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Review

Key Success Factors for the Practical Application of New Geomaterials

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Abstract: Geomaterials comprise naturally formed materials through geological processes, such as soils and rocks, or artificially processed materials, including mineral waste and geosynthetics. These materials find extensive use in geotechnical structures, such as slopes, dams, and pavements, among others. However, two issues commonly arise in earthworks: the materials available in the region do not meet the minimum engineering requirements, resulting in high transportation costs, and the exploitation of new deposits increases environmental impacts. Consequently, there is a need to develop stabilization and reinforcement techniques aimed at creating new geomaterials (NGs) to expand the range of local material applications. In this context, the present study evaluates the key success factors (KSFs) related to the application of NGs in geotechnical structures. The Delphi method was employed through a structured questionnaire developed after an extensive literature review. Brazilian experts from the public, private, and academic sectors were selected to identify the obstacles and potential pathways for the practical application of NGs. The outcomes of the study indicated that the lack of standardization, the complex behavior of geomaterials under varying conditions, as well as technical and economic limitations serve as barriers impeding the widespread adoption of NGs. Finally, a roadmap proposal was devised, encompassing a series of actions intended to facilitate the broader utilization of NGs.

Keywords: new geomaterials; key success factors; geotechnical structures; Delphi method

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1. Introduction

Efforts towards achieving the Sustainable Development Goals (SDGs) outlined in Agenda 2030 and meeting the Nationally Determined Contributions (NDCs) on climate change presented in the Paris Agreement are essential for the world's sustainable growth [1]. Sustainable infrastructure is critical in achieving these goals by ensuring economic, financial, social, environmental, and institutional sustainability throughout the project life cycle [2,3]. Therefore, solutions are required to achieve global temperature targets and mitigate the consequences of global warming by replacing polluting practices with efficient ones and developing resilient structures that can withstand the changes already underway [4].

New geomaterials (NGs) are innovative material solutions applied to geotechnical structures that aim to adapt local materials to the required engineering behavior. This is a key strategy to reduce the exploitation of natural materials and the costs and emissions associated with transportation. The application of NGs can be an attractive way to work towards mitigation strategies by reducing the emissions related to material transportation and adapting in cases where composites perform more effectively in the face of hazards [5,6].

For the development of NGs, stabilization and reinforcement techniques are applied [7–9]. The stabilization technique covers solutions with chemical additives, which react with the natural material, or mixing materials with complementary particle size distributions to form a more stable structure. The reinforcement technique aims to form composites with inclusions of materials with a tensile strength to complement the behavior of the granular materials, enabling a wide range of engineering applications, including slope stabilization, retaining wall construction, and pavement design. These technologies can be used individually or in combination [10–20], maximizing the benefits inherent to the techniques.

The main advantage of using these materials lies in the substitution of conventional construction materials, such as sand and gravel, which may be associated with significant environmental impacts due to the need for natural deposit extraction [21–23]. Furthermore, many of the new technologies have the characteristic of better quality control of the products, allowing for a better prediction of the behavior of the final structure, even in the design phase.

However, the use of NGs in geotechnical engineering projects can be limited by a lack of established testing standards, higher initial costs, and potential sourcing concerns. Despite a general understanding of the possible factors related to the limitations of using NGs, there is a gap in the literature regarding potential key success factors (KSFs) that could alter this scenario and facilitate the implementation of NGs in earth structures.

Based on the above, the following research questions emerged: (i) What are the key success factors (KSFs) for the practical application of NGs? and (ii) How can stakeholders involved in decision-making contribute to support the development and use of NGs?

In this context, this paper aims to identify the KSFs for the usage of NGs on a large scale. Additionally, this paper proposes a roadmap to address the barriers identified based on the opinion of renowned Brazilian professionals who work in geotechnical engineering. The opinion of the experts was evaluated by using the Delphi method. Based on the results, it was possible to identify the KSFs for the large-scale usage of NGs, along with correlated barriers. The identified barriers then served as catalysts for devising a comprehensive roadmap aimed at facilitating the broader implementation of these materials.

This study introduces a novel dimension to the field by pioneering the application of the Delphi method in the specific context of new geomaterials. To the best of our knowledge, no previous literature has documented the utilization of the Delphi method in this particular context. This distinctive application not only underscores the innovative nature of this research but also expands the boundaries of traditional evaluation methodologies. By venturing into uncharted territory, we aim to contribute to the existing body of knowledge and provide fresh insights that advance the understanding and practice of the practical application of new geomaterials.

