Effects of Early Structural Changes of Engineered Soils on Green Roof and Bioretention Performance

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Abstract. Engineered soils play an important role in urban hydrology e.g. in the functioning of green roofs and storm water bioretention beds. Water infiltration, colloid transport and heat transport are affected by changes in pore system geometry particularly due to development of macropores and clogging by particles. The rate of pedogenesis is often faster than in natural soils due to higher loads of particles as well as by extreme water regimes. In the presented project we assess the temporal changes of hydraulic properties of engineered soils in typical bioretention beds and green roofs by conducting field scale experiments. The aim is to elucidate changes in hydraulic properties by studying the structural changes of soils at the microscale by invasive and noninvasive methods. The outcomes of the research will lead to improved design and management procedures for green roofs and bioretention beds.

1. Introduction

Intense urban population growth is associated with negative environmental effects. As urbanization increases the imperviousness of watersheds, the volume of storm water reaching municipal storm sewers, and eventually streams, has increased dramatically. Increasing runoff strains storm water systems that must operate beyond design capacity. Storm water also threatens the health of water resources by carrying pollutants from roads, parking lots, and rooftops to local waterways. As a consequence of rapid water drainage from urban areas, ground water levels drop, and the resulting lack of water available for evapotranspiration, in combination with the high proportion of impervious surfaces contributes to the development of urban heat islands [1]. Low Impact Development (LID) or Water Sensitive Urban Design (WSUD) approaches [2] contribute to mitigation of these adverse effects of urbanization, by improving the retention of storm water close to its source, removing contaminants from storm water, and enhancing groundwater recharge and evapotranspiration. Bioretention cells and green roofs are typical examples of LID approaches. The properties of the soils and substrates used in the bioretention and green roof construction are the key to the optimal LID function.
1.1. Bioretention cells
Bioretention cells (also called rain gardens) rely on a capacity of soil to conduct, retain, and evaporate water, and to remove water pollutants by sorption and degradation processes. The efficiency of these functions depends on the physical and chemical properties of the soil, which are, in the case of engineered soils, a function of its initial composition and subsequent soil pedogenesis [3, 4, 5]. Pedogenesis determines the development of soil structure, changes in organic matter content, formation of macropores, clogging of pores by particles, and alterations of soil wettability. Therefore, for the successful design and long-term reliable performance of bioretention cells detailed knowledge of evolution of transport processes in engineered soils is needed [6].

1.2. Green roofs
The recent increased number of green roof installations is related with the need for mitigation of Urban Heat Island (UHI) effects [7]. Depending on the geographic region, green roofing can be also useful for storm water management, pollutant loading reduction, aesthetic improvement, biodiversity enhancement, energy conservation, etc. The reduction of storm water discharge is often considered one of the greatest environmental benefits of green roofs. In this context, and in respect to hydrological and thermal behavior, the most important element of green roof systems is the growing medium. The most frequently used media are engineered soils (Technosols), i.e. redeposited soils subjected to a strong human influence, containing a large proportion of artifacts [8]. The selection of the growing medium is critical in terms of securing long term performance of green roof. Another study [9] pointed out the importance of grain size distribution of the growing medium on green roof water regime. The experiments showed that artificially constructed locally prepared soil with admixed crushed bricks and overall finer particle content in short term exhibited better water retention and plant growth (Sedum spp.) than the commercial mixture based mostly on coarser crushed expanded clay. The former growing medium was however prone to surface runoff and unwelcomed changes in the internal soil structure.

1.3. Soil media characterization by noninvasive methods
Pore space geometry of soils can be visualized effectively by X-ray computed tomography (CT). High spatial resolution of X-ray tomography allows imaging of certain types of porous media at the pore scale. A number of studies have shown that neutron imaging is capable of mapping the water content distribution in soils quantitatively in 3D [10, 11]. Bi-modal imaging technique that uses two means of imaging represent the most efficient method of imaging to observe soil processes [12].

1.4. Research aim
This contribution presents two pieces of investigation into physical properties of urban green infrastructure soils. Firstly, the aim was to establish new experimental bioretention cell facility at University Centre for Energy Efficient Buildings of the Czech Technical University in Prague (UCEEB). The second goal of the research was extending previous experiments on green roofs raised beds [13] conducted at UCEEB building roof. The raised beds infrastructure has been amended based on accumulated experience. Using this upgraded infrastructure, the effort has focused on long term hydraulic and thermal performance of the green roofs.

