Comparing dry and wet sieving with laser diffraction to the hydrometer method for particle size analysis of bioretention soil media

Comparaison du tamisage à sec et humide avec la diffraction laser et la méthode de l'hydromètre pour l'analyse granulométrique des médias de sols de biorétention

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RÉSUMÉ

La standardisation de l'analyse granulométrique (PSA) est essentielle pour assurer le mélange adéquat des médias filtrants utilisés pour le traitement des eaux pluviales, tels que les médias de sols de biorétention (BSM). Les BSM contiennent généralement plus de 80 % de sable et sont amendés avec de la matière organique et des fines (c.-à-d. limon et argile) afin de favoriser l'élimination des polluants. Toutefois, il n'existe actuellement aucune méthode PSA normalisée permettant de vérifier si les BSM respectent les spécifications de conception avant leur installation. Cette étude compare trois méthodes PSA — l'hydromètre, le tamisage à sec avec diffraction laser (DS + LD) et le tamisage humide avec diffraction laser (WS + LD) — afin d'évaluer leur précision et leur répétabilité pour l'analyse des BSM. Vingt-sept échantillons de BSM ont été prélevés dans trois noues de biorétention situées en Ohio, aux États-Unis. Pour la méthode de l'hydromètre, une variabilité importante des résultats a été observée selon la masse d'échantillon utilisée pour l'analyse. Les analyses triplicates de BSM par DS + LD (83,9 ± 1,7 % sable, 9,6 ± 3,0 % limon, 6,5 ± 2,7 % argile) et par WS + LD (84,1 ± 1,7 % sable, 10,6 ± 2,2 % limon, 5,3 ± 1,7 % argile) ont montré une forte concordance intra- et inter-méthodes, particulièrement pour la teneur en sable. Les méthodes hydromètre et WS + LD ont été les plus cohérentes pour la mesure de la fraction argileuse. Nous recommandons de mesurer séparément les fractions sable et fines après une dispersion appropriée lors de l'exécution d'une PSA sur des sols sableux comme les BSM. Bien que la PSA nécessite du temps et des coûts supplémentaires, garantir la livraison adéquate d'un BSM conforme aux spécifications de conception et aux exigences réglementaires l'emporte sur les coûts potentiels de colmatage et de reconstruction des noues de biorétention.

ABSTRACT

Standardization of particle size analysis (PSA) is crucial to ensure the proper blending of filter media used for stormwater treatment such as bioretention soil media (BSM). BSM typically contains of >80% sand and is amended with organic matter and fines (i.e., silt and clay) to support pollutant removal. However, there is currently no standardized PSA method to verify whether BSM meets design specifications before installation. This study compares three PSA methods—hydrometer, dry sieving with laser diffraction (DS + LD), and wet sieving with laser diffraction (WS + LD)—to evaluate their accuracy and repeatability for analyzing BSM. Twenty-seven BSM samples were collected from three bioretention cells in Ohio, USA. For the hydrometer method, substantial variability in results was observed depending on the BSM sample mass used for analysis. Triplicate BSM analyses by both DS + LD (83.9 ± 1.7% sand, 9.6 ± 3.0% silt, 6.5 ± 2.7% clay) and WS + LD (84.1 ± 1.7% sand, 10.6 ± 2.2% silt, 5.3 ± 1.7% clay) demonstrated high intra- and inter-method agreement, especially for sand content. The hydrometer and WS + LD methods were the most consistent for measuring clay content. We recommend measuring the sand and fines fractions separately after appropriate dispersion when conducting PSA on sandy soils like BSM. Although PSA requires additional time and cost, ensuring the proper delivery of BSM which complies with design and regulatory specifications outweighs the costs of potential bioretention cell clogging and reconstruction.

