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Determining the Soil Particle Shape by Use of Dynamic Image Analysis

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Abstract
In Soil Science, it is well established that the geometry of individual soil particles, including their shape and size, has a significant impact on a number of key physical properties of the soil and on the processes involved with it. The shape and size of soil particles directly impact aspects such as permeability, water retention, stability of soil aggregates and the availability of nutrients for plants. Therefore, accurate determination of these characteristics of soil particles becomes extremely important for understanding and effective soil management.
Nowadays, dynamic image analysis (DIA) is emerging as an exceptionally versatile and effective technique that enables precise determination of particle characteristics, including shape and size, in a dynamic and non-invasive manner. DIA enables the automatic analysis of thousands of microscopic images, allowing rapid and accurate study of the morphology of soil particles at micro and macro scales.
The use of dynamic image analysis in soil research provides insight into the complex structures of soil particles and better prediction of their impact on various soil processes. Moreover, DIA enables the examination of a large number of samples in a short time, which contributes to the efficiency and precision of soil testing. Therefore, dynamic image analysis is becoming a widely used technique for determining particles' characteristics, such as shape and size.
In the context of an ever-increasing awareness of the sustainable use of natural resources and the need to optimize agricultural and engineering practices, dynamic image analysis is becoming an indispensable tool for soil scientists, environmental scientists and engineers. Its versatile use can contribute to further expanding our knowledge about soil and developing innovative solutions for sustainable soil and environmental management.

Keywords
Particle Shape Analysis, Dynamic Image Analysis, soil particle size

Introduction

The shape and size are some of the primary soil properties in view of such environmental issues as oil contamination (Chuvilin and Miklyaeva, 2003; Bhat and Gaga, 2022)), predicting hydraulic properties of soils (Tarnawski et al., 2000; Orman and Chatys, 2011; Wojnowska-Heciak M. et al., 2020), determining soil-water characteristics (Satyanaga et al., 2013, Nartowska et al., 2021), heavy metals environmental mobility and retention, (Gong et al., 2014, Janaszek and Kowalik, 2023; Bhat et al., 2023; Janaszek et al., 2024) sediment transport and deposition (Garzanti et al., 2009). Grain shape and size analysis also play a major role in characterizing fly ashes (Uzarowicz et al., 2018; Bhat, 2023). Especially in the case of clayey soils, characteristics of the shape of the particles have a significant impact on their properties. This issue was considered by many researchers, resulting in particle shape being defined as a factor for the behavior of soils (Masada, 2005), as well as the interaction between the grains (Pena et al., 2007).

In the light of references, there is no clear and comprehensive description of particle shape characteristics and the methods of their determination. This was confirmed, inter alia, by (Bell, 1987), who indicated that the shape is probably the most fundamental property of a particle, but unfortunately, it is very difficult to determine. The analysis in this area was carried out from the beginning of the twentieth century (Lees, 1964), but none of the proposed methods attempted to express the variability of several features of particle shape in one parameter (Frosard, 1979). This problem, despite the development of technology and research methods, remained unresolved (Cox and Badhu, 2007).

Particle shape analysis is closely related to particle size analysis. Therefore, the results of both methods should be analyzed as complementary.

Particle Size Analysis

The particle size analysis is a test which determines the fraction of mineral particles in each needed class. Chemically and biologically, the fine fraction (i.e. clay and silt) below 63µm is the most active component of soil and has the greatest surface area, affecting the soil's characteristics and behavior (Kowalik et al., 2021).

The size distribution of the soil particles determines the surface area and the texture, as well as many physical and chemical properties. The particle size distribution is a basis for a general classification of soil according to the Polish and European standards (PN-B-02480:1986, PN-B-04481:1988, PN-EN ISO 14688-1:2006, PN-EN ISO 14688-2:2006),

Standards (*PN-B-02480:1986*, *PN-EN ISO 14688-1:2006*) for size analyses of broadly distributed samples require splitting into two fractions: the fine (< 63 microns) and the coarse (> 63 microns). The sedimentation method is recommended for measuring the size of particles < 63 µm (for instance, Areometer Analyses, Andreasen Pipette or Köhn Pipette) and for particles > 63 µm, the sieve method is recommended. Both of these techniques have their own limitations. The sedimentation methods are time-consuming. Sometimes, they last even longer than 72 hours (Kotwa et al., 2023). The settling velocity depends, besides the particle size, on the physical density and the shape of the minerals. The size of particles from different minerals with different physical densities contained in one sample can't be determined properly (Sanetra, 2011).

