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PEDOLOGY

Rapid bulk density measurement using mobile device photogrammetry

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Abstract

Soil bulk density (D_b), the ratio of soil solid mass to bulk soil volume, is an important but difficult soil property to measure. Existing methods are either expensive, time consuming, or destructive to the sample. The goal of this research was to investigate the utility of photogrammetry for measuring D_b. Photogrammetry is the determination of shape and volume from multiple overlapping photos. Photos of soil peds placed on a 3D-printed turntable were obtained using two mobile devices. Photogrammetry-measured volume and D_b were compared with volume and D_b measured using the clod and 3D laser-scanning methods. No significant differences between D_b measured by any method were found. No statistical difference between cameras types was found. We conclude that photogrammetry is a useful method for measuring D_b. Measuring D_b using photogrammetry was much easier than the other methods and was less expensive and faster than 3D laser scanning.

1 | INTRODUCTION

Soil bulk density (D_b) is an important but difficult soil property to measure. Accurate and reliable D_b measurements are critical to convert nutrient stocks from a mass basis (g kg^{-1}) to an area basis (kg ha^{-1}), the most common of which includes soil carbon stocks. Areal estimates allow for the comparison of soil characteristics between sites as well as in resource assessments such as comparing nutrient stocks (Ellert & Bettany, 1995; Gál, Vyn, Michéli, Kladivko, & McFee, 2007; Throop et al., 2012; Sequeira et al., 2014).

Soil D_b is the ratio of the soil solid mass to the bulk soil volume (Rossi, Hirmas, Graham, & Sternberg, 2008). The key difficulty in measuring D_b is the determination of volume. Current direct measurements of bulk soil volume depend on soil coherence. Samples coherent enough to be collected intact can be collected as a ped of unknown volume. The *clod method* (Brasher, Branzmeir, Valasis, & Davidson, 1966; Hirmas & Furquim, 2006) coats soil peds with a semi permeable resin membrane (e.g., paraffin wax) and subsequent submergence to determine volume. The *3D-laser scanning method* (Rossi et al., 2008) uses a laser to digitally capture the shape of a ped and subsequent measure volume. Rossi et al. (2008) showed excellent agreement between D_b measured using 3D laser scanning and the clod method. While 3D laser scanning is comparable in accuracy to the clod method and preserves the sample for subsequent analysis, this method requires specialized equipment and approximately 1.5 hours per sample. As D_b can be highly variable in space and time (Iqbal, Thomasson, Jenkins, Owens, & Whisler, 1978; Karlen et al., 1997), using a quick, effective, and less-intensive measurement of soil volume will allow for meaningful spatial and temporal analysis of soil patterns (Viscarra-Rossel, Mcbratney, & Minasny, 2010).

Recent advances in computational power, software and inexpensive, high resolution cameras on mobile devices open the possibility of using photogrammetry to rapidly and inexpensively calculate volume. Photogrammetry consists of methods to make precise measurements from multiple-overlapping photos to determine the relative locations of points from which distances, angles, areas, volumes, size, and shapes of objects can be determined (Wolf, Dewitt, & Wilkinson, 2014). Photogrammetry has been used to measure soil clod volume at different water contents to estimate the soil shrinkage curve with minimal difference between displacement and photogrammetric methods (Sander & Gerke, 2007; Stewart, Abou Najm, Rupp, & Selker, 2012). Photogrammetry has also been used to estimate D_b of small (<8 mm) soil aggregates, which are challenging to measure using coating and displacement (Moret-Fernández, Latorre, Peña, González-Cebollada, & López, 2016). Thus, we hypothesized that photogrammetry could be used to estimate soil D_b of soil peds. In particular, we were interested in the ability of photogrammetry from mobile device imagery to estimate D_b because of the ubiquity of relatively inexpensive mobile devices and the generally high-resolution images available from such devices. We first compare volume measurements between photogrammetry and 3D laser scanning and then compare D_b measurements between photogrammetry and the clod method.