KEYWORDS

green infrastructure, nature-based solutions, laboratory methods, soil science, textural analysis

1 INTRODUCTION

Bioretention cells (BRCs), also known as biofilters or rain gardens, are a widely used stormwater control measure due to their demonstrated success in mitigating the impacts of urban runoff on downstream waterways. Bioretention soil media (BSM) typically consists of >80% sand, while the remainder is composed of fines (i.e., silt and clay). BSM should have a minimum infiltration capacity of 25 mm/hr to ensure that surface ponding drains within 24 hours; all soil water in the filter media should drain within 48 hours of the end of rainfall. Given that the accumulation of fines from influent runoff can inhibit the hydraulics of BRCs, there is growing interest in measuring whether BSM mixes are accurately blended in accordance with design plans and specifications. Installing BSM that does not meet specifications can negatively affect the hydraulic function of BRCs, reduce water quality performance, and potentially spark a cycle of expensive maintenance and rehabilitation.

Methods for particle size analysis (PSA) are not specified in guidance documents in the U.S., leaving uncertainty in comparing laboratory results to design specifications. Consequently, past studies have employed several methods to quantify the particle size distribution (PSD) of BSM. BSM pretreatment protocols, apparatus specifications, or the analytical methods are often not specified, which are crucial since resulting PSDs are protocol- and method-dependent. Soil scientists frequently compare multiple standardized methods to assess soil PSD, particularly when developing novel methods. Yet stormwater practitioners use various methods in the absence of a standard method and may make decisions on whether to reject or accept BSM at a construction site in the absence of solid evidence for its PSD. Given the critical role of BSM in BRC performance, there is a need to establish standard testing methods to ensure BSM PSAs adhere to regulatory design guidance. To that end, the objectives of this study were to: 1) compare existing methods for PSA for sandy BSM and 2) recommend repeatable methods as a step towards a standard method for PSA of sandy BSM. The study focuses on three bioretention cells in northern Ohio, USA. Findings from this study (Smith et al., 2025) will inform the develoment of ASTM WK95684 « New Guide for quality control check on bioretention media ».

2 METHODOLOGY

2.1 Site description

In summer 2017, BRCs were installed at Lions Park in Sandusky, Ohio, USA, to treat runoff from the parking lot before it discharged into Lake Erie, located immediately to the north of the park (Table 1). In autumn 2021, BSM samples were collected from three BRCs, referred to as "North" (41.448862°N, 82.745761°W), "Middle" (41.448650°N, 82.745605°W), and "South" (41.447814°N, 82.745592°W) based on their geographic location. From the surface downward, BRCs were constructed with 8 cm of hardwood mulch, 46 cm of BSM, 8 cm of washed concrete sand, 8 cm of ASTM No. 8 aggregate, and a 25 cm drainage layer of ASTM No. 57 aggregate surrounding a 10 cm diameter PVC underdrain pipe. Internal water storage zones were formed by raising the elevation of the underdrain outlet, allowing water to reach 33-43 cm below ground surface before discharge to Lake Erie. BRCs were planted with perennial grasses, shrubs, and flowering species.

Table 1: As-built characteristics of Lions Park BRCs and their drainage areas.

Characteristic	Middle Cell	North Cell	South Cell
Drainage area (ha)	0.17	0.16	0.04
Drainage area impervious cover (%)	73	55	64
Bioretention surface area (m^2)	50	64	43
Hydraulic loading ratio[a]	33.3	25.5	9.4
BSM composition[b]	85% sand, 5% silt, 10% clay	88% sand, 2% silt, 10% clay	83% sand, 5% silt, 12% clay
BSM texture classification	Loamy Sand	Loamy Sand	Loamy Sand
BSM organic matter content (% by weight)[c]	5	1.8	3.3
BSM Mehlich-3 phosphorus content (ppm)	62	25	39

[a]Ratio of drainage area to BRC surface area, [b]Determined using dry sieve methods, [c]Determined by loss on ignition

2.2 Data collection and analysis

BSM textural class was determined according to the United States Department of Agriculture soil classification system. In 2017, one as-built BSM soil sample for each BRC was tested by a qualified lab prior to its delivery onsite. In November 2021, twenty-seven BSM samples [3 BRCs × 3 locations per cell (inlet, center, and outlet) × 3 depths per location (0-5 cm, 10-15 cm, 30-50 cm)] were collected in an airtight bag using a hand trowel. Approximately 1 kg of BSM was extracted for each sample. Upon returning to the lab, samples were air dried, crushed using a mortar and pestle to break apart aggregates, passed through a 2-mm sieve to remove gravel and macro-organic matter (OM), and divided with a sample splitter to provide subsamples for each PSA method. Given the OM content of the BSM samples and that more than 1% OM may lead to PSD inaccuracies due to aggregation by OM (Bieganowski et al., 2018), OM was burned off in a muffle furnace at 550°C for 24 hours. The average PSD data by method were not normally distributed, so the Kruskal-Wallis test followed by Dunn's test with Bonferroni correction were used to compare the groups.