The resolution of the sieve method depends on the number of sieves. It can be more than ten classes between 63µm and > 2 mm. Such precise sieve analysis also takes about one hour. To achieve a complete particle size analysis from below 2µm up to several mm, the combination of both methods is necessary. Therefore, the different influences of the particle shape on the results of these different methods have to be considered. Both methods can't provide any shape information of the soil particles. The study of soil particle shape using dynamic image analysis can also be applied in the context of selective municipal waste collection. The shape of waste particles can significantly impact their physical and mechanical properties, which can influence the efficiency of segregation and recycling processes (Latosińska et al., 2021).

Particle Shape Analysis

Particles of a natural origin, such as soils, are three-dimensional objects with arbitrary shapes. A complete description of the particle shape is almost impossible. Nevertheless, theoretical and empiric models based on two-dimensional projections of the particles provide a reliable description of the soil and their properties. Besides simplifying the particle shape description, the variety of soil samples must be considered. For a significant characterization of a sample's particle shape and size, each class should have a minimum of ten thousand particles to achieve a standard deviation of less than 1% (Witt et al., 2005). For soil analyses with, for instance, ten particle size classes, a minimum of one hundred thousand particles of a sample with the same particle number in each class has to be analyzed for such precision.

The shape analysis in Soil Science has been extended from sedimentary petrology origins to express the frequency distribution of size and shape ranges of soil material (Brewer, 1964). It has been used to interpret the origin and processes of the formation of particulate deposits (Schafer, 2006).

Soil particle shape refers to the morphology of individual grains or mineral aggregates (Schafer, 2006).

Particle shape can be described by parameters such as sphericity, convexity, aspect ratio and roundness (Krumbein, 1941; Griffiths, 1967; Bhat et al., 2023a). Convexity is an important shape parameter that describes the compactness of a particle. The aspect ratio gives information about particle elongation. Sphericity refers to the perimeter of a particle in relation to the circle's perimeter with the same area and gives information about the surface structure. Roundness describes the angularity of particle corners and refers to spikeness (Brewer, 1964; Bhat, 2024).

Sphericity and roundness assessments are commonly made visually on individual grains and are not precise due to the partly modified nature of minerals, making it difficult to identify their origin in source material positively. They require the skills of optical mineralogy techniques and an appreciation of sedimentary petrology (Schafer, 2006).

Wadell (1932) defined the sphericity index as the ratio of the surface area of a sphere (with the same volume as the test particle) to the surface area of the test particle, while Riley (1941) defined the sphericity as the ratio of the diameter of the smallest circumscribing circle to the largest inscribed circle. The closer the particles are to a perfect sphere, the closer the sphericity index is to 1.

Considering that the particle shape is complementary to the size of the particles and is used to interpret the abrasion effect of the transport processes of rocks, a correct estimation of the shape is necessary.

The traditional static image analysis, where particles are positioned manually in the microscope's focal plane, does not allow objective, three-dimensional shape assessment. There is also uncertainty about statistically reliable numbers of particles. Nowadays, modern technology overcomes the problems encountered with the classic method, allowing a three-dimensional measurement of size and shape for larger particles. The soil samples could be analyzed using modern measuring techniques, i.e., dynamic image analysis. A dynamic image analyzer is based on a camera system, which takes pictures of the particles. State-of-the-art instruments can take up to 500 frames per second. For the evaluation of the particle size and shape, it is also very important to feed the particles well dispersed and separated as single particles through the measuring zone. Different dispersing modules can fulfill these requirements for solid and wet applications. Based on the video stream, a sophisticated particle size and shape analysis software calculates the size and shape distribution and sorts the particles in a gallery based on different measures.