This paper is organized as follows: The introduction section provides an overview of the context and the motivation behind this study. Following that, the methodology section outlines the research approach, detailing the identification of key success factors (KSFs), introducing the sample utilized, and explaining the statistical methodology applied. The subsequent section presents the obtained results, offering a clear insight into the outcomes of the study. The ensuing discussion section delves into the implications of the results and introduces a comprehensive roadmap as a strategic response to the identified barriers. Finally, the conclusion section encapsulates the key findings and emphasizes their significance within the broader context, providing insights for future research directions and applications.

2. Research Method

Although much progress has been made in recent years regarding the development of NGs, there remains a gap in the practical application of this group of materials. To explore this gap, a four-stage process was employed (Figure 1), consisting of a conceptual phase, application of the Delphi method, and proposal of a roadmap.

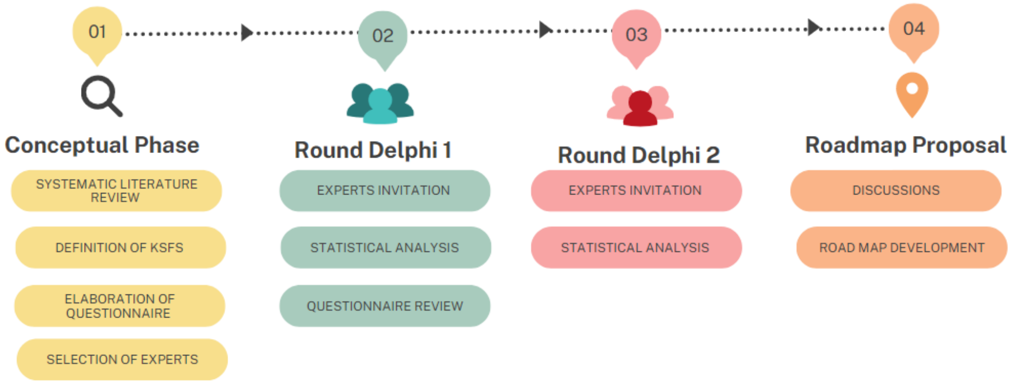

Figure 1. Four-stage research method.

In the conceptual phase, a systematic literature review (SLR) was conducted by using the Scopus database. The keywords used were "geomaterials", "new geomaterials", "new geotechnical materials", "soil reinforcement", "soil stabilization", "soil improvement", "tailings improvement", "tailings reinforcement", and "tailings stabilization". The following combinations of words were also used: "New Geomaterials" AND "Sustainable Materials", "Soil Reinforcement" AND "Soil Stabilization", and "Tailings Reinforcement" AND "Tailings Stabilization". The search considered papers as a document type, published in English from 2009 to 2023, in the following subject areas: engineering, materials science, environmental science, and multidisciplinary subjects. Based on this procedure, 143 papers were found.

After analysis, 112 papers were selected for in-depth reading to identify the KSFs for the usage of NGs, categorized into five groups [24]: (1) technical, economic, and financial; (2) socio-environmental; (3) logistical; (4) institutional; and (5) educational. These KSFs were the basis to structure a questionnaire considering the Delphi method, which was presented for evaluation using a 5-point Likert scale.

The Delphi method was chosen due to the need for expert judgment in the investigation. It is a structured and iterative research technique used to gather and distill expert opinions on a particular topic or issue. It involves a panel of experts, typically selected for their knowledge and experience in the subject matter, who provide anonymous input through a series of questionnaires or rounds of communication. This approach allows for structured communication without the need for direct confrontation among the experts, which can help to avoid unconscious biases and ensure a consensus on a topic that is not yet well explored. Over the years, this method has been primarily used to make forecasts, identify priority issues, and develop frameworks [25,26].

However, this method requires evaluating the reliability and the consensus of the responses. The reliability of the responses was measured by using Cronbach's alpha. This is a useful measure for assessing the internal reliability of a measurement instrument, such as a questionnaire. It helps determine whether the items consistently measure the same attribute and to what extent the results are reliable.

High internal consistency is essential to ensure that the research results are reliable and consistent. Values above 0.7 are considered highly acceptable [27]. The consensus was measured by calculating the mean score, standard deviation (SD), interquartile range (IQR), and change in SD [28–30]. The consensus was based on IQR < 1 and a negative SD change after the second round. Therefore, the experts were invited to evaluate the KSFs in the first round, the consensus was analyzed, and those factors without consensus were presented again to respondents. The KSFs considered relevant had a mean value above 4. The convergence was found in two rounds. Once the KSFs were identified, a roadmap was designed to highlight the actions of those involved in the use of NGs.

