# Unlocking the water retention behaviour of turf construction materials

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**Abstract.** Turf is not a material frequently associated with construction. However, as a cheap, easily available, and versatile material it was used in antiquity (and has been used in various contexts since) to form unit-based and mass walls, embankments, and ramparts. Some of the best-preserved evidence for historical turf use comes from the Roman period, when it was a mainstay of military construction, being widely used in forts (e.g. along the Rhine and in Britain) and large-scale linear earthworks, most notably the walls of Hadrian (northern England) and Antoninus Pius (central Scotland). To our knowledge, turf has never been examined as a construction material; its interest has, until now, been restricted to the soil and agricultural sciences and sports engineering. This paper presents the first exploration of turf water retention properties, assessed to understand whether turf behaviour can be collated with that of more traditional earthen materials, for example cob or rammed earth. Tensiometer and psychrometer methods were used to estimate the water retention curves of turf, representative of that used for construction, harvested from two sites near Crieff, Scotland. The obtained data were analysed in terms of unimodal type functions to understand qualities of the full range of the soil water retention curve for Scottish turf. This work supports a larger project examining how engineering materials principles can explain ancient construction practices. In so doing, we will be well positioned to reintroduce this low-carbon material to the modern construction market.

## 1 Introduction

In recent years, sustainability has been recognised as one of the key aspects for engineering applications to tackle climate change. This is most true for building construction, which was responsible for 37% of global energy and process-related CO2 emissions in 2021 [16]. As a result, engineers have been looking into building materials with low embodied carbon that can apply to modern construction. Hence, earthen construction has been reintroduced into the construction sector due to its low embodied carbon characteristics [10].

Earth construction, such as rammed earth, mud bricks, and cob, .is a building technique used from as early as the prehistoric period onwards; mudbrick is even mentioned in the Old Testament [4]. Earthen materials compose some of the great structures in the world, for example the Medieval Maghreb and southern Europe, central Asia, and China, where it was extensively used in the pre-Ming Dynasty phases (15th century) of the Great Wall of China. Nowadays, it is estimated that up to one third of the world’s population live in earthen dwellings of some form and bespoke earthen construction is a key component of modern architectural practice [9].

When the earth is used as a building material, it is normally obtained from the subsoil layer. Topsoil, on the other hand, is rarely used for modern construction because its high organic content can be used as a fertiliser or for landscaping. Turf (Irish/North America – "sod"; Latin – "*caespes*") for construction can be defined as blocks of topsoil cut from the ground which include the upper layer of living vegetation and the underlying root mesh (the O and A soil horizons, which is necessary to hold the blocks together). The vegetation and soil type influence the form and dimension of turf blocks. Sometimes part of the subsoil (the B horizon) might be included the turf blocks if the root system of the vegetation is sufficiently deep to encroach upon the subsoil layer [13, 15].

Turf is unlikely to be the first material that occurs to a modern designer or engineer when considering construction options. However, turf might be a potential solution for green construction due to its low embodied carbon. Furthermore, it is versatile and cheap, and a turf structure tends to blend well with the environment, providing an appealing aesthetic. Like earthen materials, when used as a building material some turf structures were made with a combination of other materials, such as stones and timbers [15].

Turf was used as a building material in various areas of the North Atlantic region until the 19th century. There are particularly well-understood traditions of turf building in Scotland and especially Iceland. On the latter, turf became important due to limited natural resources and well-built turf houses could sustain heat

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within the building better than stone and timber buildings [15]. In antiquity, turf was widely used military construction material for fort ramparts during the Roman period (for example, the Antonine wall, situated in central Scotland, [13,14]). Turf was also used recently in Scotland to construct dykes and embankments [18].

Although there is a long history of using turf as a building material, studies related to the mechanical properties of turf are limited and it is unclear, as yet, how to relate turf materials into the existing engineering lexicon. As it is, in part, an earthen material, it seems appropriate to investigate the hydro-mechanical properties of turf construction using an unsaturated soil mechanics approach. Principally, as turf structures were exposed to the environment, water exchange occurred between the atmosphere and turf due to climate and evapotranspiration at the exposed vegetated surface. It is reasonable to assume, in the first instance, that changes in the material's moisture content will therefore affect the turf shear strength [6]. Therefore, this study aims to begin to unlock a new understanding of turf construction materials by evaluating the turf's soil water retention curve (SWRC) as a first step towards determining the strength and possible structural behaviour of turf materials for building design.

