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Technical Note: Hydraulic Property Determination of Denitrifying Bioreactor Fill Media

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Abstract

Denitrification bioreactors are one of the newest options for nitrate removal in agricultural drainage waters. Optimization of denitrification bioreactor design requires the ability to identify concrete values for the hydraulic properties of bioreactor fill media. Hydraulic properties, chiefly saturated hydraulic conductivity but also porosity and particle size, are not known for many types of possible bioreactor media though they have a significant impact upon bioreactor design and performance. This work was undertaken to more fully quantify the hydraulic properties of the major type of fill media used in Iowa denitrification bioreactors through a series of porosity, hydraulic conductivity, and particle size analysis tests. In addition, a particle size analysis was performed for two types of woodchips and one type of wood shreds in order to quantify and highlight the differences between what is commonly referred to as "wood fill." Saturated hydraulic conductivity was determined for blends of woodchips, corn cobs, and pea gravel. For one of the most common types of woodchips used in bioreactors, the porosity varied from 66% to 78% depending on packing density and the average saturated hydraulic conductivity was 9.5 cm/s. It was found that additions of pea gravel significantly increased the hydraulic conductivity of woodchips though additions of corn cobs did not. Regardless of the fill mixture used, it is vital to design the bioreactor using the hydraulic properties for that specific media.

Keywords

Denitrification bioreactor, Saturated hydraulic conductivity, Porosity, Particle size analysis, Woodchip, Corn cob, Pea gravel

Disciplines

Agriculture | Bioresource and Agricultural Engineering

Comments

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TECHNICAL NOTE:

HYDRAULIC PROPERTY DETERMINATION OF DENITRIFYING BIOREACTOR FILL MEDIA

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ABSTRACT. *Denitrification bioreactors are one of the newest options for nitrate removal in agricultural drainage waters. Optimization of denitrification bioreactor design requires the ability to identify concrete values for the hydraulic properties of bioreactor fill media. Hydraulic properties, chiefly saturated hydraulic conductivity but also porosity and particle size, are not known for many types of possible bioreactor media though they have a significant impact upon bioreactor design and performance. This work was undertaken to more fully quantify the hydraulic properties of the major type of fill media used in Iowa denitrification bioreactors through a series of porosity, hydraulic conductivity, and particle size analysis tests. In addition, a particle size analysis was performed for two types of woodchips and one type of wood shreds in order to quantify and highlight the differences between what is commonly referred to as "wood fill." Saturated hydraulic conductivity was determined for blends of woodchips, corn cobs, and pea gravel. For one of the most common types of woodchips used in bioreactors, the porosity varied from 66% to 78% depending on packing density and the average saturated hydraulic conductivity was 9.5 cm/s. It was found that additions of pea gravel significantly increased the hydraulic conductivity of woodchips though additions of corn cobs did not. Regardless of the fill mixture used, it is vital to design the bioreactor using the hydraulic properties for that specific media.*

Keywords. *Denitrification bioreactor, Saturated hydraulic conductivity, Porosity, Particle size analysis, Woodchip, Corn cob, Pea gravel.*

Nitrate is one of the biggest concerns for drainage water quality in the midwestern United States (Dinnes et al., 2002). Subsurface drainage in combination with intensively cropped agricultural lands may lead to high nitrate mass loadings in surface waters with many authors documenting high nitrate concentrations and loadings in midwestern drainage (Baker et al., 1975; Kalita et al., 2006; Jaynes et al., 2008). These agricultural sources of nitrogen in the Upper Mississippi River Basin are thought to be a significant contributor to the hypoxic zone in the Gulf of Mexico, and the U.S. EPA Science Advisory Board has called for loading reductions of 45% of riverine total nitrogen flux in order to decrease the size of the hypoxic zone (USEPA , 2007).

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Denitrification drainage bioreactors have been proposed as a cost-effective practice for edge of field nitrate removal from tile flow (Blowes et al., 1994; Robertson et al., 2000; Rodrigue, 2004; Jaynes et al., 2008). This technology has also rapidly gained interest with watershed groups in the Midwest. In the simplest terms, denitrification bioreactors are carbon-filled excavations through which subsurface drainage is routed allowing denitrification to be enhanced. There is much ongoing research into the design and operation of these systems in order to understand how to maximize nitrate removal given varying drainage flow rates and field conditions.