2.1. Description of the Sample

Experts were selected following the guidelines outlined by [26], focusing on a diverse sample of participants from academia and public and private sectors. A total of 7 experts were chosen, which falls within the recommended range of 5 to 20 experts [26,28,30]. The selection process prioritized individuals with knowledge and recognized research works in NGs. A profile of the sample respondents is shown in Table 1. All experts participated in both rounds.

Table 1. Profile of the sample respondents.

ID	Academic Qualifications	Employment Sector	Experience (Years)
FB	Master in Transportation Engineering	Private—Infrastructure	10
JW	Ph.D. in Civil Engineering	Academia—Researcher	8
MR	Master in Civil Engineering	Private—Environmental	10
NC	Ph.D. in Civil Engineering	Academia—Researcher	25
RP	Ph.D. in Civil Engineering	Academia—Researcher	10
SA	Ph.D. in Architecture	Academia—Researcher	15
TD	Civil Engineering	Public—Transportation	12

2.2. Identification of KSFs

Table 2 summarizes the materials used, their main properties and potentials, examples of applications, and additional factors to consider for using NGs. Most of the literature regarding composites focuses on technical testing, particularly those using traditional geotechnical methods [14,31–33]. However, microstructural analysis is required for a comprehensive understanding of the behavior of composites in tailings. Since tailings materials have not undergone the typical soil formation process, classical soil mechanics may not accurately represent their behavior [34–37].

More recently, scholars have explored the cost–benefit analysis of new materials [38,39]. Although environmental analyses are also beginning to be addressed in the literature regarding geomaterials, they remain incipient [40]. However, logistical, institutional, and educational aspects have received little attention. To address this gap, institutional and educational aspects were added to support the roadmap, which aims to identify the main actions of stakeholders toward an inclusive and coordinated decision-making process [2].

Table 2. Geomaterials for soil stabilization and reinforcement.

Category	Materials Employed	Main Properties and Potentials	Additional Factors to Consider	Examples of Applications
Cementitious materials	Portland cement, fly ash, silica fume, and slag, for instance	Cementitious materials can boost soil strength, decrease compressibility, suppress soil expansiveness, and improve durability [41–43].	Potential concerns related to energy consumption and greenhouse gas emissions, the influence of curing conditions, cementitious material age and content, and potential damage from seawater environments [8,32,44–47].	Cementitious materials find application in road and pavement construction and airport and industrial yard pavements, as well as soil improvement and remediation, including the treatment of contaminated soils [12,23,48–50].
Lime	Lime, in general, including quicklime and hydrated lime	Using locally available lime materials has the potential to enhance soil strength and stability, reduce plasticity and construction costs, and increase durability and frost resistance capabilities [22].	It is important to consider the possible effects of carbonation, pore fluid–soil structure interactions, wetting–drying cycles, and aggregate size, as well as compaction mode, density, and suction [51–53].	Lime stabilization can be used in road and airfield construction, embankment, and slope stabilization, building and foundation construction, and landfill liners and covers. Additionally, it can be used for soil improvement and remediation, including the protection of earthen sites [54].
Asphalt	Asphalt, in general, including a foamed sulfur asphalt and asphalt emulsion	Enhanced soil strength, reduced erosion, increased durability, and improved water resistance. It has the potential to provide control of the swell and collapse potential and can also increase the load-bearing capacity of pavements [55].	Asphalt can be sensitive to temperature variation. Overuse can lead to rutting and cracking, which can affect their long-term performance and increase maintenance costs.	Asphalts are typically used for the construction of road bases [56,57].

