Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 10, October, 2024

Geopolymers: Enhancing Environmental Safety and Sustainability in Construction

Muhammad S. Aiman [1], Idris Othman [1], Ahsan Waqar [1], Nadhim Hamah Sor [2*], Haytham F. Isleem [3, 4], Hadee M. Najm [5], Omrane Benjeddou [6], Mohanad Muayad Sabri Sabri [7]

[1] *Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Bandar Seri Is-kandar, 32610, Malaysia.*

[2] *Civil Engineering Department, University of Garmian, Kalar 46021, Kurdistan Region, Iraq.*

[3] *Department of Computer Science, University of York, York YO10 5DD, United Kingdom.*

[4] *Jadara University Research Center, Jadara University, Irbid 21110, Jordan.*

[5] *New Era and Development in Civil Engineering Research Group, Scientific Research Center, Al-Ayen University, Thi-Qar, Nasiriyah, 64001, Iraq.*

[6] *Department of Civil Engineering, College of Engineering, Prince Sattam bin Abdulaziz University, Alkharj 11942, Saudi Arabia.*

[7] *Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia.*

Received 17 November 2023; Revised 19 September 2024; Accepted 27 September 2024; Published 01 October 2024

Abstract

This study underscores the significant environmental advantages of geopolymer, notably its capacity for substantial CO_2 emission reduction and sustainable waste management by repurposing industrial by-products, enhancing the environmental safety in oil and gas projects. Central to our investigation is the identification and strategic overcoming of critical obstacles to the broader application of geopolymer, aiming to bridge the gap between its recognized potential and practical implementation in construction practices. Through a comprehensive analysis involving pilot, main, and validation surveys among construction industry professionals, we employed exploratory factor analysis (EFA) and structural equation modeling (SEM) to elucidate the relationships between various barriers and the success of geopolymer concrete applications. Our findings reveal that standards and knowledge significantly influence the adoption of geopolymer concrete, with an R^2 value of 0.873 indicating a high predictive utility of these constructs. The research underscores the critical need for enhanced support in research and development to improve geopolymer concrete's durability and performance over time. Significantly, this study contributes novel insights into overcoming the industry's hesitancy towards geopolymer concrete, highlighting its importance for sustainable construction practices and reducing the environmental footprint of building materials.

Keywords: Geopolymer Concrete; Success in Construction; Building Industry; Barriers.

1. Introduction

Modern infrastructure is dependent on the usage of concrete in buildings. Yet, manufacturing conventional Portland cement concrete has a considerable effect on the environment due to the high CO_2 emissions involved. In recent years, there has been a rise in the usage of alternative cementitious materials, such as geopolymer concrete, which provides

* Corresponding author: nadhim.abdulwahid@garmian.edu.krd

http://dx.doi.org/10.28991/CEJ-2024-010-10-015

various benefits over standard Portland cement concrete [1, 2]. Geopolymer concrete is produced from industrial waste and has a lower carbon footprint, excellent strength, and other benefits. The production of concrete accounts for around 8% of worldwide CO_2 emissions. Concrete is the most frequently used construction material in the world. Many of these emissions may be attributed to manufacturing Portland cement, the principal component of conventional concrete [3, 4]. As a result of this environmental effect, academics and industry experts have sought alternate materials that may lower the carbon footprint of concrete manufacturing. Geopolymer concrete is a possible replacement for conventional Portland cement concrete. Geopolymers are substances derived from industrial wastes such as fly ash, slag, and other similar substances. Geopolymer concrete provides various benefits over conventional concrete, such as a lower carbon footprint, excellent durability, and enhanced resilience to acid and alkali assaults. In addition, geopolymer concrete has a longer lifetime than conventional concrete, which reduces the need for maintenance and repairs. Despite its potential advantages, there are still obstacles to the widespread usage of geopolymer concrete [5, 6]. The need for standards and restrictions for its usage is one of the main obstacles. There is a need for precise criteria for using geopolymer concrete, including its composition, characteristics, and testing procedures [7, 8].

