

Impact of Hydraulic Retention Time on Phosphorus Removal from Wastewater using Reactive Media

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Abstract

Phosphorus (P) discharge from wastewater treatment plants into the environment contributes to eutrophication issues. Reactive media filters represent an effective, simple and cost-effective solution to decrease the phosphorus content. Previous research used various experimental designs and often synthetic wastewater, making assessment of real-world performance difficult. This study assesses the impact of the hydraulic retention time (HRT) on P removal using real wastewater to refine design criteria for full-scale installations.

Four media were compared in column experiments for >200 days. Different HRTs were applied and initially the media achieved low P effluent concentrations of >0.1 mg/L PO₄-P, increasing over time. Best P removal was observed for the highest HRT with on average >99%. HRT was seen to be the driving factor for P removal rather than media capacity. Three of the four materials showed pH levels above 12 initially, decreasing over time.

Water quality parameters including organics, solids and metals were monitored.

In-depths analysis confirmed formation of calcium phosphate precipitation on the media's surface. The results suggest the importance of an optimal HRT to achieve high P removal and shows that the reactive media application is an appropriate technology for P removal on small sites if the elevated pH is addressed.

Keywords

Columns; reactive media; phosphorus removal; wastewater treatment

INTRODUCTION

Nowadays the removal of phosphorus from wastewater is of major concern to water management. The phosphorus discharged from sewage works into the environment contributes to increasing levels of eutrophication. As new phosphorus discharge regulations for small wastewater treatment plants (WWTPs) are expected, a need for cheap, more efficient and sustainable technologies arises (European Water Framework Directive 2000/60/EC). This study aims to assess P removal via reactive media in a filter bed application. Reactive media filters can be applied as a tertiary treatment on small WWTPs to reduce the P discharge to very low levels <1 mg/L PO₄-P via adsorption and precipitation processes. The reactive media system is a suitable alternative to chemical or biological P removal technologies due to their low maintenance and operational simplicity (Bunce et al., 2018). For more than a decade researchers all over the world have been investigating efficient, long-lasting and at the same time low-cost adsorbents (Callery *et al.* 2016). More than 100 materials (natural, industrial and man-made) have been tested for P removal in lab environments as well as field studies (Vohla *et al.* 2011). Various waste materials from industries, such as aluminium or steel making, have shown good P removal in previous research (Blanco et al., 2016; Cusack et al., 2018). Suitable media for this study were selected due to their composition, specifically in regards to their metal content, availability, cost,

56 particle size and capacity. The chosen media were steel slag, calcium silicate bedrock and two types
57 of granulated apatite as they were assumed to remove P to a very low effluent level and the output of
58 previous trials were promising (Barca et al., 2014; Rodríguez-Gómez & Renman, 2017; Troesch et
59 al., 2016). Physical characteristics such as density and porosity vary between different materials and
60 have to be accounted for in the determination of the size of the filter. Many previous studies were
61 based on synthetic wastewater solutions and/ or conditions, which can lead to misleading results due
62 to the impact of wastewater characteristics, whereas this study utilises real wastewater and real-world
63 conditions. Additionally, it is very difficult to compare the performance of the adsorptive materials
64 in different studies due to highly variable experimental conditions such as P inlet concentration, HRT,
65 media particle size, wastewater characteristics, flow configuration and filter size. This study therefore
66 provides direct comparison of different materials under the same conditions.
67 The purpose of this study is to evaluate the performance of four different filter materials for their
68 ability to remove P by means of a column experiment mimicking a filter system in the field, and to
69 further investigate the P removal mechanisms by means of x-ray powder diffraction (XRD), x-ray
70 fluorescence (XRF) and scanning electron microscope (SEM) analysis. An optimal HRT which
71 achieves high P removal is one of the most important parameters for the design of a full-size filter
72 application. Since previous research has mainly investigated only one HRT, this study simultaneously
73 examined three different HRTs for each of the media types. The selection of a suitable HRT
74 determines the effluent P concentration, lifetime of the media and size of the filter system. In a second
75 trial, triplicate columns were established at a suitable HRT selected by the results of the first
76 experiment to test the P removal performance of the media at a higher concentration and over a longer
77 period of time. For a year, data was collected from the triplicates of each media in regards to soluble
78 reactive phosphorus (SRP), total phosphorus (TP), biological oxygen demand (BOD), chemical
79 oxygen demand (COD), total suspended solids (TSS) and alkalinity.

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82 **MATERIALS**

83 Four different commercially available materials have been tested and their properties are shown in
84 Table 1.

85 Steel slag is a by-product from the steel industry. Due to the abundance of steel slag and it being a
86 waste product, the costs are low. The composition and characteristics of the steel slag media depend
87 on the source and kind of furnace it has been processed in. Steel slag from a basic oxygen furnace
88 (BOF) was trialled in the first column study and slag from an electric arc furnace (EAF) in the second.
89 It primarily contains Ca and Fe oxides.

90 Two types of apatite (1 and 2) vary in the binder of the granulation process, the manufacturer did not
91 reveal the specific binders used for commercial reasons. The analysis in Table 1 shows apatite 1 had
92 a higher percentage of CaO, which suggests a cementitious binder, and apatite 2 had a higher SO₃
93 content suggesting that some or all of the cementations material had been replaced, possibly with
94 gypsum.

Table 1. Media characteristics

	Ca-silicate bedrock	BOF slag	Apatite 1	Apatite 2
Main minerals	SiO ₂ , CaO	CaO, Fe ₂ O ₃	apatite	apatite
Main composition	SiO ₂ (55.2%)	CaO (30.6%)	CaO (65.1%)	CaO (63.9%)
	CaO (31.2%)	Fe ₂ O ₃ (28.9%)	P ₂ O ₅ (24.8%)	P ₂ O ₅ (25.4%)
	Al ₂ O ₃ (6.3%)	SiO ₂ (16.7%)	SiO ₂ (4.1%)	SiO ₂ (3.6%)
	Fe ₂ O ₃ (4.0%)	Al ₂ O ₃ (11.2%)	SO ₃ (1.9%)	SO ₃ (2.5%)
	K ₂ O (1.4%)	MnO (4.3%)		Al ₂ O ₃ (2.4%)
		Mg (3.4%)		
		Cr ₂ O ₃ (2.3%)		
Particle size (mm)	2-6	2-10	2-6	2-5
Bulk density (g/cm ³)	0.8	1.7	1.4	1.2
Porosity (%)	56	39	39	50
pH	12.4	12.3	11.1	9.0

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METHODS

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The characteristics of the four materials and their P retention in column trials were studied.

