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Ph.D. THESIS

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CONTRIBUTION ON SOIL IMPROVEMENT USING NANOMATERIALS

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Contents

ABSTRACT

The purpose of this study was to evaluate numerically and experimentally the effect of using nanomaterials to improve soft soils collected from Romanian sites. With the urban development and the rapid increase in population, including projects to expand cities, the need has become urgent to implement various types of projects such as buildings, dams, highways, and others. The soil of some sites is weak and do not have the necessary and required engineering properties. Because of that, the ground properties should be improved from poor soil to soil with good efficiency, like increasing the shear force in the soil, reducing soil compressibility and reducing soil permeability. Therefore, soil improvement is an essential solution to enhance its characteristics. Soil samples had been taken from Perisoru, Calarasi County and Viisoara sud, Vaslui county Romania, from sites where there is a need for soil improvement, due to very low soil consistency and poor mechanical soil parameters. The soil used is classified according to the texture classification system. Nanomaterials can be described as chemical materials with particles that are smaller than 100 nm, which are used in various domains. Two different types of nanomaterials were used in this study, which are namely Nano-MgO with different percentages (0.5%, 0.75%, 1%, and 2%), and Nano-Al_2O_3 with percentages (0.5%,1%, and 2%). The procedure is as it follows: several soil samples had been mixed with various amounts of Nano-MgO and Nano-Al_2O_3 (percentages between 0.5 and 2%) and some soil samples had been mixed with 2% cement. The mixed soil samples were left for at least 48 hours for curing and compacted using the modified proctor test procedure and tested. The compacted treated soil had been tested in the laboratory for soil strength, consistency, and compressibility. A set of laboratory tests were done on the soil samples, like Atterberg limits, grain size analyses, modified Proctor test, oedometer test, and direct shear test. To observe the changes in the microstructure of the soil samples, because of the addition of nanomaterials, Scanning Electron Microscopy (SEM), and X-ray Diffraction tests were done. A numerical model was developed to simulate the ground problems and the structural failures observed and to assess the settlement and the damaging mechanism of an old masonry church, by using finite element software Plaxis 3D. The rectangular foundation is placed on yellowish silty clay (loess), at 1.5 m depth from the ground surface, with applied an effective pressure of 200 kPa was modeled and analyzed. Mohr-Coulomb soil model was used for the soil and the linear elastic model was used for the foundation. After computing the settlements, it has resulted the need of improving the soil. The results have been compared with the soil treated with

2% cement. The numerical analysis results showed that the value of the settlements beneath the foundation reduced with an increase in the amount ranging from 0.5% to 2% of the Nano-MgO and Nano-Al_2O_3. However, the experimental results showed that there was a small effect on the Atterberg limits, little decrease in the value of the liquid limit and plastic limit, small increases in the shear resistance of the soil and the compressibility of the soil samples increased with an increase in the amount of nanomaterials.

1 INTRODUCTION

1.1 General

Soil is natural mineral particles that can be separated into relatively small pieces that have been formed by the breaks down of rocks because of weathering processes and may contain water, air, or organic materials (formed by the decomposition of plants). On another hand, it is considered the oldest and the cheapest material used in construction works [1].

The rapid urban development and expansion, it has become necessary to take advantage of poor soils and improve their engineering properties to become suitable for use in various civil engineering works. The civil engineering structures like buildings, bridges, roads, tunnels, dams, etc., to be in safe, suitable and stable soils are required with considerations of strength, settlement, permeability, bearing capacity, consistency, and density.

Soft soil is the general term that describes silt and silty soil with large water content, low shear strength, high compressibility, and low permeability. All that leads to decrease in the bearing capacity and settlement problem. Soil stabilization is a term for any physical, chemical, or mechanical method to change the nature of the soil and make it suitable and more acceptable to meet an engineering purpose [2]. Soil stabilization is a change in the mechanical properties of the soil, to increase its ability to support the applied loads. The physical, chemical, and biological consider three types of stabilization. Physical stabilizations are modifications of the soil's texture, to improve its properties, modifying porosity and friction between its particles, to achieve soil stability and ensure the safety of the structure that builds on it [2]. Mechanical compaction is widely used in soil stabilization by using mechanical methods to expel the air from the spaces between soil particles so that will make the soil more resistant to the applied load. The chemical treatment is considered one of the important factors for many geotechnical engineering applications, due to the settlement of weak or soft soil. [3] Chemical stabilization is divided into two parts, traditional and non-traditional additives. Examples of traditional additives are cement, lime, and fly ash and they are usually based on calcium. Those materials when are exposed to water a chemical change occurs, which leads to improvement of the soil properties, reducing settlements, and improving shear strength. Cement is one of the oldest materials that are added to the soil to improve its properties, due to its high efficiency, The use of cement also has many limitations. For example, the content of the organic material must not exceed 2% for the soil wanted to mix with cement, it contain a small amount of clay, and is without salts, such as sulfate salts that affect the formation time of the cement soil. [4].

Non-traditional "soil stabilization additives consist of a wide range of chemical agents that are different in their composition, they react with the soil" [5]. The nanotechnologies idea was suggested by Richard Feynman for the first time in 1959 [6]. After that, this technology developed in all the branches of the sciences. Soil enhancement using nanomaterial comes from the inter-particles, which occurs because of the difference in the size of the particles. Some researchers have introduced nanomaterials as chemical additives to use in soil stabilization. Not much work has been done on studying the effect of using nanomaterials on the geotechnical properties of the soil and their fundamental stabilization mechanism are yet to be, fully explored.