Table 2. *Cont.*

Category	Materials Employed	Main Properties and Potentials	Additional Factors to Consider	Examples of Applications
Polymers	Geopolymers, biopolymers, and synthetic organic polymers	Improved strength, reduced permeability, inhibited swell and collapse potential, enhanced durability and stability, improved dynamic responses under cyclic loading, and improved resistance to freeze–thaw action [9,58–64].	The use of polymer materials in construction may face challenges such as costs, limited long-term durability studies, and environmental concerns regarding the potential leaching of these materials into the surrounding environment.	Eco-friendly urban renewal projects, tailings structures, and pavement applications [34,46].
Enzymes	Urease and phosphatase, among others	The use of enzymatically induced carbonate precipitation can lead to enhanced soil strength, reduced compaction, increased water retention, improved nutrient availability, and environmentally friendly and biodegradable promotion of plant growth and soil fertility [65].	More research is needed to understand the long-term effects and efficacy of new technology, especially regarding potential moisture degradation [66,67].	Soil stabilization for transportation infrastructure, dust and erosion control, land reclamation, and soil remediation [68].
Synthetic fibers	Examples include polypropylene and polyester fibers	Improved soil strength and durability, reduction in swelling and shrinkage potential, erosion control, resistance to degradation, flexibility, and crack control [61,69,70].	Considerable knowledge has already been gathered on the use of synthetic fiber reinforcement. More research may be needed to understand the influence of fiber inclusion on the mechanical behavior of cemented/stabilized mixtures [13].	Applications include structural use under freeze–thaw cycling, transportation subgrades, and mining tailings [37,71,72].
Natural fibers	Coir, jute, palm, and kenaf, as examples	Improved soil strength, cost-effectiveness, high availability, eco-friendliness, and healing ability for wetting–drying cycles [73–77].	Not suitable for high-stress applications, due to the susceptibility of fiber degradation from environmental factors, and can require proper surface treatment to improve performance [78,79].	Used for temporary structures, erosion control, slope stabilization, and pavement construction [80].
Geosynthetics	Examples include woven geotextiles, geogrids, and geostrips	Improved soil strength, durability, and erosion reduction using lightweight, flexible, and degradation-resistant materials.	Specialized installation and maintenance are required, performance limitations in fine-grained soils, the potential for UV degradation, and chemical resistance issues [81].	Applications include reinforced soil structures, pile-supported embankments, bridge abutments, and subgrade soil stabilization [6,7,78,82–85].
Rubber	Examples include tire chips, crumb rubber, and rubber-soil	Improved soil strength, reduced compaction, erosion, noise, and vibration, and enhanced frost resistance, as well as swelling potential reduction through the use of appropriate additives and geotechnical seismic isolation (GSI) [86–88].	Specialized processing and installation techniques may be required, and the materials may be susceptible to degradation and chemical leaching. The effect of rubber size and format should also be considered [89].	Applications in erosion control, slope stabilization, retaining structures, and fillers in various construction methods, including a remediation technique for mitigating soil liquefaction [50,90–92]. Geotechnical seismic isolation entails absorbing seismic energy from the soil into the superstructure through the introduction of a surface soil layer, aimed at mitigating the transmission of accelerations from the ground to the structure. This method of mitigation is especially well-suited for developing nations, as GSI serves as an affordable seismic isolation system [93–96].

The KSFs identified based on the SLR are listed in Table 3. Group A composes technical, economic, and financial factors. Field tests and validations for specific cases, such as in transportation infrastructure, were deemed highly relevant for proving and promoting the application of these materials. Additionally, cost–benefit analyses that consider quantitative, as well as socio-environmental aspects, were also considered highly important. Conducting these analyses in parallel to case studies would allow for monitoring indicators to be obtained in a more controlled and efficient manner. Group B includes the socio-environmental aspects, which discussed key global issues in the upcoming years, particularly considering climate change effects, including decarbonization and the creation of more resilient structures [97]. Furthermore, the potential for distributing these materials to disadvantaged communities as a cost-effective solution for constructing safer structures was also assessed.

Group C includes the logistical aspects. The use of local materials is the most relevant item, especially when considering the Brazilian context. It is a crucial aspect that promotes sustainable solutions in a country with diverse geology [98]. The use of local materials presents numerous opportunities, such as: (i) reducing transportation distances, which leads to lower greenhouse gas emissions; (ii) creating opportunities for local skilled labor, which boosts the regional economy; (iii) utilizing waste and non-conventional materials that are abundant in the region; and (iv) developing budgeting techniques and guidelines that are tailored to the local context.

Group D includes the institutional aspects, which aim to identify the responsibilities of the different stakeholders, including multilateral and international organizations, governments, and public institutions. Finally, Group E includes the educational aspects, which aim to evaluate the KSFs related to the dissemination of knowledge about NGs. No relevant references were found in the literature for the last two groups. Their formulation was based on the authors' experience.

Table 3. KSFs identified in the SLR.

