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Assessing soil aggregate stability by measuring light transmission decrease during aggregate disintegration

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Abstract: Advancements in technology have recently enabled to assess soil aggregate stability (SAS) using digital devices. To address the need for a faster and more efficient method of measuring SAS, we have developed a simple yet effective approach using a specialized device. The innovative method named SlakeLight involves measuring the changes in light transmittance as aggregates undergo slaking. The device consists of the measuring chamber, which is placed on a LED light source with a surface-homogeneous distribution of luminosity. During the disintegration process of aggregates immersed in water, reduction in the light emitted to the photodiodes is proportional to SAS. The functionality of the device was tested using topsoil samples from two field fertilization trials. The recorded SAS_{trans} values were compared with the wet sieving method (WSA) and SLAKE test. The new method showed a strong correlation with both reference methods (r = 0.89 for WSA, r = –0.86 for SLAKE). The device was able to detect a statistically significant differences in SAS between the grassland and the cropland at both sites. Although differences in SAS_{trans} were not significant between different fertilization treatments unlike WSA, the simplicity and speed of the measurement increase the potential of the method for practical implementation in agriculture, surpassing the limitations of traditional and labor-intensive laboratory techniques.

Keywords: field experiment; optoelectronics; sensors; soil health monitoring; soil structure

The ability of soil aggregates to resist breaking into smaller particles when exposed to water is a crucial factor in assessing the physical quality of the soil (Amézketa 1999). Various techniques have been employed to assess aggregate stability, with different methods applying different types of disruptive energy to the aggregates (Almajmaie et al. 2017). The most commonly used procedures to accurately measure the water stability of soil aggregates involve determining the weight loss of these aggregates as they are subjected to periodic movement on a sieve in water (Kandeler 1996) or exposed to falling water drops under specific experimental conditions (Low 1967; Ogden et al. 1997). Other methods belong to the category of indirect approaches, relying on monitoring the turbidity caused by the breakdown of aggregates (Davidson & Evans 1960; Zhu et al. 2016). Ultrasound can also be used as a means to measure the stability of soil aggregates (Schomakers et al. 2011). In addition to these accurate but time-consuming laboratory techniques, more straightforward methods have been devised for adoption by farmers, students, or the general public. These methods primarily involve monitoring the changes in the area occupied by the disintegrating soil aggregates. Volumetric Aggregate Stability Test, by Solvita® (VAST) is an example of a visual method

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that assesses the remaining quantity of aggregates after dissolution using a mat featuring concentric circles. Fajardo et al. (2016) introduced a perspective approach that utilizes a digital camera on a mobile device to record the process of aggregate disintegration. The integrated SLAKES application then calculates the area size and derives the stability index based on this measurement. However, the visual assessment in the VAST method may have some subjectivity and lacks precise quantification. While the method offers simplicity and reduced time requirements, its accuracy in measuring aggregate stability raises doubts (Cobo 2019). On the other hand, it was shown that the SLAKES method requires optimized lighting, preferably from an external source to ensure that side shadows do not affect the scanned aggregate area, otherwise, the application tends to mistake soil aggregates for shadows or fails to distinguish between soil aggregates and the background (Brown 2021; Obour et al. 2023) and can give unreliable results for some soil types (Adetsu 2021).

Considering the above factors, our objective was to create a straightforward device capable of measuring soil aggregate stability with the following attributes: (1) ensuring consistent measurements regardless of the surrounding light conditions; (2) being accurate and reliable enough for use by non-scientific users; and (3) being cost-effective without the need for advanced digital technologies. The development led to a patented SlakeLight method for determining soil aggregate stability and to a construction of the device (Madaras & Krejčí 2020). The aim of this publication is to describe the properties of the developed device and to compare the aggregate stability measurement results with well-established methods for studying soil aggregates.

MATERIAL AND METHODS

Method principle. The principle of the SlakeLight method is the determination of the stability of soil aggregates by measuring the light transmittance with the measuring chamber in which the soil aggregates immersed in the water break down, while this measuring chamber is placed on a light source with a surface-homogeneous distribution of luminosity. The invention takes advantage of the fact that the soil material is, with rare exceptions, opaque even in a thin layer, or significantly reduces light transmission. The soil aggregate immersed in water on a surface light source will then shade the light during its gradual disintegration. The process of disintegration of the soil aggregates results in a reduction of light transmission through the measuring vessel, to a level exactly corresponding to the area covered by the soil material. Determining the rate of the breakdown of aggregates is possible by measuring the light transmission through the measuring vessel, i.e., by measuring the decrease in light flux above the vessel by photodiode.