RESEARCH MATERIAL

Selection of soil for laboratory tests and their location

As part of macroscopic tests in accordance with the Polish standard PN-88/B-04481, four natural cohesive soils from Poland were selected, characterized by various physical parameters and depositional environments. In order to identify the samples, individual soils were numbered from 1 to 4.

Sampling sites were selected randomly, without specific selection criteria. Three samples (numbers 1-3) were taken from the Świętokrzyskie Voivodeship, while the fourth sample (number 4) was taken from the Masovian Voivodeship. Samples 1, 2 and 3 were taken from a depth of approximately 3.5 meters below the ground surface, and sample number 4 was taken from a depth of 7.5 meters below the ground level. The location of sampling points is presented in Fig. 1.

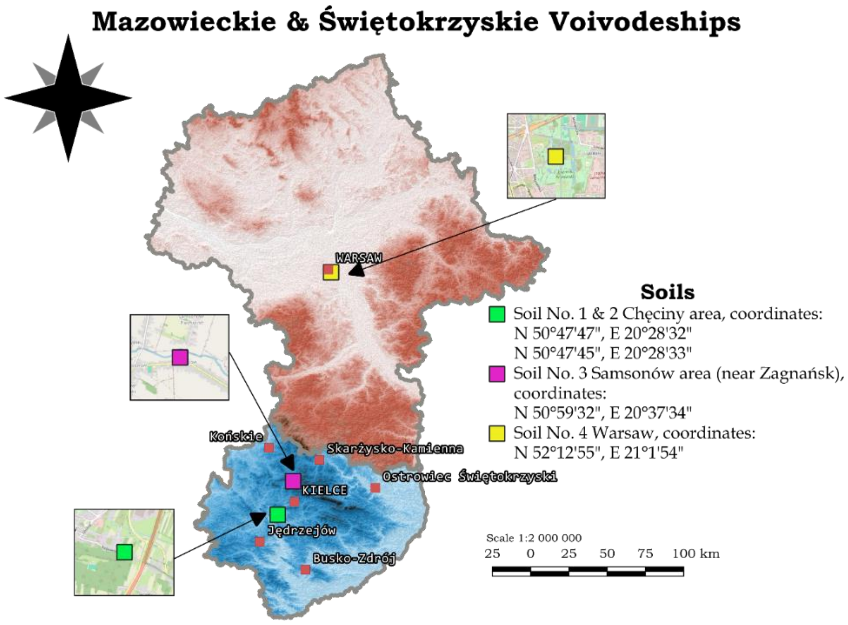

Fig. 1. Location of sampling points

Geological origin of the soil

Soil No. 1, with the geographical coordinates of the sampling site N 50°47'47", E 20°28'32" and soil No. 2, with coordinates N 50°47'45", E 20°28'33", were taken from the Chęciny commune area. This area is located in the western part of the Paleozoic core of the Świętokrzyskie Mountains, close to the border with their southern Mesozoic fringe. It is located within the wing of the Chęciny Anticline, made of Middle Devonian limestones and dolomites. Morphologically, it is a fragment of the denudation surface formed on glacial sediments. Cambrian deposits in this region are represented by strongly folded sandstones and shales. However, the collected soils are Quaternary formations represented by clayey sands, various-grained sands and glacial sandy clays (Filonowicz, sheet Chęciny) (Kondracki, 1998).

Soil No. 3 with the geographical coordinates of the sampling site N 50°59'32", E 20°37'34" was collected from the town of Samsonów (Zagnańsk commune), i.e. from the area located within the north-western Permian-Mesozoic fringe of the Paleozoic core of the Świętokrzyskie Mountains. According to geological maps, the older subsoil of this area is composed of sandstones, mudstones and claystones with intercalations of Upper Triassic conglomerates. In some places, these formations are covered with a thin cover of Quaternary sediments. In the Samsonowo area, Quaternary deposits are formed mainly in the form of clays, silts and reservoir sands, as well as glacial and river sands and gravels. The thickness of the Quaternary sediments from which soil no. 3 was collected ranging from a few to a dozen meters (Filonowicz, sheet Odwrożąż).

