Prof. Joanna Bzówka, PhD, DSc., Eng.
Silesian University of Technology
Faculty of Civil Engineering
Department of Geotechnics and Roads
Akademicka str., 5
44–100 Gliwice

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R E V I E W O F D O C T O R A L D I S S E R T A T I O N
entitled „Experimental studies of microbiologically induced improvement of fine sands"
written by Nadella Marchelina, M.Sc., Eng.

Polish title
„Badania eksperymentalne mikrobiologicznego wzmacniania piasków"

1. Formal basis

This review has been prepared on the request of the Vice-Head of the Council in the *Discipline of Civil Engineering, Geodesy and Transport* under contract 2025/X/01.

The subject is the doctoral dissertation entitled *„Experimental studies of microbiologically induced improvement of fine sands"* written by Mrs. Nadella Marchelina, M.Sc., Eng., under the supervisions of prof. Małgorzata Franus and dr. Joanna Fronczyk.

2. Substantive assessment of the dissertation

2.1. Subject and general description of the dissertation

As it was mentioned by Mrs. Nadella Marchelina at the beginning of the PhD dissertation, Microbially Induced Carbonate Precipitation MICP is a promising technique for soil biocementation, involving biological and chemical processes that facilitate the precipitation of carbonates, thereby improving soil properties by binding soil particles within the matrix. There are two different approaches in MICP: bioaugmentation, which involves introducing non-native bacteria directly into the soil, and biostimulation, which optimizes the growth environment for native bacteria. The Microbially Induced Carbonate Precipitation process can be classified into ureolytic and non-ureolytic, depending on the bacteria's ability to break down urea or use other metabolic pathways for carbonate production.

The aim of the PhD thesis was to investigate the potential of MICP for various geotechnical applications. By focusing on optimizing bacterial densities, chemical composition, and injection procedures, the PhD work aimed to maximize the mechanical properties of cemented soils. Statistical analyses were conducted to evaluate the effects of MICP treatments on soil strength and carbonate precipitation. The main methods included microstructure analysis, measurement of shear wave velocity and unconfined compressive strength tests. All aimed at quantifying improvements brought by MICP.

Bacterial strains such as *Bacillus subtilis*, *Sporosarcina pasteurii* and *Arthrobacter sp.* were utilized, alongside cementation solutions containing urea, calcium chloride, and magnesium chloride.

Optimization analyses examined how variations in chemical and bacterial concentrations influence carbonate precipitation, with a focus on enhancing the cementation process through bioaugmentation and biostimulation methods of the ureolytic pathway with non-ureolytic support, as well as non-ureolytic pathways.

The potential advantages of both techniques and pathways, particularly biostimulation, were explored in the context of improving overall cementation efficiency. Another primary focus of the PhD Candidate work was evaluating MICP's capacity to mitigate wind erosion by forming a protective biocemented crust on soil surfaces. The following parameters were estimated during this work: carbonate precipitation, erosion depth, and crust thickness to assess the method's effectiveness.

Generally, it can be stated that the novelty of the PhD research lies in the direct comparison of the ureolytic pathway, supported by non-ureolytic mechanisms, with the non-ureolytic pathway, examined under both bioaugmentation and biostimulation approaches, which provides new insights into how application methods affect soil cementation. Mrs. Nadella Marchelina, the PhD Candidate, concluded that MICP, when implemented via both pathways, has the potential to serve as a sustainable and adaptable technology for soil improvement, erosion control, and wider geotechnical engineering applications.

2.2. Characteristics and evaluation of individual chapters of the dissertation

The manuscript of the dissertation is a paper book written in English, with 210 pages in A4 format consisting of: 9 main chapters, general abstracts written in English and Polish languages, a list of abbreviations and publications and appendixes 1÷15.

The chapters cover: Introduction, Microbially induced carbonate precipitation (MICP) – literature review, Research thesis, objectives, and research plan, Materials and methods, Optimization of chemical and bacterial densities for bioaugmentation based MICP, MICP application via biostimulation method, Optimization of injection procedures under sand column conditions with the compressive strength evaluation, Lab-scale assessment analysis, Conclusions and further research.

