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Particle size distribution analysis of pine sawdust: comparison of traditional oscillating screen method and photo-optical analysis

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Abstract. Particle size and particle size distribution (PSD) are crucial parameters which affect properties of particulate and agglomerated materials, and have an impact on a quality and utilization of a final product. The aim of this paper was to determine PSD as well as to assess dimensional features of pine sawdust fractions via mechanical sieve analysis and photo-optical analysis. The first one is a traditional and standard method taking into account only one parameter of particle shape and the second one is a modern method based on a digital image processing that considers also irregular shapes of biomass particles. Pine sawdust was grinded into three fractions: 4, 8 and 12 mm and analysed using two mentioned methods. A horizontal vibrating sieve shaker comprising 11 sieves and a bottom pan was used, and the obtained data of retained particles on each sieve were evaluated. For comparison, a computerized photo-optical particle analyser was applied with max Feret's diameter as a measurement algorithm for a particle length, and PSD was analyzed by grouping the particles according to their distinct lengths adjusted to the sieves' sizes used in the screening method. Moreover, additional results in dimensions and parameters of PSD were obtained and evaluated through the photo-optical method. Pine sawdust particles can be described as non-uniform, mainly prolonged, finer particles dominated in all fraction samples. The study showed differences in the results, inaccuracy and other drawbacks of the conventional sieving method such as clogging and falling-through phenomena as well as the limitations of the machine vision. Strong sides of both methods were discussed, too. Overall, the results contributed to a better knowledge of the material properties and different methods of PSD analysis.

Key words: computerized particle analyzer, image analysis, mechanical sieving, machine vision, particle size classification.

INTRODUCTION

Obligations to comply stated norms of EU directives on green energy production and the increasing demand for biofuels from various organic waste materials including forest biomass go hand in hand with a necessity of a better knowledge about an input material's properties (Gendek et al., 2018). Particle size and particle size distribution (PSD) are listed among the main physical factors influencing different properties of particulate and agglomerated materials, and provide important information about overall material's/product's quality and performance. They significantly affect flow ability and handling, compaction, compressibility, bulk density, strength and durability of densified products (Pietsch, 2008; Tumuluru et al., 2011; Guo et al., 2012; Shanthi et al., 2014; Zhang & Guo, 2014; Febbie et al., 2015; Muntean et al., 2017; Chaloupková et al., 2018). Due to the fact that biomass is comprised of diversely shaped and sized particles (Guo et al., 2012; Febbi et al., 2015) it is essential to control and measure the PSD precisely and rapidly to secure the high-quality final products (Igathinathane et al., 2009a).

PSD analysis is a procedure assessing dimensional and morphological characteristics of particulate materials (Igathinathane et al., 2009a; Vaezi et al., 2013). Commonly, the results of PSD analysis indicate percentage of particles retained on the sieves, cumulative undersize distribution, geometric and arithmetic mean value, and the related standard deviation as well as other parameters depending on an applied method (Igathinathane et al., 2009a). PSD of biomass material is standardly determined by the mechanical sieving/screening procedure (UNE-EN ISO 17827-1:2016, 2016), where the material is separated by sieves of different sized apertures/openings. A number of studies have reported the PSD results of different biomass materials, e.g. wheat straw, switchgrass, corn stover (Bitra et al., 2009), barley straw (Mani et al., 2006), *Cynara cardunculus* L. (Igathinathane et al., 2009b), miscanthus, pine sawdust (Igathinathane et al., 2009b; Chaloupková et al., 2016), wood sawdust and shavings mixture (Vítěz & Trávníček, 2010), industrial wood particles (Li et al., 2014) and hemp (Dinh, 2014; Chaloupková et al., 2016). The conventional method considers only one parameter: general particle shape. This is given by the aperture of a sieve (no detailed individual results of particles' lengths, width or shapes could be obtained), thus it is solely suitable for spherical particles (Igathinathane et al., 2009a). Although biomass particles are characterized by highly irregular sizes and shapes (Guo et al., 2012; Febbi et al., 2015), these irregularities increase errors in the PSD estimation (Shanthi et al., 2014). Therefore, many authors propounded that more precise results could be acquired by machine vision and image analysis (Igathinathane et al., 2009a; Igathinathane et al., 2009b; Souza & Menegalli, 2011; Kumara et al., 2012; Vaezi et al., 2013; Gil et al., 2014; Febbi et al., 2015). However, the results of the conventional sieving method and the advanced photo-optical analysis were not found to be confronted in one study before, and selected machine vision method was not applied for pine sawdust.