Woodchips are commonly used as the carbon substrate in denitrification bioreactors in the Midwest due to their longevity, good performance, and easy availability (Cooke et al., 2001; Greenan et al., 2006). However, other solid carbon sources may also be used. Some of the earliest work on denitrification bioreactors evaluated packing media and carbon sources such as sand, tree bark, woodchips, and compost (Blowes et al., 1994). Other investigators have tested pine bark, almond and walnut shells, newspaper, wheat straw, alfalfa straw, cellulose, and sawdust as potential carbon sources (Vogan, 1993; Volokita et al., 1996; Diaz et al., 2003). Overall, the selection of the specific bioreactor fill material should be based upon cost, porosity, C:N ratio, and longevity of the material (Robertson et al., 2005a).

The potential for using corn biomass, another common carbon source in the U.S. Midwest, has also been studied. Greenan et al. (2006) found that corn stalks had the highest denitrification rates compared with cardboard, woodchips, and woodchip plus oil. However, the corn stalk denitrification rate appeared to slow over time leading to

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questions about this carbon source's longevity in a field situation. Cooke et al. (2001) compared corn cobs and wood mulch and found that the wood outperformed the cobs in nitrate removal most likely due to the greater surface area of the wood pieces.

The hydraulic properties of the carbonaceous fill material can influence the sizing of a denitrification bioreactor. Van Driel et al. (2006b) found that coarse wood fill (1- to 50-mm diameter particles) and fine wood fill (1- to 5-mm diameter) resulted in similar denitrification rates. Other work by Van Driel et al. (2006a) estimated that the horizontal hydraulic conductivity through a coarse wood fill layer (1- to 50-mm size wood particles) was 1.2 ± 1.0 cm/s with little change over several months. Their calculated porosity was 0.7. Chun et al. (2009) documented a similar range of hydraulic conductivies (2.7-4.9 cm/s) for wood particles with a mean screen size of 1.3 cm. The ability to identify a realistic saturated hydraulic conductivity and porosity of a given fill is critical to designing the system for adequate retention time. Although it is important to know these hydraulic properties of carbonaceous fill material in order to create accurate designs which lead to consistent field performance, there is a lack of relevant information for commonly used carbonaceous and inert bioreactor media. This research was performed to quantify the porosity, saturated hydraulic conductivity, bulk density, and particle size distribution of the primary wood fill media used in denitrification bioreactors in Iowa with supplementary information about other possible fill media. This type of information, chiefly the saturated hydraulic conductivity, is vital to the design of reliable and effective denitrification bioreactors.

Methodology

Porosity Determination

The wood media (Chip 1) used in this test was obtained from a local vendor at a cost of $20 per cubic yard (i.e. $20 per 0.76m^3). Chip 1 was a mixture of various local hardwood species chipped obliquely in respect to the axis of the wood fibers with a C:N of 247. These chips are typically used in landscaping and playgrounds and are similar to those used in field bioreactor installations. A high percent of these chips were rectangular in shape. The porosity of Chip 1 was determined similarly to the methods described by Saliling et al. (2007) and Ima and Mann (2007). Air-dried woodchips were packed in 1-L bottles at the desired packing density, and the pore volume was filled with water. The bottles were capped and allowed to sit for 12 to 24 h for water to be absorbed by the woodchips. More water was added to refill the container and the total volume of water added to the bottle was used to determine the porosity.

Saturated Hydraulic Conductivity Analysis

The constant head standard method, ASTM D 2434-68, was used to determine the saturated hydraulic conductivity due to the large particle sizes of the tested media (ASTM, 2000). This standard was used as it is specifically intended for "granular soils containing not more than 10% passing through the 75-µm (No. 200) sieve."