Core Ideas

- Photogrammetry using mobile device imagery accurately measures ped volume
- Measurements of bulk density using photogrammetry are as accurate as the clod and laser scanning methods
- Photogrammetry is cheaper and faster than 3D laser scanning

2 | MATERIALS AND METHODS

2.1 | Soil sample characteristics, preparation, and analysis

Intact structural units (i.e., peds) were collected from a total of seven different horizons from three different soil profiles in southern New Mexico and represent common soil conditions in this area (Table 1). Samples were transported in a cushioned box to avoid ped disintegration during transit and were oven-dried at 105 ˚C overnight and stored to avoid the potential of any atmospheric moisture absorbance.

Eight peds from each horizon were analyzed. The volume of four of the eight peds was calculated using the photogrammetry method and 3D laser scanning method, except for one ped from the Leyendecker 2C (fine sand) sample because the sample disintegrated before 3D laser scanning was complete. Volume measurement agreement between 3D laser scanning and photogrammetry was quantified using Lin's concordance correlation coefficient (CCC) which is the concordance between a new measurement (i.e., photogrammetry) and a "gold-standard" measurement (i.e., 3D laser scanning) (Signorell, 2019). The higher the concordance, the closer the new measurement reproduces the gold-standard measurement. These samples were then discarded because mass was lost during handling and atmospheric water was absorbed into these peds. The remaining four samples were then analyzed for D_b using photogrammetry and the clod method. Soil bulk density was calculated by dividing the mass of each sample by the volume of the sample obtained from each method.

Samples analyzed with the 3D laser scanning and photogrammetry methods were "shaved" flat on one side using a razor blade to ensure that samples would not shift during analysis. The mass of each sample was recorded prior to each analysis to account for any changes in mass during sample handling. Sample replicates were averaged and the standard deviation calculated. The resulting D_b were compared with one-way ANOVA with contrasts between methods within the same horizon. All statistical analysis and plotting were performed using R 3.6.1 in Rstudio 1.2.1335 (R Core Team, 2019; RStudio Team, 2018) and SAS 9.4 (SAS Institute, Cary, NC). The following R packages were also used: tidyverse (Wickham, 2017), readxl (Wickham & Bryan, 2019), and DescTools (Signorell, 2019).

2.2 | Photogrammetry

The experimental setup is shown in Figure 1. A custom turntable and sample stand were 3D printed to ensure consistent sample orientation and distance from the camera as the sample rotated (https://www.thingiverse.com/thing:1762299). Matte white poster paper was attached to the side of the turntable opposite the mobile device holder and white matte paper was placed under the sample stand to ensure a consistent background. A small table lamp with a 39 W, 550 lumen halogen light bulb was used to provide consistent illumination.

Each ped was shaved flat on one side and placed on top of a rectangular 2.162 cm (wide) by 2.0 (tall) cm plastic sample stand that positioned the sample in-line with the camera lens. The 2.162 cm side of the stand was marked so that it was identifiable in the photos. The turntable was then used to rotate the sample and a picture was manually taken at each quarter rotation of the handle. This resulted in thirty-five overlapping photos being taken at approximately 10° angles for one complete rotation of the sample. All photos were imaged with a Samsung Galaxy Note 8 with a 12-MP camera with a f/1.7 aperture. Additionally, a subset of the samples was also

TABLE 1 Characteristics of the soils used to measure D_b using the clod, 3D laser scanning, and photogrammetry methods

Sampling location	Horizon designation	Horizon thickness	Texture class	Structure
		cm		Grade, Size, Type
Leyendecker	A	0-40	Clay Loam	Moderate, Medium, Subangular blocky
Leyendecker	Bt	40-55	Clay	Strong, Medium, Platy
Leyendecker	2C	55-200	Fine Sand	Weak, Medium, Subangular blocky → Single-Grain
La Mesa	Bt	30-75	Clay Loam	Moderate, Coarse, Subangular blocky
La Mesa	Bk	75-100	Clay Loam	Weak, Medium, Subangular blocky
Hwy 70	Bt	50-65	Sandy Clay Loam	Moderate, Fine, Prismatic
Hwy 70	Btk	65-120	Sandy Loam	Moderate, Fine, Subangular blocky