The aim of the present study was to compare two PSD analysis methods: conventional screening vs. photo-optical measuring. While photo-optical method is efficient and time saving, it is not yet to be standardized employing different biomass types. Three fractions of pine sawdust were tested for the purpose of this study.

MATERIALS AND METHODS

Pine sawdust (*Pinus* L.), a traditional wooden feedstock material for production of densified biofuels (Deac et al., 2015) was used in the present study. The material was obtained from the Czech Republic and for comparison purposes it was grinded by a hammer mill (model 9FQ-40C, Pest Control Corporation, Vlčnov, Czech Republic) into three different initial fraction sizes of 4, 8 and 12 mm. Shape of obtained particles was irregular and prolonged/elongated particles were predominated, as it was identified by the analysis of sphericity (the overall particle shape and similarity to a sphere) and roundness (the description of the particles' corners) within a photo-optical analysis method. Moisture content (w.b.) of 4 mm, 8 mm and 12 mm samples was 9.91%, 8.82%, and 10.35%, respectively.

PSD of the pine sawdust fractions was determined by the sieve analysis according to a valid standard (UNE-EN ISO 17827-1:2016, 2016). A horizontal vibrating sieve shaker Cisa (model RP 08, Mervilab, S.A., Madrid, Spain) comprising 11 standard calibrated sieves with the diameter of 20 cm and opening sizes of 16.0, 8.0, 3.15, 2.8, 2.0, 1.4, 1.0, 0.5, 0.25, 0.125, 0.063 mm, and the bottom pan was used. During the sieve analysis, a representative weighed sample was poured into the top sieve with the largest screen opening size, and 30-minute sieve shaking time and amplitude 3.0 mm g^{-1} were applied. After the sieving process the material retained on each sieve was analysed. The percentage of the material retained on any sieve was found by the Eq. 1 below. Three repetitions were performed for each fraction (with sieving loss error approx. 0.3%) and the average value was considered as the final result.

$$\%\ \mathrm{Retained} = \frac{\mathrm{W\ Sieve}}{\mathrm{W\ Total}} \times 100\% \qquad (1)$$

where W Sieve – weight of the material in the sieve (g); W Total – total weight of the material (g).

For comparison, a computerized photo-optical particle analyser Haver (model CPA 4–2, Haver & Boecker OHG, Oelde, Germany) was used to analyse PSD together with the other particle characteristics (number of analysed particles, maximum and minimum particle length, average particle size and amount of variation). The analyzer worked under the particle measuring range from 0.091 up to 90 mm, which was selected with respect to the material character (according to the manual another measuring possibility is a range of 0.035–15 mm, but it is suitable mainly for fine materials like ash). The analyser consisted of a feeding unit with the high of 6 mm beeing set for the regular particle spread on a vibration channel, a vibratory channel itself, a CCD-line digital scan camera with the high-resolution (4,096 pixels line resolution), which scanned all free-falling particles of the studied samples against the background of a LED lighting array module with a high recording frequency (up to 28,000 line scans per second) (Haver & Boecker, 2015). Amplitude of the vibrating feeder was automatically regulated by the analyzer. All individual particles were measured, and their profile parameters processed via Haver CpaServ software (Haver & Boecker OHG, Oelde, Germany). The suitable shape of analysed sample was assigned as an elongated. The data were transferred into spreadsheet for further analyses. The maximum Feret's diameter was set as a measurement algorithm (Fig. 1) for particle length. This parameter gives the value of the minimum sieve size through which the particle can pass through without any obstacle (Shanthi et al., 2014). To compare PSD results with the conventional sieve method,the data were grouped into the groups in accordance with the particles' distinct lengths corresponding to the sieve sizes used in the screening method. PSD analyses

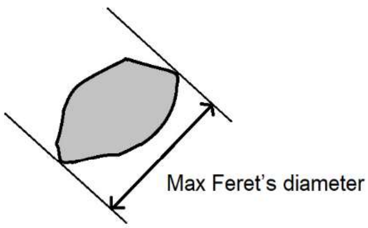

Figure 1. Max Feret's diameter as a measurement algorithm of a particle size (length).

were confronted as the percentages of particles' weights retained on the sieves and the percentages of particles' numbers retained on virtual sieves.

