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Amit Prashant
Ajanta Sachan
Chandrakant S. Desai *Editors*

Advances in Computer Methods and Geomechanics

IACMAG Symposium 2019 Volume 2

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Editors
Amit Prashant
Indian Institute of Technology Gandhinagar
Gandhinagar, Gujarat, India

Ajanta Sachan
Indian Institute of Technology Gandhinagar
Gandhinagar, Gujarat, India

Chandrakant S. Desai
University of Arizona
Tuscon, AZ, USA

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Preface

The Symposium of the International Association for Computer Methods and Advances in Geomechanics (IACMAG) was held at the Indian Institute of Technology Gandhinagar, Gujarat, India, during the period 5–7 March 2019. Computer applications of geomechanics have been gaining much popularity from the early days of the International Conference on Numerical Methods in Geomechanics at Vicksburg, in 1972, Blacksburg, in 1976, and Innsbruck, Austria, in 1988. It was in that very context the IACMAG was established and it has been growing ever since with various stakeholders contributing significantly from different nations across the world. IACMAG aims at fostering multidisciplinary research and ideas pertaining to geomechanics with particular emphasis on integrating both the practical and the fundamental aspects. The field of geomechanics has evolved with time, and in this regard, IACMAG takes into account the need for judicious simplification of fundamental aspects of geomechanics with proper amalgamation of theory and experimentation in order that they find their use in practical problems and challenges faced in the industry today.

IACMAG has grown steadfastly in its scope and size encompassing various aspects of constitutive modelling of geomaterials, computational methods and emerging fields of bio-cementation as well as treatment of geomaterials. The Symposium at IIT Gandhinagar aimed at providing a platform for exchanging ideas and recent developments as well as for discussing future visions related to the field of geomechanics and geotechnical engineering. A pre-symposium workshop on "Behaviour of Civil Engineering Materials" was also held in this regard on 4 March 2019 with its focus on the material models commonly used in analysis and design of structures. It also included a hands-on session for implementing simple computer applications of geotechnical engineering for industry and the academia. The IACMAG Symposium 2019 included 11 keynote/invited speakers of repute from different backgrounds of the geotechnical engineering community. It involved four parallel sessions with main themes of the symposium being primarily focussed on (i) geomaterial behaviour and material modelling, including multi-scale modelling, micro-structural instabilities, liquefaction, chemical and bio-effects in geomaterials, field/laboratory testing; (ii) earthquake engineering, including dynamics of geomaterials, earth embankments, and dams; (iii) geosynthetics and ground improvement with thrust areas on bio-treatment, soft and expansive clays; and (iv) analysis and design of structures, including bridges and foundations as well as soil–structure interaction problems.

We thank all the authors for their contribution to the IACMAG Symposium 2019 that has resulted in the proceedings which is being published in two volumes. IACMAG follows its long-standing tradition in selecting and reviewing these papers with great rigour, and we hope that the proceedings will provide a glimpse of the state-of-the-art practices followed in different fields related to geomechanics and its allied branches. We would also like to express our sincerest of appreciation to the reviewers of the papers and to various technical and financial sponsors for making this event a grand success.

Gandhinagar, India — Amit Prashant
Gandhinagar, India — Ajanta Sachan
Tuscon, AZ, USA — Chandrakant S. Desai

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About the Editors

Amit Prashant is a Professor in Indian Institute of Technology Gandhinagar, India. After his PhD and post-doctoral work in the University of Tennessee at Knoxville (USA), he went on to work as an Assistant Professor in IIT Kanpur from 2005 to 2010, before joining IIT Gandhinagar in 2010. His research interests include constitutive modeling for granular materials, numerical modeling of geotechnical structures, and earthquake geotechnical engineering. In 2005, he received the Young Researcher Fellowship Award from Massachusetts Institute of Technology, Cambridge (USA) during the 3rd M.I.T. Conference on Computational Fluid and Solid Mechanics. He has also been awarded the Excellence Award in Institution Building and Outreach in 2013 and 2015 respectively. Prof Prashant has published more than 60 research articles in reputed journals and conferences, and organizes activities to encourage student initiatives and increase industry-academia interaction.

Ajanta Sachan is an Associate Professor in Indian Institute of Technology Gandhinagar, India.After her B.E in Civil Engineering, she worked in WAPCOS Limited and IIT Kanpur, India before pursuing her PhD in University of Tennessee at Knoxville, USA. Her research interests include material characterization, studying shear strength and compressibility behavior in soils, etc. Dr Sachan serves as a reviewer in 7 journals and is a member of American Society of Civil Engineers (ASCE), USA, Earthquake Engineering Research Institute (EERI), USA and the National Information Centre for Earthquake Engineering (NICEE), India. She has published more than 50 research papers, and has served in various administrative capacities.