1.2 Problem statement

The church Adormirea Maicii Domnului is located in commune Perisoru, in Calarasi county, about 120 km in the east of Bucharest, Romania. This region from the geotechnical point of view is known as of loessial deposits which are wetting sensitive as shown in figure 1, with a thickness 10m and can be reached until 25m [7]. Loess covered approximately 19% of the area in Romania generally. Loess is a sedimentary rock made of fine particles, light brown in color, unconsolidated, with very low plasticity, high porosity (40-50) % with a low degree of cementation, which leads to a dusty appearance observed especially during dry summer periods. Loess composition is made of quartz, clay, and limestone [8]. The physical condition of the church is precarious: fractures, cracks, and fissures have been identified in the masonry, caused by deferential settlement. These settlements which are exceeding 30-40cm are mainly caused by the increase of groundwater table level in time. The roof sheet is corroded, and the water collection and drainage system are damaged. The vertical systematization of the land is improperly made, unfinished and damaged. The rectangular foundation of the church Adormirea Maicii Domnului is placed on saturated yellowish silty clay, soft consistency (wetted loess) at 1.5m depth from the ground surface. We had considered and applied an effective pressure of 200kPa. The foundation is that part of a structure that transmits loads directly to the soil, a process known as soil-structure interaction. The foundation must be designed to have sufficient capacity or resistance to support the applied load and to avoid any large deformation under these loads, which might damage the structure [9].

For many years the settlements did not cause any structural problems. One may consider that the consolidation process took place, and no problems were recorded. At year 1994 many wells have been drilled in different locations of the Perisoru village, and large quantities of the water were pumped for irrigation uses, these processes were leads to record an increase in the groundwater table level in the region, which wetted the loess layer and caused additional settlements to many buildings in the area, including the church. These deferential settlements are mainly caused by the increase of groundwater table levels in time. The main reason for the problems of the structural failure elements is the rising in the groundwater level, in addition, most of the existing buildings were built during this period when seismic action was not considered in the design, so they were built from the beginning by traditional methods and designed only for rapacious actions.

1.3 Objective of the study

1. To investigate the influence of the nanomaterials (i.e., Nano-MgO and Nano-Al_2O_3) on the geotechnical properties of the soil.
2. To study the changes in the soil matrix by mixing it with different percentages of nanomaterials.
3. To determine the effect of the different types of nanomaterials on the stability of the treated soils under the applied effective pressure.

1.4 The scope of this study

The soil may enhancement by using nanomaterials, that comes from the inter-particles, which occur because of the difference in the size of the particles. The scopes of this study is to encompass the main objectives of this research and include:

a) The soil samples were obtained from a different site in Romania. The first soil was from commune Perisoru, Church Adormirea Maicii Domnului, which is located at approximately 120 km East of Bucharest. The second soil that was collected was from commune Viisoara Sud, Vaslui county which is located approximately 300 km in the north of Bucharest.

b) Several soil samples have been tested in the laboratory for soil consistency, compressibility, and shear strength before and after being mixed with two types of nanomaterials (Nano MgO and Nano-Al_2O_3) with different percentages

c) Experimentally evaluated the effect of the nanomaterials on the geotechnical properties of the soil and compared it with soil treated with 2% cement.

d) Numerically investigated the ground problems and study the ability of nanomaterials to improve and increasing the bearing capacity of the soil.

1.5 Nanomaterials

Nanomaterials can be described as materials with particles of at least one dimension between 1-100 nm. Nanometer is one million of millimeter. Nanomaterials can occur naturally, be created as the by-products of combustion reactions, or be produced purposefully through engineering to perform a specialized function. Nanomaterials can have different physical and chemical properties than their bulk-form counterparts. They can be found in single, agglomerated forms with spherical, tubular, and irregular shapes [10]**.** Three groups of nanomaterials can be classified depending on their geometry [11]. For example, nanoparticles have all three dimensions between (1-100) nanometer, nanofibers have just two of their dimensions in the nanometer range and in the case of nanoplate there is just one dimension below 100nm [12]. In recent years, these materials have a high interested to use in many fields because it has surface area to volume ratio, which can make it more chemical reactivity with large fraction of surface atoms.

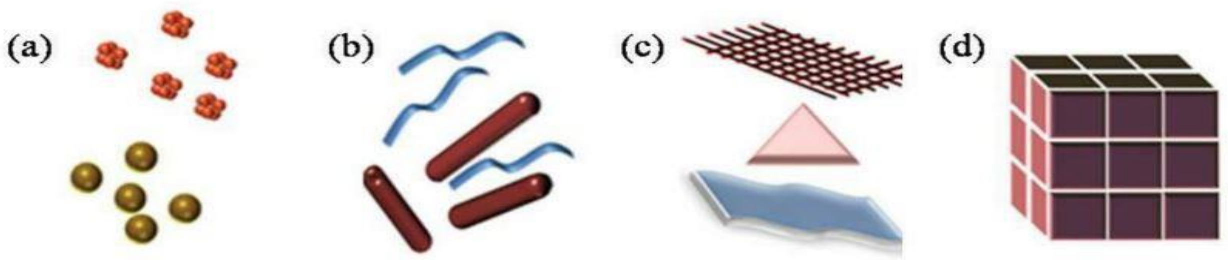


Fig. 1-1. Classification of nanomaterials a)0D spheres and clusters, b) one-dimension nanofibers, c)2D nanoplate, d)3D nanoparticles [13].