The data from both analyses were processed using MS Excel (version 2007, Microsoft, Redmond, WA, USA) and Statistica software (version 13.3, TIBCO Software Inc., Palo Alto, CA, USA); afterwards the obtained results were tabulated, graphically plotted and discussed.

RESULTS AND DISCUSSION

Oscillating screen analysis

The weight values and the percentage weight values of different particle sizes of sawdust fractions obtained by sieving analysis are presented in the Table 1, together with the cumulative percentage of the material's weight. Fig. 2 presents the plotted cumulative percentage values.

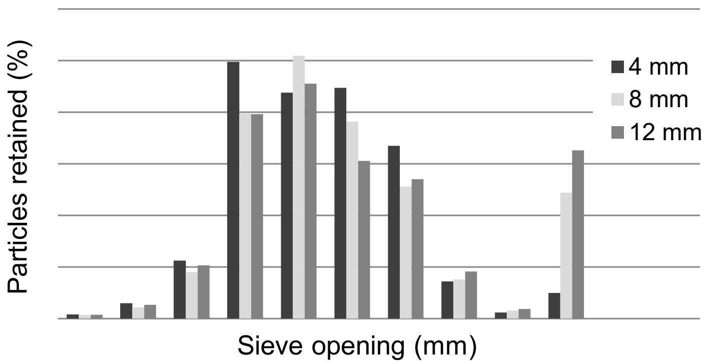

Figure 2. Plotted comparison of PSD of examined fractions via the sieve analysis.

Table 1. Tabulated PSD of the examined material's fractions via the sieve method

Sieve opening	4 mm fraction			8 mm fraction			12 mm fraction		
size (mm)	g	%	Cum.%	g	%	Cum.%	g	%	Cum.%
16.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.15	0.99	2.48	2.48	4.90	12.20	12.20	6.56	16.29	16.29
2.80	0.23	0.58	3.06	0.31	0.77	12.97	0.38	0.94	17.23
2.00	1.44	3.61	6.67	1.52	3.79	16.76	1.84	4.57	21.80
1.40	6.68	16.73	23.40	5.14	12.80	29.56	5.44	13.51	35.31
1.00	8.93	22.36	45.76	7.67	19.10	48.66	6.15	15.27	50.58
0.50	8.74	21.89	67.65	10.22	25.45	74.11	9.17	22.77	73.35
0.25	9.93	24.87	92.52	8.00	19.93	94.04	7.98	19.82	93.17
0.125	2.24	5.61	98.13	1.81	4.51	98.55	2.07	5.14	98.31
0.063	0.59	1.48	99.61	0.44	1.10	99.65	0.53	1.32	99.63
<0.063	0.16	0.40	100.00	0.14	0.35	100.00	0.15	0.37	100.00

And as it can be seen from the results (Table 1, Fig. 2), all fraction samples had very fine particles. Majority of the material comprised of the particles with a size between 0.25 and 1.4 mm; for 4 mm fraction it was 86% of the material, for 8 and 12 mm it was 71% and 77%, respectively. Privious study of Chaloupková et al. (2016) also determined that the pine sawdust fraction of 12 mm consists mainly of the particles smaller than 1.5 mm.

Sieves 8.0 and 16.00 mm did not catch any material. The minimum of the material was captured by the sieve 2.8 mm as well as by the smallest sieve 0.063 mm and the bottom pan. Besides, decreased screens' opening size resulted in decreased particle sizes partly.

Photo-optical analysis

Number of particles determined by the photo-optical procedure and grouped based on sieve sizes used in the screening method, together with the percentage values and cumulative percentage values are presented in the Table 2 and Fig. 3.