Soil No. 4 was taken from the central part of the Warsaw Basin (N 52°12'55" E 21°1'54"), which was created as a result of relief processes in the Quaternary period. The basin is located within a tectonic unit called the Marginal Synclinorium. The older substrate here is composed of Tertiary sediments, represented by Oligocene, Miocene and Pliocene sediments. They are covered by a thick package of Quaternary formations represented by Pleistocene and Holocene sediments. The boulder clays found in the Warsaw Basin are divided into two levels, and in some places, even three levels, separated by glacial and river sands. The oldest and lowest level of clay comes from the period of the South Polish glaciations and occurs mainly within the Pliocene depression of the basement. In these places, the clay thickness is up to 30 m. The younger clay horizons, from which the soil was collected for the purposes of this work, come from the Central Poland glaciations - Odra glaciation and Warta glaciation (Sarnacka, sheet Warszawa Wschód), (Morawski, sheet Warszawa Zachód), (Kondracki, 1998).

Applied measuring method

The particle shape information was obtained with the Dynamic Image analyses technology. The QIQPIC instrument manufactured by Sympatec GmbH was used. The principles of the applied method are based on the operation as follows:
1. An adaptable beam is emitted by the pulsed laser light source.
2. The beam goes through an expansion unit, which creates a parallel beam.
3. The beam illuminates the particles in motion inside the measuring zone; their projected shadow is magnified by an imaging lens system, and a high-speed camera takes the picture.
4. The particle flow is created by the dispersing unit specialized for dry or wet applications (Witt, 2007).

In this study, the measuring range was chosen, as shown in Table 1.

Tab. 1. Chosen measuring ranges of the QICPIC sensor

measuring range	detection range (μm)	evaluation range (μm) regarding ISO 13322 - 2
M7	10 - 10,240	10 - 3,410
M8	20 - 20,480	20 - 6,820
M9	30 - 30,720	30 - 10,000

Experimental tests and results

In the current study, four clayey soils were analyzed. For this method, the separation of particles into grade scale classes is needed. Hence, we used the following procedure:

1. The humid samples were dried at approximately 70 °C in an oven.
2. The completely dried samples were weighed.
3. The dried fractions were wet-sieved at 63 μm.
4. After drying the residues, the quantities of the fractions, as shown in Table 2 and Table 3, were determined.

Tab. 2. The quantities of the fraction < 63µm

	fraction (%)
sample no. 1	34.73
sample no. 2	45.06
sample no. 3	59.45
sample no. 4	49.75

Tab. 3. The quantities of the fraction > 63µm

	fraction (%)
sample no. 1	65.27
sample no. 2	54.94
sample no. 3	40.55
sample no. 4	50.25

Since the goal of this study is to determine the shape of the particles precisely, only the fractions > 63 µm were considered. The coarse fraction of each sample was measured three times. For this, the sample material was collected beneath the measuring zone and re-analyzed to avoid errors.
For the calculation of the QICPIC measurements, the diameter EQPC was applied. EQPC is the diameter of a circle that has the same area as the projection area of the particle.
All printouts and graphical presentations in this study were produced using features of the WINDOX software package. Standard values of the calculated particle size distributions are given in Table 4.

Tab. 4. The characteristic values of the QICPIC analyses all sample fractions>63µm

measuring range	X_{10} [µm]	X_{50} [µm]	X_{90} [µm]
sample no. 1	99.27	194.93	693.30
sample no. 2	106.08	216.11	572.01
sample no. 3	135.34	1388.54	6648.18
sample no. 4	95.35	200.50	720.50

Particle shape information is given with the QICPIC system in multiple ways. Examples of sphericity (the ratio of the perimeter of the equivalent circle to the real perimeter) and aspect ratio (the ratio of the minimum and the maximum FERET diameter) are presented in Figs. 1-4, not only as average shape values per size class but as cumulative volume shape distribution as well.