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Media properties

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Mineral composition was evaluated via XRD analysis (Panalytical X'Pert3 Powder) and main oxides via XRF analysis (Panalytical Epsilon 4). Dry sieving determined the particle size. Bulk density was measured by the volume of water displaced by a known mass of medium. Porosity was determined from the amount of water needed to saturate a known volume of media. After 24 h suspension of 1:2.5 media (w): distilled water (V) the pH was recorded. All measurements were conducted in triplicates. Media samples before and after the column experiment were coated with carbon for Scanning Electron Microscope (SEM) analysis (Zeiss EV0 MA10).

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Columns

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Bench-scale column experiments are the most commonly used method to predict pilot-scale design and operation parameters. To assess the selected media in this trial, a bank of 13 columns have been established and experiments of varying HRTs were undertaken. Perspex columns with an inner diameter of 10 cm and a media height of 30 cm were setup as a saturated up-flow filter system. A constant flow rate was achieved by a 24-channel peristaltic pump. Columns were kept at room temperature. Filtered final effluent from the Petersfield WWTP (51°00'00.1"N 0°54'18.1"W), UK, was used as the inlet water and spiked to the desired P concentration of 10 mg/L PO₄-P with KH₂PO₄. Samples were taken from the column outlets and inlet.

Three different HRTs of 8, 15 and 23 h were tested for each of the four media, the vHRT (considering the void space) varied between the media due to their difference in porosity (39-56%). The columns were operated for a total of 200 days with three breaks due to operational issues with pumps, between day 60-75 and 110-124 and 159-185 in which the columns have been drained during the first break and kept saturated during the two others.

A second trial was conducted under the same conditions with an increased inlet SRP concentration of 13 mg/L and a HRT of 15 h. Columns were established in triplicates for Ca-silicate bedrock, apatite

126 1 and steel slag (apatite 2 was no longer available at that stage). The columns have been operated and
127 sampled for a year and stopped for 12 days at day 164-176 when they were drained.
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129 Analysis methods

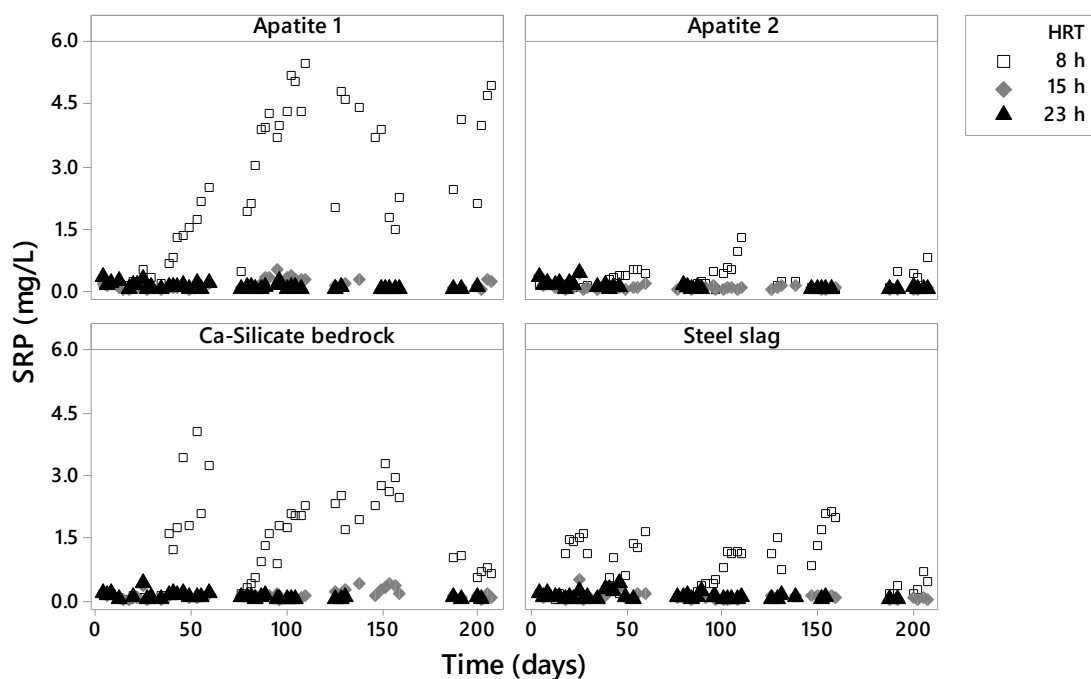
130 SRP analysis expressed as $\text{PO}_4\text{-P}$ was performed according to the Molybdenum Blue Method using
131 the Autoanalyser 3 (Seal Analytics). The pH and water temperature were measured with the pH meter
132 3310 (Jenway). BOD_5 was determined according to Methods for the Examination of Waters and
133 Associated Materials (Standing Committee of Analysts 1988). COD was analysed according to the
134 Closed Reflux Colorimetric Method using the Palintest. Measurement of TSS was conducted via
135 filtration. TP and alkalinity were determined via the colorimetric method using the Palintest. Metals
136 were analysed by Inductively Coupled Plasma Optical Emission Spectrometry (Spectroblue). All of
137 the analysis, unless otherwise stated, followed methods according to Standard Methods for the
138 Examination of Water and Wastewater (2012).