Chandrakant S. Desai is a Regents' Professor (Emeritus) in the Department of Civil and Architectural Engineering and Mechanics at the University of Arizona, Tucson, USA. After completing his MS and PhD from Rice University Houston and University of Texas, Austin in 1966 and 1968 respectively, he joined the U.S. Army Corps of Engineers' Waterways Experiment Station, where he worked till 1974. Subsequently, he joined The University of Arizona, where he has served on various capacities. Prof Desai has authored or edited 23 books and over 345 research papers over the course of his career, which has involved the development and application of constitutive laws with design and fabrication of new and innovative test devices, and of computer methods for solution of a wide range of problems in civil, mechanical and electronics engineering. He has been the founding president of the IACMAG and founding Editor-in-Chief for two international journals in Geomechanics. He has received many awards and distinctions, and is a member of a number of technical societies including an elected Distinguished Member of the American Society of Civil Engineers, USA.

Exfoliation and Extraction of Nanoclay from Montmorillonite Mineral Rich Bentonite Soil

Naman Kantesaria and Sudhanshu Sharma

Abstract Nanoclay is a fine-grained crystalline material, which contains a mineral of alumina and silica with high aspect ratio and at least one dimension of a particle in the nanometer (1 nm = 10^{-9} m) range. Nanoclays have various applications in many fields, including problematic soil treatment, pharmacy, medicine, catalysis, cosmetics, food packaging, and textile industry. The raw cost of Nanoclay is high due to its costly manufacturing process that involves heavy chemicals and machinery. Therefore, the aim of the current research is to extract Nanoclay from the montmorillonite-rich commercially available Bentonite soil using a cost-effective method. The process involves the exfoliation of the nanosized lamina from the stacked 2:1 tetrahedral–octahedral laminae of montmorillonite minerals with the help of surfactant. Three different types of surfactants (cationic, nonionic, and anionic) were chosen in the current study to evaluate their effect on the exfoliation process of highly expansive Bentonite soil. A series of chemical processes including solution preparation, sonication, centrifugation, and drying were performed using selected proportion of surfactant and Bentonite soil mixture. Physical and chemical properties of the end product were investigated by performing X-ray diffraction (XRD) technique and scanning electron microscope (SEM) image analysis. Nanoclay of the particle size range of 10–15 nm is successfully exfoliated from montmorillonite sheet structure by the chemical interaction between cationic surfactant and Bentonite soil. Nonionic surfactant was observed to be just intercalated between the sheets of montmorillonite mineral with additional growth of small needle-like structures. Anionic surfactant has no prominent effect on Bentonite soil.

Keywords Nanoclay · Exfoliation · Montmorillonite · Bentonite soil · Surfactant · SEM · XRD

N. Kantesaria (✉)
Civil Engineering, Indian Institute of Technology Gandhinagar, Gandhinagar, India
e-mail: naman.kantesaria@iitgn.ac.in

S. Sharma
Chemistry Department, Indian Institute of Technology Gandhinagar, Gandhinagar, India
e-mail: ssharma@iitgn.ac.in

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1 Introduction

Bentonite soil is a high plasticity clayey soil made from the very high amount of montmorillonite ((Na, Ca)$_{0.33}$(Al, Mg)$_2$(Si$_4$O$_{10}$)(OH)$_2$·nH$_2$O) minerals. Due to the presence of these minerals, the expansiveness of this soil is very high. Montmorillonite minerals are alumino silicates generated from the combination of sheet-like structures attached together by weak Van der Waals forces. Each sheet of this structure is a 2:1 structure in which, two tetrahedral silica $(SiO_4)^{4-}$ are connected to one octahedral alumina $[AlO_3(OH)_3]_6$ sheet. The thickness of this single sheet can be 1 nm. When these single sheets are combined together by Van der Waals forces, their thickness increases to a few hundreds of nanometers. In nature, montmorillonite mineral is present in the stacked form only. Hence, the aim of the current research is to break this stacked structure and separate the individual 2:1 sheet of montmorillonite mineral termed as Nanoclay.

Nanoclays are fine-grained crystalline materials where at least one dimension is in nanoscale [6]. They are synthesized from artificial or natural bulk clay fraction by various procedures such as centrifugation, ultracentrifugation, and freezing–drying [1, 5, 6, 8]. All these processes required high-end equipment and costly raw products. Nanoclays have various applications in many fields, including problematic soil treatment, pharmacy, medicine, catalysis, cosmetics, food packaging, and textile industry [2, 5, 7, 8]. Usefulness of Nanoclays in various fields is attributed to the amenability of Nanoclays for modification, and the dispersion characteristics of clay layers into individual lamellae [7]. Amenability of Nanoclays for modification is due to the interchangeability of the desired cations or other molecules on their negatively charged surface [1, 5, 7, 8]. Simple procedures are required to interchange the desired ions and modify the surface chemistry of Nanoclays. The biggest advantage of Nanoclays are the high specific surface area (SSA) and that increases scope for altering the properties of clays like their polarity, zeta potential, acidity, cation exchange capacity (CEC), pore size, and many others that govern their performances in various applications [1, 5, 6, 8].

The current study presents a brief insight of economical extraction procedure of Nanoclay from commercially available Bentonite soil. Effect of different types of surfactant on the chemical and physical properties of Bentonite soil is determined. An attempt was made to give chemical hypothesis regarding surfactant and Bentonite reaction in the extraction procedure of Nanoclay. X-ray diffraction technique (XRD) and scanning electron microscopy (SEM) were used to determine chemical and physical properties of various reaction products.