Media Tested

Hydraulic conductivity testing was done for various mixes of carbonaceous and inert packing media that are likely to be used in denitrification bioreactors. These included woodchips (Chip 1), corn cobs, and pea gravel. The Corn cobs were obtained free of charge from white seed corn grown at a local farm used in a hybridizing program for seed production. Two different lengths of corn cobs were tested: whole cobs, 5.08 to 11.43 cm in length and half cobs, 2.54 to 5.08 cm in length. Two cob lengths were tested because it was thought the half cob mixtures would yield conductivities similar to 100% woodchips due to the similar particle sizes while the whole cob mixtures would have a significantly higher conductivity because of the relatively large particle sizes. The pea gravel was not a carbon source, but acted to modify the hydraulic properties of the mixture. Commercial river pea gravel was obtained from a local vendor in 14-L bags at approximately $5 per bag. The oval gravel particles were 0.82 ± 0.30 cm in diameter along their median axis. Hydraulic conductivity tests were performed with 100% woodchips and various mass percentages (10%, 25%, and 50%) of alternative media (whole cobs, half cobs, and pea gravel) added to the woodchips.

Constant Head Test Apparatus

A permeameter consisting of a 241-cm long, 15.24-cm diameter PVC pipe was used to determine hydraulic conductivity of the packing media (fig. 1). The media packing lengths varied from 227 to 241 cm. Both ends of the permeameter were capped. The inflow/outflow tubing (1.3-cm diameter) and the manometer tubing (0.6-cm diameter) were connected to the permeameter through holes in the PVC caps. Metal diffuser plates (15.24-cm diameter, 2-mm holes) were placed inside the permeameter at each end and the remaining volume was filled with media. Inside the caps, six metallic springs were fitted to ensure the diffuser plates were secure during testing. The spring compression with a closed, media-filled permeameter was 2.5 cm with a compression of approximately 4 kg-force (40 N), i.e., within recommendation of ASTM (2000). The caps were secured with friction fit. All tests and replications were performed using this permeameter. Because the primary purpose of this work was to determine the hydraulic conductivity of Chip 1, the type of media most widely used in Iowan bioreactors, the permeameter was sized mainly for this purpose. The packing media was compacted by shaking the permeameter in roughly three stages as it was being packed. A small diameter PVC pipe was also used to compact the media inside the permeameter cylinder by tamping the material after the permeameter had been shaken. The mass of fill media was recorded to determine packing density while compacting the media to the density anticipated *in situ*. Tests were performed at room temperature (22±1°C) with water temperature between 10°C and 3°C.

A 25-L reservoir was connected to a municipal water supply faucet in the laboratory and placed at an elevation of 112 cm above the permeameter to provide a constant head water source for the conductivity tests. Hydraulic gradients across the permeameter were controlled by raising or lowering the position of the pipe at the effluent port of the permeameter. The flow rate exiting the permeameter and the pressure loss in the permeameter (observed in the

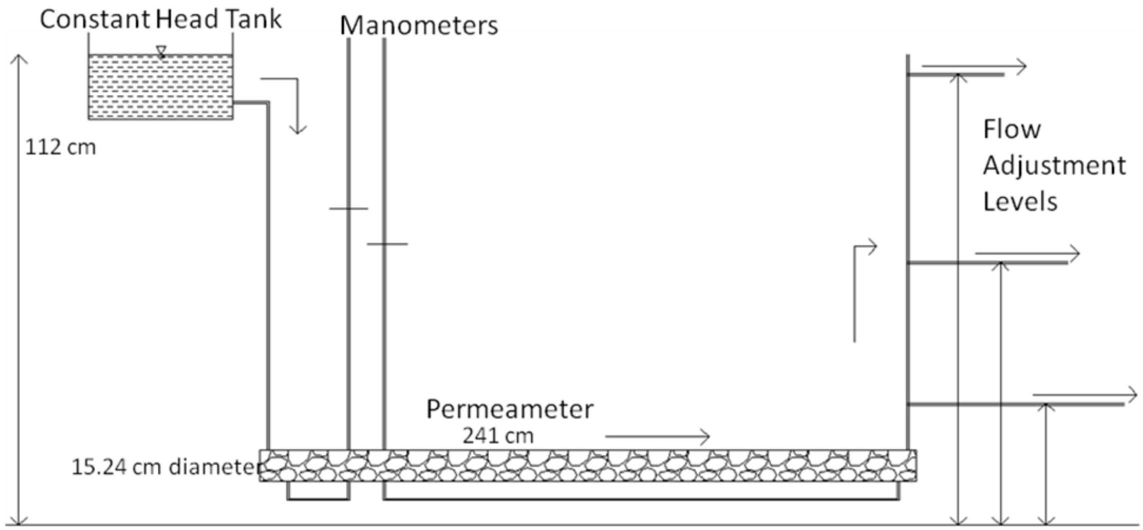

Figure 1. Schematic of saturated hydraulic conductivity testing apparatus.