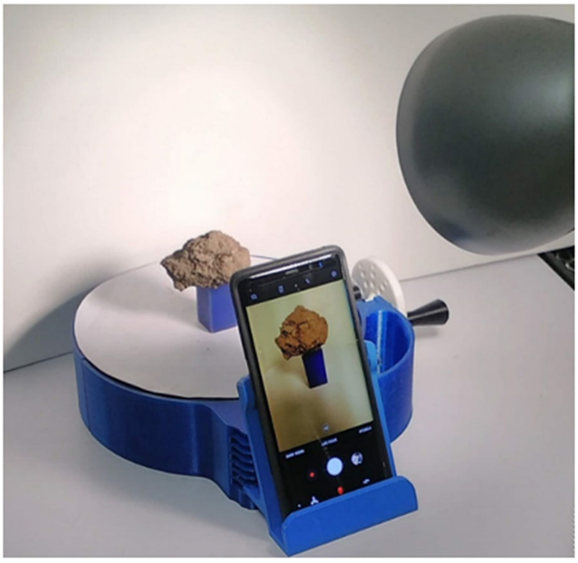

FIGURE 1 Experimental setup of 3D printed turntable with mobile phone (https://www.thingiverse.com/thing:1762299). Each soil ped was shaved flat on one side and was placed on the blue plastic rectangular sample stand. The sample was then rotated 360 degrees and thirty-five over-lapping photos were taken as the sample rotated in front of the camera. The table lamp was used to provide consistent illumination. White paper was placed under the sample stand and white poster board was used as a backdrop to avoid artifacts in the photogrammetric 3D render.

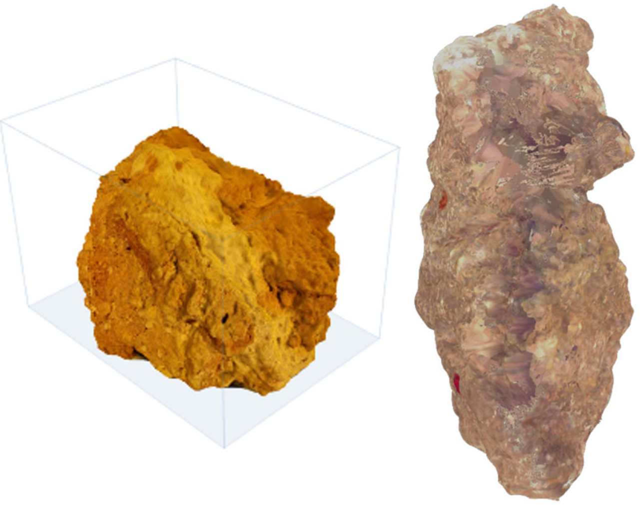

FIGURE 2 Examples of 3D renders derived from photogrammetry (left) and 3D laser scanning (right). The photogrammetry resulted in a render with the highest resolution.

imaged with an Apple iPhone 5s with a 8-MP camera with a f/2.2 aperture to compare the effects of different cameras.

After imaging was completed, all pictures of each sample were uploaded to an Autodesk Recap cloud server and rendered into a 3D point cloud, 3D mesh, and a fully surfaced 3D render (Figure 2). The 3D render was downloaded and manually trimmed (termed ‘slicing’) in the Autodesk Recap software to remove parts of the rectangular sample stand that had been included in the render. A key component of volume estimation was to manually identify a known calibration distance in the software (Moret-Fernández et al., 2016; Stewart et al., 2012). The 2.162-cm side of the sample stand was used to manually set this distance. The “analyze” tool was then used to calculate the sample volume.

2.3 | Three dimensional laser scanning

A commercially available 3D scanner was used to calculate volume (NextEngine Desktop 3D Scanner Model 2020i, NextEngine, Inc., Santa Monica, CA). This is the same type of instrument as used by Rossi et al. (2008). Prior to scanning, three different colored dots were marked on different faces of each sample with a permanent marker. This was done to ensure that scanned renders could be aligned post scanning. The sample was then placed on the instrument stand and a scan initialized. Each 360° scan took approximately 40 minutes and a minimum of two scans were required to scan all the sides. Once completed, the two 3D renders were aligned in the instrument software using the dots. The base software license supplied with the instrument does not calculate volume, thus each 3D render (Figure 2) was exported to Autodesk ReCap and subsequently analyzed for volume.