139 Samples were taken from the column inlet tank and outlets for $\text{PO}_4\text{-P}$ and pH analysis three times a
140 week during the first column study and biweekly for the second trial. BOD and TSS were measured
141 weekly and COD, TP and alkalinity fortnightly. Metals were analysed fortnightly for the first 90 days
142 of the experiment (n=5-6).
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144 RESULTS & DISCUSSION

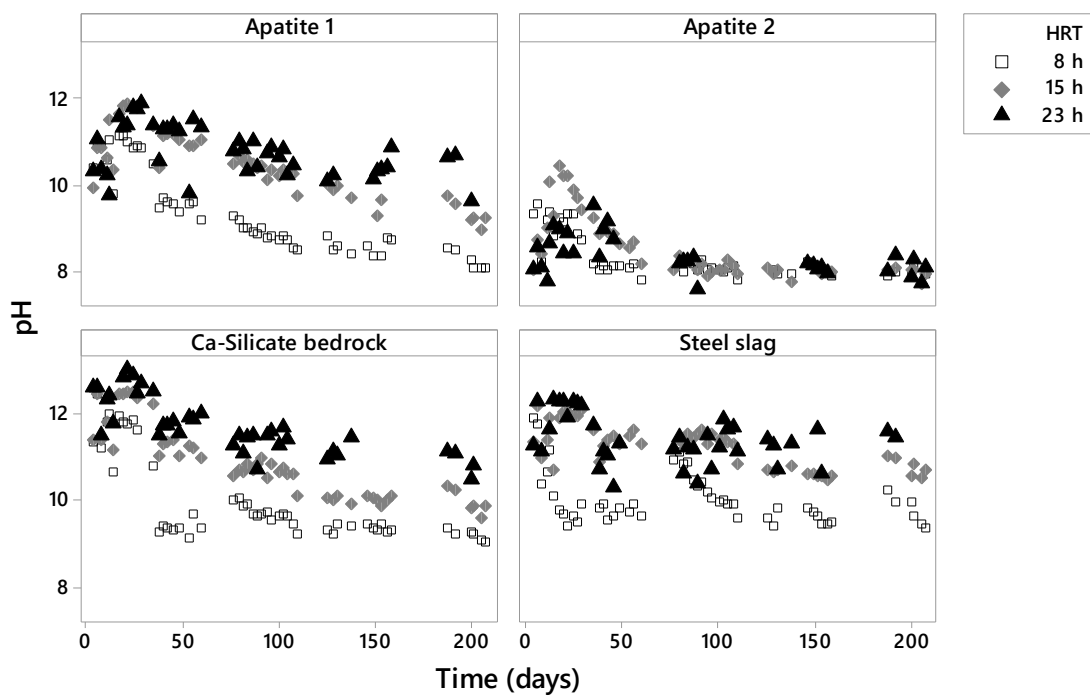
146 First column trial: P removal and pH over time

147 All four media initially removed $\text{PO}_4\text{-P}$ to levels below 0.5 mg/L (Figure 1). Concentrations of >1
148 mg/L $\text{PO}_4\text{-P}$ were received after 20- 40 days of operation from the column outlets containing Ca-
149 silicate bedrock, steel slag as well as apatite 1 at the low HRT. Apatite 2 however still showed good
150 P removal after 90 days and is therefore the best performing media concerning P removal efficiency
151 at high flow rates. The column effluent P concentration started to increase at the lower HRT of only
152 8 h, whereas the concentrations at higher retention times were still below 0.5 mg/L at that point.
153 Therefore, the higher the HRT, the better the P removal of the media. This is supported by other
154 studies, for example Barca *et al.* (2013).



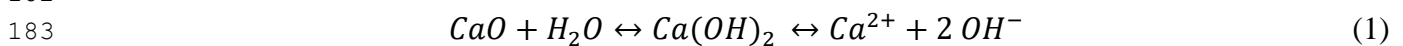
155 **Figure 1.** SRP concentration of the column effluents for different HRTs for each of the media
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157 After the 2 week resting period at day 60 – 75, the performance of the media at 8 h HRT, which
 158 previously showed an increase in the outlet P concentration of the columns, improved for a short
 159 period of time. At the same time, the pH increased (Figure 2). Enhanced P removal following a
 160 regeneration period of the media was also observed by Bird & Drizo (2010) and Karczmarczyk *et al.*
 161 (2019). Drizo *et al.* (2002) suggests the increase in P removal performance can be explained by new
 162 P adsorption sites due to the transformation of minerals to more amorphous forms resulting from a
 163 decrease in redox potential. Also, metal ions such as Ca, Fe and Al could have moved to the surface
 164 of the media during the resting period due to an increase in pH which created supersaturated
 165 conditions. Media recovery is also seen after the second and third break (day 124 and 185), but to a
 166 lesser extent. Although new adsorption sites can be generated during the resting period, the amount
 167 of adsorption sites will always be less than at the start of the experiment, which means the media
 168 cannot be fully regenerated and the P uptake will still decrease over time.
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170
 171 **Figure 2.** pH of the column effluents over time for the different HRTs for each of the media
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173 All four media elevated the pH. The inlet water showed an average pH of 8.2 ± 0.2 . Values for the
 174 columns filled with Ca-silicate bedrock, steel slag and apatite 1 increased the pH to 10-12.5, whereas
 175 apatite 2 seems to only have a small impact on the pH, elevating it to 8.4 on average. Highest pH
 176 values were recorded at the beginning of the experiment and there was a trend of decreasing pH with
 177 time in all cases. This is explained by less CaO dissolution over time due to a decrease in CaO
 178 availability and clogging of the surface due to precipitation, solid deposition and biofilm development
 179 (Troesch *et al.*, 2016). In terms of real-world application, 200 days is still regarded as the initial phase,
 180 considering a lifetime of several years and the pH is expected to drop further after the first few months
 181 (Barca *et al.* 2013).
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 185 The HRT influences the pH. The longer the contact time, the higher the pH, as the media has more
 186 time to release OH^- into the water by CaO dissolution (Barca *et al.* 2014).

187 For the design of a full-size filter system a high HRT means better P removal however, at the same
188 time requires a greater volume of media. Therefore a larger filter bed is needed and the resulting
189 effluent pH is higher.