## 2 Methodology

### 2.1 Turf collection

Turf blocks were cut and collected from non-cultivated land on the Abercairney Estate close to Crieff in Perthshire, Scotland. This site was selected based on recommendations made by Dr Daniël Postma of Archaeo Build, who is an experienced turf construction expert and constructed the medieval turf museum at Firdgum, Friesland [11]. Non- cultivated turf was chosen as it was the type of turf that builders generally preferred for building turf structures (the resulting root architecture of the turf provides the drainage path, elastic characteristic of the material and, most importantly, it acts as reinforcement to improve the tensile strength of the turf). The turf was cut into 450 mm × 300 mm × 125 mm blocks, based approximately on dimensions provided by the Roman military writer Vegetius [5].

The Atterberg limits and the particle size distribution of the turf material are yet to be determined and are not discuss in this paper. Although important characteristics for earthen materials, we note that the presence of organic material and roots complicates the meaning and measuring of these parameters. However, it is understood [11] that the parent soil texture and minerology governs the suitability of the turf for construction, e.g. by providing appropriate drainage conditions.

### 2.2 Compression testing

The hydraulic properties of turf extracted from the ground are unlikely to represent those of turf forming a load-bearing structure due to the actions of compression, consolidation, and drying. It is also a material which evolves through time through organic processes, e.g. root and shoot growth and bio-turbidity. This process may create plant debris that fills up the large pores of the material, hence reducing the inter-particle pore space beyond that associated with hydromechanical effects. Three 1500 mm × 500 mm × 1000 mm test walls were therefore constructed for compression testing, as shown in Figure 1. The turf blocks were laid in an alternating header and stretcher pattern to encourage good bonding between the layers. All of the blocks were laid grass side down: this was common (but not uniform) practice in Roman structures to judge from archaeological evidence and is also convenient for the masons, as transporting a block with the grass on the underside prevents it from cracking when spanned between the mason's arms (if the grass were uppermost, the relatively uncompacted soil side would be subjected to the highest tensile stresses when carried and, experience demonstrates, would crack). Once built, the walls were subjected to a 2 kPa surcharge to represent a typical roof load (thatched roof, resting on a ring beam) and exposed to the external atmosphere (Edinburgh, UK) for twelve months to achieve moisture equilibration and to observe shrinkage. The wall testing is not reported in this paper however we believe that these samples provide a more reliable representation of turf used for construction than fresh turf.

**Fig. 1.** Turf walls manufactured for compression testing (under a 2 kPa surcharge)

We should note here that multiple species (arachnids, insects, and vermiculites) were discovered inhabiting the walls after testing. It is not clear whether these creatures colonised the walls during the equilibration period or were already present in the turf when harvested. Although efforts were made to avoid mammals (field mice) during harvesting, we note that traditional turf would have an active soil bio-culture and it was decided not to sterilise the material (X-ray or gamma ray treatment) prior to construction to avoid damaging the turf organic component. We also note that those creatures that remained in the walls were sufficiently small to avoid injury during testing.

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## 2.3 Retention property testing

After testing the walls to destruction, three cylindrical turf samples (D= 80 mm, H = 50 mm) were extracted from two well-preserved turf blocks from walls one and three (TW1 and TW3-A and -B, respectively, so labelled for reverse compatibility with future publications) for SWRC measurement. Sample physical and hydraulic properties are given in Table 1. From Table 1, it was noted that the void ratio of the turf material was very high and the density low compared to other earthen material; this was due to the voids created by the root architecture of the vegetation and the low density of organic matter. Cob data is shown for comparison as an earthen material that also comprises organic material (straw).

**Table 1.** Turf sample physical and hydraulic properties

| | TW1 | TW3-A | TW3-B | Cob |
|---|---|---|---|---|
| Porosity | 0.55 | 0.52 | 0.5 | 0.52-0.64 |
| Dry density [g/cm3] | 0.71 | 0.75 | 0.79 | 1.4-1.7 [19] |
| Void ratio | 1.22 | 1.08 | 0.99 | 1.08-1.7 |
| Initial volumetric water content (%) | 97.14 | 74.03 | 71.06 | - |
| Initial degree of saturation (%) | 100 | 100 | 100 | - |

To establish the SWRC of turf material, evaporation and chilled mirror dew point techniques were used in this study. Both methods were carried out using the HYPROP (hydraulic property analyser) measurement system and WP4C (water potentiometer 4C), respectively (Figure 2).