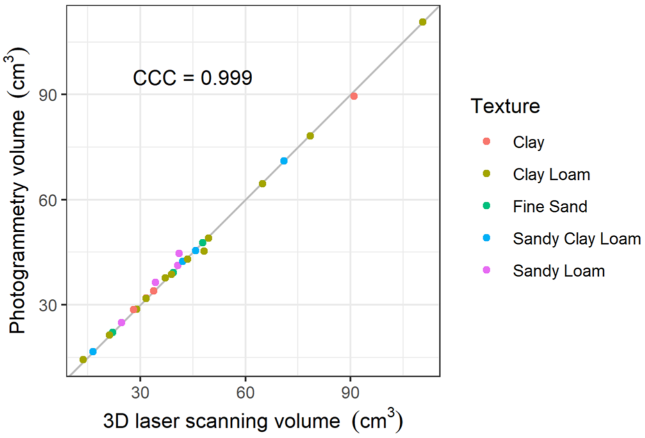

FIGURE 3 Concordance between volume estimates using photogrammetry and laser 3D scanning. The line represents a 1:1 relationship. CCC = concordance coefficient.

2.4 | Clod method

Each soil sample was analyzed using the clod method (Blake & Hartge, 1986; Grossman & Reinsch, 2002; Soil Survey Staff, 2014). Oven-dried samples were secured in a hairnet and weighed. The hairnet with the sample was then dipped into paraffin wax in three quick successions to ensure a complete coating. The sample was then allowed to hang until the paraffin solidified and was then re-weighted. A water filled beaker was weighed. Each sample was then suspended in the water filled beaker and the beaker reweighed. The change in weight is equivalent to the volume of the soil + hairnet + paraffin so the weight of the hairnet + paraffin wax was subtracted from the weight of the soil measured earlier to obtain the volume the soil sample only. Throughout the process, any soil material lost was collected in a sample dish and included in the mass of the sample.

3 | RESULTS AND DISCUSSION

3.1 | Volume comparison between photogrammetry and 3D laser scanning

The correlation between ped volumes estimated by 3D laser scanning and photogrammetry are presented in Figure 3. Concordance was high (0.999). The few samples that did deviate farther from the 1:1 line had irregular microstructure that created a rough surface that was challenging for all methods of volume estimation. These results suggests that photogrammetry was as accurate as laser 3D scanning for estimating the volume of soil ped, however, photogrammetry was cheaper than 3D laser scanning (i.e. \$100s vs. \$1000s). Photogrammetry was faster than 3D laser scanning as well. On average it took approximately 1.5 hours to complete a 3D laser scan of a ped while photogrammetry required approximately 15 minutes per ped. This time estimate includes the physical time required to shave and arrange the ped on the turntable, collect the images, upload the images into the 3D rendering software, and trim the render. This time estimate however, does not include the wait time for the photogrammetric render because this varied between samples and did not depend upon the physical handing of the sample. Autodesk ReCap, the software that performed the photogrammetry, is a cloud-based software meaning that the actual photogrammetry calculations are performed on a remote server. After the images were uploaded, we experienced variable wait times until the completed render could be downloaded, which ranged from two minutes to several hours. This was because the academic software license used for this study placed the uploaded images into a queue, which varied in length. If desirable, it is possible that wait times could be consistently reduced to several minutes by using a nonacademic license or by performing photogrammetry locally, for example on a desktop computer with a high-performance graphical processing unit (GPU).

3.2 | Bulk density comparison

Soil bulk density measurements between methods are presented in Figure 4. No statistical differences were found between methods for each horizon except for the clod method in the Leyendecker 2C horizon. This difference is not due to differences between methods, but because parts of the peds broke off during the clod measurement resulting in lower mass and higher bulk density. Interestingly, photogrammetry generally has smaller standard errors than the other methods indicating less variability in D_b measurement. These results suggest that photogrammetry is as accurate as the other methods tested, and maybe more precise.

A comparison of D_b measurements on a subset of samples using two different cameras is presented in Figure 5. No statistical difference was detected between cameras types suggesting that the choice of camera does not affect photogrammetry-measured D_b. However; it does appear that D_b measurements using the Android-based camera had slightly lower standard errors, and that the mean D_b value was consistent lower using the iPhone-based camera. This may result from either the difference in camera resolution (12 vs. 8 MP) or the physical position of the camera; the Android-based camera was centered on the device while the iPhone-based camera was offset from the center of the device, which made consistent positioning and stabilization difficult.

