Improving the Ability of Steel Slag to Filter Phosphorus from Runoff

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Summary

A landscape filter that contained steel slag was examined for its ability to retain phosphorus (P) after being spent, meaning after it had been saturated with P during prior runoff events. In addition, the use of slag "interception ditches" was investigated for viability in P removal. Testing indicated that a smaller size fraction of slag (>0.5 mm) was found to remove more P than larger sized slag (>6.35 mm) without severely compromising hydraulic conductivity.

- Previously spent slag from a P removal structure was mostly stable as evidenced by its ability to retain P when exposed to clean water.
- Runoff interception trenches filled with slag were able to effectively remove dissolved P in runoff without the need for construction of a more expensive structure.
- Slag sieved to >0.5 mm removed more P and had a longer lifetime than >6.35 mm slag without greatly compromising hydraulic conductivity.
- The smaller slag size fraction removed 33% of cumulative P over 18 months compared to a larger slag size fraction that only removed 25% of cumulative P over 6 to 8 months.
- Dissolved P removal by sieved slag was impacted by structure retention time as the slag became more saturated with P. Retention time must be considered when constructing a P removal structure with sieved steel slag.
- Software for designing a P removal structure can be found at:

  Soil Chemistry—Design a Structure

Figure 1. Construction of the slag interception trenches on the runoff plots located at the Botanical Gardens at Oklahoma State University (Top photo). Tubs were filled with steel slag (>6.35 mm) to allow runoff (perpendicular to trench) to flow into the phosphorus sorption material before draining into plastic pipe. ISCO samplers collected drainage water to determine the amount of phosphorus present.

Phosphorus (P) is often the most important nutrient for encouraging eutrophication in surface waters. While many best management practices (BMPs) are efficient at preventing the transport of particulate P (i.e. sediment–bound P), they do little to impede dissolved P. This is important for two reasons: dissolved P is immediately bio–available upon entering a water body and also because soils previously built up to high P

levels will require decades of biomass removal (assuming cessation of P applications) before they are no longer a source of dissolved P in runoff. A potential solution in certain situations is the construction of landscape "filters" consisting of media possessing a high affinity for dissolved P, that serve to intercept P–rich runoff water and prevent dissolved P from being transported to surface waters. These "P removal

Figure 2. Picture of the various sized fractions of slag samples tested for hydraulic conductivity. Size fractions included >6.35, >3.36, >2.38, >0.5 mm, and non−sieved.

structures" are designed to allow for the P sorption media to be replaced after it becomes saturated with P and is no longer effective.

Several by−products from various industries such as power production, steel production, drinking water treatment, and mine reclamation can potentially serve as suitable P sorption materials (PSMs; McGrath et al., 2012, Penn et al., 2011, Penn and McGrath, 2011). A previously constructed P removal structure consisting of sieved (> 6.35 mm) slag located on a golf course in Stillwater, OK was able to remove 25% of the total dissolved P that flowed into it over a 6−8 month period before it was no longer effective (Penn et al., 2012A and 2012B). Although the sieved slag possessed a large hydraulic conductivity that allowed for a flow rate of 578 L min^{-1} in the structure, there was a need to increase the P removal capacity of the material. While un−sieved slag has a much greater P sorption capacity than sieved slag, un−sieved slag eventually "clogs" due to the precipitation of solid calcium carbonate and calcium sulfate in the pore space. Thus, after the conclusion of that study there were several questions that remained:

- Regarding spent slag material, how tightly bound is the P?
- Is there a suitable slag particle size range that can maintain a large hydraulic conductivity yet remove more P than the >6.35 mm size range?
- Can the slag simply be placed in a drainage ditch rather than be contained in a structure and still be effective?

Used slag filter material: phosphorus stability

The ability of spent slag to desorb P was tested to determine the best end use for slag filter material that had already reached its useful lifetime as a P filter media. If the material is able to desorb an appreciable amount of P then its best disposal option would be as a type of landscape mulch where the soluble P could supply plants. However, the spent slag (>6.35 mm) from the P removal structure described by Penn et al. (2012A and 2012B) only desorbed a small amount of P resulting in a concentration of 0.03 mg P L^{-1} when clean water was reacted with the material for several hours. As a result, the material was disposed of through application to a road surface at the Oklahoma State University Agronomy Farm. Road construction is currently the most common use for fresh slag. Unless the material becomes exposed to highly acid conditions, the P is likely to remain stable. In addition to testing used slag for P desorption, we also measured a large amount of sediment retained by the structure. After washing all of the sediment off of the spent slag, we calculated that 59 kg of sediment was retained by the structure. Total P was not measured on the sediment, but particulate matter typically carries a large amount of P. Although particulate P is not the target pollutant for this technology, it is clearly capable of removing it.

