations for phosphorus outlets from wastewater treatment plants are usually 0.3-0.5mg/L (Svenskt Vatten, 2005), set by The Swedish Environmental Protection Agency that provide guidance in environmental management systems. So in this case 2kg Polonite®/m³ was not enough. At the highest concentration tested (4kg/m³) the reduction is very good and phosphorus amounts are low enough after 5 minutes. Even when the starting

concentration is as high as 7.0mg/L the outlet limits are clearly accomplished after only 5 minutes. From erlier tests in the lab, one could see that there is enough material for the phosphorus to attach when adding 1kg/m³, but in this case with wastewater and its contents the pH does not rise to high enough for a complete reduction. The daily usage at a small plant like the one in Skokloster would be around 2000kg, which is to much to apply. One interesting aspect with the material is that it could be possible to use more than once. A basic theoretical calculation with approximate numbers from the test runs shows that the capacity is far from being reached. When reducing the phosphorus contents for example in 1000L (1m³) wastewater from 5mg/L to 0.1mg/L the Polonite® is not fully loaded. According to Brogowski and Renman (2004) the sorption capacity can be up to 119gPhosphorus/kgPolonite®, Cucarella Cabañas (2000) presented sorption capacity of 117g/kg and Bertrand 2008 had similar results with 99g/kg. The phosphorus sorption from 1000L would in this