2 Experimental Program

2.1 *Material Properties*

2.1.1 Bentonite Soil

The soil used for the current study was the commercially available Bentonite soil supplied by local suppliers. Bentonite soil was chosen because of the presence of high amount of montmorillonite mineral in it. The soil is classified as clay of high plasticity (CH) type of soil according to Indian Standard Soil Classification. Differential free swell index (DFSI) value of Bentonite soil is 662%, which indicates the soil is highly expansive in nature (IS: 2911 Part III-1980). Basic geotechnical properties of Bentonite soil including liquid limit, plastic limit, shrinkage limit, and specific gravity are mentioned in Table 1.

2.1.2 Surfactant

Surfactants are defined as the compounds which reduced the surface tension between liquid and solid, between two liquids or between liquid and gas. Surfactants may act as wetting agents, detergents, emulsifiers, dispersants, and foaming agents. In the present study, surfactants are chosen to perform the function of dispersing agents. They consist of mainly two part structures: a hydrophilic head and a hydrophobic tail. Surfactants are classified into four main groups based on the ions present into their hydrophilic tail as described in Fig. 1. In the current study, the surfactants chosen were Cetrimonium Bromide (CTAB), Polyethylene glycol (PEG), and Trisodium citrate as the cationic, nonionic, and anionic surfactants, respectively. The chemical formulas of these surfactants are shown in Table 2.

2.2 *Testing Procedure*

The exfoliation and extraction procedure of Bentonite soil was done by performing a series of chemical procedures. The total testing procedure is divided into four major portions and they are explained as follows.

Table 1 Geotechnical properties of Bentonite soil

Specific gravity G_s	Liquid limit, w_L (%)	Plastic limit, w_P (%)	Shrinkage limit, w_S (%)	Plasticity index, I_p (%)	DFSI (%)
2.8	609	51	6	558	662

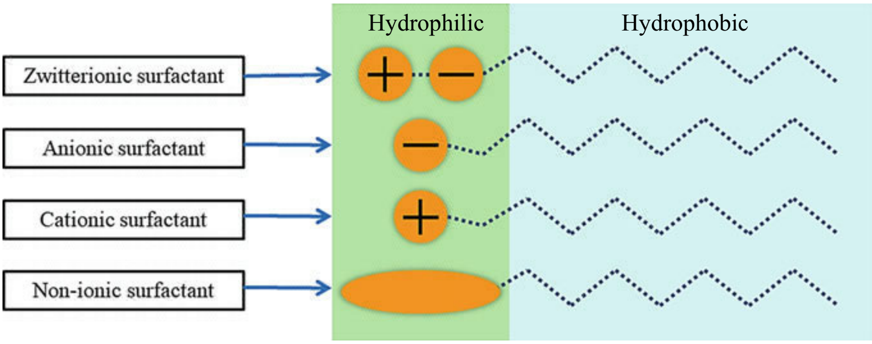

Fig. 1 Types of surfactants

Table 2 Types of surfactant used and sample prepared

Sample number	Surfactant used	Type of surfactant group	Chemical composition
S-0	Sonication of pure Bentonite (without the addition of any surfactant)		
S-1	Cetrimonium bromide (CTAB)	Cationic	$C_{19}H_{42}BrN$
S-2	Polyethylene glycol (PEG)	Nonionic	$C_{2n}H_{4n+2}O_{n+1}$
S-3	Trisodium citrate	Anionic	$Na_3C_6H_5O_7$

2.2.1 Solution Preparation

The molar solution of the chosen surfactant is prepared in 100 ml of distilled water. To dissolve it properly into the water, the sonication was done for 10 min. Five gram of 75-micron sieve passed Bentonite soil is then mixed with a prepared solution and stirred well for proper mixing. This procedure is shown in Fig. 2. Four different samples were prepared and details of these samples with the chosen surfactant are provided in Table 2. For S-0 sample, pure Bentonite soil is sonicated for 90 min without any addition of surfactant.

2.2.2 Sonication

The prepared mixture was sonicated for 90 min to break down the structure of the soil and mixed uniformly with the surfactant. In this procedure, ultrasonic waves were applied to the mixture through the sonicator. This will impart extra energy to break the structure.