There are many different techniques that are used to investigate the purity and determine the size of the nanoparticles in the nanometric range, see table 1.

Tab.1 Common methods to measure the particle size of the nanomaterials [13].

Technique name	Measurement range	Types of size distribution of raw data
Electron microscopy (EM)	1 nm or higher	Number based
Centrifugal liquid sedimentation (CLS)	20 nm and higher	Extinction intensity based
Small-angle X-ray scattering (SAXS)	5 nm and higher	Scattering intensity based
X-ray diffraction (XRD)	1 nm and higher;	No distribution measured

1.6 Nanomaterials applications

The materials which have particles with size from 0.001 micrometer (1nanometer) and smaller than 0.1micrometer (100 nanometer) are termed as nanomaterials [14]. According to the European commission, nanomaterials defined as natural, incidental, or manufactured material with particles have one or more dimension between the range (1-100) nm [15]. Recent days nanotechnology has become a very important in the research field in the world. Nanomaterials have many different applications, in different branches of science, such as medicine, physics, chemistry, biomedical and environmental etc. [16].

These materials have a special specification, like a bigger strength and conductivity as well as a chemical reactivity. if compared with the same materials without nanoscale, on the other hand, it has also a negative effect, like potential effects of toxicity and ecotoxicity [17]. Currently, nanomaterials are widely used in the field of civil engineering, mainly in conventional construction materials to improve the properties of cementation materials and to give a strong structure element, also to reduce the workability of cementation composites [18]. Nanomaterials become more relevant in the construction works specially they are able to use as addition or additives materials to enhance and stabilize the properties of different constructions materials like concrete, asphalt, subbase, and soils etc. [19]. All civil works and structures are found on the soil, soil is considered one of the oldest materials which had used as a construction material. The importance of soil stabilization from the point of view of nanotechnology is because soil has a great variety of sizes ranging from nanometers to millimeters [20].

Tab. 1-1 Overview of nanoparticles and their application [21].

NO	Nano particles	Applications
1	Nano-Silica Sio_2	Replace part of cement to density concrete
2	Micro Silica	Increase compressive strength and flexural strength in concrete
3	Nano carbon tubes	Use as a sensor to monitor structure conditions in concrete
4	Nano phosphorus	Improving road visibility
5	Nano Tio_2	Self-cleaning of concrete pavement
6	Polymeric fiber matrix with Nano-Silica	Self-structure health monitoring system in repairs and rehabilitations
7	High performance steel using copper nanoparticles	In bridge for corrosion resistance and improved weldability
8	Nanotechnology enables sensors	For monitoring and controlling temperature, humidity, smoke, noise stresses and cracks

1.7 Review of literature soil improvement by using nanomaterials:

Jarrahzade1 and Bajestan [22] studied the change of clay structure by nanotechnology due to soil stabilization in both urban and rural roads. They have suggested a new and cheaper method to improve soil properties than normal methods. Their studies are based on the changing clay structure by nanotechnology, it will change to be hydrophobic after it was hydrophilic. They used several sheets made of silica and alumina. The water is strongly bound to the surface of the clay particles and cannot be removed by sunlight drying or using ovens, but it can be removed easily by using chemicals called con-aid. Which, in turn causes an ion exchange and takes a place on the surface of the clay. On the other hand, the adsorbed water will displace or remove to make the clay in a hydrophobic state. Their results show that nanocomposites of clays can reduce the thickness of the asphalt from 27cm to 5cm.

Majeed and Taha [23] studied the influence of adding nanomaterial on the properties of Penang soft soil. A different nanomaterial, nano MgO, nano clay, and nano Cu, with proportions ranging from 0.05% to 1%, were added to soft soil samples from the State of Penang, to investigate and study their effect on geotechnical properties. Atterberg limits, linear shrinkage, unit weight, moisture content, and shear strength of the soil were determined, and it is decreased with increasing of the quantity of nanomaterials. On the other hand the increase of nanomaterials is due to an increase in the maximum dry density, that means generally indicates soil improvement. Also, the optimum moisture content increased, the results also showed the compressive strength of the soil increased with the addition of nanomaterials.

They also investigated in 2014 [24]. how to modify and stabilize soft soil by using nanomaterials. Three types with an amount less than 1% are used in this research which are, nano-magnesium, nano-copper, and nano-clay. Nanomaterials were added to the soft samples collected from two different sites in Malaysia. The results show that the addition of nanomaterials due to decreases the linear shrinkage, liquid limits, plastic limit, and plasticity index. On another hand, the dry maximum density and the compressive strength of the soil increases with increasing the amount of nanomaterial and decreases the optimum water content.

Babu and Joseph [25] presented an experimental work and studied the effect of adding different nanomaterials nano Fly ash and nano Titanium Dioxide (TiO_2) with a proportion of (0.5%, 1%, 1.5%, 2%). On the samples of soft soil that collected from Nedumudi region of Kuttanadu. their results showed that the increasing amount of nano fly ash and TiO_2 decreased the liquid limit and plastic limit by around 60%. Optimum moisture content decreased by 5.2 %, the maximum dry density increased by 2.94 %, and the shear strength increases to twice the original value. Also, they noticed that the nano fly ash is better than TiO_2 for reduction settlement at the optimum percentage of nano fly ash and Titanium Dioxide (67%,60%) respectively.