2.3 Hydrometer method

To analyze samples, an ASTM type 152H hydrometer was used according to the methods of Gee & Bauder (1986). For coarse sands like BSM, 60 to 100 grams of oven-dried sample is needed to obtain reproducible results. Two hydrometer tests were performed for each BSM sample, one with a sample size of 60 grams and the other with a sample size of 100 grams to observe how sample size affected results. Samples were pretreated with 0.5% sodium hexametaphosphate (HMP) solution and stirred with a stirring rod for 30 minutes, after which the soil suspension was mixed for 15 minutes with a multimix machine. The soil suspension was then transferred to a 1000 mL settling cylinder, which was inverted multiple times, and a plunger was used to ensure complete suspension of the particles. The hydrometer was carefully inserted into the suspension, and the first reading was taken after 40 seconds to measure the percentage of silt in suspension. The hydrometer was removed, and the suspension temperature was recorded. Three hours later, a second hydrometer reading was taken to measure the percentage of clay in suspension. A blank reading made in the dispersing solution at the same temperature was used to correct the raw hydrometer reading. Temperature corrections were applied to the hydrometer readings based on deviations from 20°C. For quality assurance and quality control, the predicted sand fraction by the hydrometer method was confirmed by wet sieving (53 µm) the suspension for 11% of samples.

2.4 Dry sieving followed by laser diffraction (DS+LD) PSA

Dry sieving was performed in triplicate according to ASTM (2007) methods. BSM samples were pretreated by rolling on a roller mill for 6 hours. Empty sieves with mesh sizes #5, 10, 18, 35, 60, 100, and 270 were weighed individually. Afterward, 50 grams of BSM was passed through the sieve stack, which was shaken at approximately 278 cycles per minute for 2.5 minutes using a Meinzer II mechanical sieve shaker (Advantech Manufacturing Inc., New Berlin, Wisconsin, USA). The sieves were weighed again to determine the PSD. The particles that passed through the entire sieve stack (fines) were analyzed using laser diffraction, as described in the following section.

2.5 Wet sieving followed by laser diffraction (WS+LD) PSA

WS+LD PSA was conducted in triplicate following the methods of Faé & Montes et al. (2019). Briefly, 5 grams of BSM mineral fraction was dispersed in 0.5% sodium HMP for 24 hours, sonicated using a VibraCell VCX750 ultrasonic meter (Sonics and Materials Inc., Newtown, Connecticut, USA) to dissociate aggregates, and wet sieved through a 53 µm mesh. Sand retained on the sieve was oven dried and weighed. Fines that passed through the sieve were analyzed using a Beckman Coulter LS 13 320 laser diffraction particle size analyzer (Beckman Coulter, Brea, California, USA). One replicate of each fines sample was also analyzed using a Malvern Mastersizer 2000 laser particle size analyzer (Malvern Instruments Ltd., Worcestershire, UK). Laser diffraction involves exposing soil particles to a laser beam and applying the Mie theory of light scattering to determine the PSD of fine particles. Both instruments sonicated the fines once again prior to PSD determination. Volumetric measurements of the fines were converted to gravimetric values applying the approach described by Faé & Montes et al. (2019). Specifically, the mass fraction not accounted for by the sand was assigned to the clay and silt fractions based on their respective volume percentages obtained from laser diffraction PSA (Faé & Montes et al., 2019). This approach assumes spherical particles and the same particle density for the fines. Particle sizes were compared between instruments using percentiles (d-values), where d10, d50, and d90 represent the particle sizes below which 10%, 50%, and 90% of the total volume of particles occur, respectively.