The long term aim of the research is to experimentally enlighten the water and heat transport processes in the green infrastructure soils.

2. Experimental bioretention cells
Two identical experimental bioretention cells were established on the premises of UCEEB (N 50°9.43753', E 14°10.16800') in December 2017. The first bioretention cell collects the storm water from a roof of the nearby experimental building (roof area 38 m²). The second bioretention cell is supplied from 2000 litres tank using a controlled pump system. The bioretention cell is, conceptually, an infiltration swale planted by four perennial plants (Aster novae-angliae “Purple Dome”; Hemerocallis 'Lemon Bells'; Euphorbia amygdaloides; Molinia caerulea).
Each bioretention cell is 2.4 m wide and 4 m long. The maximum depth of the ponding is 0.3 m. The 5 cm-thick mulching layer made of 16/32 mm gravel fraction protects the surface. The 0.3 m-thick filter layer (bioretention medium) is a sand, compost and top soil mixture in 50:30:20 % mass ratio. The 0.27-thick drainage layer consists of 16/32 mm gravel fraction. Drainage layer and the filter layers are separated by a 0.1 m-thick sand layer (0/4 mm fraction) designed for fine particles trapping. The body of experimental bioretention cell is entirely isolated from the surrounding soil by PVC membrane. Any water that passes through the filter and separation layers is collected via perforated drainage pipe into a shaft equipped with a tipping bucket flowmeter (PF500 flowmeter, Fiedler AMS, Ltd., Czech Republic).

Soil water content is monitored in each of two bioretention cells in the filter layer by four water content (TDR) probes (CS635, Campbell Scientific, U.S.A.) connected to the reflectometer (TDR100, Campbell Scientific, U.S.A.). Water content probes are placed in the depth of 0.15 m, below filter layer surface (i.e. 0.2 m below the surface of the mulch layer). Water potential in each bioretention cell is under wet conditions continuously monitored using five tensiometers (T8, Meter Environment, Germany) and at dry conditions by two water potential meters (MPS-6, Meter Environment, Germany) placed in the depth of 0.05 m below the surface of filter layer. Fig. 1 depicts the experimental rain garden set-up.

Soil hydraulic conductivity and water retention in the filter layer directly depends on the soil’s grain size distribution. Grain size analysis was performed by combination of sieving and Casagrande’s hydrometer methods for particles smaller than 2 mm. The mass fraction of clay (<0.002 mm) is 12 %, mass fraction of silt (0.002–0.05 mm) is 14% and mass fraction of sand (0.05–2 mm) is 74 %. The particle density of filter layer soil is 2563 kg.m\(^{-3}\).

Soil water retention curve of the filter layer soil has been determined on replicated undisturbed samples of 143.5 cm\(^3\) by a combination of drainage at the sand box (pressure heads between 0 and −50 cm H\(_2\)O) and on a Tempe cell (pressure heads of 100, 300 and 900 cm H\(_2\)O). Average saturated water content of the filter layer soil \(\theta_s\) is 0.43 m\(^3\).m\(^{-3}\), which is the expected value for sandy soil. Fig. 2 depicts the shape of the measured retention curve.
Figure 2. a) Particle size distribution and b) soil water retention curves of the filter soil layer of the experimental bioretention cells. V1A and V2A are replicated samples. Measured retention curve data (symbols) were fitted with van Genuchten model of the retention curve (lines).

Pore geometry is another key property determining the soil hydraulic properties and the bioretention cell performance. The regular soil sampling program was initiated in 2017 in order to visualize and quantify the soil structure and internal pore geometry of samples. The samples for a preliminary soil structure study were extracted from small pre-testing beds, constructed in a year preceding the construction of the bioretention cell itself. The pre-testing plots had the same filter and mulch layer as the bioretention cell. Samples were collected in depth of approximately 100 mm into aluminum cylinder of 29 mm internal diameter. The sample height was 50 mm. The first sample series, that represented freshly established filter layer was packed in the laboratory, whereas the second series was collected from the pilot plots two months after planting the vegetation.