190 Since the pH is elevated above 9, there is a need for a pH correction step after the media application
191 in order to decrease the pH for the discharge into the environment. Preferably, this is achieved by a
192 passive system such as wood bark filters or aeration.

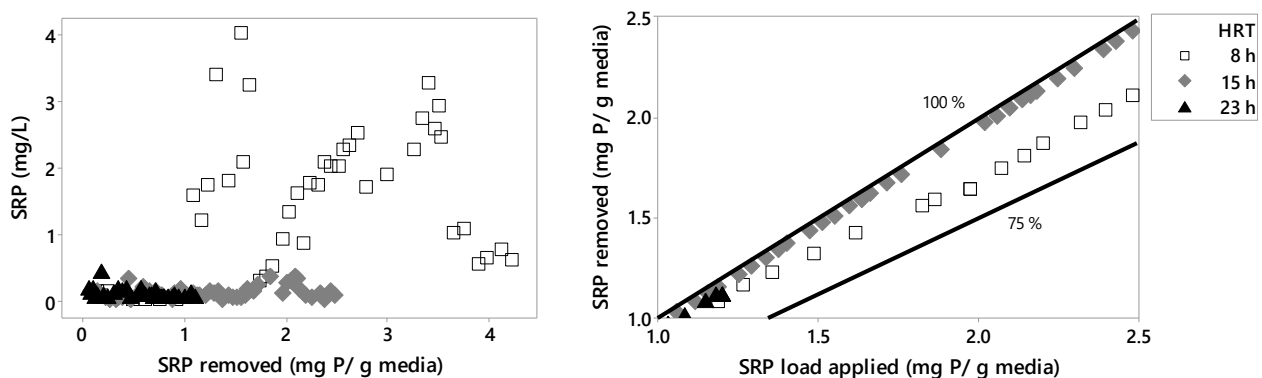
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194 The removal efficiency was calculated using following equation:

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196 Efficiency:
$$P (\%) = \frac{C_{in} - C_{out}}{C_{in}} \cdot 100 \quad (2)$$

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198 where C_{in} is the inlet and C_{out} the outlet concentration of the column in mg/L PO₄-P.

200 P removal rate

201 The HRT is a crucial factor for the P removal performance of a media. The higher the contact time
202 between the P in the water and the media, the more P can adsorb to the media's surface and/
203 precipitate. At the beginning of the experiment, up to a load of 0.3-1 mg P/ g media, depending on
204 the media (Figure 3), >99% of the PO₄-P were removed due to the high CaO dissolution rate at the
205 start (a high pH is observed) and plenty of free adsorption sites on the surface of the media. Over
206 time, after 0.3-1 mg P/ g media uptake, the removal decreased to >90% for the columns running at a
207 low HRT of 8 h accompanied by a decreased pH of below 10. However, at the same P uptake, the
208 columns with a 15 h retention time still removed P by >97-99 % at a pH level of 10-11.6. This leads
209 to the assumption that HRT determines the rate of P adsorption and precipitation rather than media
210 capacity.



211
212 **Figure 3.** Phosphorus removal and load applied during the six months column experiment for Ca-
213 silicate bedrock for the different HRTs

215 Metal removal/ leaching

216 Metals were analysed in order to evaluate if the media leaches any metals into the water and/ or if the
217 media is able to remove any additional elements to P. All four media showed a reduction in Fe from
218 the highly concentrated influent due to ferric dosing on site. Concentrations of Zn and Pb were
219 significantly less at the outlet of the columns, with the exception of the Pb concentration of the 7 h
220 column filled with apatite 2. A study on steel slag and Ca-silicate bedrock by Renman *et al.* (2009)
221 also observed uptake of Cu, Mn, Pb and Zn by the two materials which confirms the findings from
222 this research. All of the media release Ca, especially at the beginning of the experiment, which goes
223 along with an increase in pH levels due to the CaO dissolution. Some Si and Cr leaching were
224 observed as well (Table 2).

225 All metal concentration values were below the standards for drinking water according to the Council
226 Directive 98/83/EC (European Commission 1998) with the exception of Cd and Pb. Cd leaching from

227 the steel slag and apatite 1 (8 h HRT) exceeded the 5 µg/L threshold as well as the Pb concentration
 228 (>10 µg/L).
 229 Metal retention onto the media and leaching have to be considered for the potential use as slow release
 230 fertiliser on agricultural land after its WWTP application, as it could leach the accumulated metal
 231 back into the soil and therefore the food chain.
 232

233 **Table 2.** Total metal concentration of the column effluents and inlet

	Inlet	Ca-silicate bedrock		BOF slag		Apatite 1		Apatite 2	
		8 h	23 h	8 h	23 h	8 h	23 h	8 h	23 h
HRT		8 h	23 h	8 h	23 h	8 h	23 h	8 h	23 h
Ca (mg/L)	48.6	72.8	159.8	144.2	110.7	113.1	98.4	87.6	64.9
Cd (µg/L)	4.6	4.0	4.0	8.6	12.5	8.8	4.6	5.1	5.2
Cr (µg/L)	2.86	4.9	10.0	9.1	16.5	8.9	30.4	4.9	18.5
Cu (µg/L)	10.4	6.6	2.3	10.5	13.2	13.8	5.7	51.5	39.7
Fe (µg/L)	428.5	161.5	22.2	212.7	96.9	226.1	43.7	200	90.9
Mg (mg/L)	3.2	4.4	0.4	0.02	2.9	1.1	1.6	0.9	5.2
Mn (µg/L)	5.9	3.9	2.1	5.5	18.1	5.1	2.4	2.5	3.8
Ni (µg/L)	4.5	4.0	4.4	6.9	9.4	7.2	3.7	5.1	4.0
Si (mg/L)	0.6	10.6	7.1	0.8	12.4	4.8	6.6	6.0	1.8
Pb (µg/L)	13.7	11.3	11.4	9.8	7.4	8.6	5.0	15.9	8.4
V (µg/L)	<LOD	11.2	15.1	19.5	32.0	18.1	9.2	40.8	34.5
Zn (µg/L)	45.4	26.8	5.5	25.6	20.3	12.2	7.2	27.0	15.7