**Fig. 2.** Control PC (left), HYPROP (middle), WP4C (right).

### *2.3.1 HYPROP measurement*

The HYPROP can only measure matric suction between saturation and maximum 300 kPa. It involves measuring the pressure head at two depths using two 5 mm diameter tensiometers positioned 12.5 mm and 37.5 mm from the evaporation surface (it is a 1-D evaporation system). For the HYPROP used in this study, the default air-entry value of the ceramic tips in the tensiometers is 880 kPa.

The tensiometers allow the system to record the total head gradient across the soil profile. For the HYPROP setup, the turf sample and the tensiometers were fully saturated (the former achieved through capillary wetting) by degassed deionised water before being attached to the sensor unit. The combined piece was then placed on a balance to measure mass loss during evaporation. Finally, the automated weighing of the balance measured the mass changes for the evaporation rate and hydraulic conductivity of the turf material (8).

Due to the natural composite (horizoned) characteristic of turf material, the samples from HYPROP were extracted horizontally from the turf blocks (Figure 3) to ensure that both tensiometers were exposed to similar conditions (assuming horizontal homogeneity but vertical heterogeneity). The tensiometers were inserted approximately 41.5 mm from the turf grass surface. Part of the turf blocks were used to determine the specific gravity of turf solid by using a gas pycnometer according to ASTM-D5550-14, giving a specific gravity for the HYPROP measurements of 1.57.

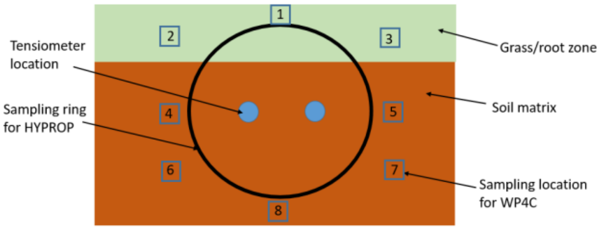

**Fig. 3.** Retention sample extraction locations relative to the HYPROP sampling ring (black circle) and tensiometers (blue circles)

### *2.3.2 WP4C measurement*

The WP4C examines samples with high suction and low water content and measures total suction between 0.1 and -300MPa. The matric forces typically dominate the strength of the unsaturated soil; however, due to root structures within the samples, osmotic potential should also be considered. The WP4C functions using the “chilled mirror” or “dew point” technique by detecting condensation on the device’s internal mirror when the sample is equilibrated with the headspace of a sealed chamber. The total suction $\psi$ is automatically calculated by the device using the Kelvin equation:

$$\psi = (\frac{RT}{M}) \times ln \frac{p}{p_0} \tag{1}$$

where $R$ is the universal gas constant, $T$ is the absolute temperature, $M$ is the molar mass of water, and $p$ and $p_0$ are the partial pressure and saturated partial pressure of water in air.

At least eight WP4C samples per HYPROP sample were taken around the HYPROP sampling ring (numbered locations in Figure 3). Turf samples were wetted by using a dropper to increase their water content and the material’s water potential was measured during its drying process to avoid any hysteresis effect. The drying process was done stepwise in the same laboratory as the HYPROP device, which had a relative humidity of 35%-55%. The equilibration time for each turf sample took around 30 min.

After measurements, samples were dried in the oven at 60ºC for at least 48 hours to determine the dry mass. This temperature was used instead of the standard drying temperature of 105°C to avoid the degradation of the root structures.

## 3 Results and Discussion

As shown in Table 1, the initial saturation ratios of all the turf samples are recorded 100% as the samples were fully saturated yet the measured values of the initial degree of saturation for the turf samples are beyond 100%; this scenario was caused by the water uptake of the root structures within the turf samples. The roots within the turf experienced swelling during water infiltration because of moisture sorption and shrinks when the roots dried. The constant swelling and shrinkage of the roots likely resulted in the microcrack formation within the turf material [7]. This degree of swelling may not represent the material *in situ*, which is confined by the mass of the wall. However, when the samples were taken from the wall and later saturated with water (using capillary action) for the wet range of SWRC, the samples absorbed water and expanded vertically due to the lack of confinement. This was observed before starting the HYPROP measurement as an increase in the height of the samples by between 2 and 3 mm. Hence, the expansion of the turf and swelling of the root structure increased its original porosity and void space.