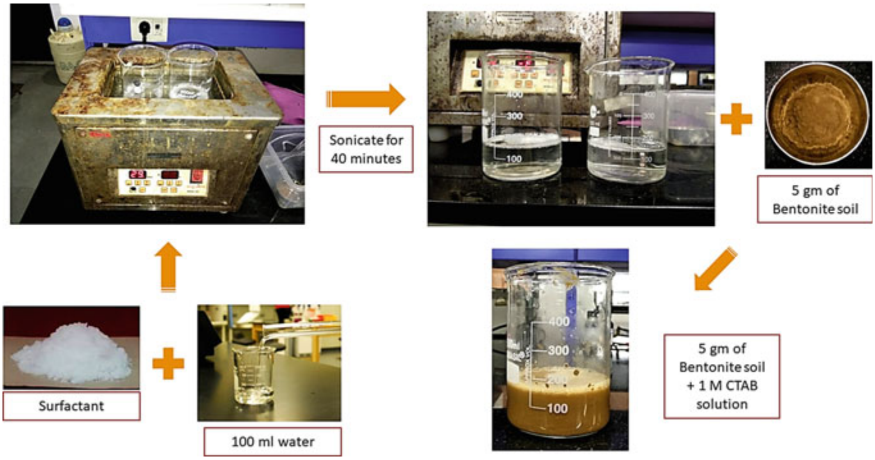

Fig. 2 Solution preparation stage

2.2.3 Washing

To remove the surfactant from the mixture, washing was done with the help of centrifuge. Initially, the mixture was centrifuged at 8000 RPM for 20 min. Settled parts in the tube were extracted and again mixed with water. This mixture was again centrifuged at the same RPM and for the same time duration. This procedure was repeated twice to remove most part of the surfactant from the mixture.

2.2.4 Drying

The settled samples were collected in the container and put inside the oven for drying at 105 °C for at least 24 h. After drying, it was crushed into fine powder for further analysis. The detailed procedure of stage 2–4 is shown in Fig. 3.

3 Results

X-ray diffraction (XRD) analysis and scanning electron microscope (SEM) analysis were performed to evaluate the results of the chemical process. Both the analysis was performed on pure Bentonite soil and processed soil. To characterize the modification of the lattice structure quantitatively, the XRD analysis was performed. SEM analyses were performed to identify the changes visually by seeing the modified clay structure through a microscope with high zoom-in capacity.

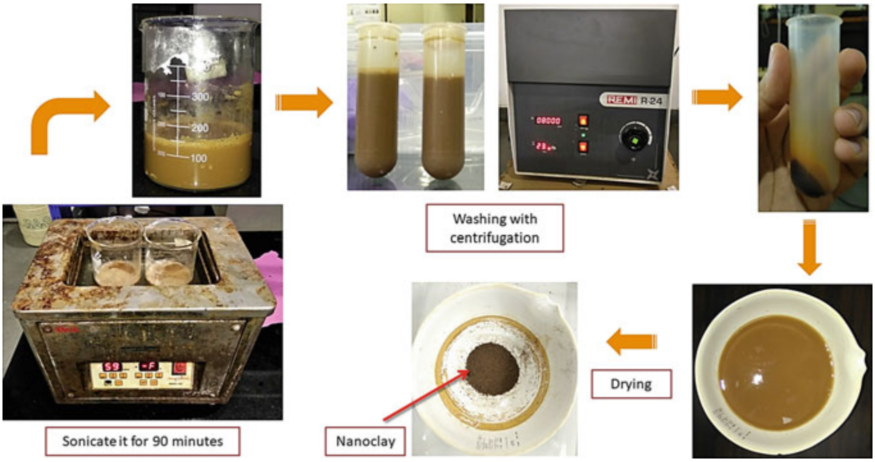

Fig. 3 Sonication, washing, and drying stage

3.1 X-Ray Diffraction (XRD) Analysis

Pure Bentonite soil and S-0–S-3 samples were analyzed in the powder form on Bruker AXS D8 Discover XRD equipment. The plot of the intensity versus 2θ (angle) were plotted for both the samples. It is shown in Fig. 4. The intensity is plotted in terms of arbitrary units (a.u.) to compare the results of different samples on a single curve. In Fig. 4, the values of the intensity have no significance, hence these values were removed. The 2θ values were limited to 25° as the montmorillonite mineral presence is majorly indicated until this value only. As seen from the curve, there was no change observed for the XRD patterns of pure Bentonite soil and samples S-0, S-2, and S-3. This indicates no change in the crystal lattice structure by interaction with anionic and nonionic surfactant. Widening of the montmorillonite mineral peak (0 0 1) is observed for S-1 sample when pure Bentonite soil was processed with Cationic surfactant (CTAB). This is the indication of a particular mineral's particle size reduction. The reduction in the particle size can be quantitatively determined by Scherrer's equation. Scherrer's equation can give lower bound of reduced particle size. It is expressed as follows:

$$d_c = \frac{k * \lambda}{\beta * \cos\theta}$$

where d_c is the averaged dimension of crystallites; K is the Scherrer constant, a somewhat arbitrary value that falls in the range 0.87–1.0 (it is usually assumed to be 1); λ is the wavelength of the X-ray; and β is the integral breadth of a reflection (in radians 2θ) located at 2θ. For S-1 sample's XRD data, lower bound of particle size determined is d_c = 3.84 nm. It is the indication of particle size reduction from pure Bentonite soil.