Globally, geopolymer concrete has been used in several high-profile building projects. In 2013, the Sydney Harbor Bridge in Australia, for instance, was restored using a geopolymer concrete mix [9, 10]. The project's usage of geopolymer concrete was able to resist the hostile coastal climate, indicating its appropriateness for infrastructure construction. In recent years, the usage of geopolymer concrete in Europe has significantly increased. According to research by the European Union, geopolymer concrete output in Europe has been growing at a pace of 10% annually. According to the report, the use of geopolymers substantial in Europe has the potential to cut construction sector CO_2 emissions by up to 80%. In Asia, geopolymer concrete is also gaining popularity. Mainly, China has been investing in geopolymers concrete research and development. In 2017, a Chinese firm constructed a geopolymer concrete bridge that could endure severe traffic and environmental conditions in Shanghai [11, 12]. The project established the viability and innovation of geopolymer concrete as a construction material. The worldwide market for geopolymer materials is anticipated to develop at a CAGR of 27% from 2020 to 2025. Increasing demand for sustainable and long-lasting construction materials is cited as the primary growth driver of the geopolymer materials market. Compared to conventional concrete, the usage of geopolymer concrete is still relatively limited. According to research by the International Energy Agency, geopolymer concrete manufacturing accounted for less than one percent of the worldwide cement and concrete industry in 2019 [13, 14].

Nevertheless, the study also indicates that the usage of geopolymer concrete is anticipated to expand as more research is undertaken and legislation is enacted to encourage its use. Several nations have previously created geopolymer concrete legislation and standards. In Australia, for instance, the National Building Code stipulates using geopolymer concrete in construction projects. Likewise, the European Union has set testing and characterization criteria for geopolymer materials [15, 16]. It has also been shown that using geopolymer concrete provides economic advantages. According to research by the University of Melbourne, using geopolymer concrete in infrastructure projects may result in up to 40% cost savings compared to conventional concrete. The analysis also indicated that using geopolymer concrete might result in substantial savings in CO_2 emissions, making it a more sustainable and eco-friendly solution [17, 18].

Recent literature underscores the environmental imperative of reducing the construction industry's reliance on traditional Portland cement. Studies [19, 20] have highlighted geopolymer concrete's advantages, including its resilience against environmental stressors and potential to significantly cut global CO2 emissions. However, the adoption of geopolymer concrete is hindered by technical, regulatory, and market acceptance challenges, revealing a critical gap in the current body of research—particularly in understanding and overcoming these barriers. A substantial study has been conducted on geopolymer concrete, but there still needs to be a significant knowledge gap about the obstacles to its use and how to overcome them. Only some studies have examined the social, economic, and environmental issues that may influence the use of geopolymer concrete in the building sector. There is a need for more great studies on the impediments to the construction industry's use of geopolymer concrete. This study should thoroughly investigate the elements that influence the decision-making processes of stakeholders, such as contractors, developers, and regulators. In addition, an analysis of the economic viability of employing geopolymer concrete instead of conventional concrete is required.

This paper endeavors to fill the identified literature gap by offering a nuanced exploration of the technical, social, economic, and environmental dimensions influencing geopolymer concrete's adoption. Our approach is grounded in a robust review of existing studies, paired with an original empirical analysis, to chart a path forward for the material's integration into mainstream construction practices. By doing so, we contribute a significant leap in knowledge towards the sustainable transformation of the construction industry, aligning with global efforts to mitigate climate change.

In response, our study proposes a novel analytical approach, employing both exploratory factor analysis (EFA) and structural equation modeling (SEM), to dissect the multifaceted obstacles to geopolymer concrete's broader application. By synthesizing insights from industry professionals and existing research, we aim to map out a comprehensive framework that not only identifies but also proposes strategies to mitigate these impediments. This research gives a complete knowledge of the aspects that contribute to the acceptance and success of geopolymer concrete in the construction sector by analyzing these qualities and their link to its success. In addition, Smart PLS 4, a program for SEM analysis, is used to verify the precision and dependability of the data. This program is renowned for its capacity to handle complex data and provide accurate findings, making it a suitable instrument for assessing the complex interactions between the variables investigated in this study. This research adds to the body of knowledge by shedding light on the obstacles that impede the use of geopolymer concrete in building projects. This research presents a roadmap for overcoming these challenges and advancing the adoption of geopolymer concrete as a sustainable and long-lasting alternative to conventional concrete by identifying these obstacles and their relevance to the success of geopolymer concrete.