manometers) were recorded and the saturated hydraulic conductivity was calculated according to Darcy's flow:

$$k = \frac{QL}{A\Delta h}$$

where k is the saturated hydraulic conductivity (cm/s), Q is the flow rate of water discharged (cm^3/s), L is the length of the permeameter (cm), A is the cross sectional area of the permeameter (cm^2), and Δh is the head difference across the length of the permeameter as measured by water levels in the manometers (cm). Each test consisted of fourteen different elevations of the outflow pipe, each resulting in a different flow rate through the permeameter. The test was replicated four to five times for each media mixture and resulting conductivity data were analyzed statistically with t tests and an analysis of variance procedure ($\alpha = 0.05$) (SAS statistical software).

Particle Size Analysis

Woodchips (Chip 1) used in the porosity and hydraulic conductivity experiments were also subjected to a particle size analysis. ASTM standard sieves with 25-, 19-, 12.5-, 9.5-, 4.75-, and 2.36-mm screen sizes were used to fractionate between 227 and 627 g of each type of wood media by shaking in a shaker (Rotasift by ELE International) for 5 min (ANSI/ASAE 2007). Two other woody materials – Chip 2 and wood shreds – obtained from a field bioreactor installation in central Iowa were also subjected to particle size analysis in order to quantify and highlight the differences between what is commonly referred to as "wood fill." These media types were "fresh" wood fill collected during installation of the bioreactor. While Chip 2, a product used in landscaping and play grounds, was similar in size, consistency, and cost to Chip 1, the wood shreds consisted of shredded tree limbs and leaf matter obtained free of charge from a municipal source.. All media were oven dried at 70°C until constant weight before performing particle size analysis. Particle size analysis was repeated three times for the wood shreds and Chip 2 and twice for Chip 1.

Results

Porosity

The porosity of Chip 1 was observed to range between 66% and 78% at packing densities expected under field conditions. Ima and Mann (2007) reported a porosity of 63% for woodchips containing 40% moisture and packed at a density of 285 kg/m^3, Van Driel et al. (2006a) calculated a porosity of 70% for an *in situ* bioreactor and Chun et al. (2010) estimated a porosity of 79% for a field-scale woodchip bioreactor. Chip 1 porosity was observed to be inversely correlated to the packing density of the media (fig. 2). At a lower range of oven-dried packing density (around 200 kg/m^3), the resulting porosity was between 74.7% and 78%, while at a higher density (between 235 and 243 kg/m^3), the porosity was between 66.4% and 68.6%. The particle density of the wood chips can be calculated using the following porosity-bulk density relationship:

$$\rho_p = \frac{\rho_b}{1-\eta}$$

where η is the porosity, ρ_b is the bulk density, and ρ_p is the particle density. The calculated range of particle density for Chip 1 was 720 to 880 kg/m^3 which is similar to reported values for hardwoods such as oak (820 kg/m^3) (Guyette and Stambaugh, 2003).

Saturated Hydraulic Conductivity

Flow velocities (*Q*/*A*) were plotted as a function of the hydraulic gradient ($\Delta h/L$) observed in the permeameter tests and hydraulic conductivity values were obtained from the slopes of linear fits to the experimental data(forced through zero). Figure 3 illustrates results of five replicate conductivity determination for 100% woodchips (Chip 1) packing. The observed hydraulic conductivity values ranged between 7.33 and 11.11 cm/s for 100% woodchips with a mean of 9.50 cm/s (standard deviation 1.60 cm/s). This is on the order of previously reported values for wood chip bioreactors. Robertson et al. (2005b) calculated the hydraulic conductivity of wood media in an *in situ* denitrification barrier as 11 ± 3 cm/s while Van Driel et al. (2006a) estimated 1.2 ± 1.0 cm/s for lateral flow in the coarse media