Priyadharshini and Arumairaj [26] investigated experimentally the effect of adding three types of nanomaterials nano Al_2O_3 and Nano MgO and nano clay with a different percentage to soft clay samples, with consistency between (0.25-0.5) and UCS between (25 to 50) kN/m^2. Their model studied the conducted in a steel tank of (30x30x30) cm with (6x6) cm square footing to determine the load-carrying capacity of the footing for soft clay with nanomaterials. The results showed that the increasing amount of Nano Al_2O_3 and Nano MgO decreased Atterberg's limits and increase in nano clay amount increase the Atterberg's limits. The optimum moisture content increase when increasing the amount of Nano Al_2O_3 and nano clay, and vice versa for Nano MgO. Also, increasing the amount of Nano Al_2O_3 and nano clay leads to a decrease in the maximum dry density, and an increase in the amount of Nano MgO leads to an increase in the maximum dry density. The compressive strength increases up to 43% for 0.75% of Nano Al_2O_3 and 41% for 0.3% Nano MgO and 48% for 1% nano clay. In their study, they also found that nano MgO is reducing the settlement better than the nano clay and nano Al_2O_3.

Subramani and Sridevi [27] studied the effect of nanomaterials nano cement and nano clay, with the various percentages ranging from (0.5% to 2%) on the soft soil (peat). Consistency limits, compaction characteristics, and compressive strength are determined in their investigation. The results showed that the increase of the percentage of nanomaterials increases the maximum dry density. That gives an indication of improvement in geotechnical properties, the unconfined compressive strength increases when one increased the amount of nanomaterials. The plasticity index decrease with increase the amount of nanomaterials. Also, they found that when combined addition (1% nano clay and 1% nano cement) gave maximum strength when compared with the addition of 2% nano cement and 2% nano clay.

Mostafa et al. [28] investigated the stabilization of subgrade pavement using nanomaterials (nano-silica and silica fume) with various amounts. They used 1,2 and 3 % for nano-silica and 5,10 and 15% for silica fume while used 2,4,6 and 8% for lime. Their study was to estimate the physical and mechanical properties, using the Atterberg limits test, direct shear test, free swelling, modified proctor test, unconfined compressive strength, and California bearing ratio. They did unconfined compressive strength and free swelling test after two curing periods 7 and 28 days. The results showed that the maximum dry density decreased, and an increasing in the optimum moisture content was observed for all user activities, the unconfined compressive strength increased, also they noticed that the maximum drop in free swelling was when used a combination of (8% lime + 15% silica fume) and (8% lime +3%nano silica).

Majed and Taha [29] analyzed and studied the geotechnical properties of the soft soil after mixing it with a different percent of nanomaterials (nano MgO, nano Al_2O_3, and nano Cu_2O). They determined the compressive strength, dry unit weight, and moisture content. They found that the compressive strength and the dry density of the soft soil increased with increasing the amount of nanomaterials, at the same time the moisture content decreased.

Naval et al. [30] studied the effect of different percent of nanomaterials, 0.5%, 1.0%, 1.5%, and 2.0% from Nano Al_2O_3 and Nano MgO on the properties of expansive soils. They found out that the swelling potential of the soil decreased when the amount of nanomaterials increased from 0 to 2%. The reason for this decrease is due to a decrease in the values of liquid limit, plastic limits, and plasticity index of the soil. The explanation for this may be a structural unit of kaolinite mineral composed of silica and gibbsite sheets, and when water enters their causes swelling. On the other hand the addition of nanomaterials led to filling the tiny pores, and therefore reduced the amount of water into these units of the structure, and thus decrease the swelling of the minerals. Also, the maximum dry density increases with increasing the amount of nanomaterials.

Rajendiran and Vadivel [31] study was made on a neat cementitious grout with a w/c ratio 1.20 incorporated with different percent (0%, 0.10%, 0.50%, 1.0%, 1.50%) of nano-silica (SiO_2). They found that the bleeding potential decreased with an increase in the amount of nano-silica. On the other hand, they found that the neat cement grout had unstable high bleed ability. Also, the specimen that treated nano cementitious grouted was found more impermeable to water, compressive strength increases 1.6 times than that treatment with neat cement grouted. the Nano silica (SiO_2) added cementitious grout shows improvement of the engineering properties as well as the fresh mixed grout properties.

Taha et al. [32] studied the effect of Carbon Nanomaterials (carbon nanotube was compared to carbon nanofiber) on sandy clay soil improvement. The maximum percentage of nanomaterials was used in their study was 0.2%. They found that the PH, the specific gravity, and the maximum dry density of the mixture soil-nanomaterials increase with the addition of nanomaterials. The results of the hydraulic conductivity test showed that nanomaterials reduce the value coefficient of permeability and the sample of the soil treatment with carbon nanofiber (CNF) appears a higher reduction of hydraulic conductivity when compared with the use carbon nanotube (CNT).