The advantage of the invention is that determining of the size of the area covered by the disintegrated aggregate is objective and more accurate compared to the visual assessment, but on the other hand, the use of digital imaging with subsequent software processing is avoided. Furthermore, there is no unwanted distortion of the measured area by shadows or changing lighting conditions. The invention also makes it possible to determine the average value of the disintegration of several aggregates at once.

Technical implementation. The device working on the above principle is shown in Figure 1. The lower part of the device contains 9 white light LEDs (type OSPW-5161A-PQ), a lighting diffuser to ensure surface homogeneity of lighting, a chamber of the 85 mm diameter with a pad of 9 measuring vessels of 10 mm diameter and a mechanism ensuring simultaneous immersion of soil aggregates into the water. The top hinged part contains 9 silicone PIN photodiodes (type SFH 203), a control module, a display and buttons for calibration and starting measurements.

The device is built into an opaque box made of polycarbonate and PVC (ambient light is prevented). It operates with a power supply of 9 V/400 mA.

Measurement procedure. (1) Water is poured into the measuring chamber to a height of 1 cm. The chamber is placed to a bottom of the device.

(2) Soil aggregates measuring 3.5–4 mm in size are carefully positioned within the matrix, which is placed on top of the measuring chamber. Each aggregate is inserted into a separate hole of the matrix. The device cover is closed, and the calibration button is pressed. The system will measure the reference voltage on the photodiodes and set the device sensitivity.

(3) The Start button is pressed. The aggregates are then immersed into the water by manual shift of the plate underlying the matrix. This “drawer” ensures their simultaneous immersion into the water and at the same time their placement to the measuring vessel exactly above the LEDs. The device calibrates

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automatically by recording the starting voltage on the photodiodes (U1).

(4) The measurement takes place for 2, 4 and 10 min. The aggregates gradually disintegrate in the water and thus cover an increasing area in the measuring vessel. This reduces the transmittance of the light emitted from the LEDs to the photodiodes. Photodiodes are connected in photoconductive mode, so they react to a decrease in light by increasing their resistance. The control microprocessor measures the voltage simultaneously on each photodiode with 12-bit accuracy, with 16 times oversampling that increases the accuracy to 16 bits. The processor evaluates the change in voltage drop relative to the reference value U1. The voltage drop is directly proportional to the area occupied by the newly formed material resulting from the breakdown of the aggregate. The ratio of both voltages (× 100) is continuously shown on the display.

(5) After the measurement time has elapsed, the device signals the end of the measurement, records the voltage at the beginning (U1) and at the end of the measurement (U2) and displays the final value

$$SAS_{trans} = 100 \times U2/U1$$

corresponding to the stability of the soil aggregates. The displayed value represents the median of all 9 measurements. The highest value of 100 is displayed when no disintegration of aggregates occurs. The lower the value, the less stable the soil aggregates are.

Device testing. To test the performance and functionality of the device, we utilized soil samples obtained in 2020 from two Czech field fertilization experiments (Table 1). The field trial at Jaroměřice nad Rokytnou was focused on the evaluation of organic fertilizers effect on soil and crops. The trial involved conventional tillage and a 6-year crop rotation, with treatments replicated 4 times. Soil samples were collected from all plots representing unfertilized control, mineral fertilization only, and fertilization

Figure 1. Device for measurement of soil aggregate stability by measuring light transmission decrease: device closed – measurement in progress (A), open – preparation for inserting aggregates (B), view of the measuring chamber with 9 vessels after the measurement is finished (C), open – after cleaning (D)
Photo by R. Krejčí

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Table 1. Experimental site characteristics

	Jaroměřice	Ivanovice
Longitude	15.52°E	17.05°E
Latitude	49.05°N	49.19°N
Altitude (m a.s.l.)	425	225
Soil type	haplic Luvisols on loessy deluvial sediments	haplic Chernozem on loess
Soil texture	silt loam	loam
Soil organic matter content (%)	2.3	3.8
Average annual temperature (°C)	8.0	9.17
Average annual rainfall total (mm)	481	548
pH_{H_2O}	6.9	7.1

pH was measured using a glass electrode in a 1:5 (volume fraction) suspension of soil in water (pH_{H_2O}) according to the ISO 10390:2005 standard

with biogas digestate. A more detailed trial design is described in Mayerová et al. (2023).