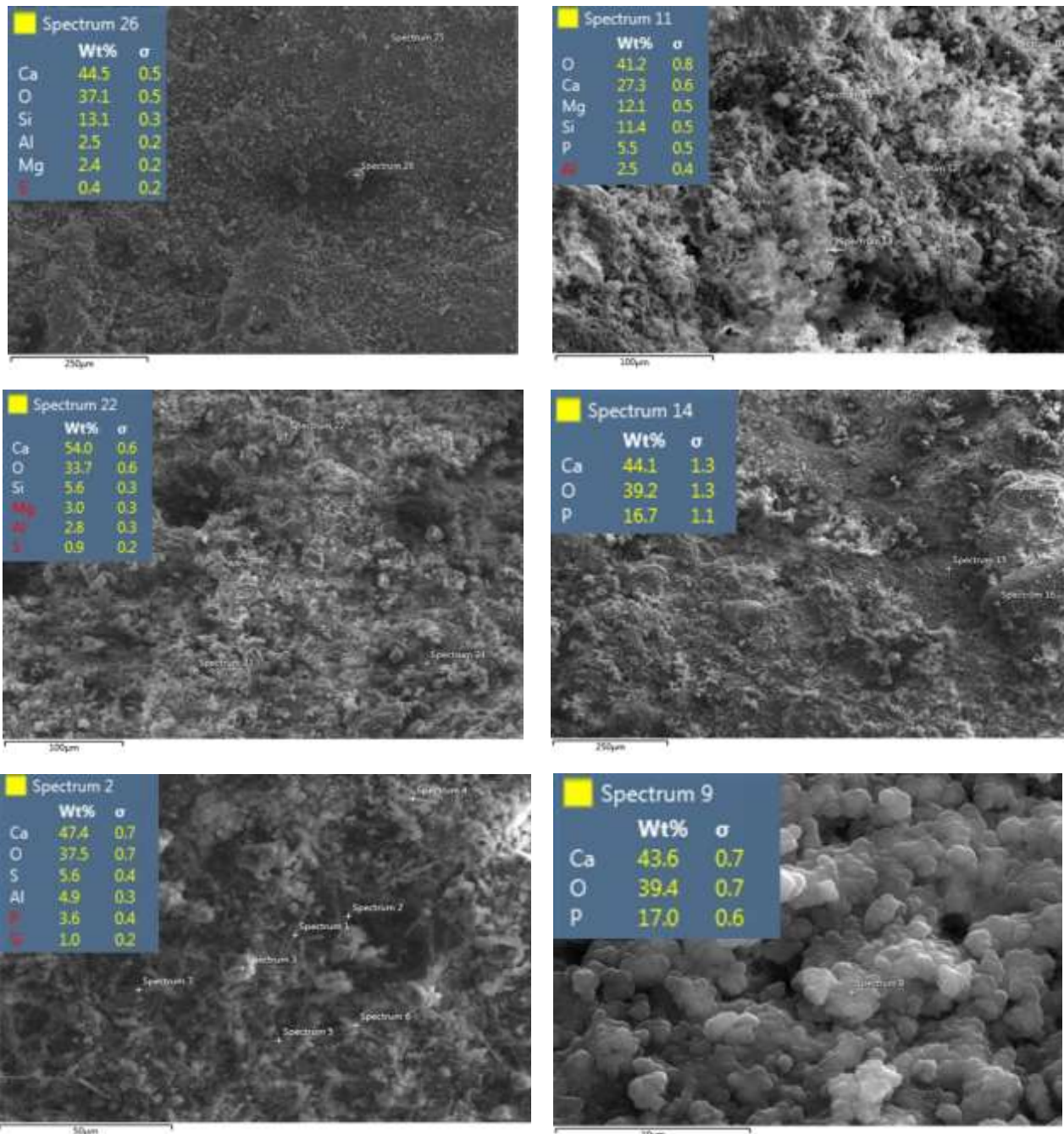
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SEM

237 SEM images show the difference in morphology on the media surface before and after the first column
 238 experiment. Spherical shaped precipitation can be seen on the surface of apatite 1 after the trial (Figure
 239 4). Multiple spot samples analysed by Energy-dispersive X-ray spectroscopy (EDX) determine the
 240 formation of calcium phosphates on the surface of steel slag and apatite 1 and the presence of P on
 241 the Ca-silicate bedrock after the experiment in comparison to the absence of P before. The P content
 242 on the surface of apatite 1, P naturally occurring in apatite on the raw material, is much higher after
 243 the trial. Additionally, as found by Barca *et al.* (2014), P can be incorporated into CaCO₃ precipitation
 244 on the surface, which cannot be detected by EDX in this study due to coating with carbon.



245 **Figure 4.** SEM images of the media before (left) and after (right) the column experiment. From top to bottom: Ca-silicate bedrock, steel slag and apatite 1.

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248 **SECOND COLUMN TRIAL**

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All media removed SRP to very low levels < 0.2 mg/L $\text{PO}_4\text{-P}$ initially but the P removal efficiency decreased over time (Figure 5), which complies with results obtained from the first column study.

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The media effluents exceeded 2 mg/L $\text{PO}_4\text{-P}$ after 254, 140 and 163 days for Ca-silicate bedrock, steel slag and apatite respectively. After 282 days the removal was still quite high (62-84 % depending on the media), but at that point the HRT was increased to 28 h to investigate if the P removal performance would improve. For all media the effluent concentration decreased to below 2 mg/L for the remainder of the experiment, >80 days. This again highlights that high effluent concentration is not due to the media's capacity but dependant on HRT.