Cui, Hongzhi, et al [33]. studied the effects of Nano-silica and carbon fiber on the geotechnical properties of silty soils. Soil samples were prepared by mixing with a different amount of Nano-Silica and carbon fiber. The laboratory tests results indicated that the adding of nanomaterials leads to increase the shear strength of the soil. Also, they observed that in the case of make a combination (2% wt of carbon fiber and 3% Nano-Silica) the shear strength increase about 128.3% compared with untreated soil.

Choobbasti et al. [34] investigated the influence of using different percentage of nano calcium carbonate (0.4%, 0.8%, 1.2%) and carpet waste fibers (0.2%, 0.4%, 0.6%) on the geotechnical properties of the clayey soil. The soil samples which were left for curing about 42 days showed a significant strength improvement, also the results showed reducing in the value of the liquid limit and increase in the plastic limit, in other hand they observed that addition a small quantity of carpet waste fiber (less than 0.2% by weight of the soil) does not have a sufficient effect on the strength of the soil.

AH Vakili et al. [35] investigated experimentally and studied the stabilization of dispersive soils by using Nano-Silica. Different percentage of Nano-Silica were used to improve the soil and let it 28days for curing. They observed that increase in the amount of the Nano-Silica led to increase the potential of the treated soil samples, provided that the amount of the additive material should not exceed 1%. The results showed that the unconfined compressive strength increase, and the plasticity index decrease when increase the percentage of Nano-Silica, in addition its workability improved.

1.8 Experimental tests – results and disscutions

This study investigated experimentally the effect of different types of nanomaterials on the geotechnical properties of soils collected from two different sites in Romania. Two different types of nanomaterials were used in this research, which are namely Nano-MgO with different percentages (0.5%, 0.75%, 1%, and 2%), and Nano-Al_2O_3 with percentages (0.5%,1%, and 2%).

The improvement soil properties using nanomaterials depends on the type and the amount of these materials. Insoluble nano materials, like nano-MgO show a small chemical effect on the soil as the results of the Scanning Electron Microscopy showed, thus, the using of nano-magnesium oxide had a small effect on the properties of the soil.

From the analysis of the results obtained with SEM, we can observe that a visible change in the microstructure of the samples, occurs especially on the soil samples mixed with 2% Nano Al_2O_3. In the case of 0.5% and 1%, the microstructure of soil-nano-alumina mixtures indicated that the new phase formed by adding Nano Al_2O_3 had a small interaction and consisted of some new bonds between the particles of the soil samples.
The results showed that There was a small effect on the Atterberg limits, there are little decreases in the value of the liquid limit and plastic limit, the compressibility of the soil increased with an

increase in the amount of added nanomaterials for both soils, Also, observed that the shear strength of the soil increased with increase the amount of nanomaterials.

As a result, we can conclude that the nanomaterials may help to improve the geotechnical properties of the soil, but, from a technical point of view, they had little impact on the geotechnical properties of the soil. Also, from the economical point of view, compared to other and common chemical additives like cement, they are an expensive option. They may work well as an additive to cement mixing technologies.

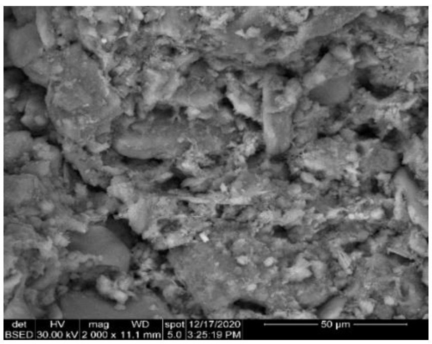
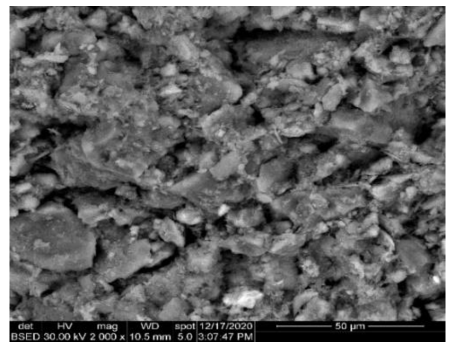
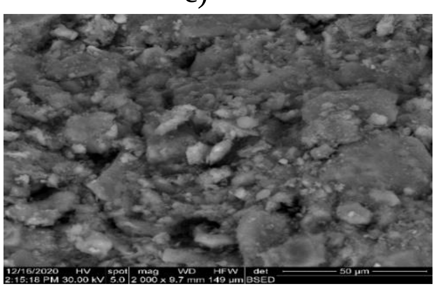
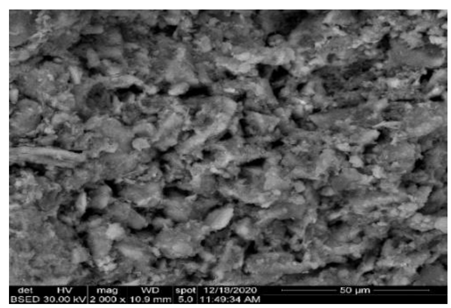
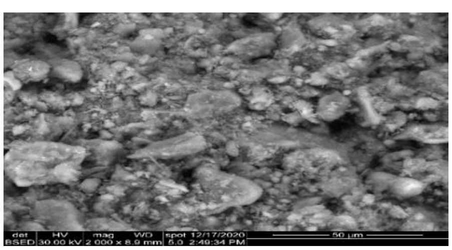
Non treated soiL	Soil treated with 0.5% Nano-MgO
 a)	 b)
c) 	 d)
Soil treated with 0.75% Nano-MgO	Soil treated with 1% Nano-MgO
 c)	
Soil treated with 2% Nano-MgO	