The field trial at Ivanovice na Hané referred to in Stehlíková et al. (2016) was focused on mineral fertilizers effect on soil and crops. The trial involved conventional tillage and an 8-year crop rotation, with treatments replicated 4 times. Soil samples were collected from all plots representing unfertilized control and mineral and manure fertilization. Disturbed soil samples were taken with field-shovel from the 0–7 cm upper soil layer at both sites. A mixed sample of approximately 2 kg consisting of 15–20 subsamples from different points was collected on each plot.

Soil samples were also taken from nearby permanent grasslands at both sites and were regarded as additional treatment. Altogether, testing comprised 22 samples – 13 samples from the Jaroměřice and 9 samples from Ivanovice. The collected samples were air-dried and sieved to obtain aggregates within the size class of 3–5 mm. These aggregates were then subjected to measurement of SAS_{trans}. For comparison, we utilized the SAS determination by wet sieving method following Kandeler (1996) and the slaking index (α coefficient) determination according to the method of Fajardo et al. (2016), both with 3–5 mm aggregates. To enhance result reproducibility, the second reference method incorporated an improvement in lighting conditions. Specifically, the measuring petri dish was illuminated from the back using surface LED lighting and a lighting diffuser.

Measurements for each method were performed in 3 replicates for each sample.

Statistical analyses. The basic statistical values including averages, standard errors, and Pearson's correlation coefficients were calculated by STATISTICA 14.0.0.14 software (TIBCO Software Inc., USA). The 10-min interval was chosen for better comparison with the SLAKES method and SAS_{trans} value obtained after 10 min was correlated with α coefficient and wet sieving method (WSA). Analysis of variance (ANOVA) was by STATISTICA software (Ver. 14.0.0.14), and Scheffe's multiple comparison test at α = 0.05 was then employed to determine homogenous groups.

RESULTS AND DISCUSSION

Soil aggregate stability measured by SlakeLight method (SAS_{trans}), as well as by WSA and slaking index (α coefficient) were significantly affected by the treatment (Table 2). The device was able to detect statistically significant differences in soil aggregate stability between the grassland and the cropland

Table 2. Significance of the effects of treatment on soil aggregate stability revealed by one-way ANOVA at Jaroměřice and Ivanovice

Dependent variable	Statistic	Treatment	
		Jaroměřice	Ivanovice
SAS_{trans}	*P*	0.0000	0.0000
	F-value	8.44	8.78
WSA	*P*	0.0000	0.0000
	F-value	62.44	231.31
α coefficient	*P*	0.00001	0.0000
	F-value	12.023	51.144

SAS_{trans} – soil aggregate stability measured by reduction of light transmittance and obtained after 10 min; WSA – soil aggregate stability measured by wet sieving method; α coefficient – slaking index

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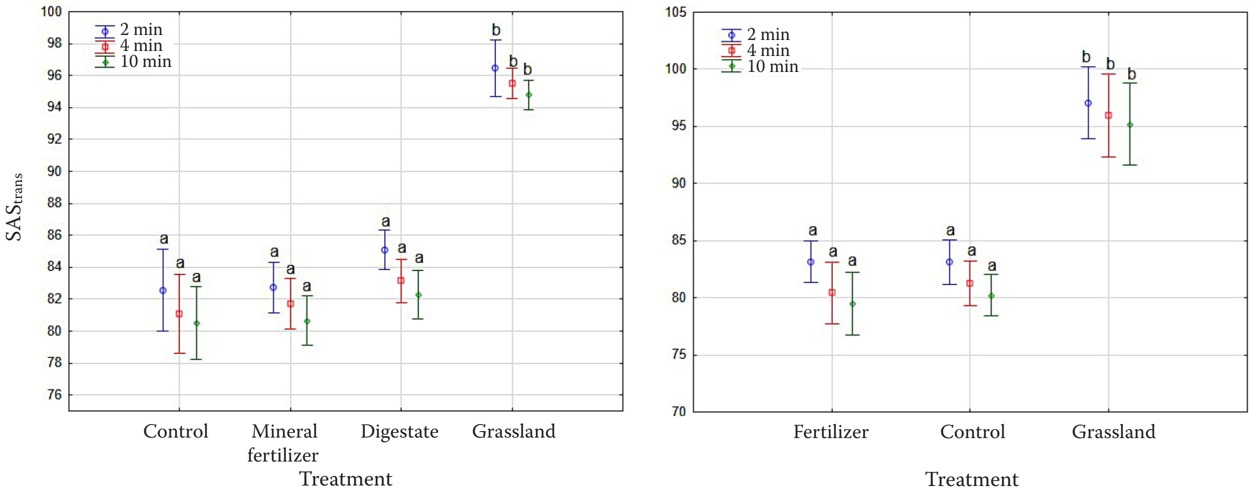