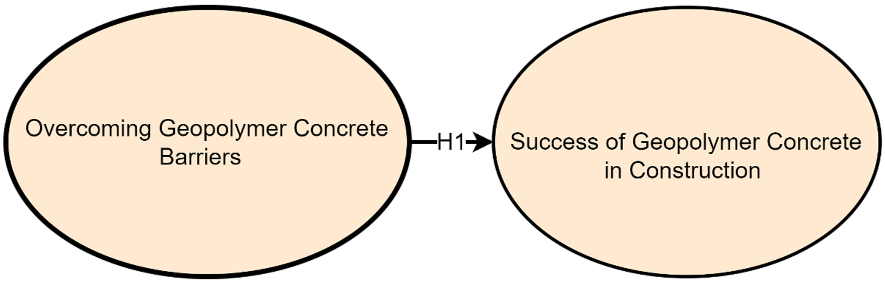

Figure 1. Adopting geopolymer concrete by overcoming its barriers have significant effect on the success of geopolymer concrete in construction

2. Identification of Barriers

Civil engineering and construction professionals participated in structured interviews to identify the impediments to the acceptance and success of geopolymer concrete in building projects. Individuals with expertise in planning, building, and managing infrastructure projects with geopolymer concrete were interviewed. The interviews were performed using a standardized questionnaire to elicit comments about the numerous obstacles to the adoption and success of geopolymer concrete [21, 22]. The questions aimed to collect data on the perceived technical, economic, regulatory, and societal impediments to geopolymer concrete. The interviews were transcribed and processed using NVivo, a computer program developed to evaluate qualitative data. The study used a thematic method to find significant themes and patterns within the data [23, 24]. The interview data analysis identified some obstacles to the adoption and success of geopolymer concrete. Technical, economic, regulatory, and societal categories were used to classify these impediments.

The investigation found that there needs to be more standardization, and the restricted availability of materials and equipment necessary to manufacture geopolymer concrete are technical barriers to its adoption [25, 26]. Additional noted technical impediments include the requirement for specific expertise and training to utilize geopolymer concrete and the need for more reliable information about its long-term durability and performance [27, 28]. It is also found that the economic hurdles to adopting geopolymer concrete consist of its higher manufacturing costs than conventional concrete, the absence of incentives for its usage, and the restricted availability of finance for geopolymer concrete projects [29, 30]. The investigation indicated that the regulatory hurdles to using geopolymer concrete include the absence of defined norms and standards for its usage in building projects, the need for more regulatory assistance, and the restricted availability of testing and certification services [31, 32]. It is indicated that the societal hurdles to adopting geopolymer concrete include a need for more public understanding and acceptance of the material, a shortage of specialized labor for its manufacture and usage, and reluctance to change the status quo [33, 34].

The study of interview data provides significant insights into the obstacles to the adoption and success of geopolymer concrete in building projects [34, 35]. These results may be utilized to overcome these obstacles and promote geopolymer concrete as a sustainable and long-lasting alternative to conventional concrete [36, 37].

In conclusion, the analysis of the structured interviews conducted with NVivo has shown several technical, economic, regulatory, and social obstacles that impede the adoption and development of geopolymer concrete in the construction industry. It is conceivable to expedite the adoption of geopolymer concrete as a viable choice for sustainable and long-lasting infrastructure projects by solving these obstacles.