Fig. 1 SEM microscopy on soil samples with a measurement 50 μm

<table>
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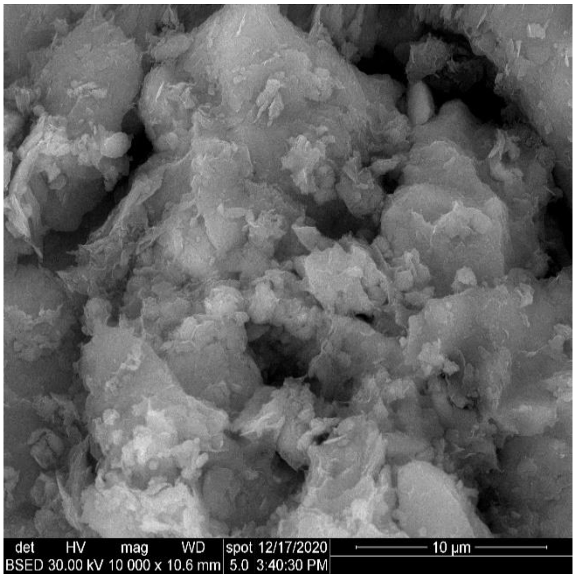
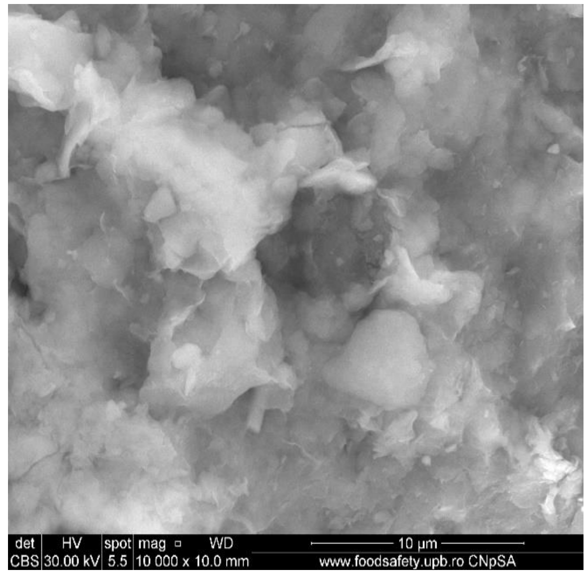
<tr><td>

a)</td><td>

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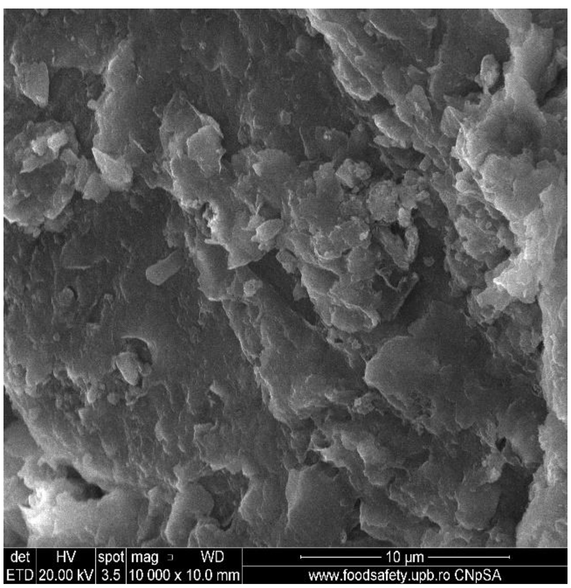
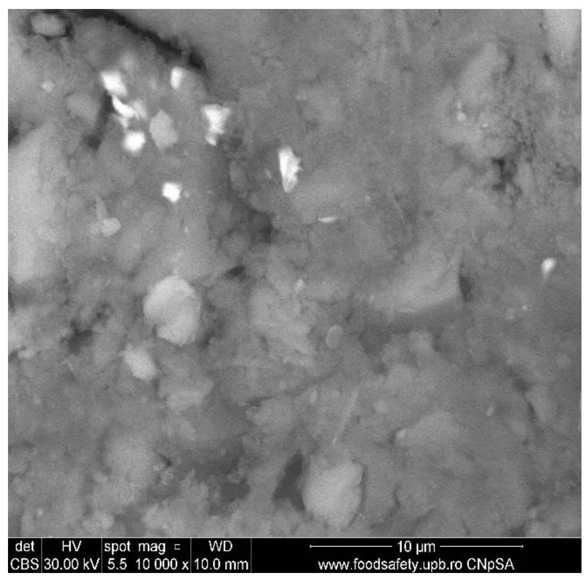
<tr><td>