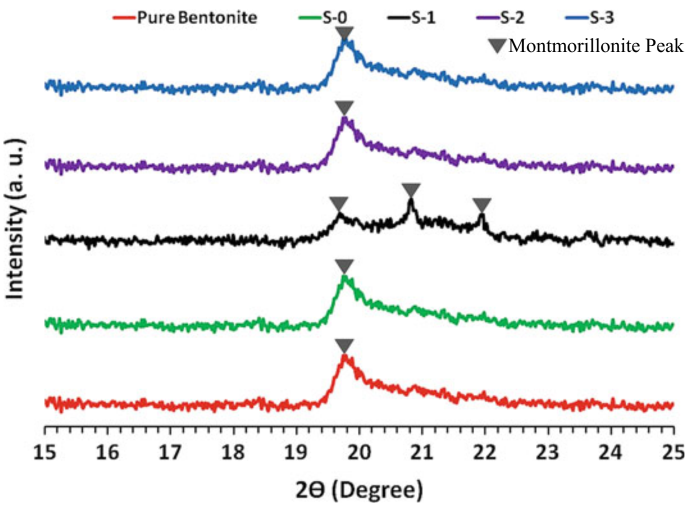

Fig. 4 XRD result: intensity versus 2θ curve for all the samples

3.2 Scanning Electron Microscope (SEM) Analysis

SEM image analysis was done on the powder specimens of pure Bentonite soil and S-0–S-3 specimens. This analysis was done to characterize and identify the changes in the sheet-like structure of montmorillonite mineral with the addition of different surfactants. SEM images of 1 μm–100 nm scale are presented for different samples as follows:

(a) Pure Bentonite: Sheet-like densely packed structure is observed in the SEM images of pure Bentonite soil. It is the original stacked form of montmorillonite mineral as shown in Fig. 5a.
(b) S-0 Sample: Due to sonication, very small amount of exfoliation is achieved. But, the effect of sonication alone is not sufficient to exfoliate Bentonite to nanoscale. The observed small fragments in the images were generated due to the breakage of mineral structure from sonication. It is shown in Fig. 5b.
(c) S-1 Sample: Successfully exfoliated structure of montmorillonite mineral is observed in the SEM images of CTAB surfactant processed Bentonite. Individual sheets of montmorillonite mineral in the scale of nanometer were observed to be separated from the stacked structure. One dimension of Nanoclay is observed in the order of 10–15 nm as shown in Fig. 5c.
(d) S-2 Sample: Some extent of exfoliation is observed with the intrusion of PEG into the Bentonite soil. But it is not prominently in the nanometre size range. PEG penetrates within the soil mass as observed in the SEM images. The square-shaped particles observed inside the clay sheets were particles of PEG. Small, unidentifiable needle-type structures were observed to grow within the grooves of the particles. It is shown in Fig. 5d.

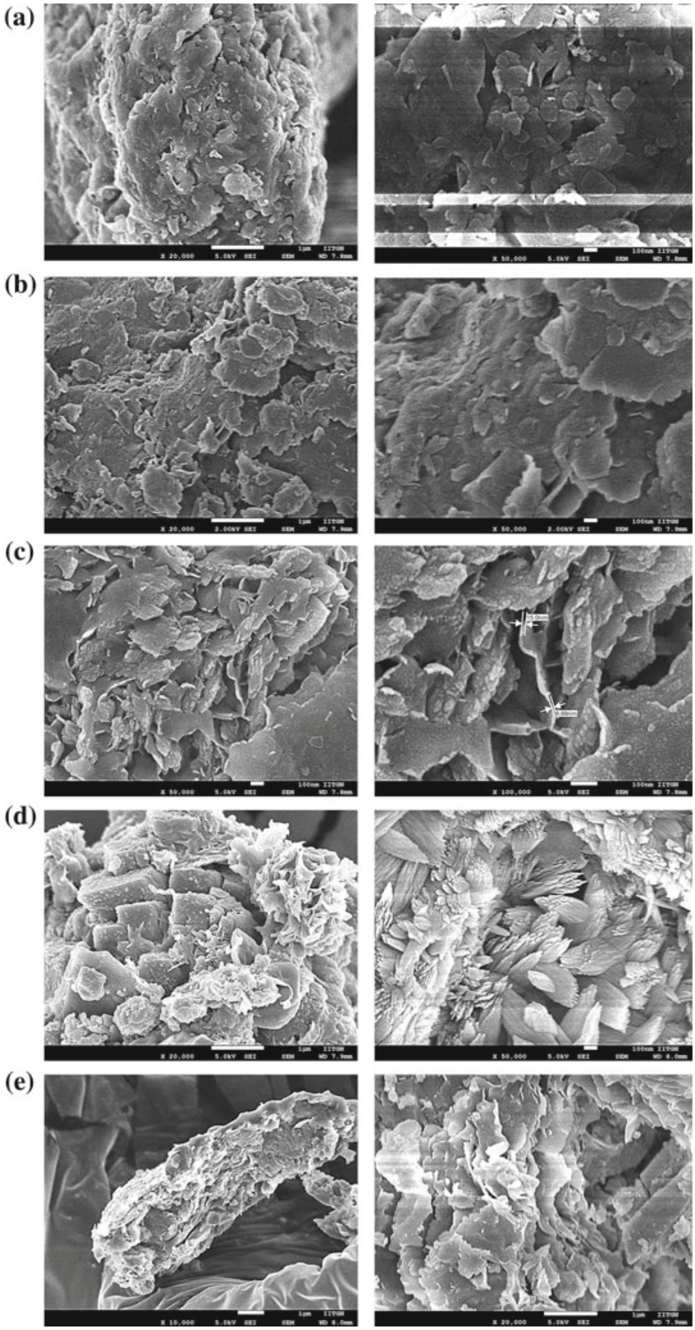

Fig. 5 SEM images of **a** pure Bentonite, **b** S-0, **c** S-1, **d** S-2, **e** S-3 samples