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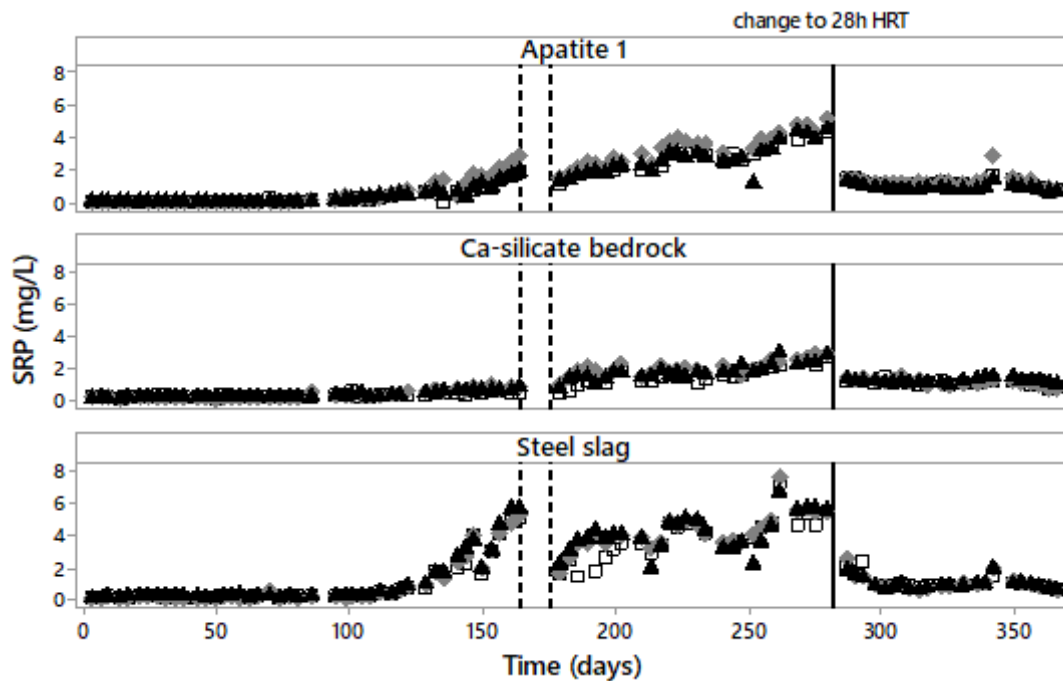
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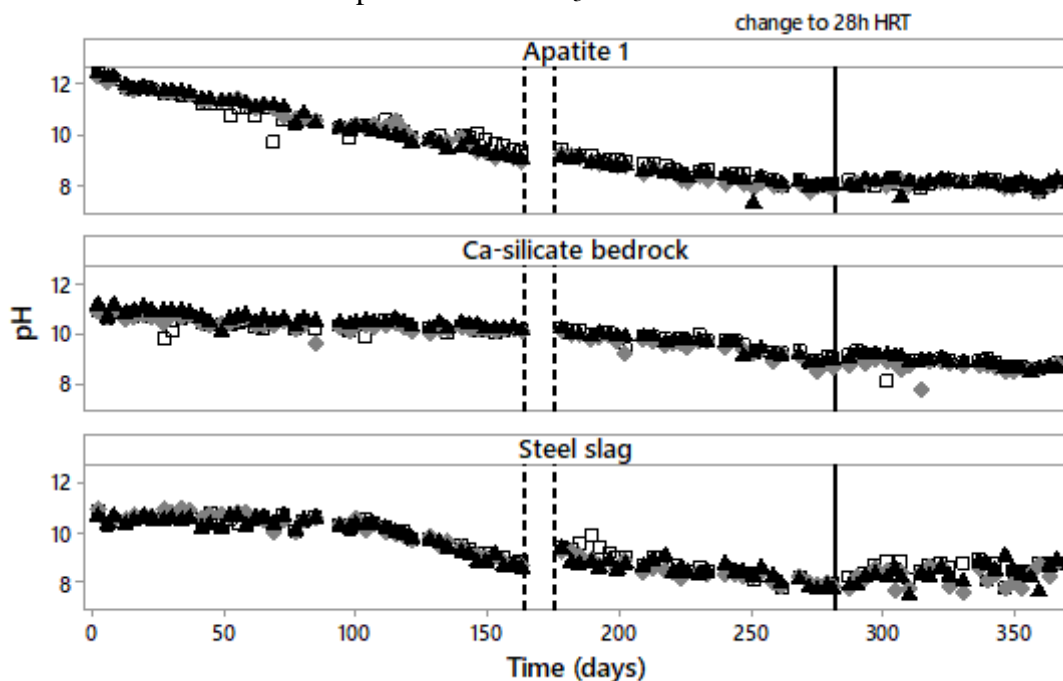
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 258 **Figure 5.** Media P effluent concentration for the triplicates over the period of one year. Change in
 259 HRT from 14 h to 28 h at day 282 of the experiment, dotted lines indicate the 12 day break
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261 Along with an increase in HRT a higher pH was expected due to results from the first column study.
 262 However, when the HRT was doubled no significant increase in pH could be seen (Figure 6). The
 263 improved P removal efficiency can therefore not be explained by an increased CaO dissolution as the
 264 pH stayed low. This leads to the assumption that the higher HRT favours increased P adsorption onto
 265 the media and possibly onto CaCO_3 as found by Barca *et al.* (2014). On the one hand, carbonate from
 266 the water (high alkalinity from the inlet water, with a mean of 122 mg/L CaCO_3) competes with
 267 phosphate for adsorption sites and free Ca^{2+} , but on the other hand it can provide additional adsorption
 268 sites for P and some P can be incorporated in CaCO_3 formation.