In **Chapter 1** - Introduction, the PhD Candidate presents Microbially Induced Calcite Precipitation MICP method which offers a sustainable pathway for soil improvement, reducing environmental impacts, while addressing modern priorities, such as lowering carbon footprints, conserving resources and enhancing climate resilience. The PhD Candidate stated that the effectiveness of MICP is directly tied to the chemical reactants injected into soil samples. A higher chemical concentration, in combination with bacteria strain *Bacillus subtilis*, led to an increase in the unconfined compressive strength and the amount of carbonate content of treated soil. Another key investigation in MICP optimization lies in the technique that is used during treatment. There are two most common techniques: bioaugmentation and biostimulation.

Bioaugmentation technique injects non-native bacteria into the soil to begin the MICP process, while biostimulation uses native bacteria in soil by applying nutrient solutions or other growth-promoting substances to stimulate their activity and then introducing the cementation solution to begin the MICP process.

These two techniques have been the subject of the research; the challenge arises within the application. Several factors need to be specifically considered, among others: the method of application, such as spraying, injecting, and mixing. Different methods could result in different cementation distributions in terms of homogenity or carbonate content. The PhD Candidate shows that understanding the interactions between the application method and these factors is very important for optimizing MICP processes, especially for larger scale applications and by conducting this research, it is aimed to develop a better understanding of these factors and establish firm strategies for MICP application, leading to more efficient and effective improvement methods.

In **Chapter 2**, the Author characterizes soil biocementation which is a biogeochemical process that improves the mechanical properties of soil by causing the precipitation of carbonates through the action of microbial activity; one of the techniques is by using MICP. The MICP mechanism can take place through several main pathways, such as ureolytic, non-ureolytic, and denitrification. The effectiveness of MICP is influenced by several factors, including chemicals concentration, calcium and/or magnesium availability, and environmental conditions such as pH and temperature.

As the PhD Candidate mentioned in the **Chapter 2**, the effectiveness of bioaugmentation depends on selecting the right bacterial strains that are capable of inducing carbonate precipitation under specific environmental conditions and also capable of competing with native bacteria in soil. Biostimulation uses native bacteria in an environment that is simulated to enhance their activity for specific purposes, such as the degradation of pollutants, bioremediation, or mineral precipitation. This technique is generally accomplished by introducing nutrient solutions, electron donors, or acceptors, or by modifying environmental parameters such as pH, temperature, or moisture to enhance the growth and metabolic function of native bacteria.

As it was stated, the pathways of MICP application are following: ureolytic, non-ureolytic and for the factors affecting MICP efficiency belong: soil type and grain size, bacteria strain and densities, cementation sources and concentrations and application methods (injection, spraying or percolation method, premixing). In **Chapter 2**, the effect of cementation on soil improvement is described. The PhD Candidate confirms that several soil properties were improved because of MICP treatment, including an increase in shear strength, enhancing unconfined compressive strength. The value of shear wave velocity could be affected by the number of injections during the treatment; a greater number of injections results in a higher percentage of carbonate within the soil matrix, which can lead to denser cementation. Also the precipitation of $CaCO_3$/$MgCO_3$ in the MICP process creates connections between particles in sandy soil. This causes significant changes in the mechanical properties of the soil by creating bonds between sand particles, which can enhance strength, stiffness, and erosion resistance.

The Author gives also the detailed description of the individual bonding mechanisms of soil particle treated by MICP: grain coating, contact cementing and matrix supporting. **Chapter 2** is summarized by the PhD Candidate the statement that MICP is a promising and innovative method for enhancing soil properties, however the method's success depends on precise control over bacterial activity, nutrient availability, environmental factors, soil characteristics, the application method and types of cementation solution.

Chapter 3 contains research thesis, objectives of the work, and research plan. The PhD Candidate presents three main hypothesis which are following:

- the degree to which MICP enhances the geotechnical properties of fine sands is influenced by the application method, bacterial species, and densities; however, these effects are not uniform and depend on complex interactions that require systematic investigation,
- soil improvement achieved through biostimulation of non-ureolytic bacteria exhibits comparable efficiency to bioaugmentation using the ureolytic pathway with non-ureolytic support,
- the combined action of ureolytic and non-ureolytic pathways enhances the effectiveness of MICP treatment.

The objectives of the work were divided by Mrs. Nadella Marchelina into four main points:

- optimizing chemical and bacterial densities for the MICP process through the ureolytic pathway with non-ureolytic support, and the non-ureolytic pathway,

- developing alternative biostimulation-based techniques for applying the biocement solution by optimizing the nutrient formulations targeting both the ureolytic pathway with non-ureolytic support, and the non-ureolytic pathway,
- optimizing the injection procedures for biocementation to enhance the strength of treated soils,
- assessing the effectiveness of MICP procedures on laboratory-scale samples, with particular attention to the role of MICP in controlling wind erosion.