Group	KSFs	References
A	A1: The technical validation through laboratory testing from a mechanical standpoint	[14,31,99,100]
	A2: Technical validation through laboratory testing from a hydraulic standpoint	[13,33,88,101–103]
	A3: Technical validation through field tests	[104–106]
	A4: Technical validation for a specific application	[101,107–109]
	A5: Experimental evaluation of environmental contamination aspects	[35,101]
	A6: Collaboration between universities and governmental agencies for the development of applied research	[110]
	A7: Verification of cost–benefits through quantitative financial methods	[38,111]
	A8: Verification of cost–benefits through socio-environmental justifications	[38]
	A9: Low implementation complexity	[112,113]
	A10: Clear, concise, and easily accessible information on the advantages of new geotechnical materials compared to traditional construction methods	[38,71,111]
	A11: Promotion of solutions suitable for the regional context	[33,108]
B	B1: Development of materials more resistant to the effects of climate change	[24,114–118]
	B2: Development of materials that use waste as reinforcement or matrix	[99,103,119,120]
	B3: Development of materials that propose decarbonization	[38,40,121,122]
	B4: Life cycle analysis of materials and verification of carbon footprint	[39,121]
	B5: Compatibility with the Sustainable Development Goals	[24,123–125]
	B6: Compatibility with the Nationally Determined Contributions	[13,111]
	B7: Development of construction techniques that stimulate regional development	[108,119,126]
	B8: Development of materials that generate less polluting waste	[13,38,112,127,128]
	B9: Development of materials that generate less solid waste	[31,124,129,130]
	B10: Public policies for the distribution of new geotechnical materials to vulnerable populations	
C	C1: Development of solutions that use local materials	[13,36,40,118,131,132]
	C2: Analysis of the available material supply	[40,133]
	C3: Analysis of the potential demand for available material	[102,111,117,129]
	C4: Verification of the infrastructure for the availability of materials	[124]
	C5: Financial and tax incentives granted for the use of industrial waste in construction	[121]
	C6: Logistical planning for the distribution of materials for use in civil construction	[121]
	C7: Logistical planning for the storage of materials for use in civil construction	[121]
D	D1: Promotion of projects by multilateral organizations for the research and development of new geotechnical materials	[110]
	D2: Promotion of projects by federal-level public institutions for the development of new geotechnical materials	
	D3: Promotion of projects by state-level public institutions for the development of new geotechnical materials	
	D4: Promotion of projects by municipal-level public institutions for the development of new geotechnical materials	
	D5: Development of knowledge materials by international organizations on the subject	
	D6: Mandatory use of new geotechnical materials established by government authorities	

Table 3. *Cont.*

Group	KSFs	References
E	E1: Development of knowledge materials in Portuguese	
	E2: Courses, lectures, and workshops in partnership with public entities	
	D3: Courses, lectures, and workshops for undergraduate students on new geotechnical materials	

3. Results

The Delphi method was then applied to the selected experts through a structured questionnaire presented in the previous section. Two rounds were conducted to establish convergence criteria, and all experts participated in both rounds. All responses were considered reliable, with alpha de Cronbach values being 0.895 and 0.778 for the first and second rounds, respectively. The next subsection details the results of the groups.

3.1. Technical, Economic, and Financial Aspects

Table 4 summarizes the results of the technical, economic, and financial aspects. This first group emphasizes technical results, including laboratory and field tests, as well as cost–benefit financial outcomes. All aspects of this group, except for implementation complexity, were identified as relevant by the experts. They considered mechanical verification more important than hydraulic verification since the latter would only be necessary for flow-related applications. Mechanical tests were identified as the first validation necessary for the new geomaterials. Developing solutions that are suitable for the regional context is a crucial aspect, and it received a mean score of 4.43, making it highly relevant. To achieve this, having access to clear information was also deemed essential, with a mean score of 4.29.

Table 4. KSFs for technical, economic, and financial aspects.

Key Success Factors (KSFs)	Round 1			Round 2			SD Change
	Mean	SD	IQR	Mean	SD	IQR	
Technical validation through laboratory testing from a mechanical standpoint	4.86	0.38	0				
Technical validation through laboratory testing from a hydraulic standpoint	4.00	0.58	0				
Technical validation through field tests	4.71	0.49	0.5				
Technical validation for a specific application, such as road infrastructure	4.57	0.54	1				
Experimental evaluation of environmental contamination aspects	4.29	0.76	1				
Collaboration between universities and governmental agencies for the development of applied research	4.57	0.54	1				
Verification of cost–benefits through quantitative financial methods	4.57	0.54	1				
Verification of cost–benefits through socio-environmental justifications	4.29	0.76	1				
Low implementation complexity	3.71	1.11	1.50	4.00	0.58	0.0	−48.1%
Clear, concise, and easily accessible information on the advantages of new geotechnical materials compared to traditional construction methods	4.29	1.11	1.00				
Promotion of solutions suitable for the regional context	4.43	0.79	1.00				

The only item that did not achieve a consensus and received an average score below 4 was related to the implementation complexity. However, participants believed that engineering techniques could be employed in diverse situations, indicating that this factor would not impede the application of these materials.