3 RESULTS AND DISCUSSION

Using the hydrometer method, notable discrepancies were observed between the 60 and 100 gram BSM PSD tests (Figure 1). The 60 gram tests yielded % sand measurements consistent with analysis of the as-built samples and those verified by wet sieving through a 53 µm sieve. Conversely, the 100 gram tests resulted in % sand values that varied by 15-20% compared to those obtained from wet sieving. A 40 second settling time for sand determination does not align with traditional sedimentation theory; the % sand values derived from 40 second hydrometer readings frequently deviated from the masses retained on a 53 µm sieve by more than 5% of the total sample weight. Considering that BSM is intended to contain > 80% sand and that the sand fraction as determined by the hydrometer method is based on particles settling within 40 seconds, the hydrometer method proved inadequate for precise BSM PSD determination.

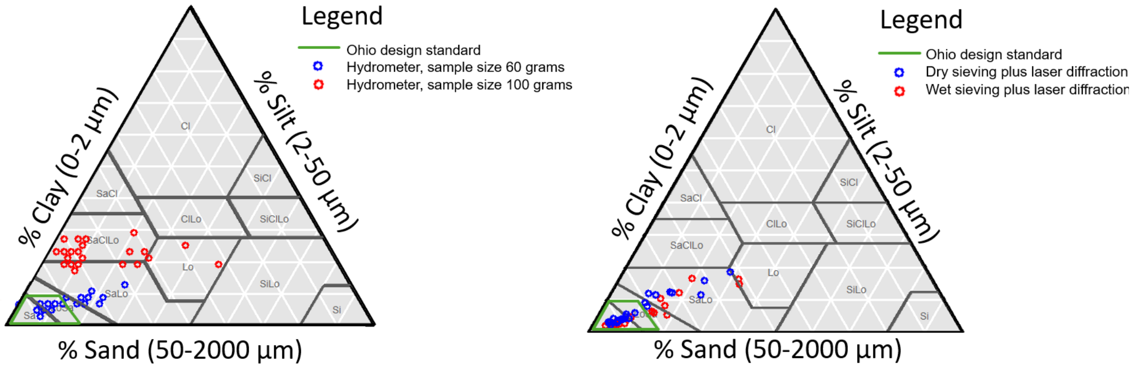

Figure 1: Particle size analysis results for hydrometer method (left) and laser diffraction methods (right)

Figure 1 shows the BSM samples analyzed by the hydrometer, DS+LD, and WS+LD methods with respect to the Ohio design standard for BSM overlayed on a USDA textural classification triangle. Except for some 0-5 cm depth samples – which likely contained accumulated fine particles washed off from the catchments – all samples analyzed by DS+LD and WS+LD methods, and all but one analyzed by the hydrometer method (sample size of 60 grams), had PSDs which met the Ohio design standard. Past laboratory column and field studies agree that influent total suspended solids and associated fines do not significantly penetrate below 5-10 cm of BSM; deeper depths evolve more slowly and have been considered a "pristine" layer of the BSM.

Our results indicate that methods such as DS+LD and WS+LD, which directly measure sand mass, yield high consistency in % sand measurements, while the hydrometer method (which relies on sedimentation) is more variable depending on the sample mass used. Methods involving wetting fines (e.g., hydrometer and WS+LD) offer the most consistent % clay measurements. We recommend weighing the sand fraction by mass and wetting-based methods for fines analysis to enhance repeatability. The tradeoffs of labor-saving potential versus BSM PSA cost must be considered; as of 2019, the average texture analysis cost $22 USD (Faé & Montes et al., 2019) or tenfold more expensive for LD, which is much cheaper than the cost of complete reconstruction of BRCs.

4 CONCLUSIONS

This study demonstrates variability in PSD results across different BSM analysis methods, emphasizing the need for clear reporting of PSA methods used. Direct sand measurement methods (DS+LD, WS+LD) provided consistent sand content, while hydrometer results varied substantially with sample mass. Wetting-based methods (hydrometer, WS+LD) showed agreement for clay content. Based on these findings, we recommend measuring sand content by mass and wetting methods for fines to improve reliability and repeatability of BSM PSDs.

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