In **Chapter 4**, materials and methods in the research plan are described. The PhD Candidate prepared soil characterization, showing the parameters of silica sand (Niemce sand) sourced from mining operations in the Lublin Voivodeship, Mrozy sand from the vicinity of Warsaw and Zemborzyce sand from Zemborzyce Lake in Lublin.

In the PhD work, primarily vegetative cells of *Bacillus subtilis* were utilized. In addition to *Bacillus subtilis*, other bacterial strains, including *Sporosarcina pasteurii* and *Arthrobacter* sp., were also used for comparison to fulfill the objectives for the non-ureolytic pathway. Various chemicals were used to prepare the biocement solutions, which included urea and calcium lactate as sources of dissolved inorganic carbon, while calcium chloride and magnesium chloride served as sources of calcium and magnesium.

In Chapter 4.2, sample preparation and treatment are described, including optimization of MICP solutions for soil improvement via bioaugmentation and via biostimulation. Also optimization of injection conditions in the MICP-treated soil column, as well as wind erosion resistance and lab-scale samples are presented.

The PhD Candidate carried out sample evaluation method; there are following measurements that were taken into account: the pH and electrical conductivity, strength tests (unconfined compressive strength, shear wave velocity, pocket penetrometer test, penetration measurement, shear strength measurement), environmental durability tests (freeze-thaw resistance, wind erosion resistance test), carbonate content and chemical efficiency, microstructural analysis (optical microscopy image analysis, X-ray diffraction, scanning electron microscopy and energy dispersive X-ray spectroscopy).

Mrs. Nadella Marchelina carried out the analysis of dependent variables, characterized by a normal distribution, using a parametric test-analysis of variance ANOVA (Analysis Of VAriance). The result of the test examining the influence of dependent variables was the effect size.

Chapter 5 is dedicated to the optimization of chemical and bacterial densities for bioaugmentation based MICP. Optimization of MICP using ureolytic pathway with non-ureolytic support and optimization of non-ureolytic MICP are characterized in Chapters 5.1 and 5.2, respectively. The PhD Candidate stated that the results of this study indicated that among all the evaluated pathways, the ureolytic pathway with non-ureolytic support was the fastest in generating carbonate precipitation. This characteristic made it particularly advantageous for applications requiring rapid soil improvement. Although the non-ureolytic pathway could also be used for improvement purposes, it required a longer time frame because it produced a lower amount of precipitation over the same period compared to the ureolytic pathway with non-ureolytic support.

MICP application via biostimulation method is presented in **Chapter 6**, including ureolytic pathway with non-ureolytic support and non-ureolytic pathway. The PhD Candidate stated that biostimulation method demonstrated its effectiveness as a method for soil improvement, as evidence by the increased strength of treated soil samples. Ureolytic pathway with non-ureolytic support samples exhibited larger precipitation areas marked by prominent mineral deposits, indicating a higher degree of carbonate formation. Conversely, non-ureolytic samples showed markedly fewer precipitation areas within the void spaces, reflecting the more complex and slower biochemical reactions required for carbonate ion formation in this pathway.

Optimization of injection procedures under sand column conditions with the compressive strength evaluation is presented in **Chapter 7**. There are following effects and relationship analyzed in **Chapter 7**:

- effect of flow direction on the compressive strength of cemented samples,
- effect of incubation time period on the amount of precipitation,
- effect of flow rate,
- effect of bacteria densities on the homogeneity of cemented column,
- relationship between the number of cycles and the compressive strength of the soil,
- durability analysis (freeze-thaw resistance).

The PhD Candidate stated that in the treatment process, the degree of cementation is significantly influenced by the number of treatment cycles; a higher number of treatment cycles results in greater calcium carbonate precipitation, leading to an increased degree of cementation and improved soil strength and that bioaugmentation with ureolytic bacteria produced the highest unconfined compressive strength values at each cycle level. Additionally, each cycle allowed for additional precipitation of carbonates, which filled voids and increased particle contacts.

Chapter 8 contains lab-scale assessment analysis. In this chapter, the PhD Candidate confirmed that bioaugmentation via the ureolytic pathway with non-ureolytic support emerges as the most effective in terms of both time efficiency and mechanical performance. This method demonstrated better results than other methods in enhancing soil strength, especially for deeper soil improvement, and wind erosion resistance. The strength and uniformity of treatment offered by this method make it the most suitable for large-scale applications where rapid improvement is needed.