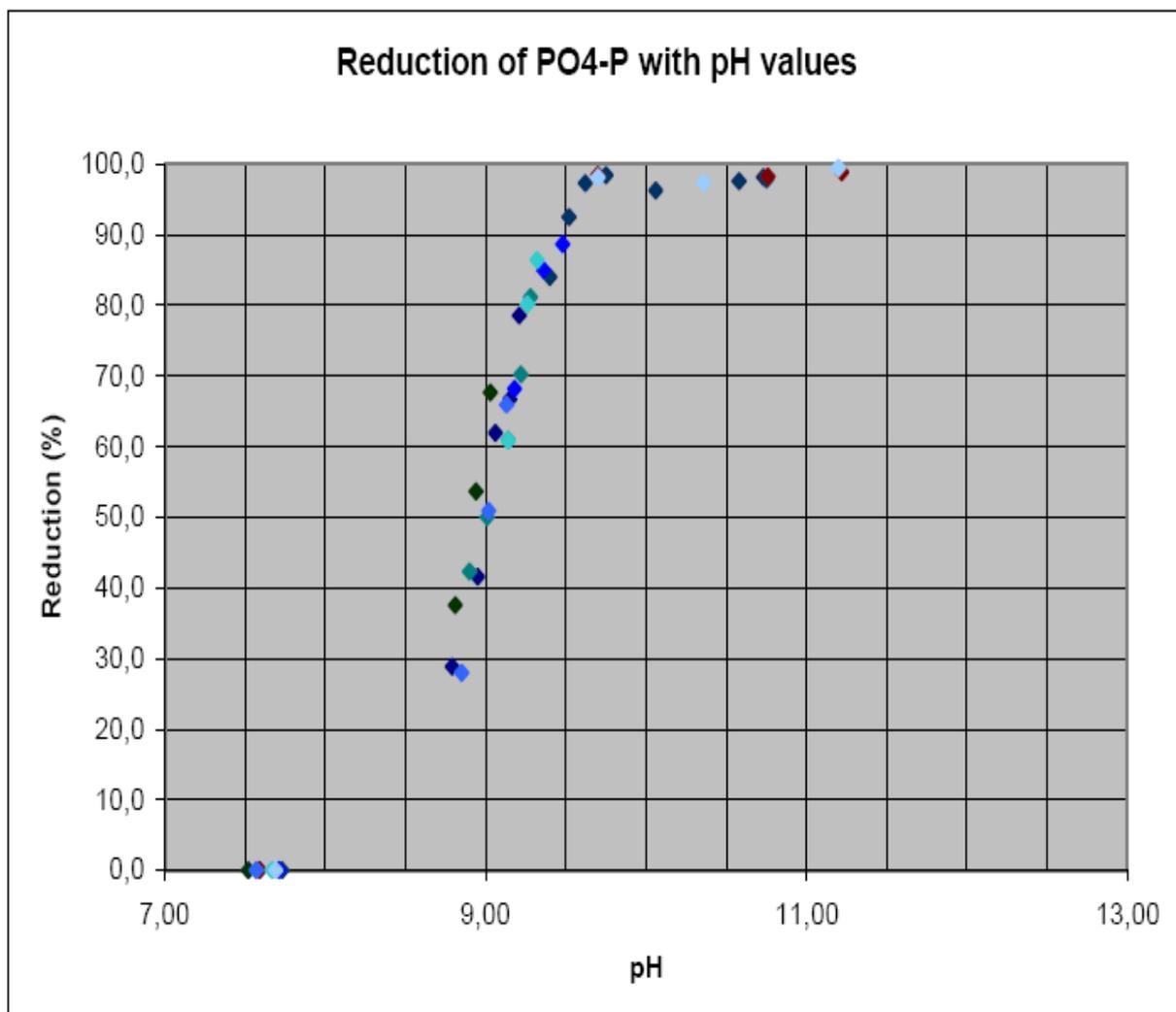


Fig. 15 Phosphorus reduction in the wastewater solution with pH variance. When pH goes over 9.5 in these solutions the reduction is over 90%. For reductions around 95% the results indicate a pH of 10.0 or higher.

example be 4.9g (4.9mg/L). So if using 1kg Polonite® for 1000L (1kg/m³) reducing the phosphorus concentration from 5.0mg/L to 0.1mg/L only 4.9g of theoretically possible 90-120g is adsorbed. So clearly the material should in theory be possible to use several times. At least according to earlier estimations of the sorption capacity. Please observe that the approximate reduction numbers and amount of wastewater are used to simplify the calculations. A more effective process is necessary not only because too much material would be required but also the fact that the attached phosphorus might not be enough for using the Polonite® as fertilizer. If a reuse of the Polonite® would be applied the question is of course if the material still is active to the same extent or it needs some kind of treatment such as drying. High BOD and organic matter in the wastewater seem to interfere with the sorption capacities. It would be interesting to see if it is possible to get a better reduction with less material if the pH of the solution was higher from some other kind of addition. This addition of a substance should of course be of a sort that does not interfere in any way with the very environmental friendly process that is evaluated in this project. However the results show that the amount of material needed for an effective reduction of phosphorus is not optimal. Storage space that would contain the volumes of new and used material should be minimized to increase possible users and not make transportation an issue. When pH has reached 10 in the wastewater solution the reduction of phosphorus is over 95% (Fig 15).

For a reduction over 90% pH over 9.5 is necessary. As expected there is a clear linear connection between the phosphorus reduction and the pH of the solutions. The dots are coloured to show which ones that comes from the same testrun.

The pH values raises with time during the mixing process (fig 16). After one hour of mixing the pH is still climbing but diminished compared to the starting minutes. It takes a while before pH raises to its maximum in the solutions. With large concentrations of Polonite® such as 4kg/m³ the necessary conditions quickly arise, but its full potential takes around one hour to achieve. Even after one hour the pH is still rising in some cases.

There is a small indication that more water and more material (same concentration) gives slightly higher reduction of phosphorus (fig 12-14) and higher pH (fig 16). However, these indications are too small to draw any conclusions from.

The recovery of used Polonite® from the prototype is another interesting aspect. Since the phosphorus loaded material could be used again, mainly for agricultural purposes and create a cycle which would be healthy for the environment, it is important that the prototype can accomplish a good recycle of the material.

The results for the recovery was simply done by observing the outgoing water stream and taking samples in sedimentation cones. Only small fractions of material that comes to the surface with turbulence, escapes from the sedimentation tank. This can be solved with a smoother inlet, into a deeper tank.