(e) S-3 Sample: No effect of Trisodium Citrate on the layers of Bentonite was observed. All the layers were in the same stacked position as shown in Fig. 5e. The side view of a staked particle is shown in Fig. 5e, whereas the top view of the staked particles were presented for pure Bentonite and S-0 samples. They resembled the same original microstructure of the montmorillonite mineral with different orientations of the particle.

4 Theory

The montmorillonite clay minerals are negatively charged particles that create high affinity of these minerals toward cations and bipolar water molecules. The aim of the current study is to exfoliate these sheets-like structures, and water molecules alone cannot exfoliate the complete structure. Hence, the additional ions are required to assist the process of exfoliation. Due to the negative charges on the clay surface, the best-suited surfactants are considered as cationic surfactants. Though, the other types of surfactants may have some different effects on the montmorillonite mineral and to study that, three different types of surfactants were chosen. The modification of the structure due to the chemical process is explained as follows.

4.1 Effect of Cationic Surfactant

Due to isomorphous substitution within the silica tetrahedral and alumina octahedral sheets of the montmorillonite mineral, the net negative charge is generated on the surface of the clay particles. Hence, when a cationic surfactant is added to the solution, the cations in the hydrophilic head are attached with the negatively charged clay surface [4–6, 8]. Due to this process, all the hydrophilic tails come closer to each other. These tails repeal each other and the distance between the two montmorillonite mineral units increases. This process is still not sufficient to break the structure completely. Hence, sonication is performed and the ultrasound waves during sonication impart additional energy to break down the structure. To remove the attached cationic surfactant from the surface of the clay particles, washing process is done. Nanoclay is determined after drying and crushing of this final product. As there were no distinct peaks observed for the CTAB surfactant in the XRD analysis, it was confirmed that almost all the hydrophilic heads were removed through the process of washing. Apart from that, no foreign material traces were observed in the SEM images. The schematic representation of this process is shown in Fig. 6.

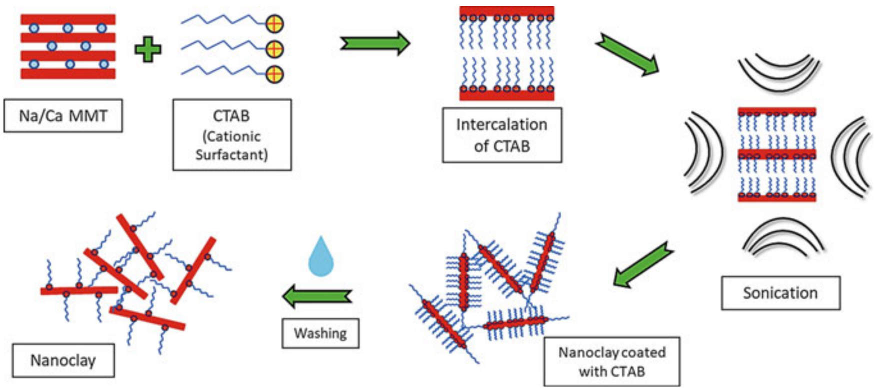

Fig. 6 Effect of cationic surfactant

4.2 Effect of Nonionic Surfactant

When nonionic surfactant is added to the solution, the oxygen in the nonionic surfactant may build the covalent bond with the negatively charged clay particles [2, 3, 9]. Their reaction with the mineral can be either in the form of microcomposite, intercalation, or exfoliation. In the present study, intercalation of PEG into the clay layers is observed from the SEM images of S-2. The possible other modes of interaction of nonionic surfactants are presented in Fig. 7. There was no remarkable effect of the anionic surfactant that was observed in the current study which further supports the given hypothesis. The reaction of the anionic surfactant with the montmorillonite mineral could have been same as the "Microcomposite" structure shown in Fig. 7.

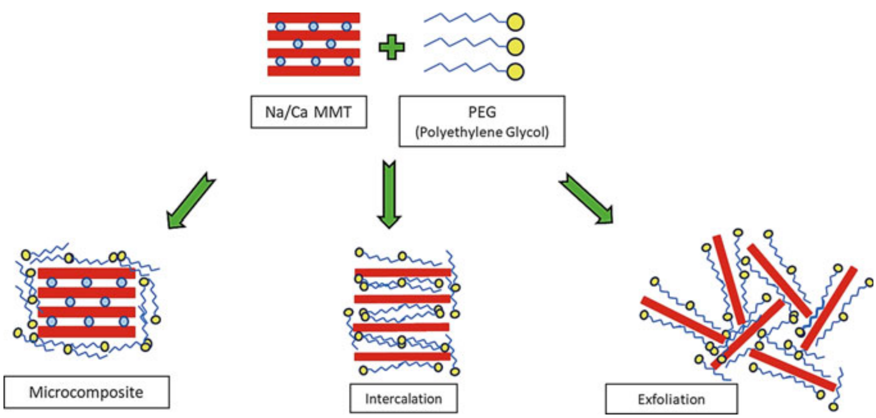

Fig. 7 Effect of nonionic surfactant

5 Conclusions

The current study examined the effect of various surfactants on the exfoliation and extraction procedure of Nanoclay from commercially available Bentonite soil. The experiments were conducted on the raw and processed Bentonite and results were analyzed in terms of X-ray diffraction (XRD) and scanning electron microscope (SEM) responses. Key observations are summarized as follows:

- With the use of cationic surfactant (CTAB), Nanoclay of the particle size range of 10–15 nm is extracted from the commercially available Bentonite soil. Successful intercalation of this surfactant and exfoliation of montmorillonite mineral was observed from both the XRD and SEM analyses.
- Effect of nonionic surfactant (PEG) on the Bentonite soil is not clearly visible in the SEM images and XRD pattern. Intercalation of PEG due to the covalent bond of oxygen with clay particles was observed with the growth of additional unidentified needle-like structures.
- No prominent exfoliations of sheets were observed in pure sonicated Bentonite and treated soil with the anionic surfactant (Trisodium Citrate).
- Less-expensive laboratory method of Nanoclay extraction from easily available Bentonite soil is successfully developed.

Acknowledgements Financial support from IIT Gandhinagar is gratefully acknowledged. The authors are indebted to Mr. Kaling Taki for providing the Bentonite soil basic property data. Any opinions, findings, and conclusions or recommendations expressed in this material are those of authors and do not necessarily reflect the views of IIT Gandhinagar.

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Uncertainties in Water Retention Curve of Bentonite

A. Prakash, B. Hazra and S. Sreedeep

Abstract Bentonites are increasingly used for various geoenvironmental applications (e.g. hydraulic barriers and waste containment) owing to its low hydraulic conductivity and high water retention capacity. Investigating the aforementioned problems necessitates the knowledge of the water retention curve (WRC) of bentonite, which maps the variation of the degree of saturation (S) with suction (ψ). It is now well established that there are various uncertainties associated with WRC. In this study, a database exclusively for the WRC of bentonite is presented. The uncertainties in the WRC parameters of the database are quantified using the copula approach and thereafter confidence intervals are created. Finally, as an application example, the confidence intervals are used to calculate uncertainty bounds in an unsaturated transient seepage problem.

Keywords Bentonite · Water retention · Uncertainty · Copula

1 Introduction

Bentonite finds its use in various geotechnical and geoenvironmental applications such as underground disposal of nuclear waste [32, 36] and waste containment [10, 14]. The reason for preferring bentonite over other materials in these projects is due to its high water retention capacity and extremely low hydraulic conductivity. Modelling the hydraulic response in the aforementioned projects essentially require the water retention curve of bentonite. Water retention curve (WRC), also known as

A. Prakash (✉) · B. Hazra · S. Sreedeep
Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India
e-mail: atma.prakash@iitg.ac.in

B. Hazra
e-mail: budhaditya.hazra@iitg.ac.in

S. Sreedeep
e-mail: srees@iitg.ac.in

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soil water characteristic curve (SWCC) is one of the most important constitutive equations which maps two key hydraulic state variables: water content and suction ψ.

However, the measurement of WRC for bentonites is not a straightforward but a time-consuming, expensive and cumbersome task. For example, obtaining a single data point (water content and suction) in the WRC of bentonites in some cases may take up to 50 days [9]. Also, given the fact that volumetric measurements are also required in the case of bentonites, the process becomes even more tedious. Even after being measured, the obtained WRC is not sufficient as there are various sources which contribute to non-uniqueness of WRC. Some of them are choice of suction measuring instruments [1, 16–23], initial state of the material [19, 38], hysteresis [8, 37], etc. Though the WRC or SWCC is supposed to be a 'characteristic' or is unique for a material, the aforementioned and many other sources of uncertainty essentially imply that measurement of a single WRC is not sufficient. But as already mentioned, the measurement of even a single WRC is difficult for bentonites; obtaining multiple WRCs is not practically feasible.

In such cases, statistical estimate from soils of similar class or texture is extremely useful and has been successfully employed in the past for various other classes of soils. Carsel and Parrish [4] was perhaps the first one to demonstrate the usefulness of probability theory to quantify the uncertainties in various WRC parameters using the UNSODA database. A preliminary statistical analysis was conducted by Sillers and Fredlund [28] over 230 WRCs and the first and second moment was thereafter reported for various WRC parameters. Phoon et al. [20] proposed a first-order estimate from the statistical generalizations of WRCs belonging to similar class of soils. A joint lognormal model for vG WRC parameters was thereafter proposed. Chiu et al. [6] used Bayesian approach to obtain the updated PDF of uncertain parameters associated with WRC and created confidence interval for various classes of soil. Prakash et al. [21, 22] used the copula theory to construct the joint PDF of vG parameters accounting for instrumental and material uncertainty in fly ash.