269
 270 **Figure 6.** The pH of the media effluents for the triplicates over the period of one year. Change in
 271 HRT from 14 h to 28 h at day 282 of the experiment, dotted lines indicate the 12 day break

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Table 3. Mean water quality parameters of column effluents and inlet for one year

	Sample n	Inlet	Ca-silicate bedrock	Steel slag	Apatite 1
P removal (%)	94	12.9 ± 4.2 mg/L	93.2 ± 6.2	85.5 ± 18.9	90.3 ± 10.8
pH (min- max)	94	7.2 – 8.8	7.7 – 11.1	7.4 – 11.0	7.2 – 12.4
BOD ₅ (mg/L DO)	48	2 ± 1.7	1.2 ± 1.0	1.7 ± 1.8	1.3 ± 1.3
COD (mg/L)	19	50 ± 16	39 ± 8	46 ± 15	48 ± 13
TSS (mg/L)	47	6.5 ± 8.7	5.7 ± 16	6.2 ± 12.1	11.9 ± 28.5
TP (%)	14	14.6 ± 5.5 mg/L	88.3 ± 10.7	75.5 ± 21.9	84.8 ± 16.1
Alk. (mg/L CaCO ₃)	28	122 ± 23	145 ± 30	129 ± 45	139 ± 100

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The main parameter monitored was SRP as the media mainly removed the soluble reactive phosphorus, whereas legal discharge requirements are usually expressed in TP. The SRP/ TP relation was between 0.8 and 0.9. BOD₅ levels were very low in all cases and the columns slightly decreased COD levels. TSS were also low. The inlet alkalinity on site was quite high and was further increased by the media (Table 3).

Media capacity in mg PO₄-P/ g media was calculated via following equation:

$$Q_t \left(\frac{mg}{g} \right) = \frac{(c_0 - c_t) \cdot V}{M} \quad (3)$$

where Q_t is the capacity of P onto the media at time t , c_0 is the inlet P concentration in mg/L and c_t the concentration of P at time t in mg/L, V is the volume of treated wastewater in L and M the mass of media in g.

After one year of operation, the columns removed a total of 7.21 (Ca-silicate bedrock), 3.28 (steel slag) and 3.85 mg PO₄-P/ g media (apatite), which relates to 838, 1229 and 1240 pore volumes of treated wastewater respectively, or a total of 1196 ± 12 L per column. The Ca-silicate bedrock showed by far the highest P removal, when the capacity is expressed as mg/ g but only because it has the lowest density. This is why a comparison of total mg removed per volume of media is more appropriate for the comparison of the performance between different media. Since the volume of the media was equal in all of the columns (2356 cm³), the amount of P removed (g) can be compared directly. In total, Ca-silicate bedrock removed the highest amount of P (13.8 g) per column, 12.8 g and 13.5 g for steel slag and apatite respectively.

Relationship between P and pH

As seen in Figure 7, the pH is negatively correlated to the effluent P concentration of the columns. At the beginning of the experiment, when the effluent pH is high, very low P concentrations were observed. Over time, a decrease in P removal was seen along with a drop in pH levels.

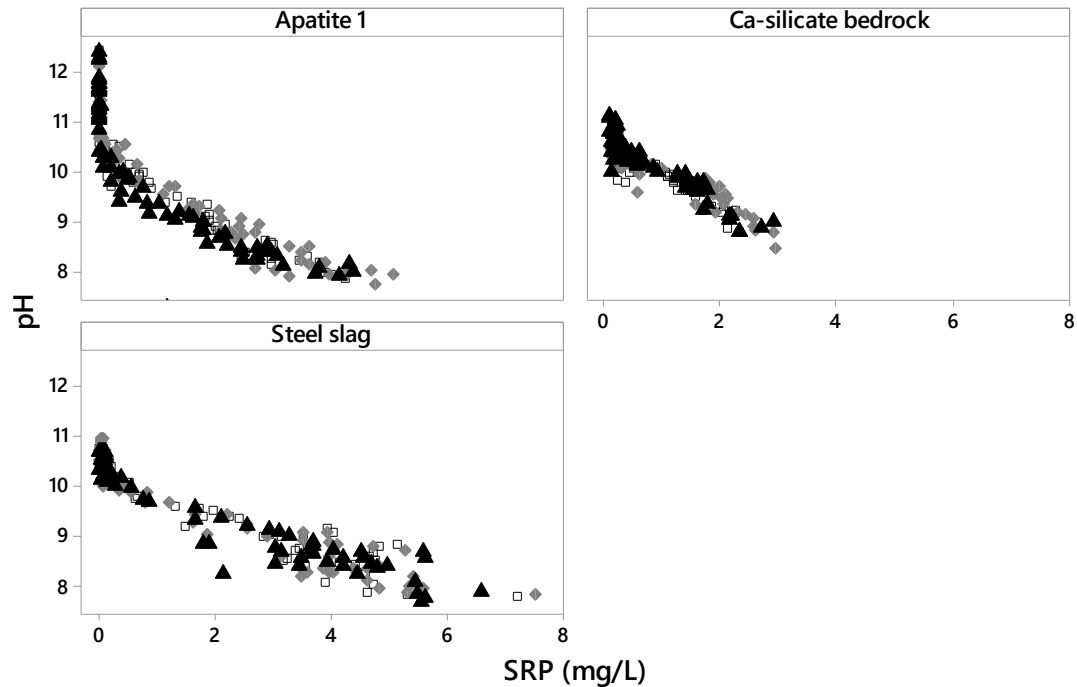


Figure 7. Correlation between effluent SRP and pH of the columns in triplicates for the first 281 days

CONCLUSION

The media in this study all showed high P removal efficiencies in both column experiments with very low P effluent concentrations of <0.2 mg/L achieved.

HRT plays a crucial role in the design and sizing of full-size filter beds. From this study, it is evident that a HRT below 8 h is not sufficient to remove P and sustain low concentrations below 1 mg/L for a long period of time. Short HRTs also overloaded the uptake rate of media which would reduce any economic benefits of smaller filters. However, although higher HRTs are recommended to achieve optimal performance in P removal, they were associated with elevated pH and increased metal concentration in the effluents. Higher HRTs also require a larger volume of media for the design of the filter bed, which increases the footprint of the system and its associated cost. The media effluents do not pose a risk to other consented water quality parameters (such as BOD, COD and TSS) and most cases improved general effluent quality.