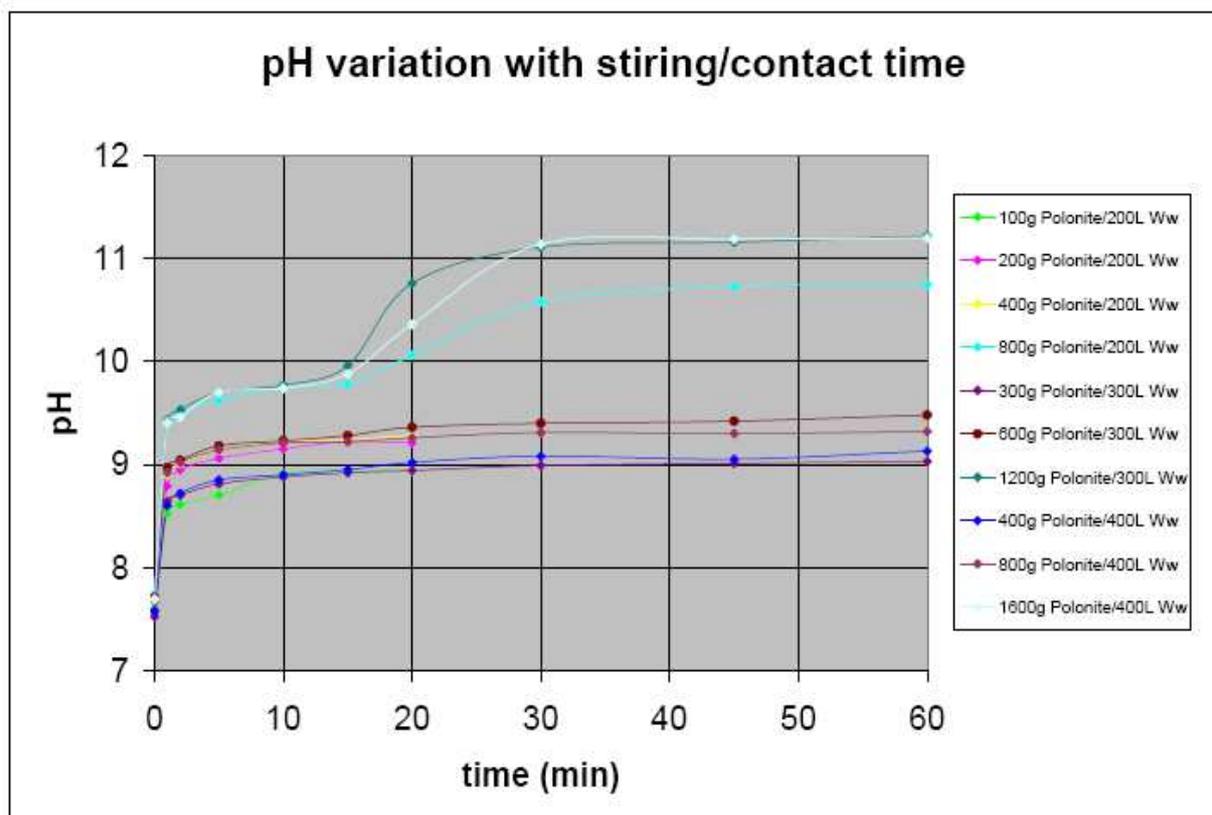


Fig. 16 Variation of pH in the wastewater at different contact times with the Polonite®.

The drumfilter seems to separate the Polonite® well and together with the sedimentation tank with the special designed edge it seem to recover at least 90% of the Polonite® used in the process.

The used Polonite® has in erlier mentioned references proven to be a promising fertilizer which could be used without adding chemical substances.

So by using Polonite® when removing the phosphorus from wastewater, the phosphorus is preserved and can be used again. This would make Polonite® useful not only for wastewater management but also for farmers and agricultural purposes.

In some wastewater treatment plants the incoming phosphorus concentration can be low (0.5-1mg/L) because of leakage from groundwater and heavy rainfalls. This is not optimal for this kind of process. The calcium phosphate compound that is formed when attaching the phosphorus on the Polonite® depends on the calcium/phosphorus ratio (Griffin and Jurinak 1974). This means that more material is needed for lower concentrations to get the same reduction percentage. It also means that Polonite® is more appropriate and very effective with high phosphorus concentrations. Thereby the extremely high sorption capacities in the laboratory tests (up to 119g P/kg) with unlimited access to phosphorus.