3.2. Socio-Environmental Aspects

The results of KSFs regarding the socio-environmental aspects are presented in Table 5. Among this group, the most significant factors related to utilizing waste for developing new materials and conducting a life cycle analysis to minimize pollutant generation and greenhouse gas emissions. Life cycle analysis has become a prevailing practice in the realm of emerging materials, aimed at evaluating the complete production chain [91,134]. Nevertheless, the literature references still indicate a knowledge gap regarding this type of analysis and a lack of standardization, resulting in ambiguity and difficulty in comparing solutions [135].

Table 5. KSFs for socio-environmental aspects.

Key Success Factors (KSFs)	Round 1			Round 2			SD Change
	Mean	SD	IQR	Mean	SD	IQR	
Development of materials more resistant to the effects of climate change	4.00	1.15	1.50	4.42	0.78	1.0	−31.86%
Development of materials that use waste as reinforcement or matrix	4.71	0.48	0.50				
Development of materials that propose decarbonization	4.42	0.78	1.00				
Life cycle analysis of materials and verification of carbon footprint	4.42	0.78	1.00				
Compatibility with the United Nations' Sustainable Development Goals (SDGs)	3.71	1.70	1.50	3.85	1.21	2.0	−28.71%
Compatibility with the Nationally Determined Contributions (NDCs)	4.14	1.21	1.50	4.00	1.15	1.5	−4.96%
Development of construction techniques that stimulate regional development	4.42	0.53	1.00				
Development of materials that generate less polluting waste	4.28	0.75	1.00				
Development of materials that generate less solid waste	3.85	0.37	0.00				
Public policies for the distribution of new geotechnical materials to vulnerable populations	3.85	1.34	1.50	3.85	0.90	1.5	−33.11%

Four items failed to reach a consensus among the interviewees, namely: (1) the development of materials that are more resistant to climate change effects; (2) compatibility with the United Nations' Sustainable Development Goals (SDGs); (3) compatibility with the Nationally Determined Contributions (NDCs); and (4) the need for public policies to distribute new geotechnical materials to vulnerable populations. The authors observed that bridging the gap between the global climate debate and the industry remains challenging, which may explain the current situation. Therefore, scientific studies highlighting the significance of NGs in mitigating the effects of global warming are crucial.

3.3. Logistics-Related Aspects

The logistics aspects were assessed to determine the significance of supply and demand in selecting NGs. Moreover, the utilization of local materials and logistic planning for storage and distribution were also discussed. During the first round, two items failed to reach a consensus: one pertained to demand analysis, and the other related to the necessity of financial and tax incentives to promote the use of waste as construction materials. The items that were considered of lesser importance by the experts were related to logistical distribution and storage plans. Eventually, all items achieved a consensus, as presented in Table 6.

Table 6. KSFs for logistics-related factors.

Key Success Factors (KSFs)	Round 1			Round 2			SD Change
	Mean	SD	IQR	Mean	SD	IQR	
Development of solutions that use local materials	4.57	0.54	1.00				
Analysis of the available material supply	4.43	0.54	1.00				
Analysis of the potential demand for available materials	4.00	0.89	1.50	4.57	0.54	1.0	−40.24%
Verification of the infrastructure for the availability of materials	3.86	0.69	0.50				
Financial and tax incentives granted for the use of industrial waste in construction	4.29	0.95	1.50	3.86	0.69	0.5	−27.45%
Logistical planning for the distribution of materials for use in civil construction	3.29	0.76	1.00				
Logistical planning for the storage of materials for use in civil construction	3.29	0.95	0.50				

3.4. Institutional Aspects

Table 7 shows that there was no consensus among the interviewees regarding the importance of promoting NGs by multilateral organizations and public institutions at the municipal level. The KSF with the highest average in this group refers to the participation of institutions at the federal level, which is indeed essential in the Brazilian context. The government agency responsible for transportation infrastructure, for example, also normalizes engineering materials and services. Additionally, it controls and guides contracts with the private sector that manages some assets of Brazilian infrastructure.

Table 7. KSFs for institutional aspects.

Key Success Factors (KSFs)	Round 1			Round 2			SD Change
	Mean	SD	IQR	Mean	SD	IQR	
Promotion of projects by multilateral organizations for research and development of new geotechnical materials	4.14	1.22	1.50	4.000	1.155	1.5	−4.96%
Promotion of projects by federal-level public institutions for the development of new geotechnical materials	4.29	0.49	0.50				
Promotion of projects by state-level public institutions for the development of new geotechnical materials	3.86	0.69	0.50				
Promotion of projects by municipal-level public institutions for the development of new geotechnical materials	3.57	1.40	1.50	4.14	0.90	1.5	−35.61%
Development of knowledge materials by international organizations on the subject	3.71	0.95	0.50				
Mandatory use of new geotechnical materials established by government authorities	3.71	1.25	1.00				

The municipal level of governance can be susceptible to diversion from overarching objectives and a dispersal of efforts when the community lacks a unified focus, a coherent vision, and well-defined goals. However, local government managers often assume a pivotal role in identifying decision-making challenges and prompting governing bodies to undertake self-evaluation and enhancement initiatives [136,137].