It should be noted that performing a statistical analysis requires a database, with preferably at least 30 soils in the same class. While there are databases (e.g. UNSODA) for sandy or silty soils, the same is missing for highly expansive clays like bentonite. Therefore, a database for WRC of bentonite is presented. Using the vG (1980) model, the scatter in the compiled database is reduced to a set of curve fitting parameters. Thereafter, the joint distribution of the same is evolved using Gaussian copula and thereafter the confidence intervals are created. Finally, as an application example, the confidence intervals are used to calculate uncertainty bounds in an unsaturated transient seepage problem.

2 Database

This study presents a large database for WRC of bentonites compiled from the literature in Prakash et al. [24]. For a deformable material like bentonite, S versus ψ is widely accepted as the most informative form of representation for bentonite WRC [17] since the key parameters such as air entry value (AEV) and residual degree of saturation are better identified on S versus ψ curve rather than on the θ_w versus ψ or w versus ψ curves. Hence only the sources where WRCs are reported in the form of S versus ψ were collected. The total number of WRCs compiled from the literature is 60 which corresponds to a total of 565 data points with an average of 9.4 data points per WRC. The WRCs in the database correspond to different bentonites, various initial densities, temperature, and are also subjected to different paths such as wetting or drying. As already discussed, all of these factors contribute to the non-uniqueness of WRC. An ideal case would have been to further quantify the uncertainties based on the above factors but unfortunately the number of WRCs available on further breakdown will be too less for satisfactory statistical estimation and inference. Details of the compiled database with its sources are summarized in Table 1.

Table 1 Details of the compiled database for bentonite WRC

S.I. No.	References	Bentonite	No. of WRCs
1	Zhu et al. [39]	GMZ	4
2	Chen et al. [5]	GMZ	1
3	Lloret et al. [15]	FEBEX	9
4	Villar [34]	FEBEX	2
5	Villar [36]	FEBEX	3
6	Alonso et al. [2]	FEBEX	3
7	Dai et al. [7]	FEBEX	1
8	Villar and Loret [35]	FEBEX	3
9	Tripathy et al. [31]	MX-80	1
10	Tripathy et al. [32]	MX-80	5
11	Seiphoori et al. [27]	MX-80	3
12	Hökmark et al. [13]	MX-80	1
13	Rizzi et al. [26]	MX-80	1
14	Villar [36]	MX-80	12
15	Ravi and Rao [25]	BARMER	10
16	Baille et al. [3]	German	1
		Total	60

Note GMZ = Gaomiaozi (China), FEBEX = Full-scale Engineered Barriers Experiment (Spain), MX-80 = Wyoming (USA), BARMER (India)

3 Copula Approach

This section presents a brief overview of the copula theory with respect to bivariate distribution functions. A comprehensive and more general overview of copulas can be found in Nelsen [18]. For usage of the copula theory specific to WRCs, one can refer to the literature (e.g. [16–23]). Sklar [30] theorem forms the foundation of the copula theory. According to it, every multivariate cumulative distribution function of a random vector can be expressed in terms of a copula and its marginals. When applied to bivariate case, it means that

$$H(x_1, x_2) = C(F(x_1), F(x_2); \theta) = C(u_1, u_2; \theta) \tag{1}$$

where $H(x_1, x_2)$ is the bivariate joint cumulative distribution function and $u_1 = F(x_1)$ and $u_2 = F(x_2)$ are the marginal cumulative distribution functions (CDFs), respectively, and C is the copula with parameter θ. It also states that for a bivariate distribution $H(x_1, x_2)$, the copula is unique on the Cartesian product of the range of marginal CDFs $RanF(x_1) \times RanF(x_2)$. This provides uniqueness of the copula when the marginals are continuous.

A two-dimensional copula is a function C of two variables that provides a link between its one dimensional marginal and joint distribution function. It is defined over a unit square $[0, 1]^2$ with uniform marginals. Even when strictly increasing, the transformations are applied to associated random variables, copula remain invariant. This is an advantage since the copula can exactly capture the joint distribution properties even under strictly increasing transformation. The bivariate probability density function (PDF) can be obtained by taking the derivative of the joint CDF given by Eq. (1) as follows:

$$f(x_1, x_2) = f_1(x_1) f_2(x_2) D(u_1, u_2; \theta) \tag{2}$$

where $D(u_1, u_2; \theta) = \partial^2 C(u_1, u_2; \theta)/\partial u_1 \partial u_2$ is the copula density function and $C(u_1, u_2; \theta)$ is the copula function with parameter θ. For the estimation of copula parameter θ, Kendall's τ was used. Kendall's τ can be expressed in terms of copula and its parameter θ as [26]:

$$\tau = 4 \int_0^1 \int_0^1 C(u_1, u_2 : \theta) dC(u_1, u_2 : \theta) - 1 \tag{3}$$

Solving the above integral equation for different copulas yields a unique relationship between Kendall's τ and copula parameter θ for each copula. For evaluation of the goodness of fit among the copulas, Cramer–von Mises statistic [11] is used here. The CM statistic (S_n) represents the distance between the true and