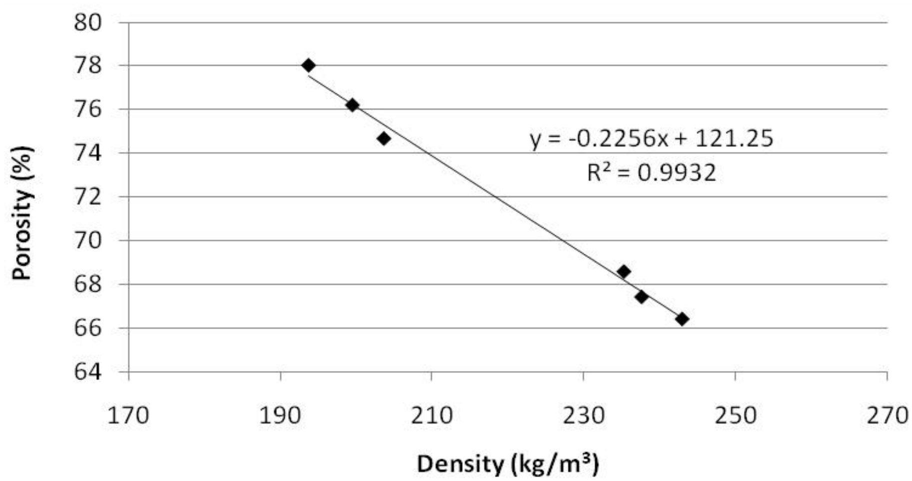

Figure 2. Porosity for various oven-dried packing densities of Chip 1.

of a bioreactor containing alternate layers of fine and coarse wood media. Chun et al. (2009) documented hydraulic conductivities of 2.7 to 4.9 cm/s in a laboratory-scale wood chip bioreactor.

When different amounts of pea gravel were mixed with woodchips, each mixture resulted in a statistically different saturated hydraulic conductivity (table 1). The addition of pea gravel to woodchips resulted in higher hydraulic conductivity. Even 10% gravel amendment produced a 162% enhancement in hydraulic conductivity of the packing media. Conductivity enhancement was highest (+260%) at 25% gravel. At 50% gravel content, conductivity was observed to be 21.63 cm/s. The increased saturated hydraulic conductivity due to the pea gravel was most likely because of greater connectivity of pores in this mixture relative to the 100% woodchip media. It is known that both media structure and texture affect saturated hydraulic conductivity (Hillel, 1998) and as the woodchips had greater surface roughness compared to the gravel, it was expected that increased hydraulic conductivity would be observed when gravel was added. Because saturated hydraulic conductivity depends so heavily upon the flow pores (i.e. width, continuity, shape, and overall tortuosity), it is difficult to relate porosity and permeability or permeability and grain size distribution (Hillel, 1998). Wildman (2001) reported that increasing percentages of pea gravel added to woodchips decreased the porosity from 0.651 to 0.492 for 100% woodchips and 50% woodchip/pea gravel, respectively. Though there may be a decrease in total porosity with this type of mixture, the increased hydraulic conductivity can be explained similarly to how a sandy soil may exhibit higher conductivities than clayey soil even when the latter may have higher total porosity. Media was packed at air-dried densities ranging from 660 kg/m^3 for 10% gravel to 995 kg/m^3 for 50% gravel.

Unlike the pea gravel amendment, addition of corn cobs to woodchips produced smaller changes in the hydraulic