TW1 has a much higher initial volumetric water content and lower density compared to the other two samples. This might be due to the root architecture, which is ostensibly unique for each block. The denser root content within the structures reduced the density of the material as the roots are not the main contributor for the mass of the samples. TW3-A and TW3-B were extracted from the same block and show similar properties and so it is reasonable that the root and pores' structures of the TW3-B and TW3-A were similar.

Figures 4-6 show the measured data from both the WP4C and HYPROP devices, where the soil hydraulic properties were described using the standard van Genuchten-Mualem formulation given by [17]:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha\psi)^n]^m} \qquad (2)$$

where $S_e$= effective saturation; $\theta_s$= volumetric water content at saturation; $\theta_r$ = residual volumetric water content; $\alpha$ = a representation of the air entry pressure; $n$ and $m$ are semi-empirical curve-fitting parameter with $m = 1 - 1/n$. Note that, as the first in the test series, few samples were taken from TW1; testing on that wall provided familiarity for more detailed analyses of the remaining walls. Fitting parameter values used for each test are given in Table 2. Given the approximate nature of the curve fitting, $\theta_r$ was assumed to be zero for all samples.

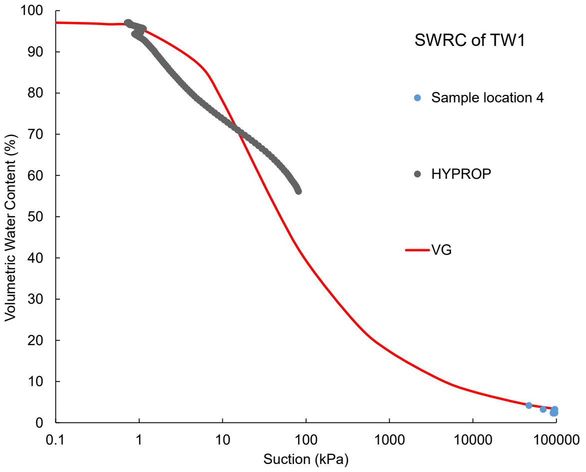

**Fig. 4.** Soil water retention results (HYPROP and WP4C) results for TW1.

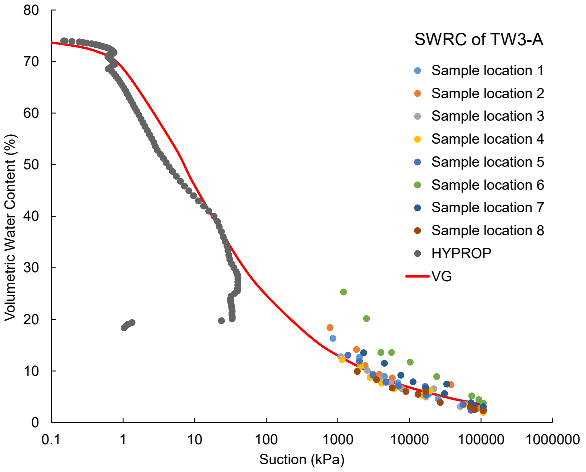

**Fig. 5.** Soil water retention results (HYPROP and WP4C) results for TW3-A.

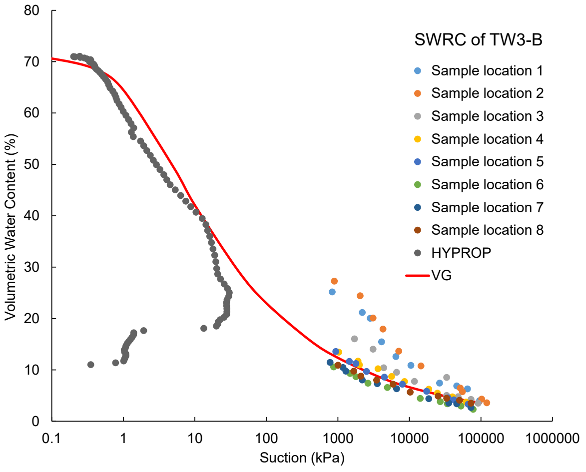

**Fig. 6.** Soil water retention results (HYPROP and WP4C) results for TW3-B.

**Table 2.** Van Genuchten-Mualem fitting parameters

| | TW1 | TW3-A | TW3-B |
|---|---|---|---|

| | | | |
|---|---|---|---|
| α (-) | 0.12 | 0.5 | 0.65 |
| n (-) | 1.36 | 1.28 | 1.27 |
| $\theta_s$ (%) | 97.14 | 74.03 | 71.06 |
| $\theta_r$ (%) | 0 | 0 | 0 |