The samples were imaged using a recently developed on-the-fly bi-modal tomographic technique at the ICON beamline of the Paul Scherrer Institut, Switzerland [14]. Method is based on passing neutrons and X-ray beam through the sample rotating along the vertical axis, while capturing the attenuated beam in two dimensional detectors. The image reconstruction [15] then produces a three-dimensional image of the sample for each modality. The example of identical central vertical sections obtained by two imaging modalities are depicted in Fig. 3. Light gray shades (highest image intensity) in X-ray images represents densest sample materials such as compact stones. Brightest regions in N-ray images on the other hand represent the organic matter e.g. compost particles or increased water content. The synthesis of both modalities will enable to trace the flow pathways as they develop between time of the filter layer build-up and after initial stages of soil formation.
3. Green roofs
To evaluate the water and thermal regimes of an extensive green roofs, four test beds has been established on the roof of UCEEB [14] in 2014. The infrastructure was partly refurbished in 2017 for the purpose of the current study. Long term experiment compares four test beds. Each test bed represent an unique combination of the roof substrate and vegetation planting technique. The schema of a test bed is depicted in Figure 4. The experimental set-up has been reported in detail elsewhere [14], therefore only brief description will be given here with emphasis on the latest amendments.

![Figure 4. Schematic of the experimental green roof raised bed at UCEEB, CTU building](image)

Test beds dimensions are $1 \times 1 \text{m}^2$ and depth of substrates is 0.05 m. Components of the water balance (precipitation, outflow from the test bed and water content) are monitored frequently. The volumetric water content is measured by eight TDR probes (two in each test bed). Outflow from each test bed is measured by tipping bucket flow meter. The soil substrate temperature is recorded on each test bed. Wind speed, wind direction, solar radiation, relative air humidity and air temperatures are measured on a weather station located on the roof. Three undisturbed samples from each segment were taken for laboratory measurements to determine the soil water retention curves.

Two types of growing media were used to build the extensive green roofs in test beds. The first is a commercially available substrate for extensive green roofs ACRE (Acre, Ltd., Czech Republic) that is composed of crushed spongolite, crushed expanded clay and peat. The second growing medium is a substrate for extensive green roofs BB com (BB com Ltd., Czech Republic) composed of crushed expanded clay, crushed bricks, peat and compost.

The test beds ACu (ACRE substrate) a BCu (BBcom substrate) were planted by mixture Sedum spp. cuttings whereas test beds ACa (ACRE substrate) and BCa (BBcom substrate) were planted with commercially available Sedum spp. carpet (Sedum Top Solution, Ltd., Czech Republic). The plants mixture included Sedum Sexangulare, Sedum Album, Sedum Al. “Coral Carpet”, Sedum Lydium, Sedum Lydium Glauca, Sedum Hispanicum Minus, Sedum Acre, Sedum Reflexum, Sedum Ref. “Angelina”, Sedum Spurium Fuldagut, Sedum Hybridum “Immergrunchen”, Sedum Kamtschaticum.
The physical properties of the growing medium were determined on samples collected during and after green roof test beds installation. The comparison of the particle size distribution of both substrates (see Fig. 5) shows that substrate BBcom is significantly coarser than the substrate ACRE.

Coarser texture of the BBcom substrate corresponds well with its the lower water holding capacity that expressed by lower water contents close to saturation (see Fig. 6).

Example of the outflow monitoring outcome on three green roof test beds is shown in Fig. 7 for a period between November 2017 and April 2018. Cumulative precipitation during was 130 mm during this period. The cumulative outflow was approximately half of the recorded precipitation in the same time interval. The water losses can be attributed to evaporation from substrate surface and sublimation from snow cover. The test beds planted with Sedum cuttings retained more water than the test bed with Sedum carpet, but the difference was not significant.
4. Summary

Experimental facilities dedicated to investigate the performance of green roofs and bioretention cells were established. The scheme of soil sampling and soil characterization using standard and noninvasive methods was developed. Experimental green roofs test beds and experimental bioretention cells were equipped with monitoring systems recording main state variables such as soil water content and water potential as well as components of water balance. The link between soil properties and changes of green infrastructure facilities performance will be sought as the collection of data continues.

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Figure 7. Response of the green roof raised bed to rain events from November 2017 through April 2018. Note that outflow from the raised bed BCa is missing due to tipping bucket failure.
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