Filtering P in drainage ditches without the use of a formal structure

Interception trenches filled with slag were constructed on the runoff research plots at the Botanical Gardens at Oklahoma State University (Figure 1). In this context we were able to test the ability of the slag to filter P in a simple drainage ditch without the use of a constructed structure such as the P removal structure previously described located at Stillwater Country Club (Penn et al., 2012B). Note that the slag used in the interception trenches was the same material (>6.35 mm) used in the structure at Stillwater Country Club (Penn et al., 2012A and 2012B). Plots with no trenches and trenches containing an inert gravel material were also used for comparison. Each trench contained 178 L of material. Both treated and non−treated runoff was tested for dissolved P and trace metals. After seven months, the slag interception trenches removed 24% of the cumulative runoff P load (8.3 mg kg^{-1} slag) which was well predicted by the equations described in Penn et al. (2012A). Trace metal concentrations were below the detection limit. The performance of the slag inter−ception trenches was nearly identical to the P removal structure previously constructed at Stillwater Country Club and suggests that the use of slag "ditches" could be a practical and inexpensive method of P removal.
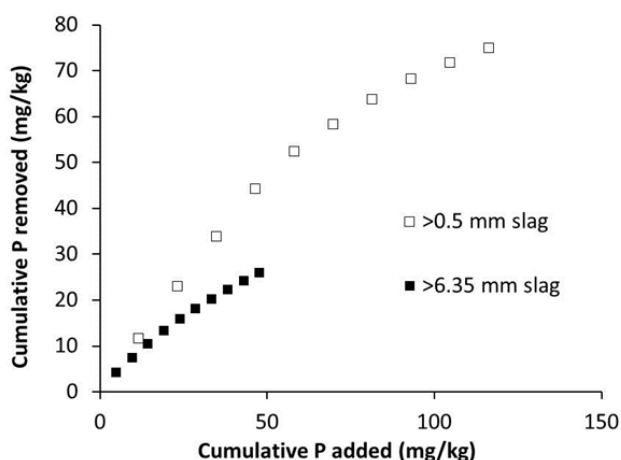
Figure 3. Cumulative phosphorus (P) removal under flow–through laboratory conditions for steel slag samples containing a particle size fraction >0.5 mm and > 6.35 mm. Experiment was conducted with an inflow solution of 0.5 mg P L⁻¹ and a retention time of 3 minutes.

### Increasing P removal with slag without decreasing hydraulic conductivity

An advantage of using a large particle size fraction of slag is its large hydraulic conductivity. On the other hand, Stoner et al. (2012) showed that the finer sized fraction has a much larger P sorption capacity; the problem is that the finer size fraction of slag tends to have a poor hydraulic conductivity. Even worse, we have found that the use of non–sieved slag eventually results in complete clogging through the precipitation of calcium sulfate and calcium carbonate minerals in the pore space. Clearly, the P removal structure can only remove P if water is able to flow through the material. Thus, our goal was to find an ideal particle size range for slag that has both high P sorption capacity and hydraulic conductivity. The different size fractions tested for hydraulic conductivity are show in Figure 2. Samples were soaked overnight in both a P solution and deionized water prior to hydraulic conductivity testing. Notice the appearance of "crusting" between large particles in the unsieved slag sample shown in Figure 2; this is the cause of a decreasing hydraulic conductivity

with time for unsieved slag. Results showed that there were no differences in hydraulic conductivity between any of the sieved samples (1–2 cm s⁻¹). However, sieved samples had significantly higher conductivity compared to unsieved slag (<0.2 cm s⁻¹).

The >0.5 mm size fraction was tested in a laboratory flow–through sorption experiment and compared to >6.35 mm size fraction. Both materials were tested using an inflow P concentration of 0.5 mg L⁻¹ and a retention time of 3 minutes. The results in Figure 3 clearly show that the smaller size fraction has a greater P sorption capacity under flow–through conditions compared to the >6.35 mm size fraction. Thus, use of the 0.5 mm sieve (i.e. the smallest size sieve tested) for slag preparation will not compromise hydraulic conductivity and will improve P sorption capacity. For this reason, the P removal structure at Stillwater Country Club was re–loaded with new slag material sieved with a 0.5 mm sieve instead of the previously used 6.35 mm sieve.