Overall we failed to reject the hypothesis that there were any differences between D_b measured by photogrammetry, 3D laser scanning, or the clod method. We also did not detect any significant differences between camera types.

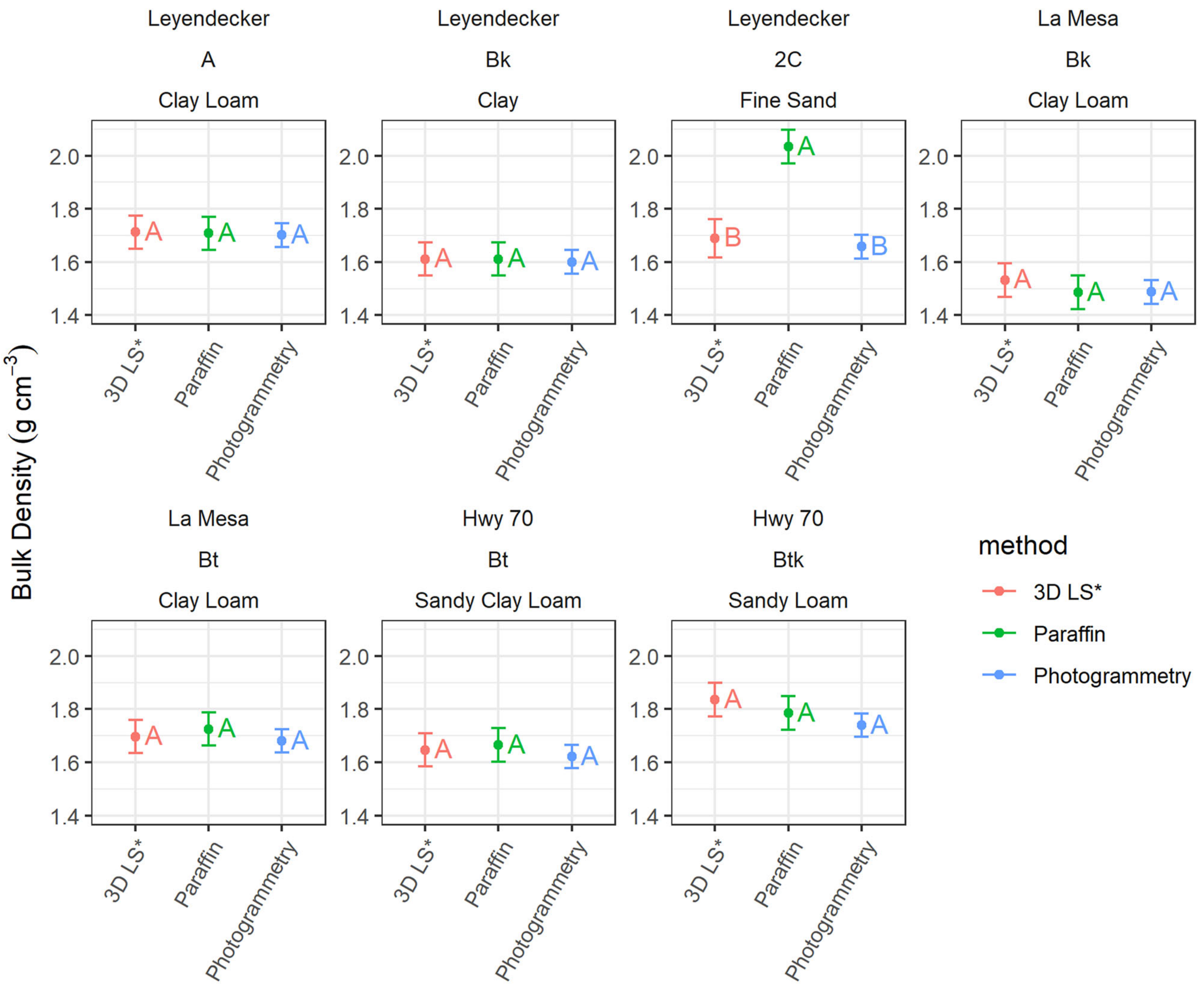

FIGURE 4 Comparison of measured D_b between different methods. Points reflect least squares means and error bars represent ± 1 standard error from ANOVA analysis. Means with different letters indicate methods with statistically significant ($p < 0.05$) differences within a panel. Photogrammetry measurements were derived using the android based camera. Photogr. = photogrammetry, 3D LS* = 3D Laser Scanning which was performed on a physically different ped from the same horizon.

