Influence of different material proportions on the physical properties of water-saving roof greening substrates

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Abstract. The choice of roof greening substrate is the key to effective roof greening. To fully analyze the influence of different material proportions on the physical properties of the substrate, three materials, namely nutrient soil, vermiculite, and ceramsite, are selected, which are mixed with the soil in different proportions to form different roof greening substrates. By measuring the indexes including the bulk density, water absorption rate, water loss rate, and hydraulic conductivity, the variation influence of material proportions on the physical properties of the substrates is analyzed.

1. Introduction
With the acceleration of urbanization, urban residents develop higher demands for the living environment. As a new type of building greening, roof greening can effectively increase the greening rate and improve the living environment. However, the environment where the roof is located is greatly restricted by natural conditions[1], which puts forward higher requirements for the planting substrate that meets the growth of plants. With the promotion of roof greening, water-retaining and lightweight roof greening substrates have become the development direction in recent years[2,3]. Scholars have carried out a series of studies on the bulk density and water retention of substrates such as sawdust, perlite, and ceramsite commonly used in roof greening, and measured them by using fly ash, cinder, straw and garden waste to configure new substrates[4-6]. Yet there is no report on the related research on water-saving roof greening substrates[7]. Considering the actual roof greening in Yinchuan, this paper screens out three commonly used materials including nutrient soil, vermiculite and ceramsite, which are mixed with local soil in proportion to configure a green roof planting substrate. Concerning the determination index of domestic green roof substrates[8,9], the physical properties are measured from four aspects including the bulk density, water absorption rate, water loss rate, and hydraulic conductivity. In this way, the suitable substrate proportion of water-saving roof greening in this area can be obtained, which will provide a reference for future roof greening.

2. Materials and methods
2.1. Materials
Combining the characteristics of horticultural soil, ordinary soil, nutrient soil, vermiculite, and ceramsite are selected as experimental materials. The ordinary soil is from Yinchuan Garden Farm.
The nutrient soil is the plant nutrient soil produced by Dewodu Fertilizer Co., Ltd in Hebei. The vermiculite is the 1-3mm golden vermiculite produced by Xuyang Mining Co., Ltd of Lingshou County. The ceramsite is the 3-5mm gray ceramsite produced by Wanjiang Environmental Protection Technology Co., Ltd in Henan.

2.2. Methods

2.2.1. Experimental design
According to the different proportions of the experimental design, the nutrient soil, vermiculite, ceramsite and ordinary soil are fully mixed into samples. Single-factor experiment is used to explore the influence of nutrient soil, vermiculite and ceramsite on the planting substrate. Three sets of parallel tests are performed on the substrate samples under the same conditions, and the results are averaged.

2.2.2. Index determination
In order to reduce the influence of the volume of different indexes in the experiment sample on the test results, the nutrient soil, vermiculite, and ceramsite are all manufactured from the same batch of products. The fully mixed samples are randomly selected, and the repetitive test samples are sealed and stored before the experiment. The ring cutting method is introduced to help determine the bulk density. After the sample is dried and weighed (accurate to 0.01g) in a thermostat, the bulk density is determined. In addition, regarding measuring the water holding capacity in the field, the water retention of the planting substrate is determined by water absorption rate. The substrate sampled by ring cutting is fully dried and put into water. The end with holes is soaked in water for 24 hours, making the water surface 1-2mm lower than the top surface of the ring cutter, so that the soil moisture is saturated. What’s more, the water loss rate of the substrate is determined by the proportion of evaporation in the fixed period of the total water loss. After the substrate is fully absorbed and saturated, it is placed in an electric thermostatic-drying oven for blast drying under the constant temperature (30°C). The substrate is weighed at 0, 24, 48, 72, 96, 120, 144, 168 hours and finally the test block is dried and weighed (accurate to 0.01g). Considering the high water permeability of the planting substrate test, the constant head permeability test is used to determine the hydraulic conductivity.

2.2.3. Data processing
The software Microsoft Excel 2010 is used to process the original data and make graphs. The statistical analysis software SPSS 18.0 is used for variance analysis.

3. Results and analysis
When the soil was constant, as the proportion between nutrient soil (Y), vermiculite (Z), and ceramsite (T) varies, the influence changing pattern of each factor on the bulk density and water permeability was obtained. The designed experiment was carried out based on the single factor experiment, and the volume by volume method was adopted. Taking the soil volume as 2, nutrient soil, vermiculite, and ceramsite were mixed with the soil in six different volumes of 2, 3, 4, 5, 6, and 7, respectively. The variation influence in nutrient soil, vermiculite, and ceramsite volume on the bulk density, water retention, and hydraulic conductivity were measured.