The items that were considered less relevant by the experts were related to promoting projects at the municipal level with the mandatory use of new geotechnical materials. In other words, projects that are already planned, tendered, and executed with NGs in mind. Additionally, the use of materials endorsed by international organizations was of lesser significance, as the experts believed that other institutions have a wider reach among local municipalities.

3.5. Educational Aspects

The results are shown in Table 8. The importance of developing training materials in Portuguese is also related to the socioeconomic background of the country. Brazil is a continental area with different levels of socioeconomic development, meaning that only part of the population can understand a foreign language. To ensure a more accessible application of these materials, especially in small and medium-sized municipalities, educational materials in Portuguese are considered essential for the application of these innovative solutions. All educational aspects reached consensus in the first round, with high mean values. Notably, the interviewees considered the training of engineering students to be equally important as the training of workers through partnerships with public institutions.

Table 8. KSFs for educational aspects.

Key Success Factors (KSFs)	Round 1			Round 2			SD Change
	Mean	SD	IQR	Mean	SD	IQR	
Development of knowledge materials in Portuguese	4.14	1.07	1.00				
Courses, lectures, and workshops in partnership with public entities	4.43	0.53	1.00				
Courses, lectures, and workshops for undergraduate students on new geotechnical materials	4.43	0.79	1.00				

4. Discussion

By applying the Delphi method, the KSFs for each aspect were identified based on a mean greater than four, as shown in Figure 2. The threshold of four was chosen as it represents the essential range. These KSFs can be used to provide recommendations and support a roadmap for the main stakeholders involved in implementing NGs. However, it is crucial to highlight that all the experts invited to this study are from Brazil. Thus, the discussion is conducted based on the Brazilian context. From a technical perspective, validating these materials becomes more complex as multiple aspects need to be addressed. Hence, it is essential to establish clear roles for each stakeholder involved in creating a workflow that enables the continuous development of new solutions.

Figure 2. Roadmap for the practical application of NGs.

Figure 2 presents a proposed roadmap to facilitate the practical application of the NGs on a large scale, organized into three phases as previously discussed. Each action has a list of stakeholders involved and their corresponding KSFs. In Brazil, universities play a major role in the advancement of science and technology [138]. Therefore, the development of NGs is often linked to academic research. Public universities and research funding agencies are considered the main agents in the technological development phase. However, this does not preclude or hinder opportunities for collaboration with the public and private sectors to provide support for research and development.

After technical development, including laboratory validations, social and environmental impact assessments, and full-scale technical performance evaluations, pilot projects should be implemented. These projects require continuous monitoring to evaluate and validate performance indicators. It is recommended to plan for pilot schemes that validate cost–benefit indicators for different applications. Developing SMART indicators (specific, measurable, achievable, relevant, and time-bound) is advised to ensure that the pilot schemes are realistic and measurable within an accelerated timeframe.

All these steps constitute phase I of the roadmap, focused on technology development and encompassing laboratory and full-scale testing for engineering applications. In summary, Phase I encompasses the development of novel solutions, validation through pilot projects, and monitoring, culminating in final a retro-analysis, followed by validation and a presentation of the results and lessons learned.

Phase II revolves around regulation and expanding the legal framework for the practical implementation of these innovative materials. The implementation process of this novel solution unfolds through distinct phases, each contributing to its successful integration. The initial stage involves the standardization of the innovative approach, ensuring its consistency and reliability across various contexts. Subsequently, legal regulation comes into play, establishing a framework within which the solution can operate effectively while adhering to relevant guidelines and requirements. As the endeavor progresses, attention shifts to the financial realm, where opportunities for financing are explored, and potential tax benefits are evaluated, aiming to incentivize adoption. Furthermore, the formulation of logistical plans is proposed, meticulously addressing the practical aspects of implementation. Collectively, these phases facilitate the holistic integration of the novel solution into existing systems, promoting both efficacy and compliance in its application.

Developing standards established by regulatory institutes, such as the Brazilian Association of Technical Standards (ABNT), and involving organizations like the Road Research Institute (IPR), linked to the National Department of Transport Infrastructure (DNIT), are crucial in this phase.