Conclusions and further research are given in **Chapter 9**. The PhD Candidate formulated 10 main conclusions and suggests directions for future investigation. Mrs. Nadella Marchelina stated that the research on the effects of selected combinations of bacterial strains and application procedures on the physical and mechanical properties of soils, including large-scale field applications of MICP for slope stabilization should be continued. Also evaluating the long-term ecological and environmental impacts of biological and chemical amendments on native microbial communities, as well as conducting pilot-scale field trials to validate laboratory findings and address issues related to scalability, cost-efficiency, and regulatory compliance might be develop in the nearest future research.

A list of the literature used in this PhD work can be found at the end of the dissertation. I evaluate the structure and content of the doctoral dissertation, as well as its title, positively.

3. Detailed discussion of the dissertation

The aim of the PhD work was to investigate the potential of Microbially Induced Carbonate Precipitation MICP technique for various geotechnical applications. The formulated hypothesis was confirmed by demonstrating the effectiveness of MICP technique application in soil. The conducted by the PhD Candidate experiments and analyses enabled to fulfill the research objectives outlined in this PhD thesis.

After carrying out many various types of laboratory experiments and after analyzing the results of these tests, the PhD Candidate formulated following main conclusions:

- the experiments effectively identified optimal chemical and bacterial concentrations for the MICP process. The ureolytic pathway with non-ureolytic support accelerates carbonate precipitation and enhances soil improvement efficiency. Bacterial optical density (OD 1) and the concentration of dissolved inorganic carbon (DIC) are the most influential factors governing carbonate precipitation. The addition of calcium lactate CaL in the MICP application enhanced both mechanical strength and carbonate content,

- assessment of the ureolytic pathway supported by the non-ureolytic mechanism found that the combination of bacterial OD 1, urea at 0.25 M, CaL at 0.2 M, 0.25 M $CaCl_2$, and 0.25 M $MgCl_2$ resulted in the highest efficiency for carbonate precipitation compared to other tested combinations,
- the non-ureolytic pathway demonstrated the ability to produce carbonate precipitation,
- through stimulating of native microbial populations in the soil, biostimulation promoted carbonate precipitation, enhancing soil strength and stability. Changes in electrical conductivity reflected shifts in ion concentrations during cementation solution application,
- biostimulation via the non-ureolytic pathway was capable of producing carbonate precipitates, it exhibited slower precipitation rates and lower carbonate content relative to the ureolytic pathway with non-ureolytic support,
- after optimizing injection procedures for biocementation, it can be stated that the number of cycles of biocement solution application and the incubation time significantly affected soil strength; a higher number of cycles and a longer incubation period were associated with increased carbonate precipitation. Moreover, higher bacterial optical density tended to produce uneven distribution of carbonate precipitates,
- the direction of injection flow significantly influenced the treatment efficacy. In particular, top-to-bottom injection was identified as the most effective method for achieving higher strength values in the treated soils. The frequency of injection cycles was identified as a crucial factor for maximizing carbonate precipitation,
- the conducted research enabled a comparison of the properties of three types of sands with different grain size distributions: poorly-graded coarse sand (Mrozy sand), poorly-graded medium sand (Zemborzyce sand) and poorly-graded fine sand (Niemce sand). Niemce sand, due to its significant limitation of strengthening through compaction, poses the greatest challenge with regard to MICP soil improvement,
- the MICP technique improved resistance to wind erosion, as evidenced by shallow erosion depths in a higher number of cycles and thicker crust formation in cemented samples; MICP treatment enhances soil durability against environmental challenges like wind erosion, supporting its application as an effective method for soil improvement in erosion-prone areas,
- it is important to optimize the MICP procedure, particularly the injection method, for effective real-world soil stabilization. The injection approach allowed controlled delivery of bacterial cultures and cementation solutions, leading to more uniform carbonate precipitation and improved soil strength and durability; this enhanced adaptability for both surface and subsurface treatment increases its potential for preventing shallow slides and protecting embankments.

Taking into account the scope of the work, it can be stated that the goal set at the beginning of the doctoral dissertation by M.Sc. Eng. Nadella Marchelina has been achieved.

