Towards Standardized Mechanical Characterization of Highly Dewatered Sludge: a bibliometrics study

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Highly dewatered sewage sludge is a complex heterogeneous material whose mechanical behaviour strongly influences handling, transport, drying, storage, and potential valorisation routes. As sludge progresses through the treatment line, its structure changes markedly, moving from a dilute suspension to a concentrated paste and, finally, to a dry granular solid, as show in Figure 1. At the dewatered stage, the material exhibits a soft-solid character dominated by viscoelasticity, rheology, texture, and interparticle interactions. Among these properties, adhesiveness and cohesiveness are particularly relevant because they affect flowability, stickiness, processability, and the energy demand of downstream operations. However, despite their practical importance, these properties have not been consistently defined or measured across the literature. Existing studies come from different disciplines, including rheology, geotechnics, food science, and materials engineering, each using its own terminology, testing conditions, and interpretation framework. This lack of standardization makes it difficult to compare results and to establish predictive relationships between sludge composition, water distribution, structure, and mechanical response [1,2]

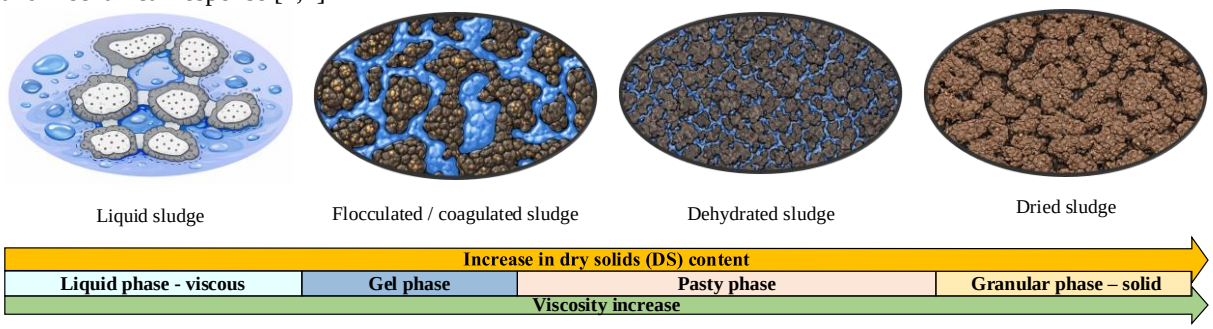

Figure 1. Structural evolution of sewage sludge during treatment.

The objective of this work is to provide an integrated overview of the theoretical basis and experimental approaches used to characterize the mechanical behaviour of highly dewatered sludge. To achieve this, a bibliographic and bibliometric review strategy was applied using major scientific databases to identify the most relevant studies related to sludge rheology, texture, viscoelasticity, and mechanical characterization [3]. The literature was then organized into thematic sections covering: the structural evolution of sludge along the treatment line; the main definitions of rheological, textural, and geotechnical descriptors; the mathematical and conceptual models used to interpret viscoelastic behaviour; and the principal experimental techniques reported for sludge characterization. In parallel, bibliometric indicators were used to identify the evolution of the field, the most influential sources, the dominant keywords, and the main knowledge gaps.

The results show that the literature on sludge mechanical characterization has grown considerably over time, with a clear concentration of studies in a limited number of journals and research groups as shown in Figure 2. Rheology emerges as the dominant research axis, reflecting the importance of flow and deformation behavior in sludge processing. At the same time, the bibliometric analysis reveals that keywords related to texture and mechanical testing appear less frequently, and terms associated with adhesion are notably scarce. This pattern suggests that, although sludge stickiness and cohesion are central to practical operations, they remain underrepresented in the scientific discourse. In addition, the review of experimental methods shows that no single technique is sufficient to capture the full mechanical complexity of highly dewatered sludge. Instead, the literature combines oscillatory rheology, penetrometry, compression tests, shear tests, and texture analysis, each providing complementary information but also presenting limitations in terms of reproducibility, sample preparation, and interpretation.