Reloading the golf course P removal structure with >0.5 mm sized slag

Based on the results of the hydraulic conductivity test and flow–through experiments, it appeared that sieving slag to a size fraction >0.5 mm would improve P retention without greatly compromising the hydraulic conductivity. For this reason, we replaced the spent slag material (>6.35 mm) contained in the P removal


$$y = 11.48\ln(x) - 19.479$$
$$R^2 = 0.90$$

$$y = -17.16\ln(x) + 112.6$$
$$R^2 = 0.97$$
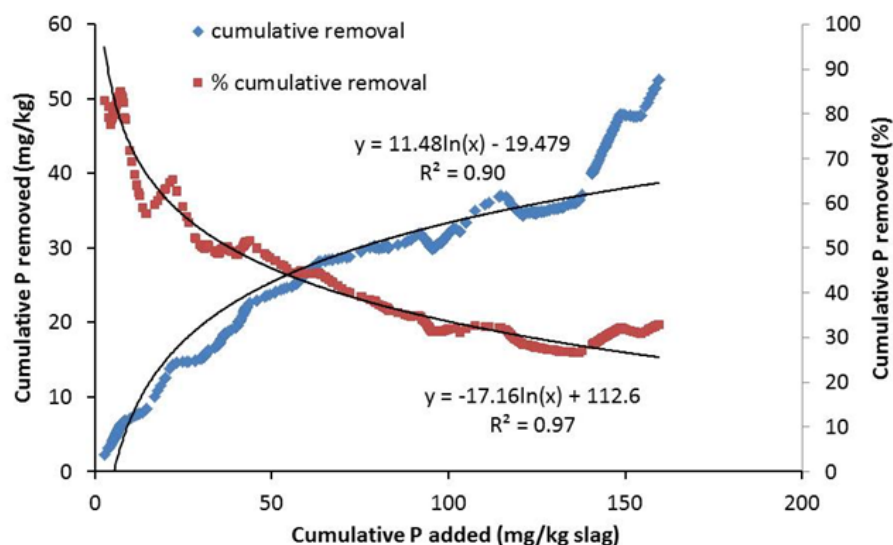
Figure 4. Cumulative phosphorus (P) removal expressed in both mg kg⁻¹ slag and % for the P removal structure located at Stillwater Country Club. Structure contained >0.5 mm slag and was installed in July, 2012. Results shown from July, 2012 to January, 2014.

structure at Stillwater Country Club and replaced it with approximately 2700 kg fresh >0.5 mm slag. Intense monitoring of the structure ceased after 18 months, although it continues to remove P after 21 months.

Over the first 18 months, 160 mg P kg^{-1} slag flowed into the structure. As expected, Figure 4 shows that the structure initially removed a high percentage of the inflow P load, but P removal decreased as the material became more saturated with P. After 18 months, the cumulative P removed was 33% of the total inflow P load, or 53 mg P kg^{-1} slag. Compared to the >6.35 mm material that was previously tested in the structure (Penn et al., 2012A and 2012B), the >0.5 mm slag removed a greater mass of dissolved P and lasted longer. The previous structure only had a lifetime of 6–8 months in which it removed 25% (~25 mg kg^{-1}) of cumulative P. In addition, the >0.5 mm slag structure was able to achieve flow rates of 800 L min^{-1}.

Intense monitoring of the structure ceased after 18 months because the material was no longer effective at removing dissolved P during large storm events that produced high flow rates i.e. short retention times in the structure. Specifically, the P removal capacity of the sieved slag was strongly influenced by retention time, which became more pronounced as the material became more saturated with P. The effect of retention time is evident in Figure 5 where there is a general trend of decreasing discrete P removal with decreasing retention time. This is especially evident in observation of the cumulative P removal curve in Figure 4. Near the end of the 18 month monitoring period (i.e., near the highest cumulative P loading) the cumulative P removal curve begins to sharply increase in P removal. This was due to the fact that the rainfall events that occurred from September, 2013 to January, 2014 were less intense and produced fairly long retention times (>5 minutes) compared to previous summer rainfall events. At that point, the material had become somewhat saturated with P and was unable to remove P from intense rainfall events but still removed >90% of P from less intense events because of longer retention times.