Incorporating NGs into technical standards enables their adoption as references in bidding processes. This not only generates funding opportunities from multilateral organizations and the private sector but also promotes the adoption of sustainable solutions aligned with the country's Sustainable Development Goals (SDGs) and Nationally Determined Contributions (NDCs).

Legalizing the use of these solutions enables the creation of logistical strategies based on the analysis of demand, supply, and regional potential. In Latin America, the transportation sector is responsible for one-third of greenhouse gas emissions [139]. Therefore, investing in the storage and distribution planning for these solutions is integral to their sustainability throughout their life cycle. However, it is necessary to explore the supply and demand outlook of a given region first. For example, composite materials containing mining waste in the pavement could be applied in the state of Minas Gerais, where a significant percentage of its roadways are unpaved and 24.41% of economic activity is related to mining. Similarly, using natural fibers in the northern region of the country could be an alternative solution, as petroleum-derived aggregates are scarce [140].

Utilizing local engineering materials and fostering the development of new technologies can have significant social impacts. When communities leverage the materials available in their immediate surroundings, it often leads to increased economic activity at the local level. This, in turn, can generate job opportunities, especially for individuals within those communities. By harnessing local resources, communities can reduce their dependence on external suppliers, contributing to enhanced self-sufficiency and economic resilience.

Furthermore, the development of new technologies can bring about transformative changes in various sectors. These technologies have the potential to improve living standards, create innovative solutions to existing problems, and enable access to better infrastructure and services. As new technologies are adopted and integrated, they can enhance efficiency, productivity, and quality of life. Additionally, technology development often requires skilled individuals, fostering the growth of educational and training programs that benefit the workforce. This, in turn, supports the development of a knowledge-based economy and can elevate the skill sets of community members.

Phase III of the roadmap involves continuous training for both public and private sectors, as well as undergraduate-level actions. This step is a cross-cutting activity in the roadmap. Brazil is currently the leading producer of scientific knowledge in Latin America [141], and the development of accessible material knowledge for different skill levels can contribute to the institutional strengthening of the whole region. Therefore, it is ideal to develop material in both Portuguese and Spanish, with support from multilateral organizations to spread it.

5. Conclusions

New geomaterials (NGs) play a crucial role in the commitment to decarbonization and sustainability. In Brazil, the identification of key success factors (KSFs) for large-scale NG projects was conducted using the Delphi method. The selection of seven experts followed the guidelines outlined by [26], and two rounds were carried out to establish convergence criteria. The following conclusions can be drawn from the study:

- Technical evidence, cost–benefit analyses, and the development of context-specific solutions are paramount for the successful implementation of NGs. It is essential to have solid scientific evidence supporting the effectiveness of these materials and to assess their economic viability in a given regional context.
- Socio-environmental considerations are crucial in the adoption of NGs. This entails utilizing waste materials for the development of new solutions, conducting life cycle analyses to minimize pollution and greenhouse gas emissions, and promoting the use of locally available resources. Moreover, it is imperative for multilateral organizations and federal-level public institutions to actively support NG initiatives. Additionally, investing in the training and education of engineering students and workers in the field of NGs is essential for their successful implementation.
- Overall, the utilization of local engineering materials and the advancement of new technologies not only drive economic growth but also contribute to social progress. By empowering communities with resources and innovative solutions, the social fabric is strengthened, fostering a sense of ownership, pride, and resilience.
- It is worth noting that not all aspects achieved a consensus among the interviewees. Some areas that require further attention include the development of materials that are more resistant to the effects of climate change, ensuring compatibility with Sustainable Development Goals (SDGs), and the need for public policies that facilitate the distribution of new geotechnical materials to vulnerable populations.

The study, though pioneering in nature, acknowledges its inherent limitations. The insights presented are intrinsically grounded in the Brazilian reality, prompting caution when extrapolating its findings to diverse contexts. Additionally, as an inaugural venture into this field, the present research signifies a preliminary exploration, positioned for expansion in subsequent investigations. Recommendations dictate that forthcoming studies engage in validating the proposed roadmap through concrete case studies, thereby reinforcing its practical applicability.

This research brings innovation by identifying the main factors that drive the use of new geotechnical materials in real-world situations. This achievement was made possible through a strong statistical method. While academic efforts have contributed significantly to developing new materials, there is still much to explore in larger studies that consider the environmental and economic effects.

In summary, the findings shared here matter to researchers and policymakers who want to promote sustainable practices in geotechnical engineering. Moving forward, there is an invitation for future researchers to test the suggested plan in real-world scenarios. This then can pave the way for progress that balances human ingenuity with caring for the environment.

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