Figure 2. The effect of treatment on soil aggregate stability measured by reduction of light transmittance (SAS_{trans}) after 2, 4 and 10 min at Jaroměřice (left) and Ivanovice (right)

Values are mean ± 95% confidence interval, and different letters indicate significant differences between treatments at α = 0.05 by Scheffe test

at the Jaroměřice and Ivanovice sites (Figure 2). The highest average SAS_{trans} values after 10 min were recorded for grasslands at both sites (94.8% and 96.3%, respectively; Table 3). Control and mineral fertilized treatment provided the lowest 80.5%, resp. 80.7% SAS_{trans} values at Jaroměřice. At this site, the SAS_{trans} did not exhibit significant differences between the various fertilization treatments, in contrast to the WSA. Soil aggregate stability measured by wet sieving revealed differences not only between grassland and cropland, but also between treatments at Jaroměřice site. Digestate fertilized treatment with 53.5% WSA differed from control and mineral fertilized treatment with 43.5 and 42.8%, respectively.

However, it should be noted that in accordance with two reference methods, the digestate fertilized plots showed higher average SAS_{trans} values (82.3%) compared to both the control and the mineral fertilized plots. None of the three methods detected differences between unfertilized control and fertilized treatments at the Ivanovice site.

For all treatments, the highest disintegration of the soil aggregates occurred within first 2 minutes of the measurement, after which the value of SAS_{trans} changed little (Figure 2).

Strong correlation between WSA and SAS_{trans} with 0.89 correlation coefficient was shown at Jaroměřice and Ivanovice, as well as between α coefficient and SAS_{trans} with −0.86 correlation coefficient (Figure 3). In the latter case, however, the data correlates only because of a single outlier (grassland sample).

Table 3. Soil aggregate stability measured by wet sieving method (WSA), α coefficients and soil aggregate stability (SAS) measured by reduction of light transmittance (SAS_{trans}) (mean ± standard error) in the experimental sites and different fertilizer treatments

Site	Treatment	WSA (%)	α coefficient	SAS_{trans} 10 min
Jaroměřice	control	43.49^{a} ± 1.542	7.55^{b} ± 0.517	80.50^{a} ± 1.024
	mineral fertilizer	42.78^{a} ± 1.882	8.05^{b} ± 0.406	80.66^{a} ± 0.705
	digestate	53.53^{b} ± 1.385	7.53^{b} ± 0.690	82.29^{a} ± 0.697
	grassland	87.70^{c} ± 0.410	1.03^{a} ± 0.561	94.80^{b} ± 0.213
Ivanovice	control	34.32^{a} ± 0.996	9.42^{b} ± 0.500	79.51^{a} ± 1.249
	fertilizer	36.65^{a} ± 0.792	6.55^{b} ± 0.263	80.23^{a} ± 0.814
	grassland	76.92^{b} ± 2.056	0.97^{a} ± 0.219	96.30^{b} ± 0.428

Different letters indicate significant differences between means at α = 0.05 for the given variables (Scheffe test)