Table 2. Tabulated comparison of PSD of the examined fractions via the photo-optical analysis

Sieve opening	4 mm fraction			8 mm fraction			12 mm fraction		
size (mm)	N	%	Cum.%	N	%	Cum.%	N	%	Cum.%
16.00	24	0.00	0.00	22	0.00	0.00	39	0.01	0.01
8.00	747	0.10	0.10	638	0.12	0.12	830	0.15	0.16
3.15	29,648	4.03	4.13	18,887	3.47	3.59	20,253	3.78	3.94
2.80	12,419	1.69	5.82	8,173	1.50	5.09	8,196	1.53	5.47
2.00	62,227	8.46	14.28	41,271	7.58	12.67	42,031	7.84	13.31
1.40	124,805	16.97	31.25	88,805	16.31	28.98	89,291	16.65	29.96
1.00	167,081	22.72	53.97	127,499	23.42	52.40	124,463	23.21	53.17
0.50	263,131	35.78	89.75	204,136	37.49	89.89	193,457	36.08	89.25
0.25	49,767	6.77	96.52	36,670	6.74	96.63	38,071	7.10	96.35
0.125	25,599	3.48	100.00	18,349	3.37	100.00	19,527	3.64	99.99
0.063	0.00	0.00	100.00	0.00	0.00	100.00	0.00	0.00	99.99
<0.063	0.00	0.00	100.00	0.00	0.00	100.00	0.00	0.00	99.99

Table 2 and Fig. 3 showed that the results of all fractions are very similar/more precise. PSD can be described as non-uniform with the finer particles dominated. In the case of photo-optical analysis, the majority of the material composed of the particles with a size between 0.5 and 1.4 mm, where more than one third of the material had the length of 0.5 mm.

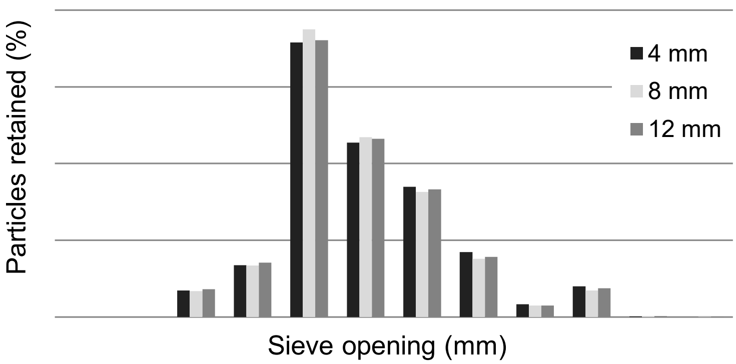

Figure 3. Plotted comparison of PSD of examined fractions via the photo-optical analysis.

According to Shanthi et al. (2014) max Feret's diameter used in image analysis as a measurement algorithm for the particle length which gives a high level of accuracy in case of irregular shapes, thus it can replace the sieve analysis method very precisely (Fernlund, 1998; Al-Thyabat & Miles, 2006, Hamilton et al., 2013).

Additional to photo-optical analysis, Table 3 provides detailed statistics about the particles, i.e. total number of analysed particles, arithmetic mean of a particle length, together with the maximum and minimum length values. Average particle length was 1.26 mm. Minimum measured length for all fractions was 0.1257 mm which can be explained and limited by the given minimum measuring range of the photo-optical analyser (0.091 mm). Maximum length of the particles was over 20 mm. Although just the minimum amount of the material had the length over 8 and 16 mm, these particles were not measured by the sieve analysis at all, most probably due to a 'falling-through' effect of prolonged particles through the smaller sieve apertures (Igathinathane et al., 2009b; Chaloupková et al., 2016).

Table 3. Descriptive statistics of the particle size

Fraction size	N of particles	Mean	Std. Dv.	Min. length	Max. length
4 mm	735,448	1.2812	0.9183	0.1257	20.0739
8 mm	544,450	1.2433	0.8936	0.1257	21.2136
12 mm	536,158	1.2638	0.9421	0.1257	20.5417

Comparison between mechanical sieving and machine vision analysis

PSD analysis from the both procedures expresed as the percentages of particles retained on sieves and cumulative particles retained is presented in the Figs 4–6, for each fraction separately. The comparison of both methods was made with respect to the weight percent and the number percent.