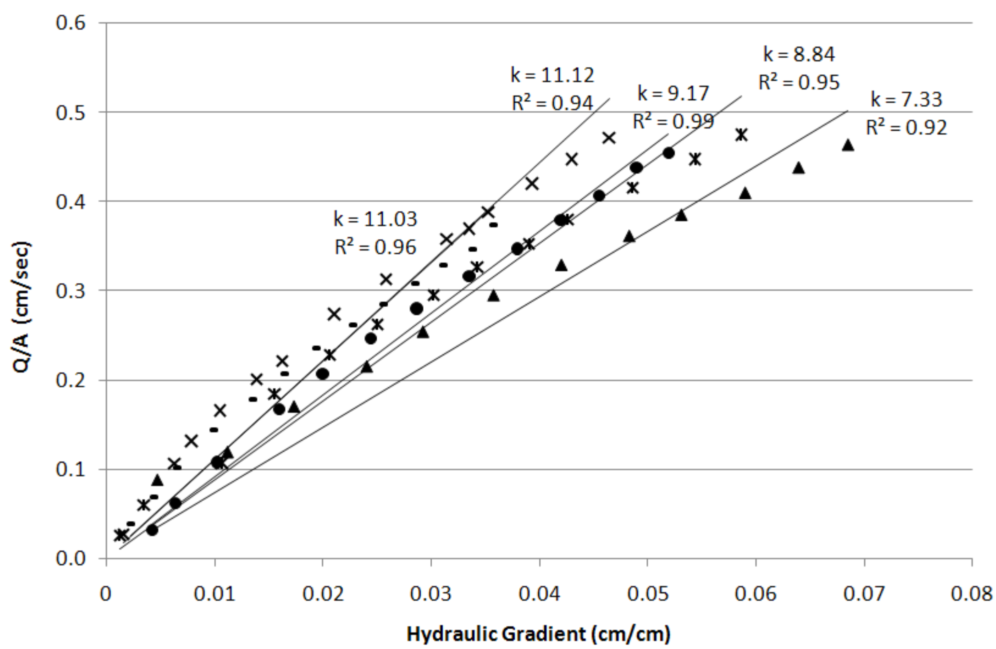

Figure 3. Hydraulic conductivity estimates (k) of 100% Chip 1 obtained from five replicate tests at packing densities of 530 to 545 kg/m^3. Values of k (cm/s) obtained from linear trend line slopes.

Table 1. Mean values of saturated hydraulic conductivity for bioreactor media mixtures; letters indicate significance at the α = 0.05 level..

	% Mixture (mixed with Chip 1)	Bulk Density (kg/m^3)	Average Saturated Hydraulic Conductivity (cm/s)	Standard Deviation (cm/s)
Chip 1	100	530 to 545	9.50 (de)	1.60
Pea gravel	10	660	15.37 (c)	1.76
	25	725	24.65 (a)	2.42
	50	995	21.63 (b)	1.70
Half cobs	10	512	8.70 (ef)	2.44
	25	530	11.46 (d)	1.54
	50	530	7.17 (f)	2.19
Whole cobs	10	530	10.30 (de)	1.57
	25	530	8.86 (ef)	1.68
	50	500	10.78 (de)	1.24

conductivity of the packing media. Conductivity of 100% woodchips was generally similar to that of other corn cob mixtures. As the percentage of corn cobs increased there was no noticeable trend for conductivity, with the exception of the 50% blend with half cobs. While the conductivity for this blend was statistically lower ($\alpha = 0.05$), than 100% Chip 1, the standard deviations of the two media were observed to overlap. Whole cob mixtures of 10%, 25%, and 50% yielded conductivities of 10.30, 8.86, and 10.78 cm/s, respectively. The half cob blends had average conductivities of 8.70, 11.46, and 7.17 cm/s for the 10%, 25%, 50% tests, respectively. This lack of significant difference between the 100% woodchips and the corn mixtures was most likely because the corn cobs had similar surface roughness to the woodchips and in all likelihood allowed similar pore connectivity. Media was packed at air-dried densities ranging from 512 to 530 kg/m^3 for whole cobs and 500 to 530 kg/m^3 for half cobs.

Particle Size Analysis

Once oven-dried materials were equilibrated with laboratory air, the wood shreds had a moisture content of 22.9% and Chip 1 and Chip 2 had moisture contents of 45.5% and 42.5%, respectively. A significant percentage of the wood shreds did not pass through the largest sieve (25 mm) as noted in the particle size distributions shown in figure 4. About 35% by mass of the shreds were retained on this sieve, primarily because they were entangled and formed large masses of shredded material. The effective size (D_{10},where only 10% by mass of the sample is of smaller size) of the wood shreds was approximately 3 mm, while its uniformity coefficient (D_{60}/D_{10}) was about 7.