3.1. Influence of different materials on the bulk density of the planting substrate
The soil bulk density referred to the dry soil mass per unit volume of undisturbed soil, which could assess the tightness and structure of the soil[10]. Under the premise of satisfying plant growth, the bulk density of the roof greening planting substrate was suggested as small as possible. By consulting related literature, it was found that the suitable bulk density was 0.1-1g/cm³. Figure 1 showed that with the volume increase of nutrient soil and vermiculite, the bulk density gradually decreased. The bulk density of group Y decreased from 0.79 to 0.13, and the bulk density of group Z decreased from 0.79
to 0.46. With the volume increase of ceramsite, the bulk density gradually increased, and the bulk density of group T increased from 0.79 to 1.52. Compared with the reference bulk density of 0.1~1g/cm³, all schemes of the nutrient soil and vermiculite in the experiment met the requirements, while only groups T1 and T2 of the ceramsite did.

By comparing and analyzing the variation trend of the bulk density of the planting substrate with different proportions, it can be seen that within the range of the test proportions, the bulk density of the nutrient soil was smaller than that of vermiculite. Besides, the nutrient soil was relatively loose, which led to the decrease in bulk density of group Y significantly faster than that of group Z. Due to the larger bulk density of ceramsite in group T, the number of ceramsites went up, followed by a gradual increase of the substrate bulk density. From further variance analysis (α=0.05) on the bulk density of the same material with different proportions, it was found that the experiment results under different proportions of nutrient soil, vermiculite, and ceramsite showed significant differences. Therefore, the bulk density of the material and the proportions of the substrate had a great impact on the bulk density of the planting substrate.

3.2. Influence of different materials on the water absorption rate of the planting substrate

Soil water retention was the ability of the soil to absorb water, equal to the water content of the saturated substrate after one single irrigation[11]. Roof greening substrates needed proper water absorption to ensure the supply of water for plants. It can be seen from Figure 2 that with the volume increase of nutrient soil and vermiculite, the water absorption of the planting substrate gradually increased. The water absorption rate of group Y increased to 47.33 and that of group Z increased to 82.14. However, with the volume increase of ceramsite, the water absorption rate of group T first increased to 42.39 and then decreased to 36.27. Based on the requirement of high water absorption for the roof greening planting substrate, all schemes of nutrient soil, vermiculite and ceramsite in the experiment can meet the requirements, except for ceramsite. When the volume of ceramsite increased from 6 to 7, the water absorption of the substrate decreased, so it should be excluded when selecting.
By comparing and analyzing the variation trend of the water absorption rate of the planting substrate with different proportions, since the nutrient soil was relatively loose within the range of the test proportions, the large voids of the mixed substrate would cause the water absorption rate to change slowly. Vermiculite had strong water absorption due to the capillary action, and the water absorption would gradually increase as the volume increased. Ceramsite is a loose granular material with a certain degree of water absorption. The substrate voids became larger as the volume increased, leading to a tendency for the water absorption to increase first and then decrease. From further variance analysis ($\alpha=0.05$) on the water absorption rate of the same material with different proportions, it was found that the experiment results under different proportions of nutrient soil and vermiculite showed significant differences, yet the results of ceramsite were no different. Therefore, the volume of nutrient soil and vermiculite had a great impact on the water absorption of the planting substrate while the volume of ceramsite had little effect, which reminded that the actual selection should pay attention to the volume control.

3.3. Influence of different materials on the water loss rate of the planting substrate

The water loss of the substrate was the ability of the substrate to retain water after absorbing it. The water loss mainly included the evaporation of water on the substrate surface and the escape of water vapor through the voids of the substrate[12]. The environment of the roof was harsh, so the requirement of the water loss was higher. Figure 3 showed that the water loss rate gradually decreased with the volume increase of the vermiculite, and group Z decreased from 69.19 to 23.98. With the volume increase of nutrient soil and ceramsite, the water loss rate increased in the early and late stages. When the volume of nutrient soil increased from 4 to 5 and the volume of ceramsite increased from 5 to 6, the water loss rate of the substrate began to increase, so it should be excluded when selecting.
By comparing and analyzing the variation trend of the water loss rate with different proportions, due to the loose texture of the nutrient soil and the large capillary porosity within the range of the test proportions, the voids inside the substrate became larger with the volume increase of nutrient soil, which led to the increased water loss rate in the later stage. Due to the internal structure, the vermiculite had strong water retention. The ceramsite itself had a certain degree of water absorption, but being granular inevitably making the void relatively large. When the volume of the ceramsite exceeded a certain range, the water loss rate increased significantly. From further variance analysis ($\alpha=0.05$) on the water loss rate of the same material with different proportions, it was found that the experiment results under different proportions of vermiculite showed significant differences, while the results of nutrient soil and ceramsite were not obvious. Therefore, the volume of the vermiculite had a great impact on the water loss rate, yet the volume of nutrient soil and ceramsite had little effect.