c)</td><td>

d)</td></tr>
<tr><td>Loess + 1% Nano-Al_2O_3</td><td>Loess + 2% Nano-Al_2O_3</td></tr>
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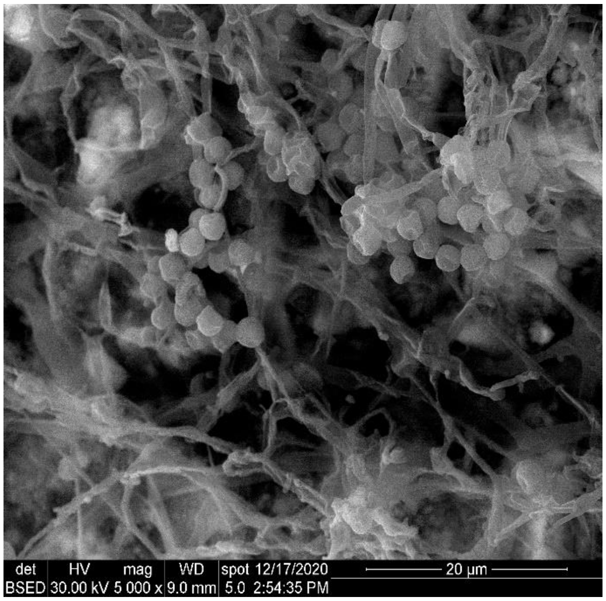
Fig. 2 SEM microscopy on soil samples with a measurement 10 µm



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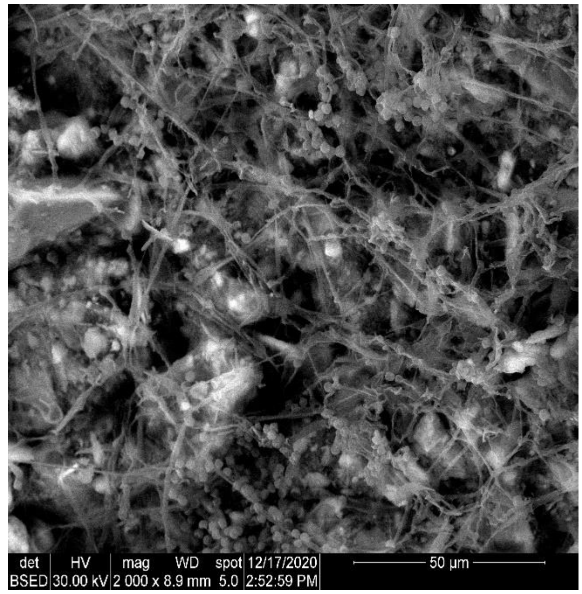
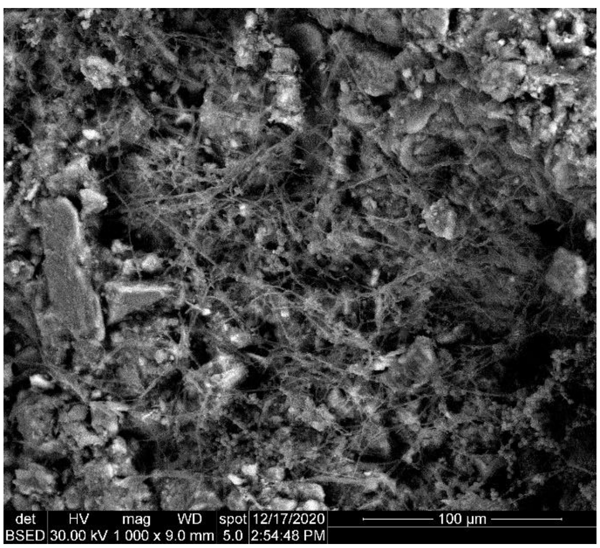


b)



c)

Fig. 3 SEM microscopy on Soil treated with 2% cement a) with a measurement of 20 μm, b) with a measurement of 50 μm, c) with a measurement of 100 μm

1.9 Numerical modeling of improvement of the ground by using nanomaterials

This study was conducted to assess the efficiency of the soil improvement meant to stabilize the settlements for the church Adormirea Maicii Domnului, commune Perisoru, Romania.
A series of laboratory tests and three-dimensional FEM analyses were used to perform this task. The soil parameters, required for the numerical analysis, were obtained from laboratory and field tests.

The results of the numerical analysis showed that the total vertical displacement of the soil was 27.2cm. The main reason for this high value of the settlement and the damages in the structures are due to the rising groundwater level in the region.

Different percentages of Nano-MgO have been used to improve and modify the soil properties. All the results have been compared with 2% soil mixtures with cement. The value of the settlement decreases with an increase in the percentage (0.5%, 0.75%, 1%, 2%) of the Nano-MgO (19.0, 15.8, 10.7, 8.0) cm, respectively, and 6.5cm when using 2% cement. It can be observed that the value of the settlement when using Nano-MgO is still larger than the value of the settlement when using 2% cement.

In conclusion, the use of cement is more suitable from a technical point of view, in addition to the high-cost difference between cement and nanomaterials in general.

1.10 Summary and study directions

The comprehensive review of the literature presented the nanotechnology and nanomaterials as additives to the soil and discusses the effects and results on the physical, mechanical, and chemical properties of the treated soils. Many types and different percentages of nanomaterials were used in this review chapter, such as Nano-clay, Nano Al_2O_3, Nano MgO, Nano Titanium Dioxide (TiO_2), nano-silica (SiO_2) and others. Scanning Electron microscopy (SEM), TEM Transmission Electron Microscopy (FEM) and X-Ray diffraction (XRD) were used to study the soil microstructure. Because of the small particle size and a higher cation exchange capacity they can be active and react on the soil matrix. This state-of-the-art study found that soil improvement using nanomaterials depends on the type and the amount of these materials. The addition of nanoparticles to the soil leads to improvement of its physical and chemical properties.