Results suggest that photogrammetry is a reliable method for measuring D_b of soil peds. Additionally, the photogrammetry method is easier (i.e., less labor intensive) than either the 3D laser scanning or clod methods as it requires less handling of the sample. When paired with a 3D printed turntable and mobile device, photogrammetry is also less expensive than the 3D laser scanner method.

A key component of the photogrammetry workflow includes the photogrammetry software used to measure volume. We tested multiple applications finding that only Autodesk ReCap provided cm-scale volume estimates. However, the software used was cloud-based requiring all images be uploaded to the software-provider cloud to produce a final render from which volume could be obtained. The cloud-based processing reduced potential time-savings over other methods. A software that provided cm-scale volume estimates that could render images locally would be desirable. Other limitations when using our experimental setup included the size of the turntable and the view-angle of the camera. The turntable we used could only accommodate samples up to ~150 cm^3. A larger turntable would be required for larger soil peds. Additionally, the camera view-angle should be about level with the sample. If parts of the ped (the top and bottom) are not visible to the camera lens the software will interpolate the ped surface in these areas resulting in ‘holes’ or ‘flat spots’. We anticipated that this might be a problem given that the entire bottom of the ped was not visible in this experimental set up, but given the general close correlation with the other measurement methods and the precision of the method, this does not appear to be a significant issue. However; if desired, this could be resolved by using two cameras or by repositioning the camera lower (easily accomplished with the adjustable

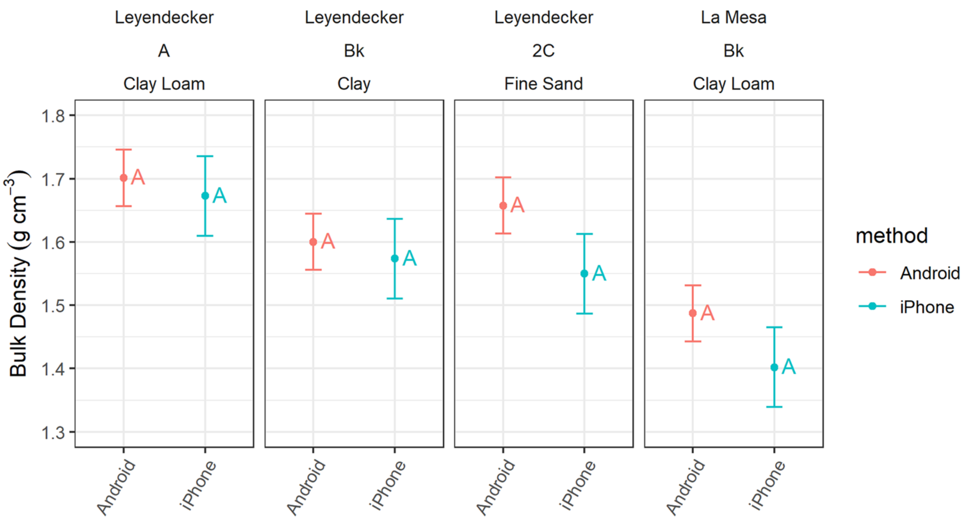

FIGURE 5 Photogrammetry measurements of D_b using two different cameras. Within a panel, means with the same letter are not different at $p = 0.05$.

turntable) to image the underside of the ped during a subsequent rotation.

4 | CONCLUSIONS

We found no significant differences between D_b measured by photogrammetry, 3D laser scanning, or the clod method and conclude that photogrammetry is a useful method for measuring D_b on soil peds. We also found no statistical difference between cameras types suggesting that the type of mobile device camera does not affect photogrammetry-measured D_b. Similar to 3D laser scanning, photogrammetry is a nondestructive technique so that the same ped can be subsequently used for further analysis such as determining course fragment content (without needing to remove the coating resin), determining water retention (without the need to re-cut a side of the ped), or for shrinkage-curve determination. Compared to 3D laser scanning however; photogrammetry was less expensive and was faster. Overall, measuring D_b using photogrammetry was easier than the other methods as it required less handling of each sample.

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