4. Critical remarks

The doctoral dissertation was written by Mrs. Nadella Marchelina, M.Sc. Eng., in correct English language. Although the Author carefully prepared all figures, tables, and formulas, minor editorial errors were not avoided. Below, there are some comments that can be easily corrected in future publications:

- in the manuscript, there are some citied publications that are not listed in the bibliography, for example: Qabany et al. (2012) – pages 15, 26, 76; Fan et al. (2024) – page 15; Casas et al. (2022) – page 18; Cho et al. (2020) – page 19; Soga et al. (2017) – page 24; Qabany (2011) – page 26; Choi et al. (2016) – pages 27, 76; Gomez et al. (2017) – page 27; Jason et al. (2020) – page 37; Pakbaz et al. (2022) – page 37; Wu et al. (2019) – page 37; Alakayleh et al. (2019) – page 41; Montoya et al. (2013) – page 42; ASTM D2487 – pages 52, 53; Soon et al. (2012) – page 55; Peng et al. (2019) – page 56; ASTM 5312-04 – page 65; Zhao et al. (2021) – pages 82, 144; Hirsch et al. (2015) – page 93; Meng et al. (2022) – page 93; Xu et al. (2013) – page 106; Li et al. (2021) – page 127; Hadi et al. (2022) – page 133; Saffari et al. (2019) – page 134; Kim et al. (2022) – page 151; Nifisi et al. (2018) – page 155,
- in the manuscript in the references list, there are not listed following publications: Alakayleh et al. (2018); Casas et al. (2020); Choi et al. (2017); Chuo et al. (2020); DeJong et al. (2017); Dubey et al. (2021); Fan et al. (2023); Gomez et al. (2018); Jiang and Soga (2017); Leukel and Tremel (2018); Montoya et al. (2014); Reeksting et al. (2020); Sun et al. (2013); Tao et al. (2025); Tsesarsky et al. (2016); Wang et al. (2021); Zhao et al. (2022),
- in the bibliography, several repeated publications are found; they are following: Feng et al. (2022); Gomez et al. (2015); Gomez et al. (2019); Gowthaman et al. (2022); Hemayati et al. (2024); Jiang and Soga (2017); Mortensen et al. (2011); Punnoi et al. (2021); Putra et al. (2016); Rahman et al. (2020); Raveh-Amit and Tsesarsky (2020); Xu et al. (2020),
- there are some incorrectly citied publications in the text of manuscript, for example: in the PhD work it is Gowthaman et al. 2022; while there are two papers of Gowthaman et al. (2022) on the references list. Gowthaman et al. (2022a or 2022b) should be citied in the text of the PhD work. There is citied Whiffin et al. (2004), while it should be citied Whiffin (2004), etc.,
- page 29: in Table 2.2. - too small letters are used in the description in the figures,
- page 37: in Figure 2.7 – for showing the results of unconfined compressive strength value against the percentage of carbonate content, too little color difference was used to show the results. It is difficult to follow the test results,
- page 46: too small letters in the description in Figure 2.10,
- page 91: in Figure 5.10 – there is a mistake in showing the results because there are shown different values of $MgCl_2$ from XRD analysis, while the description is dedicated to „*XRD analysis comparation on different Mg/Ca ratio*",
- page 91: in the text of manuscript „*Figure 5.11e*" is mentioned while there are only Fig. 5.11a, 5.11b and 5.11c; The *Figure 5.11e* does not exist,
- page 114: in the text, there is only written about Niemce sand samples while on page 115 in Figure 6.2 and in Table 6.1, the results for Niemce and Zemborzyce sands are presented. It is worth recording the results for different types of sand in one table,
- page 115: How can we explain the large discrepancy in the cohesion results for the Niemce and Zemborzyce sands??
- It is worth checking and comparing the values given in Tables 6.1 and 6.3; there are some doubts related to the surface resistance value for biostimulated sands: Niemce, Zemborzyce and Mrozy
- page 121: the description of Table 6.3. is following „*Average value of strength measurements comparing treated and untreated soil samples using the biostimulation method*" while in Table 6.3 only one value of surface resistance for different types of sand is given (without comparison for treated and untreated soil samples),

- page 121: in Chapter 6.2.3. is written „*The EDS analysis of the Niemce sample treated with the non-ureolytic pathway revealed that most of the precipitates in this sample were not acid-soluble crystals (...)*", while Table 6.4 and Figure 6.7 demonstrate the results of SEM and EDS analysis for Niemce, Zemborzyce and Mrozy sands,
- page 124: it is written „*The shear strength results for the Mrozy sample, as presented in Table 6.3, exhibited the lowest values among all tested samples*", while in Table 6.3, the value of surface resistance for different sand types are presented,
- page 128: too small letters in the description in the Figure 7.1,
- in Figures 7.6÷7.15 - no information about the type of tested sand (Niemce sand?),
- in Chapter 8 in all figures – no information about the type of tested sand.