The van Genuchten approximation provides some indication of the retention properties. However, the retention data is seemingly bimodal (at matric suctions of 1 and 10 kPa) for all tests. Given the heterogeneous nature of turf, bimodality is to be expected and might indicate prominent properties of the root cavities and soil pore network. Properties of the root and macropore network are being explored using X-Ray computed tomography but results are not reported here.

For Figures 5 and 6, the lower volumetric moisture range of the HYPROP data (below 30%) do not follow the SWRC curve. The loss of suction could be attributed to incomplete saturation of one of the tensiometers. Therefore, the data points which were below 30% volumetric moisture content that were recorded by HYPROP should not be considered into the SWRC. However, it was also noted that when turf is dried, it shrinks away from the HYPROP sampling ring, altering the volume quite significantly but also exposing the sides of the sample to drying. Shrinkage around the tensiometer tips may have broken hydraulic contact with the surrounding material and resulted in the tensiometers returning to a suction of zero but without cavitation.

The suction values measured by the HYPROP in Figures 4-6 are matric suction. However, the values measured by WP4C were total suction. Traditionally, the results of both techniques can be combined to form the complete SWRC curve as the contribution of the osmotic potential is small when the moisture content is low (2). However, as roots do not uptake salt (3), when roots uptake water for the vegetation, salt accumulates around the root area and so creates an osmotic imbalance, increasing the total suction of the upper grassy layer of turf. As turf has a set orientation with a vegetated layer at its surface, the quantity and spacing of the root fibres varies with depth. The locations selected for WP4C sampling (Figure 2), which vary vertically through the turf, allow us to explore the significance of the osmotic suction. Figure 6 indicates the osmotic suction in sampling location 1, 2 and 3 (collected between the 0-30mm depths from the grass surface of turf blocks) might be significant as they had higher suction values compare to other WP4C samples at similar volumetric water content despite being associated with looser/coarser material (as accumulates in the root matter). The same pattern, however, is not observed in Figure 5. Rather, the samples from sampling locations 1 to 8 do not deviate significantly from each other, expect for results corresponding to sampling point 6. One possible explanation for the higher water contents found at location 6 may be that residual grass from an overlying turf block may have adhered to the sampled block; the higher organic content would result in a higher salt content in the soil. However, without further investigation it would be inappropriate to attribute any deviation about an apparent trend to salt content alone. However, it is clear that, when performing total suction tests on organic material, it is important to record the extract sampling locations as the organic material influence the osmotic suction.

## 4 Conclusions

Turf is a construction material with a distinct heritage that could be a potential building material for sustainable modern construction or geotechnical applications. However, we must first work to understand its hydromechanical behaviour. This paper examined whether turf exhibits behaviour similar to unsaturated soils and explored the processes required to measure and interpret the drying soil water retention curve. Three test walls were built to observe how turf compressed under load and whilst drying and to establish suitable material properties (increased density and appropriate root and shoot growth) to test the walls' capacities under vertical load. After failure, samples were then taken from intact portions of the walls to examine their retention properties using a combination of devices: tensiometers (METER HYPROP) for low suction levels and a water potentiometer (METER WP4C) for higher suction levels.

Sampling the turf revealed a vertically arranged structure comprising organic material at the top of the block and a root mass and soil beneath. Low-suction testing positioned the tensiometers in the root mass zone to understand water retention in this region and increase the likelihood of achieving good hydraulic connectivity versus the purely organic zone. Samples for high suction testing were extracted from a range of vertical positions to determine the effect of organic content on the retention properties.

Psychrometric testing in the high suction range indicated that osmotic effects may be significant close to the turf surface (0-30 mm depth), suggestibly due to salt deposition around the root structures as the material dries. It is therefore important to consider both osmotic and matric suction when determining the strength of turf especially when the turf materials contain thick root zone.