Consequently, in order to fill the research gap in the review, we will focus in this research on selecting a new type of additives to cohesive soils-loess in Romania, such as Nano Al_2O_3 and Nano MgO, to study their effect on the physical, mechanical, and chemical properties of the soil. however, this research can be summarized into three directions:

Direction 1: Experimentally investigated the dimensions and the purity of two types of Nanomaterials (Nano-MgO and Nano-Al_2O_3) by Scanning Electron Microscopy (SEM), TEM transmission electron microscopy and X-Ray Diffraction (XRD).

Direction 2: Experimentally investigated how can many types of nanomaterials improve the geotechnical properties of the soils.

Direction 3: Numerically investigated by using finite element software 3D plaxis to assess the settlement of soft soil and study the option of improve the soil under the foundation by using nanomaterials and cement.

2 CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

The present thesis tried to answer two major questions, regarding the soil improvement with nanomaterials:

- Does it work? and
- How it works?

In order to give a reasonable answer, the author has opted for a multidisciplinary approach that covered chemistry, physics, soil mechanics and FEM modelling. Tests have been performed at Technical University of Civil Engineering Bucharest, Polytechnic University Bucharest, Life Sciences University Iasi, in their laboratories.

Does it work?

To answer this question, the author collected samples from two places located in the Eastern part of Romania and mixed them with different percentages of nano MgO and nano Al_2O_3 (obtained and bought by the author from US). Mixing them was a challenge and the author had to design and manufacture a closed system box in order to prevent the inhalation of nanomaterials. Also, the remolding of the samples has been done at optimal moisture content and at the natural void ratio obtained from blocked sampling. To have a comparison with well known and widely used methods, some samples were treated with cement.

In the soil mechanics lab soil samples were tested for Atterberg limits and for mechanical properties (oedometer test and direct shear tests) and we have obtained the following conclusions:

1. The addition of the nanomaterials had a small effect on the Atterberg limits, a small decrease in the value of the liquid and plastic limits, the reason for this may be that the nanomaterial used in this study is insoluble and cannot have a sufficient effect on the soil samples.
2. The addition of the nanomaterials to the soil samples decreased the moisture content, as the results showed that the parameter of the compressibility increased with the increasing of the

amount of the nanomaterials for both soils. This is an indication about the improvement of the soil properties.

3. The results of the direct shear tests showed that the internal friction angle and the cohesion were increased with the amount of the nanomaterials added, compared with the natural soil samples.
4. The use of nanomaterials can stabilize and enhance the soil properties, as the results of the numerical analysis showed - the value of the settlement decreases with an increase in the percentage (0.5%, 0.75%, 1%, 2%) of the Nano-MgO (19.0, 15.8, 10.7, 8.0) cm, respectively, and 6.5cm when using 2% cement. It can be observed that the value of the settlement when using Nano-MgO is still larger than the value of the settlement when using 2% cement. In fact, injecting the soil under the foundations of the church was the final proposal and it was the solution that worked.

How it works?

To obtain an answer, the author looked for changes in the mineralogical and chemical composition of the mixture of soil with nanomaterial. Many complex laboratory tests were performed at Polytechnic University and the results were discussed with the professors there, concluding the followings:

5. The improvement of soil properties using nanomaterials depends on the type and the amount of these materials and, in addition, the curing time.
6. The results of the scanning Electron Microscopy (SEM) test showed that Nano-MgO has a small interaction (chemical) effect on the treated soils. On the other hand the results of mixing Nano-Al_2O_3 with soil showed a visible change in the microstructure of the soil samples, occurs especially when the samples were mixed with 2% Nano-Al_2O_3.
7. By studying the influence of the type of nanomaterials which added to the soil samples it was observed that the addition of the Nano-MgO leads to lower agglomerates size formations and more uniform particle/agglomerates distributions in the soil samples, comparing with adding Nano-Al_2O_3.

8. The value of pH for different percentage of Nano Al_2O_3 after mixing with soil had very little changes.
9. The mineralogy of the soil samples was checked by X-Ray Diffraction tests and all the results of the soil samples that were treated with nanomaterials have new peaks as compared with the natural soil.

Final remark

As a general result, we can conclude that the nanomaterials may help to improve the geotechnical properties of the soil, but, from a technical point of view, they had little impact on the geotechnical properties of the soil. Also, from the economical point of view, compared to other and common chemical additives like cement, they are an expensive option. They may work well as an additive to cement mixing technologies.

2.2 Recommendations for further work

Further research is required to continue the current work, the following suggestion could be a starting point for the future studies:

1. This research investigated experimentally and numerically the effect of two types of nanomaterials namely (Nano-Mgo and Nano Al_2O_3), therefore the future studies should be focus on the other types of nanomaterials.
2. Partially mixing of nanomaterials with some traditional additives like (cement and lime) can be investigated to study their effect on the geotechnical properties of the soil.
3. Increasing the curing time more than 3 days or 7 days like to be (90, 100 days, etc) is recommended to study as well.
4. It is well known that soils that are rich in organic content are difficult to be mixed with cement because of their pH. Nanomaterials are changing the pH, as he author discovered in a series of tests that were done in the Pedological laboratories from Iasi and Bucharest. Mixing them with cement may work in the case of soils with organic content larger than 5%.
5. The effect of wet–dry cycles on the durability of the soil treated with nanomaterials.

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