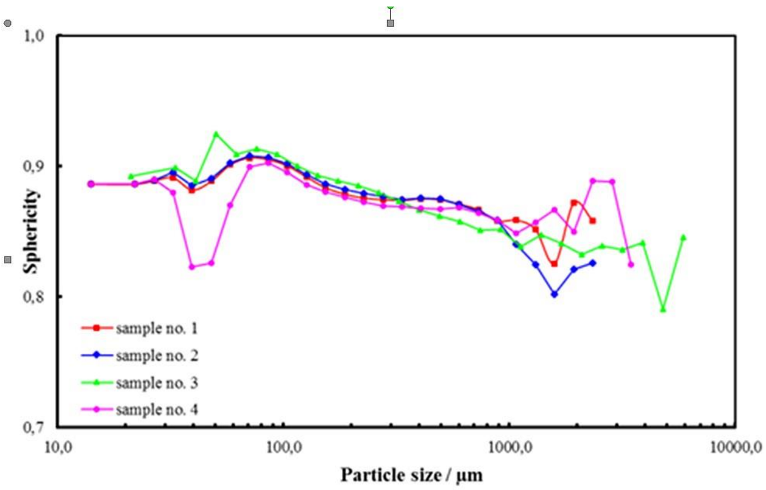

Fig. 2. Device Sphericity versus particle size (EQPC)

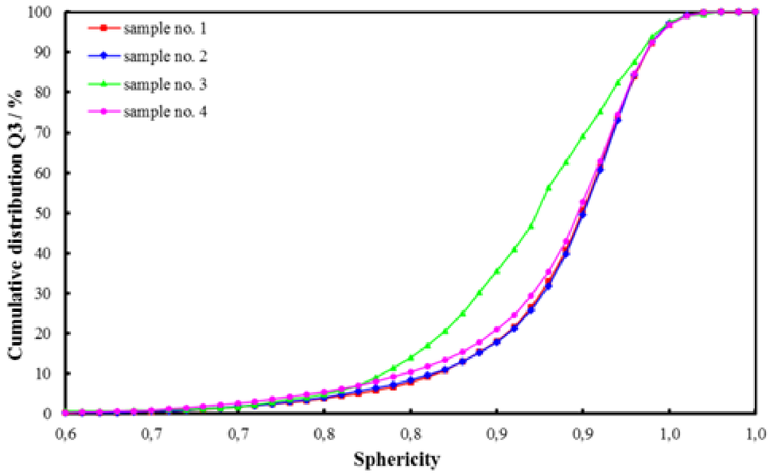

Fig. 3. Cumulative sphericity distribution Q(S) (EQPC)

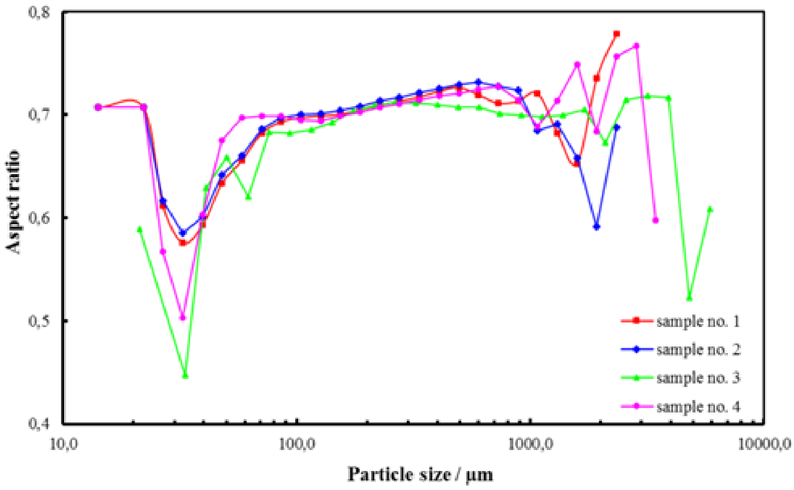

Fig. 4. Aspect ratio versus particle size (EQPC)