Tensiometer testing was successful but indicated that the excessive material shrinkage on drying may cause the material to detach from the tensiometer tips, breaking the hydraulic conductivity and returning a suction reading of close to zero.

The SWRCs in this paper were established using the drying method. Additional work is underway to characterise the material wetting curve and to understand hydraulic and volumetric contributions to hydraulic hysteresis. In particular, the shrink-swell effect needs to be investigated as might cause hazards such as heave and major cracks on the structure. Further research will be investigate how the SWRC of the material changes across the depth of the blocks as the soil-to-root ratio changes. The specific gravity of solid should be taken into consideration in this case as it changes considerably across the depth of the turf blocks as the organic content changes.

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## References

1. ASTM Standard D5550-14. (2014) Standard Test Method for Specific Gravity of Soil Solids by Gas Pycnometer, ASTM International, West Conshohocken. United States
2. ASTM Standard D6836-16. (2016). Standard Test Methods for Determination of the Soil Water Characteristic Curve for Desorption Using Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, or Centrifuge, ASTM International, West Conshohocken, PA.
3. Canning R.E, Karmer, P.J (1958) Salt Absorption and Accumulation in Various Regions of Roots, American Journal of Botany, Vol. 45, No. 5, pp. 378-382
4. Exodus 5:7,16,18; Holy Bible: Revised Standard Version
5. Flavius, V. *De Re Militari* 3.8
6. Fredlund, D. G. et al. (2012) Unsaturated Soil Mechanics in Engineering Practice. 1. Aufl. Hoboken, N.J: Wiley-Interscience.
7. Mehra, S.R.; Uppal, H.L.; Chadda, L.R. (1951), Some preliminary investigations in the use of bamboo for reinforcing concrete. Indian Concr, 25, 20–21
8. METER, (2015). Operation Manual HYPROP 2, METER Group AG, Munich, Germany. http://library.metergroup.com/Manuals/18263_HYPROP_Manual_Web.pdf.
9. Minke, G. (2021) Building with Earth : Design and Technology of a Sustainable Architecture / Gernot Minke. 4th rev. edition. Basel: Birkhäuser,.
10. Nouri, H., Safehian, M. and Mir Mohammad Hosseini, S.M. (2021), "Life cycle assessment of earthen materials for low-cost housing a comparison between rammed earth and fired clay bricks", International Journal of Building Pathology and Adaptation, Vol. ISSN: 2398-4708
11. Postma, D. (2015), *Het Zodenhuis van Firdgum. Middeleeuwse Boerderijbouw in het Friese Kustgebied tussen 400 en 1300*, Groningen., Barkhuis; 1st edition
12. Rahardjo, H., Satyanaga, A., Mohamed, H., Ip, S. C. Y., & Shah, R. S. (2019). Comparison of soil–water characteristic curves from conventional testing and combination of small-scale centrifuge and dew point methods. Geotechnical and Geological Engineering, 37(2), 659-672.
13. Russell, B.; Romankiewicz, T.; Gardner, T.; Birley, A.; Snyder, R. & Beckett, C. T. S. (2021). Building with turf at Roman Vindolanda: Multi-scalar analysis of earthen materials, construction techniques, and landscape context, The Archaeological Journal, Routledge
14. Romankiewicz, T., Russell, B., Bailey, G., Gardner, T., Snyder, J.R, and Beckett, C.T.S. (2022). "Another wall of turf': geoarchaeological analysis of the Antonine Wall at 72 Grahamsdyke Street, Laurieston, Falkirk', Proceedings of the Society of Antiquaries of Scotland 151: 103-141 (https://doi.org/10.9750/PSAS.151.1353
15. Stefánsson, H., (2013), Af jörðu. Íslensk torfhús,.Translated by Yates, A., (2019) From Earth – Earth Architecture in Iceland, National Museum of Iceland
16. United Nations Environment Programme (2022). 2022 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi.
17. Van Genuchten, M.T. (1980), A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Science Society of America Journal, 44: 892-898.
18. Walker, B. et al., (2006). Scottish turf construction, Edinburgh: Historic Scotland.
19. Ziegert C. Lehmwellerbau (2003)– Konstruktion, Schäden und Sanierung, Berichte aus dem Konstruktiven Ingenieurbau. PhD thesis, Berlin (Germany): Technical University of Berlin