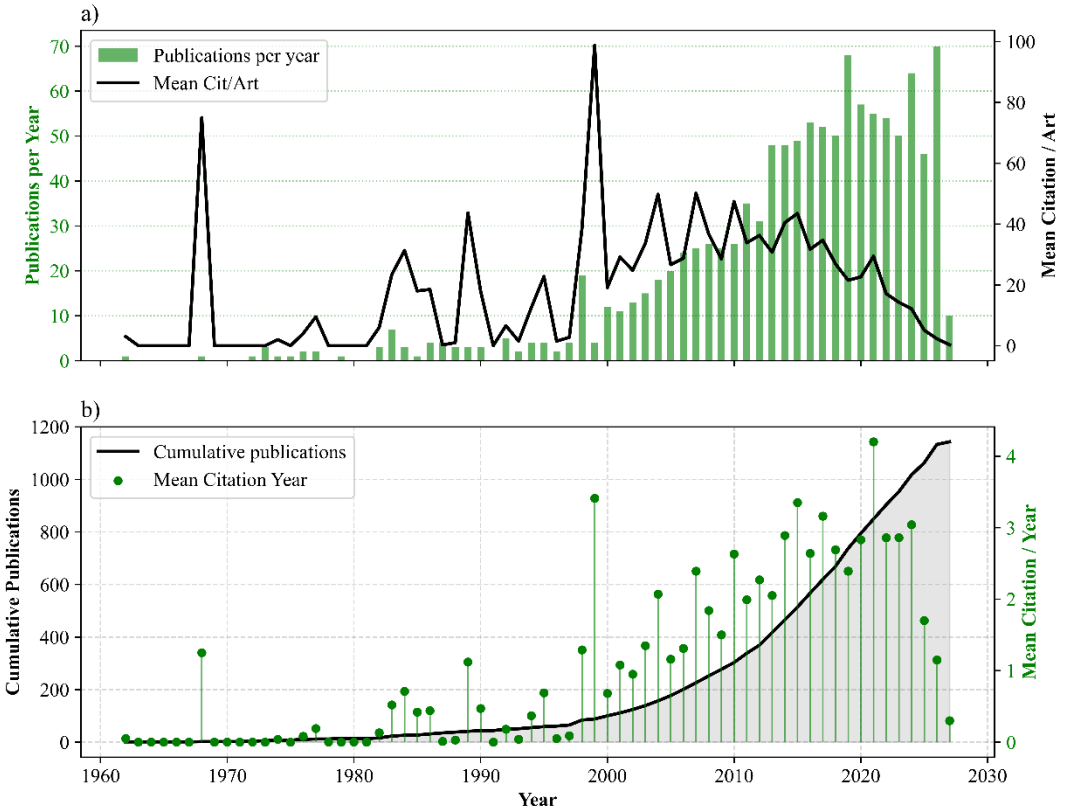

Figure 2. SC over the years: a) shows the number of articles published each year and the mean number of citations each article received; b) presents the cumulative publications in the field and the average citations each article received when divided by year.

From a theoretical perspective, the reviewed studies confirm that sludge behaviours is governed by a combination of water distribution, extracellular polymeric substances, particle packing, and structural rearrangement during dewatering and drying. As water is progressively removed, the sludge matrix becomes denser and more cohesive, which increases resistance to deformation and promotes adhesive interactions with surfaces and process equipment. This explains why adhesiveness should be considered not as a secondary property but as a key descriptor of sludge behaviour, especially in the context of dewatering, drying, conveying, and material handling. The analysis also indicates that current mechanical descriptors are often applied in a fragmented way, without a unified framework linking structure, composition, and performance. Therefore, one of the main contributions of this work is to clarify the conceptual relationships among the different property families and to highlight the need for standardized methods capable of generating comparable and predictive data.

In conclusion, this study provides a structured synthesis of the theoretical foundations, methodologies, and principal findings related to the mechanical characterization of highly dewatered sludge. The combined bibliometric and narrative review reveals a mature but still fragmented research field, with strong emphasis on rheology and insufficient attention to adhesiveness. By integrating the most relevant experimental approaches and identifying the major gaps in the literature, this work supports the development of more consistent descriptors and more robust methodologies for sludge characterization. Such advances are essential for improving process design, reducing energy demand, and enhancing the efficiency of sludge management and valorisation strategies.

References

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