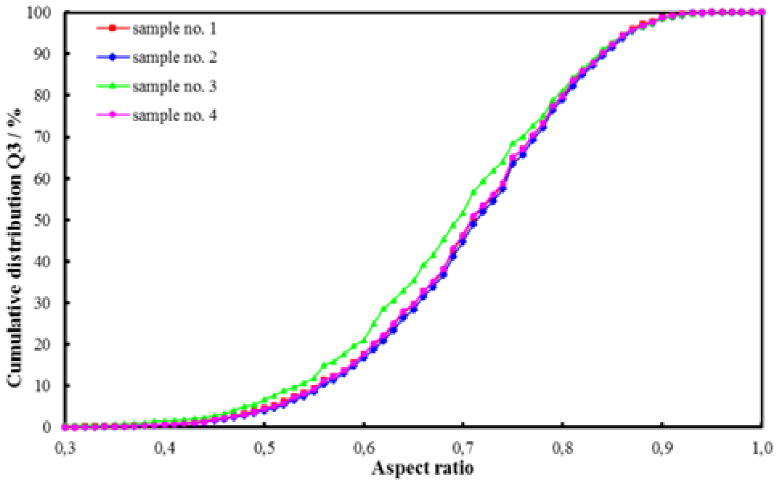

Fig. 5. Cumulative distribution Q(ar) (EQPC)

For all the sample materials, the shape factor 'sphericity' is similar and has a value of about 0.88, with a slight decrease with increasing particle size. The shape factor' aspect ratio' has values close to 0.7 for all samples. To summarize, it means that the coarser particles of the sample materials are slightly more irregularly shaped than the finer particles. The coarse end of the wide distributions is usually represented by a few numbers of particles per size class only. The statistical significance of this small number of particles is not given, and higher random fluctuations in shape characterization could be observed.

The particle size distributions and the shape factors were calculated based on binary images recorded with the QICPIC instrument during the measurement.

For visual impressions of the measurements, all frames that have been recorded are stored in the WINDOX databases and could be examined afterwards using the signal test function. During the measurement, the life video is displayed with a reduced frame rate of 10Hz.

The set of special filter criteria provides insight into galleries of particles with different sizes and shapes.

Representative excerpts from the particle galleries are listed below.