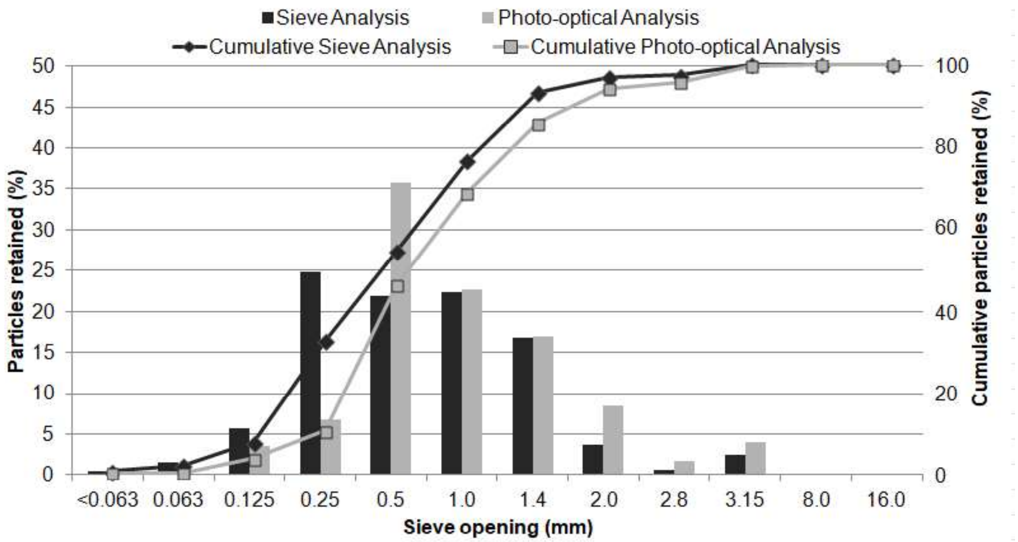

Figure 4. PSD analyses of pine sawdust fraction 4 mm.

The analyses did not show fully comparable results. And, they also confirmed a higher precision of photo-optical method and more possibilities in measurements. In accordance with Igathinathane et al. (2009a) mechanical sieving is an effective method in case of uniform spherical particles, what for the results are not so reliable in our case of prolongly shaped particles. From the presented comparisons, a consistent less number of particles retained for all fractions in the bottom pan with mechanical sceening compared to machine vision method was not caused by sieve clogging phenomenon as it is reported by Igathinathane et al. (2009a) and Glé at al. (2013). Clogging phenomenon could be observed for 3.15 mm sieve in case of 8 and 12 mm fraction (Figs 5 and 6).

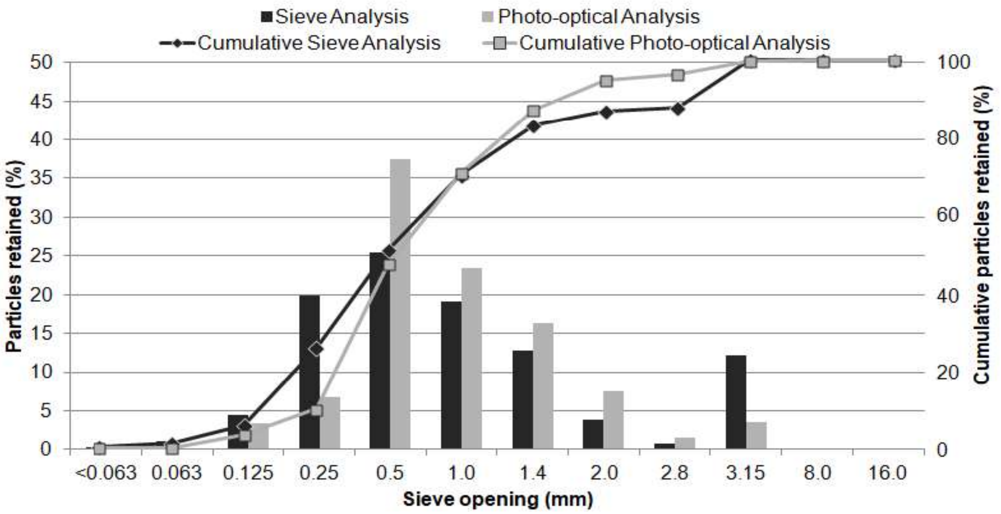

Figure 5. PSD analyses of pine sawdust fraction 8 mm.