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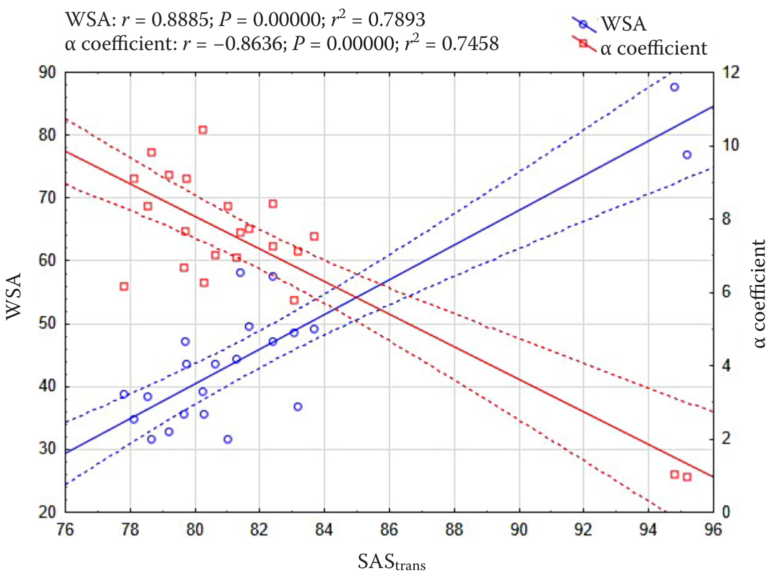

Figure 3. Correlation between soil aggregate stability measured by wet sieving method (WSA), α coefficient and soil aggregate stability (SAS) measured by reduction of light transmittance after 10 min (SAS$_{trans}$)

Regression bands show the ± 95% confidence interval; r – correlation coefficient; r^2 – coefficient of determination; correlation was performed for both sites

Correlations were usually reported in other studies testing various methods of the aggregate stability measurement (Almajmaie et al. 2017; Rieke et al. 2022). Three methods used in this study rely on the process of the deterioration of dry soil aggregates during rapid wetting, where swelling and internal pressure build-up cause compression of entrapped air by the advancing wetting front (Zaher et al. 2005). We expected a higher correlation, especially with the method of Fajardo et al. (2016) which does not use aggregate movement with respect to water. However, different techniques may exhibit discrepancies across soil types even if the breakdown mechanisms are identical (Liu et al. 2021).

Compared to the reference methods, SlakeLight method appears to be less accurate in capturing smaller differences in the stability of the aggregates, such as in the case of fertilization treatments. However, trends of soil aggregate stability depending on the treatments were similar for all three methods. Small significant differences in WSA of 1–2 mm aggregates between unfertilized and fertilized treatments at the Ivanovice site were reported by Stehlík et al. (2019). This was the reason for including these samples in our testing. However, differences in WSA between unfertilized and fertilized treatments were not shown for the larger aggregates used in this study.

The study of Rieke et al. (2022) comparing different methods concluded that no single method for measuring aggregate stability stands out as clearly superior. The choice of method should be driven by secondary factors such as cost, availability, sensitivity to specific management practices, and minimal variability for a given treatment. From this point of view, SlakeLight method appears to be suitable for evaluating changes in the stability of aggregates during soil cover changes and to a limited extent (indicatively) for more significant changes caused by the long-term application of organic fertilizers. Further research is needed to capture the influence of other factors such as soil health management practices, spatial heterogeneity etc.

It must be considered that the SAS$_{trans}$ values measured in the developed device are dependent on the size of the measured aggregates. It is therefore necessary to choose aggregates of the same size for all measurements. The method is also influenced by the soil type, and the measurement result should be compared within a specific site because may not be accurate enough in comparing the same treatments between sites. The extensive study of Rieke et al. (2022) performed at 124 long-term experimental agricultural research sites showed high variance among sites. Sand contents were significant in predicting soil aggregate stability measured with SLAKE method. The SlakeLight method is based on a similar principle to the slake test, therefore it can be expected that the interactions with the soil texture will be similar.

CONCLUSION

The newly developed SlakeLight method demonstrated good agreement with established reference methods based on wet sieving and slaking. The price of the device, even in its serial production, probably cannot compete with cheaper smartphones. However, the advantages of the SAS$_{trans}$ measurement are inde-

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pendence on ambient light conditions and the speed of the determination, as the 2-minute measurement proved to be sufficiently conclusive to detect differences in soil aggregate stability. The developed device is simple and user-friendly, making it suitable for both agricultural applications and educational purposes. The simplicity of the SlakeLight method together with the quick assessment of soil aggregate stability, increases its potential for practical implementation in various settings. Another advantage can be obtaining information for each of the aggregates and providing comprehensive measurement statistics of the entire aggregate set. This improvement would move the device more into the category of scientific use and is planned for the next development version of the device software.

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