The experiments compare different media under the same conditions using actual wastewater rather than synthetic influent, and so are closer to real world conditions. The systematic comparison of different media and HRTs provides robust design criteria for the scale-up to field scale applications. Therefore, this study demonstrates that the reactive media filters are an appropriate technology for P removal on small sites, especially when combined with a passive pH-correcting system.

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REFERENCES

American Public Health Association. (2012). *Standard methods for the examination of water and wastewater* (22nd ed.). American Public Health Association, American Water Works Association, Water Environment Federation.

- 334 Barca, C., Meyer, D., Liira, M., Drissen, P., Comeau, Y., Andrès, Y., & Chazarenc, F. (2014). Steel
335 slag filters to upgrade phosphorus removal in small wastewater treatment plants: Removal
336 mechanisms and performance. *Ecological Engineering*, 68, 214–222.
337 <https://doi.org/10.1016/j.ecoleng.2014.03.065>
- 338 Barca, C., Troesch, S., Meyer, D., Drissen, P., Andreis, Y., & Chazarenc, F. (2013). Steel slag
339 filters to upgrade phosphorus removal in constructed wetlands: Two years of field
340 experiments. *Environmental Science and Technology*. <https://doi.org/10.1021/es303778t>
- 341 Bird, S. C., & Drizo, A. (2010). EAF Steel Slag Filters for Phosphorus Removal from Milk Parlor
342 Effluent: The Effects of Solids Loading, Alternate Feeding Regimes and In-Series Design.
343 *Water*, 2(3), 484–499. <https://doi.org/10.3390/w2030484>
- 344 Blanco, I., Molle, P., Sáenz de Miera, L. E., & Ansola, G. (2016). Basic Oxygen Furnace steel slag
345 aggregates for phosphorus treatment: Evaluation of its potential use as a substrate in
346 constructed wetlands. *Water Research*, 89, 355–365.
347 <https://doi.org/10.1016/j.watres.2015.11.064>
- 348 Bunce, J. T., Ndam, E., Ofiteru, I. D., Moore, A., & Graham, D. W. (2018). A review of phosphorus
349 removal technologies and their applicability to small-scale domestic wastewater treatment
350 systems. *Frontiers in Environmental Science*, 6(FEB), 1–15.
351 <https://doi.org/10.3389/fenvs.2018.00008>
- 352 Callery, O., Healy, M. G., Rognard, F., Barthelemy, L., & Brennan, R. B. (2016). Evaluating the
353 long-term performance of low-cost adsorbents using small-scale adsorption column
354 experiments. *Water Research*, 101, 429–440. <https://doi.org/10.1016/j.watres.2016.05.093>
- 355 Cusack, P. B., Healy, M. G., Ryan, P. C., Burke, I. T., O’ Donoghue, L. M. T., Ujaczki, É., &
356 Courtney, R. (2018). Enhancement of bauxite residue as a low-cost adsorbent for phosphorus
357 in aqueous solution, using seawater and gypsum treatments. *Journal of Cleaner Production*,
358 179, 217–224. <https://doi.org/10.1016/j.jclepro.2018.01.092>
- 359 Drizo, A., Comeau, Y., Forget, C., & Chapuis, R. P. (2002). Phosphorus Saturation Potential : A
360 Parameter for Estimating the Longevity of Constructed Wetland Systems. *Environmental
361 Science and Technology*, 36(21), 4642–4648. <https://doi.org/10.1021/es011502v>
- 362 European Commission. (1998). Council Directive 98/83/EC on the quality of water intended for
363 human consumption. *Official Journal, L 330*, 32–54.
- 364 Karczmarczyk, A., Bus, A., & Baryła, A. (2019). Influence of operation time , hydraulic load and
365 drying on phosphate retention capacity of mineral filters treating natural swimming pool water.
366 *Ecological Engineering*, 130(December 2018), 176–183.
367 <https://doi.org/10.1016/j.ecoleng.2019.02.018>
- 368 Renman, A., Renman, G., Gustafsson, J. P., & Hylander, L. (2009). Metal removal by bed filter
369 materials used in domestic wastewater treatment. *Journal of Hazardous Materials*, 166(2–3),
370 734–739. <https://doi.org/10.1016/j.jhazmat.2008.11.127>
- 371 Rodríguez-Gómez, R., & Renman, G. (2017). Phosphorus removal from UASB reactor effluent by
372 reactive media filtration. *Environmental Technology (United Kingdom)*, 38(16), 2024–2031.
373 <https://doi.org/10.1080/09593330.2016.1244570>
- 374 Standing Committee of Analysts, D. of the E. (1988). *Methods for the examination of waters and
375 associated materials: 5 Day Biochemical Oxygen Demand (BOD5)* (Second Edi). Her
376 Majesty’s Stationery Office.
- 377 Troesch, S., Esser, D., & Molle, P. (2016). Natural Rock Phosphate: A Sustainable Solution for
378 Phosphorous Removal from Wastewater. *Procedia Engineering*, 138, 119–126.
379 <https://doi.org/10.1016/j.proeng.2016.02.069>
- 380 Vohla, C., Kõiv, M., Bavor, H. J., Chazarenc, F., & Mander, Ü. (2011). Filter materials for
381 phosphorus removal from wastewater in treatment wetlands-A review. *Ecological
382 Engineering*, 37(1), 70–89. <https://doi.org/10.1016/j.ecoleng.2009.08.003>
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APPENDIX

Table A1. Impact of HRT on the media filters in regards to P removal and effluent pH

PO ₄ -P removal (%)	Ca-silicate bedrock	Steel slag	Apatite 1	Apatite 2	Inlet
8 h HRT	85.8	91.8	75.5	97.3	9.7 mg/L
15 h HRT	98.8	99.2	98.5	99.5	9.7 mg/L
23 h HRT	99.4	99.4	99.4	99.4	9.7 mg/L
pH					
8 h HRT	10.0	10.0	9.3	8.3	8.2
15 h HRT	10.9	11.2	10.4	8.5	8.2
23 h HRT	11.7	11.4	10.7	8.3	8.2

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