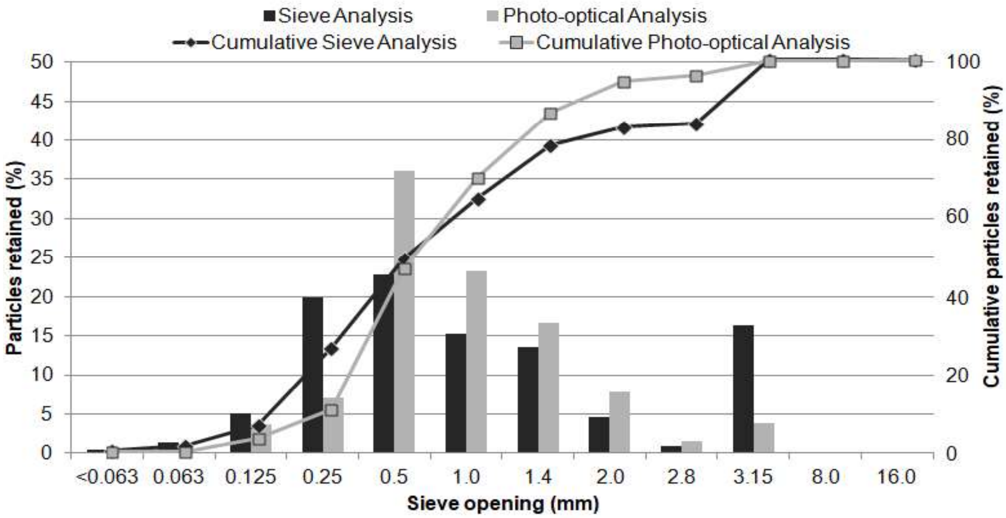

Figure 6. PSD analyses of pine sawdust fraction 12 mm.

The Figs 4–6 also indicated the mentioned 'falling-through' effect of sieve analysis, which was previously detected by Igathinathane et al. (2009b) and Chaloupková et al. (2016). As it can be seen, starting from the sieve 2.8 mm (more markedly from the sieve 2.0 mm) physically longer particles passed through the sieves with the smaller apertures and passed until the sieve 0.125 mm, where the sieve 0.125 and especially the sieve 0.25 mm captured significantly more material than in a reality should retain. In case of the last sieve (0.063 mm) and the bottom pan it was not possible to compare the results of two methods due to the limited measuring range of the photo-optical analyzer.

Besides the clogging phenomenon and the falling-through effect, sieve analysis is a time-consuming process, particles are not measured individually and their shape highly affects the final result (Fernlund, 1998; Febbi et al., 2015). It also has limited set of available standard sieves and limited number of sieves held in the shaker. On the other hand, classical sieve analysis is an easy, simple, standardized and inexpensive tool (Al-Thyabat & Miles, 2006; UNE-EN ISO 17827-1:2016, 2016) giving a possibility to physically separate the particle size fractions. In comparison, photo-optical analysis based on a machine vision and an image processing provides more accurate and precise PSD analysis results, time savings, particles are examined individually, and it gives an additional information relating to shapes and the number of particles. On the contrary, photo-optical analysis is associeted with higher investment costs, only two dimensional projection of the particles is captured and measured, and the method does not provide the possibility of separation of the particle size fractions (Fernlund, 1998; Igathinathane et al., 2009a). Also, as it was observed in this study, the analysis was limited by the minimum measuring range.

CONCLUSIONS

Particle size and PSD are both important factors that influence the final product's quality. In this study PSD analysis of pine sawdust fractions (4, 8 and 12 mm) was conducted using the photo-optical analyzer based on digital image processing and the conventional method based on sieving.

In case of sieve analysis, the material was spread and caught mostly on the sieves with the opening sizes between 0.25 mm and 1.4 mm; the photo-optical analysis showed that the material was comprised of the particle with the size between 0.5 mm and 1.4 mm, and the particle length of 0.5 mm was greatly predominant. Inequalities of used methods were caused by the clogging phenomenon and 'falling-through' effect of longer particles through smaller sieve apertures observed within the sieve analysis that was influenced by the prolonged shape of analysed particles.

During application of both methods their merits and drawbacks were reported. The procedure of sieve analysis is easy and standardized; on the contrary the results were less accurate and consistent owing to the non-spherical particle shape. The photo-optical analysis is fast, and it provided extensive and more precise results, however, the possibility of separation of particle size fractions is missing and the measuring range is limited.

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