The treated wastewater had a temperature of 5-10°C, higher temperature seem to improve the phosphate-calcium reaction (Griffin and Jurinak 1974).

High pH is needed for the process to be effective, hence there will be high pH values in the outlet water. To high pH in the outlet could have a negative impact on some organisms and ecosystems. This also needs to be evaluated and considered.

5. Conclusion

Phosphorus can be reduced and retained from wastewater using fine grain size Polonite® as the sorbent. For this purpose a prototype developed by Biotech AB is a good tool.

The results in this thesis show that there is potential. When pH is over 10 the process works well and reduces phosphorus with over 95% from wastewater. Phosphorus concentration at start as high as 7mg/L was reduced to less than 0.2mg/L in 5 minutes.

However, the volume of Polonite® material that is needed to achieve these results is a problem and the process needs to be more effective. Too much material is needed to get good reduction of phosphorus besides the fertilizer potential can probably not be guaranteed with so little phosphorus attached to the Polonite®.

The sorption capacity of the amount that is used is more than enough according to previous laboratory tests, but to achieve a high reduction of phosphorus the properties of the solution must be right. High pH is necessary for the bonding reactions where phosphorus attaches to the Polonite®. Organic matters in the wastewater and low temperature might be interfering factors. When comparing the same processes of phosphorus reduction in synthetic wastewater and real wastewater there is a difference. The composition of wastewater interferes with the adsorbing reactions when it keeps pH down.

It would be interesting to somehow raise the pH with another substance and see if less Polonite® is required. Of course it needs to be a substance that still makes the process environmentally friendly.

Except from high pH, the starting process when adding Polonite® the mixture needs to be turbulent and thoroughly mixed for an effective process. This part could be optimized with a better mixer setup.

The retaining of material after reducing phosphorus contents in the wastewater is working well with the prototype and it seems to be over 90% of material that is recovered. With a larger sedimentation tank and a smoother inlet to the tank the retention could be even more effective.

6. Future studies and investigations

Development of this subject should be pushed hard. A sustainable circulation of phosphorus is necessary since it is not an infinite resource.

Future investigations should be about creating reactive filters and prototypes that can fixate not only phosphorus but also nitrogen for further use and recycling. Instead of having these nutrients eutrophicate lakes and water streams they should be carefully managed and recycled into agriculture.

Now that it is known that Polonite® can retain phosphorus from wastewater and that it is also possible to recycle the Polonite® when it has been used, the future investigations should be about how the process can be optimized and if there is a way of using less material.

It also has to be investigated more how well the nutrient loaded material works as a fertilizer when it has been used in wastewater. The phosphorus must be available for the cultivated plants. This is necessary to close the cycle and have a sustainable process that is advantageous for the environment.

The used Polonite® also has to be checked for heavy metals, it has a tendency of binding them. Only low concentrations has so far been measured.

The prototype tested in this project was mostly tested step by step through out the process, taking in wastewater, dosage of Polonite® and separation.

Ultimately the goal should of course be to have a continual process where all steps work at once.

Using Polonite® as fertilizer would give alkaline soils.

An interesting aspect connected to this project is that when growing vegetables in a alkaline environment the vegetables only shows significant increase of Mo while same growing in acid soils gives significant increase in Ba, Br, Mn, Rb and Zn (Rosborg 2008).