It should be emphasized that minor editorial errors in the work do not in any way diminish the substantive value of the doctoral dissertation.

After reading the content of the work, certain remarks and questions arise:
- Basic dictionary with main chemical definitions would be very useful for the readers who are not fully involved in chemical processes and knowledge.
- The PhD research is dedicated to experimental studies of microbiologically induced improvement of fine sands (non-cohesive soils). Could you provide some information on the use of microbiologically induced improvement of cohesive or organic soils?
- In what situations could the microbiologically induced improvement be used?
- What is the opinion on the effects of using microbiologically induced improvement after some years? Are the parameters of improved sand stable or unstable?
- Is it possible to share with the readers with the examples of the MICP applications in large-scale beyond stabilizing sandy coastal slopes and reducing erosion in intertidal and coastal areas?
- Are there any recommendations/suggestions for MICP application (climate zone, temperature range etc.)?
- Is it possible to explain the effect of freezing and thawing on the values of unconfined compressive strength?
- What is the impact of the MICP technique on the strength parameter values several years after its first application?
- Is there a need to repeat the MICP technique several years after its first application?
- What should be done before implementing the MICP technique on a larger scale in geoengineering?
- Can we use the MICP technique for deep soil improvement?
- How can you control the behaviour of bacteria in improved subsoil?

5. Final conclusions

The PhD Candidate, based on the research background, developed three main hypothesis and divided the objective of the PhD work into four following points:
- optimizing chemical and bacterial densities for the MICP process through the ureolytic pathway with non-ureolytic supports, and the non-ureolytic pathway. This research specifically focused on investigating how variations in biocement solution concentrations influence MICP performance,
- developing alternative biostimulation-based technique for applying the biocement solution by optimizing the nutrient formulations targeting both the ureolytic pathway with non-ureolytic supports and non-ureolytic pathways. This included evaluating

the influence of environmental factors, particularly pH and electrical conductivity on the process,
- optimizing the injection procedures for biocementation to enhance the strength of treated soils. This included examining how the flow directions, injection cycles, incubation time, flow rate and bacterial densities affect the strength and uniformity of cemented samples. These treatments were tested on three soil types: Mrozy (coarse sand), Niemce (fine sand) and Zemborzyce (medium sand),
- assessing the effectiveness of MICP procedures on laboratory-scale samples, with particular attention to the role of MICP in controlling wind erosion. The effects of wind erosion on the cemented samples were evaluated through measurements of carbonates precipitation, erosion depth and crust thickness.

In my opinion, the originality of the work is demonstrated by the following achievements of the PhD Candidate:
- analysis of available literature on microbiologically induced improvement of sands,
- experimental analysis of three types of sand to determine the availability of using the MICP technique in various geotechnical situations. By focusing on optimizing bacterial densities, chemical composition and injection procedures, the aim of the PhD work was to maximize the mechanical properties of cemented soils,
- carrying out the experimental work for quantifying improvements brought by the MICP technique, such as: microstructure analysis, measurement of shear wave velocity, unconfined compressive strength,
- optimization of chemical and bacterial concentrations which influence carbonate precipitation, with a focus on enhancing the cementation process through bioaugmentation and biostimulation methods of the ureolytic pathway with non-ureolytic support, as well as non-ureolytic pathways,
- drawing the conclusions indicating that the MICP technique has the potential to become a sustainable and adaptable technology for soil improvement, erosion control and other geotechnical applications.

The PhD Candidate Nadella Marchelina has successfully achieved the assumed goal of the work and generally confirmed the hypothesis. Despite the critical remarks and doubts presented, I state that the doctoral dissertation submitted for review is an original solution to the scientific problem, and the PhD Candidate Nadella Marchelina has demonstrated general theoretical, experimental and practical knowledge in the given scientific *Discipline of Civil Engineering, Geodesy and Transport* and the ability to independently conduct scientific work and thus meets the requirements for doctoral dissertations in accordance with the applicable Act of 20 July 2018, „*Law on Higher Education in Science*" – Journal of Laws of 2024, item 1571, with subsequent amendments.

As the reviewer, I propose to the PhD board the admission of the thesis of PhD Candidate Nadella Marchelina for public defence.

Joanna Bzówka