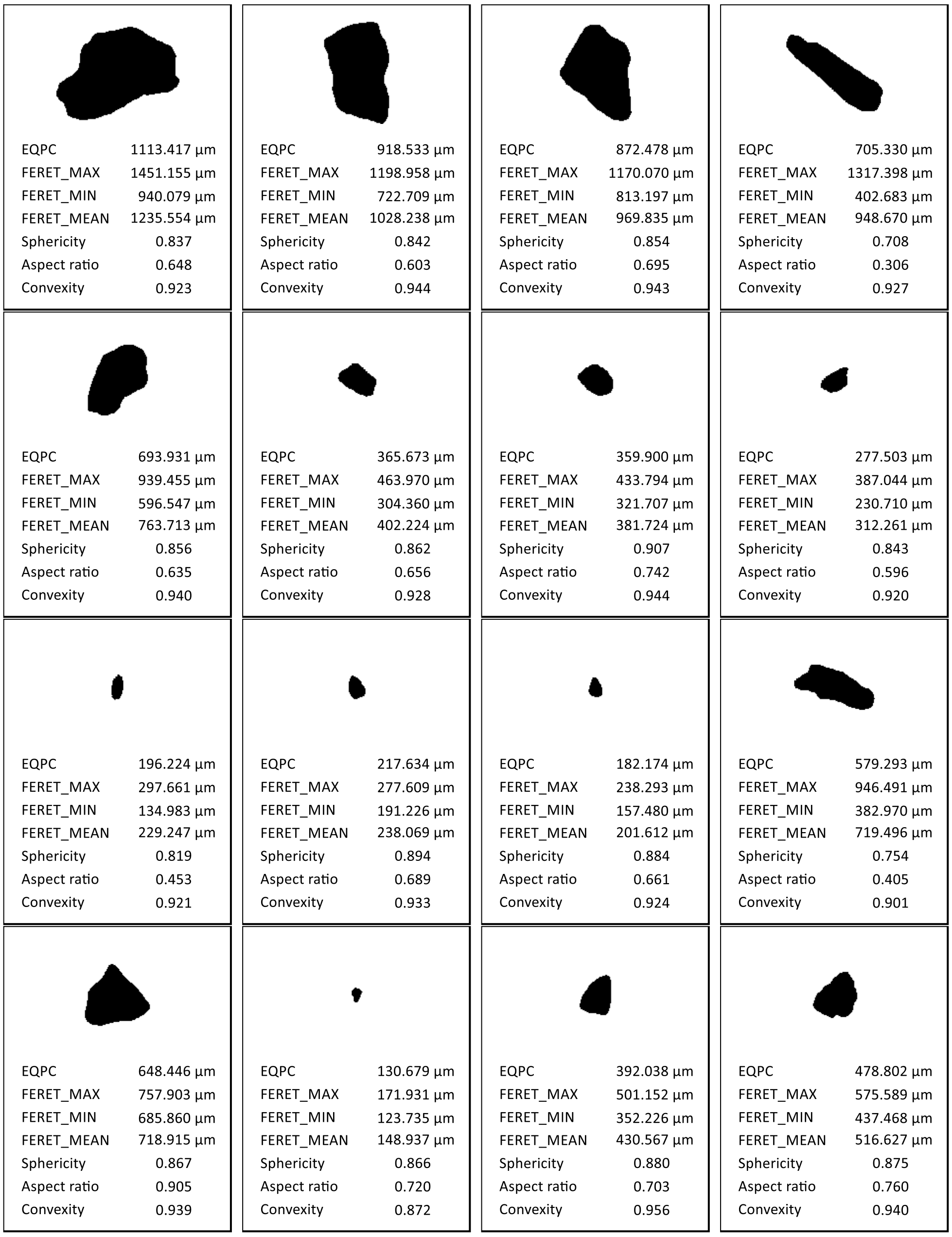

Fig. 6. Excerpts from the particle galleries

Summary

The physical and chemical properties of soil are crucial to understanding its functioning in ecological, agricultural and engineering processes. One of the important factors influencing these properties is the size and shape of soil particles. Both of these parameters significantly impact its structure and many processes occurring in the soil. Hence, the size and shape of soil particles play an important role in Soil Science.

The size of soil particles affects parameters such as strength and compressibility. For example, the smaller the particles are, the greater the contact area is between them, which can lead to greater compressive strength of the soil. In addition, particle size affects the pore size of the soil, which in turn can affect the water retention capacity and permeability of the soil.

The shape of soil particles also plays an important role. Irregularly shaped particles can create spaces between them, affecting the soil's porous structure. This, in turn, may affect the permeability of the soil and its ability to retain water and nutrients.

To precisely understand the influence of soil particle size and shape on its properties, dynamic image analysis (DIA) becomes a very important tool. DIA allows the observation and analysis of the shape and size of particles in a dynamic and precise way. This allows for a better understanding of the soil structure and the impact of various factors on its physical and chemical properties.

The conclusion is that the size and shape of soil particles significantly impact their physical and chemical properties, which in turn are crucial for many processes occurring in soil ecosystems and for agriculture and environmental engineering. Dynamic image analysis is an important tool for better understanding these complex relationships.

In addition to the aspects mentioned above, it is also worth emphasizing the importance of research on the size and shape of soil particles due to their importance for many fields of science and practice. Here are some additional aspects that can be considered:

1. **Agriculture and agri-food production:** The size and shape of soil particles significantly impact the structure of plant roots, their ability to penetrate and the availability of water and nutrients. Research on soil particles can help optimize crop cultivation techniques, improve crop yields, and improve the environmental sustainability of agricultural practices.
2. **Environmental protection:** Understanding soil particles' size and shape distribution is important for assessing soil erosion processes, pollutant transport and chemical retention in the soil environment. This research can help develop environmental protection strategies and manage water resources.
3. **Environmental engineering:** The size and shape of soil particles are also important in environmental engineering, especially in the design of drainage systems, sewage treatment systems and building foundations. Research on soil particles can help design more effective and sustainable engineering solutions.
4. **Geology and geomorphology:** Knowledge of the size and shape of soil particles is important for understanding geological and geomorphological processes such as soil formation, erosion, sedimentation and deformation of rock layers. Research on soil particles can contribute to a better understanding of the geological history of a given area and predict its future changes.

All these areas of science and practice use research on the size and shape of soil particles, which emphasizes the enormous importance of this research for a wide range of fields and problems related to soil science and environmental protection.

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