7. References

- Adam, K., Sövik, A K., Krogstad, T., Heistad, A., 2007. Phosphorus 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. *VATTEN – Tidskrift för vattenvård* 63, 245-257.
- Bertrand, J., 2008. Chemical and physical characterization of Polonite® for its use as reactive bed filter material. TRITA-LWR Master Thesis, KTH, Stockholm.
- Brogowski, Z., Renman, G., 2004. Characterisation of Opoka as a basis for its use in wastewater treatment. *Polish J. of Environmental Studies* 13 (1), 15-20.
- Brönmark, C., Hansson, L-G., 2005. The biology of lakes and ponds. Oxford University Press Inc., New York.
- Cucarella Cabañas, V., 2000. Use of sorbents for the removal of phosphorus and bacteria from wastewater, Master thesis, KTH, Stockholm.
- Cucarella Cabañas, V., 2007. Phosphorus recycling from wastewater to agriculture using reactive filter media. Licentiate Thesis in Land and Water Resource Engineering Stockholm, Sweden.
- Eveborn, D., 2003. Småskalig rening av avloppsvatten med Polonite®-filter. Master Thesis, KTH, Sthlm.
- Griffin, R.A., Jurinak, J.J., 1974. Kinetics of the Phosphate Interaction with Calcite. *Soil Sci. Soc. Amer. Proc.*, vol. 38, 75-79.
- Gustafsson, J-P., Renman, A. Renman, G. Poll, K., 2008. Phosphate removal by mineral-based sorbents used in filters for small-scale wastewater treatment. *Water Research* 42(1), 189-197.
- Hedström, A. Reactive filter systems for small scale wastewater treatment. *VATTEN – Tidskrift för vattenvård* 62, 253-263.
- House, W.A., 1999. The physico-chemical conditions for the precipitation of phosphate with calcium. *J. Environmental Technology*, 20 (7), 727-733.
- Hylander, L.D., Kietlinska, A., Renman, G., Simán, G., 2006. Phosphorusretention in filter materials for wastewater treatment and its subsequent suitability for plant production. *Bioresource Technology* 97 (7), 914-921.
- Kiely, G., 1996. Environmental engineering. McGraw-Hill International (UK) Limited.
- McKay, G., 1996. Use of Adsorbents for the removal of Pollutants from Wastewaters. CRC Press, Inc.
- Renman, A., 2008. On-site wastewater treatment – Polonite and other filter materials for removal of metals, nitrogen and phosphorus. PhD Thesis in Land and Water Resource Engineering Stockholm, Sweden.
- Rosborg, I., 2008. Well waters and vegetables from acid areas and an alkaline region – what differences are there in mineral content? *VATTEN – Tidskrift för vattenvård* 64, 215-221.
- Tsalakanidou, I., 2006. Potential of reactive filter materials for small-scale wastewater treatment in Greece. Master Thesis, KTH, Sthlm.
- Xu, D., Xu, J., Wu., J., Muhammad., A., 2006. Studies on the phosphorus sorption capacity of substrates used in constructed wetland systems. *Chemosphere* 63 (2006), 344-352.

Other references:

Håbo kommun, 2008. Skokloster reningsverk. <http://www.habo.se/Boende--Byggande/Vatten--Avlopp/Kommunalt-Vatten--Avlopp/Avloppsvatten/Skokloster-reningsverk/> (Last viewed 2008-10-07)

Petersson, M., 2007. Miljörapport 2006 kommunala avloppsreningsverket i Fagerhult, Högsby kommun. <http://www.hogsby.se/internet/FORVALTNING-TEKNISKAKONTORET/filer/miljorapporter/milj%C3%B6rapFA%202006.pdf> (Last viewed 2008-10-03)

Strand, M., 2007. Miljörapport för år 2007 – Sanda avloppsreningsverk, Karlskrona kommun. http://www.karlskrona.se/Global/Karlskrona%20kommun/Dokument/Bostad%20och%20miljo/VARenhallning%20dokument/Reningsverk/Miljorapport_Sanda_2007.pdf (Last viewed 2008-10-04)

Svenskt Vatten, 2005. Brochure: Facts on watersupply and sanitation in Sweden. http://www.svensktvatten.se/web/Fakta_om_Vatten_och_Avlopp.aspx (Last viewed 2008-09-22)

Örebro kommun 2007, Miljörapport Hidingsta avloppsverk 2007, Örebro kommun. <http://www.orebro.se/download/18.51b3e21a119b841254480002963/Hidingsta+2007.pdf> (Last viewed 2008-10-04)