3.4. Influence of different materials on the hydraulic conductivity of the planting substrate

The soil permeability was the property of water flowing through a porous medium[13]. The hydraulic conductivity directly affected the water permeability and air permeability of the substrate. On one hand, if the hydraulic conductivity of the planting substrate was too low, it meant that the substrate had poor water permeability and was not conducive to plant growth. On the other hand, if the hydraulic conductivity was too high, too much leakage after irrigation would cause serious waste of water resources. Normally, the hydraulic conductivity of sandy loam, loam and clay that were suitable for crop growth were taken as $6\times10^{-2}$, $6\times10^{-3}$, and $6\times10^{-4}$ mm/min[15]. Figure 4 showed that as the volume of nutrient soil, vermiculite, and ceramsite increased, the hydraulic conductivity of the planting substrate gradually increased. Group Y increased from 0.72 to 2.15, group Z increased from 0.72 to 3.12, and group T increased from 0.72 to 6.35. When the volume of ceramsite was increased from 4 to 5, the hydraulic conductivity changed significantly.
Fig. 4 Variation trend of hydraulic conductivity under different proportions

By comparing and analyzing the variation trend of the hydraulic conductivity of the planting substrate with different proportions, with the volume increase in the nutrient soil and vermiculite within the range of the test proportions, the hydraulic conductivity increased rapidly at the beginning, and then the increase in the substrate volume caused its increase to slow down. The main reason was that the increased volume of the nutrient soil and vermiculite made the substrate particles looser, leading to an increase in hydraulic conductivity. Due to the gaps in the vent holes, the water infiltration rate of ceramsite was faster than nutrient soil and vermiculite after irrigation. From further variance analysis ($\alpha=0.05$) on the hydraulic conductivity of the same material with different proportions, it was found that the experiment results under different proportions of nutrient soil, vermiculite, and ceramsite showed significant differences. Besides, the hydraulic conductivity of the substrate with large particles was higher than that of the substrate with small particles. This is because the small particles tended to block the pores in the substrate, resulting in reduced hydraulic conductivity.

3.5. Comprehensive analysis

To further verify the comprehensive influence of the substrate bulk density, water absorption rate, water loss rate, and hydraulic conductivity of the three substrates including nutrient soil, vermiculite, and ceramsite within the experiment proportion, the matrix method was adopted to comprehensively evaluate the 19 proportion schemes. The score evaluation criteria are small bulk density, high water absorption rate, low water loss rate, and low hydraulic conductivity, and the scores are summarized to get a comprehensive evaluation.

| Impact indicators       | O  | Y -2 | Y -3 | Y -4 | Y -5 | Y -6 | Y -7 | Z -2 | Z -3 | Z -4 | Z -5 | Z -6 | Z -7 | T -2 | T -3 | T -4 | T -5 | T -6 | T -7 |
|-------------------------|----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| bulk density            | 7  | 9    | 12   | 14   | 17   | 18   | 19   | 8    | 10   | 11   | 13   | 15   | 16   | 5    | 4    | 3    | 2    | 1    |
| water absorption rate   | 1  | 6    | 8    | 12   | 14   | 15   | 2    | 9    | 13   | 16   | 17   | 18   | 19   | 3    | 4    | 5    | 7    | 10   | 11   |
| water loss rate         | 1  | 5    | 8    | 13   | 14   | 12   | 7    | 2    | 11   | 16   | 17   | 18   | 19   | 3    | 4    | 6    | 9    | 15   | 10   |
| hydraulic conductivity  | 17 | 16   | 13   | 12   | 11   | 9    | 7    | 18   | 15   | 10   | 6    | 5    | 3    | 19   | 14   | 8    | 4    | 2    | 1    |
| Comprehensive score     | 26 | 36   | 41   | 51   | 56   | 54   | 53   | 37   | 49   | 53   | 53   | 56   | 57   | 31   | 27   | 23   | 23   | 29   | 23   |

From the comprehensive score in Table 1, it can be seen that group Z-7 ranks first, followed by Z-6 and Y-5, and T-4 and T-7 have the lowest score. In group Z, as the vermiculite volume increases, the...
overall substrate score is higher, which explains that the performance of vermiculite is better than nutrient soil and ceramsite in terms of the physical properties of the substrate. In Y group and T group, with the volume increase of nutrient soil and ceramsite, there is a tendency for the score to increase first and then decrease, so attention should be paid to adjusting actual proportion.