The impact of retention time is only significant for materials dominated with calcium that have a poorly buffered pH less than 7. This includes material such as sieved slag (described in this paper) and gypsum. Thus, design of P removal structures for such materials need to take into account retention time. On the other hand, materials dominated with aluminum (Al) and iron (Fe)
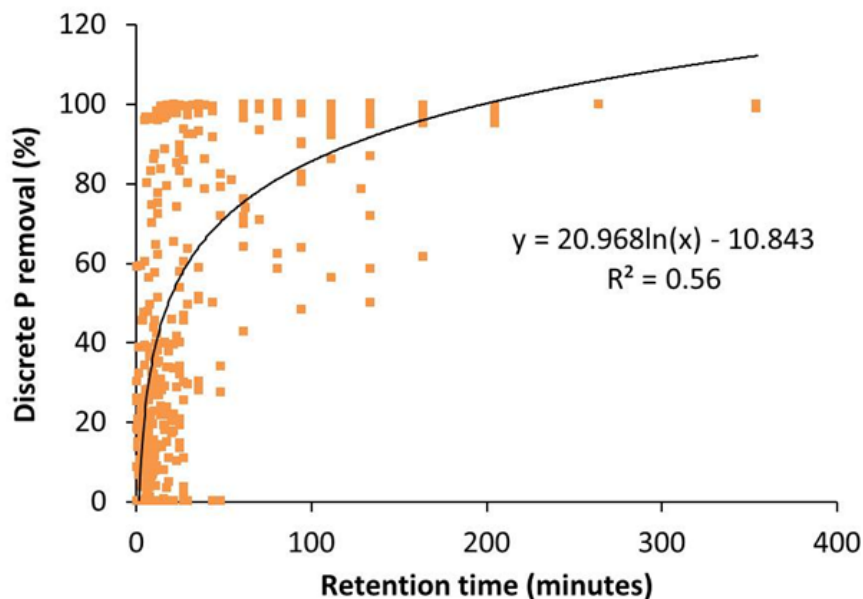
Figure 5. Discrete phosphorus (P) removal (%) as impacted by retention time for the P removal structure located at Stillwater Country Club. Structure contained >0.5 mm slag and was installed in July, 2012. Results shown from July, 2012 to January, 2014.

generally do not display much sensitivity to retention time because their P sorption kinetics are very fast. Similarly, calcium (Ca) dominated materials that strongly buffer the pH above 7, such as slag fines, are not sensitive to retention time (Stoner et al., 2012).

For more information on P removal structures, please see the following resources:

Phosphorus Structure Blog Spot

Penn, C.J., McGrath, J.M., J. Bowen, and S. Wilson. 2014. Phosphorus removal structures: a management option for legacy phosphorus. J. Soil. Wat. Cons. 69:51A–56A.

Wang, Z., G.E. Bell, C.J. Penn, and J. Moss. 2014. Phosphorus reduction in turfgrass runoff using a steel slag trench filter system. Crop Sci. In Print.

Penn, C.J., Payne, J. McGrath, and J. Vitale. 2013. Designing structures to remove phosphorus from drainage waters. E–extension waste to worth annual conference. April 1–5, Denver, CO.

Oklahoma Gardening. 2013. "Scrubbing phosphate from runoff".

References

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Penn, C.J., J.M. McGrath, E. Rounds, G. Fox, and D. Heeren. 2012A. Trapping phosphorus in runoff with a phosphorus removal structure. J. Environ. Qual. 41:672–679. (TGIF Record 249061)

Penn, C., G. Bell, J. Warren, and J. McGrath. 2012B. Improving water quality with phosphorus removal structures. USGA Turfgrass and environmental research online. 11(2):1–6. (TGIF Record 196992)

Penn, C.J. and J.M. McGrath. 2011. Predicting phosphorus sorption onto normal and modified slag using a flow–through approach. J. Wat. Res. Protec. 3:235–244. (TGIF Record 249062)

Penn, C.J., R.B. Bryant, M.A. Callahan, and J.M. McGrath. 2011. Use of industrial byproducts to sorb and retain phosphorus. Commun. Soil. Sci. Plant Anal. 42:633–644. *(TGIF Record 249063)*

Stoner, D., C.J. Penn, J.M. McGrath, and J.G. Warren. 2012. Phosphorus removal with by–products in a flow–through setting. J. Environ. Qual. 41:654–663. (TGIF Record 249064)