The particle size distribution of Chip 2 obtained from a field bioreactor installation was similar to that of Chip 1. Chips 1 and 2 had effective sizes of 6.5 and 6 mm, and uniformity coefficient values of 2 and 3, respectively. Chip 2 contained particles (20% by mass) greater than 25 mm while Chip 1 had no particles in this size fraction. Approximately 50% of both chips fell between the 13- and 25-mm sizes. Based on their particle size distributions, Chips 1 and 2 are expected to have similar hydraulic conductivities while the shredded material, may exhibit a lower conductivity although fines could be rapidly flushed or degraded.

Conclusions

Designing reliable and effective denitrification bioreactors depends upon the ability to incorporate accurate hydraulic property values for fill material into the design. This work was undertaken to better understand (1) the hydraulic properties of the major type of wood fill used in bioreactors in Iowa and (2) the variation in particle size or saturated hydraulic conductivity between different types of possible bioreactor fill mixtures. Several types of fill were compared through a series of porosity, hydraulic conductivity, and particle size analysis tests. This work was

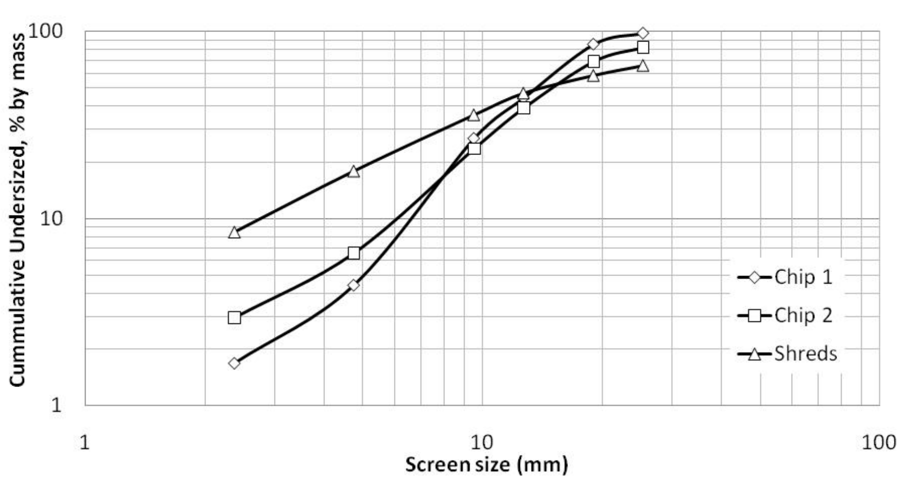

Figure 4. Particle size distribution for three kinds of wood media.

not intended to address the longevity of the fill media or the hydraulic properties of the media over time. These types of studies are recommended for further research as noted below.

The hydraulic conductivity of wood chip media most commonly used in bioreactor installations in Iowa was determined to be 9.5 ± 1.5 cm/s. Based on the particle size analysis, shredded wood media may have a tendency to lose fine particles and may be more susceptible to compaction, thus altering the hydraulic conductivity significantly from the design conductivity. Additions of pea gravel will significantly alter the hydraulic conductivity and this must be considered in any design which uses pea gravel and woodchip mixtures. However, as long as carbon is not a limiting factor within the bioreactor, pea gravel mixtures may help retain structure and flow properties over time. Utilization of corn cobs mixed with woodchips (up to 50/50 blends) do not appear to significantly alter the conductivity from what would be experienced with solely woodchips. It is important to note however, that any mixtures of materials utilized in a denitrification bioreactor must be homogenous mixtures in order to prevent preferential flow paths. Most importantly, regardless of the bioreactor mixture, it is critical to design the system using the saturated hydraulic conductivity that is specific to that mixture.

Although this study provides a good measure of the initial hydraulic conductivity of wood chip media used in denitrification bioreactors, it is thought that over several years of bioreactor operation any carbonaceous material will break down altering the hydraulic conductivity. While this study showed saturated hydraulic conductivities to not be significantly different for woodchips and woodchip-corn cob blends, it is not known if conductivities of these materials would differ after several years of utilization in a bioreactor.

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