4. Conclusion and discussion
Due to the harsh environmental conditions of the roof, different roof greening and water-saving irrigation methods have higher requirements on the physical properties of the planting substrate[15]. This experiment uses nutrient soil, vermiculite, and ceramsite in different volume proportions to determine the bulk density, water absorption rate, water loss rate, and hydraulic conductivity of the substrate. Through the analysis of experimental data, it can be seen that the bulk density of the material and the proportion of the substrate have a greater impact on the bulk density of the planting substrate. The volume of nutrient soil and vermiculite has a significant influence on the water absorption rate of the planting substrate, and the volume of ceramsite has little effect, so attention should be paid to controlling the proportion. The volume of vermiculite has a great influence on the water loss rate of the planting substrate, and the volume of nutrient soil and ceramsite has not obvious influence. The particle size and volume of the material have a greater impact on the hydraulic conductivity of the planting substrate. Further analysis shows that the volume increase in vermiculite can effectively improve the physical properties of the substrate, and the proportion should be optimized in combination with the actual situation. At the same time, in order to enhance water utilization, when the volume of the nutrient soil and ceramsite are large, the irrigation amount and frequency should be adjusted reasonably.

The configuration of the green planting structure of the water-saving roof puts forward higher requirements on the physical properties of the substrate, and the different material volume will have a certain impact on the physical properties of the substrate. Therefore, it is recommended to combine the substrate materials commonly used locally in actual construction for proportioning, such as sawdust, rice husk ash, coconut peat, and perlite. By reasonably measuring the weight, water retention, water loss and permeability of the planting substrate, comprehensive comparisons are made to improve water utilization.

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References
[1]Yang, Y., Liu,J.J. (2020) Drought Resistance of Five Kinds of Roof Greening Evergreen Plants.JOURNAL OF NORTHWEST FORESTRY UNIVERSITY,35(1):73.
[2]Wang, G., Wei, R., Huang, Y. (2018) Research Progress of Light Roof Greening.Hunan Agricultural Sciences,11:120.
[3]Wang, X.Y., Zheng, S.J., Zhang, Q.P. (2017) Comparative Study on Water Retention Characteristics of Roof Greening Media.JOURNAL OF NORTHWEST FORESTRY UNIVERSITY,32(5):257.
[4]Li, Q.S. (2005) Growing Media Selection for Green Roof.JOURNAL OF ANHUI AGRICULTURAL SCIENCES(01):84.
[5]Zhu, D. (2019) Screening of Roof Greening CultivationSubstrate in Guanzhong Area of Shaanxi.Northwest A&F University.
[6]Qin, J., Hu Y.H., Wang, L.M. (2007) Study of Economic-water Soil for Space Greening on Ecology Building.CHINESE AGRICULTURAL SCIENCE BULLETIN,(01):216.
[7]Zhou, Y., Tan, Q., Chen,F.Z. (2010) Selection of Medium in Using Waste and Adaptive Plants for Roof Greening.NORTHERN HORTICULTURE,(10):114.
[8] Shi, Z.J., Fan, Y.W. (2013) Study on the Substrate Formulation Screening of Lightweight Roof Greening. NORTHERN HORTICULTURE, (14):73.
[9] Zhang, H., Li, M., Cao, J.L. (2015) Water retention capacity of typical roof greening matrices. Journal of Chongqing Jianzhu University, 37(01):67.
[10] Zhang, T.J. (2007) The Structure Status and Effect of Topsoil in Loess Plateau. Northwest A & F University.
[11] Yan, Y.L., Yu, J., Wei, Z.M. (2007) Effects of soil properties on water absorption of super absorbent polymers. TRANSACTIONS OF THE CHINESE SOCIETY OF AGRICULTURAL ENGINEERING, (07):76.
[12] Zhang, L., S, X.Y., Tian, Y. (2012) Effects of Composite Water Retaining Agents Addition on Water Retention Property of Soilless Culture Substrate[J]. Journal of Basic Science and Engineering, 20(05):759.
[13] Li, X.F., Liu, M.X. (2018) Soil Hydrological Function of Different Altitudinal Hillslopes of the Three Gorges Mountain and Its Impact Factors. Resources and Environment in the Yangtze Basin, 27(08):1809.
[14] Gan, L., Fan, H.Y., Wu, W.Y. (2013) Water Retention Parameters of Soilless-culture Substrates. Transactions of the Chinese Society for Agricultural Machinery, 44(05):113.
[15] Wang, B. (2018) Water Saving Irrigation Technology for Roof Greening: Research Status and Development Trend. Journal of Yangtze River Scientific Research Institute, 35(12):34.