Several keyword rounds allowed us to get a total of 2,381 entries from all databases. Upon examination of their titles, abstracts, and possible impediments, 237 articles fit the requirements for this research. To identify geopolymer obstacles in building projects, we conducted a thorough literature review of 237 articles, as shown in Table 1. Most of the obstacles mentioned in the articles had similarities with those excluded. After reviewing the relevant literature, only 18 obstacles and 9 success factors were deemed to be crucial when dealing with building projects.

Table 1. Data collection summary

Database	Keywords Combination	Total Collected Studies	Relevant Studies
Springer	"Geopolymer Concrete AND Eco-Friendly Construction AND Modelling"	817	44
WoS	"Geopolymer Concrete OR Eco-Friendly Construction OR Modelling Barriers in Implementation OR Success"	210	35
ASCE	"Geopolymer Concrete AND Eco-Friendly Construction OR Modelling AND Barriers in Implementation OR Success"	416	21
Science Direct	"Geopolymer Concrete AND Eco-Friendly Construction OR Obstacles"	113	87
Scopus	"Geopolymer Concrete OR Eco-Friendly Construction AND Obstacles AND Modelling OR Barriers in Implementation OR Success"	22	6
Google Scholar	"Geopolymer Concrete OR Eco-Friendly Construction AND Modelling AND Barriers OR Implementation OR Success OR Obstacles"	691	44
Total		2381	237

Table 2 includes the identified barriers and Table 3 shows the success factors. These barriers are identified in two steps. The first step includes detailed literature studies from various journals, and the second step includes structured interviews, which not only categorize the identified barriers but also add a few new ones.

Table 2. Identification of Implementation Barriers

Sr. #	Description of Barriers	Initial Assigned Category	Reference
1	Due to the absence of set rules, regulatory bodies may be unwilling to authorize geopolymer concrete for use in the building. This may make it more difficult to secure the required permissions and approvals for geopolymer concrete buildings, limiting their use in construction.	Regulatory	Interview
2	Geopolymer concrete is a relatively new material compared to conventional concrete, and research on its long-term performance and durability is still restricted. This lack of knowledge might make establishing the proper design and construction techniques for geopolymer concrete buildings easier.	Technical	Interview
3	The building industry has a history of resistance to adopting new technology and materials. Change aversion may impede the broad adoption of geopolymer concrete, particularly if standard Portland cement concrete is seen as the default alternative.	Social	[38-40]
4	Geopolymer concrete may have different qualities than standard Portland cement concrete, making its application in retrofitting or repair projects hard. This may restrict the use of geopolymer concrete and make its integration into existing infrastructure challenging.	Technical	[41-43]
5	There are presently no industry norms or rules governing the use of geopolymer concrete in construction. This may make it challenging for architects, engineers, and contractors to integrate geopolymer concrete into their designs and maintain compliance with applicable building rules and regulations.	Regulatory	Interview
6	The manufacturing and use of geopolymer concrete need knowledge and skill that may not be commonly accessible. This might make it challenging for contractors and construction firms to use geopolymer concrete in their projects.	Technical	[44-46]
7	Using geopolymer concrete will need cooperation across several businesses, including the construction, manufacturing, and waste management sectors. Yet, coordination across various sectors may be restricted, making building the required supply networks, production methods, and standards difficult.	Social	[47, 48]
8	The manufacture and delivery of geopolymer concrete sometimes need a specific supply chain that may not be well-established or broadly accessible. This might make it difficult to get supplies and equipment promptly and economically.	Economic	[49, 50]
9	Using various raw ingredients and binder solutions in geopolymer concrete might result in differences in the concrete's physical qualities. This lack of uniformity might make predicting the performance of geopolymer concrete buildings challenging.	Technical	Interview
10	Owing to the novelty of geopolymer concrete, certain stakeholders may see it as a material of inferior quality to typical Portland cement concrete. Even though geopolymer concrete has been proven to be a better material in terms of performance and durability, this notion may prevent its widespread use.	Regulatory	[51, 52]
11	Geopolymer concrete still needs to be clarified among architects, engineers, and construction professionals. Developing interest and demand for geopolymer concrete constructions might be challenging due to a lack of knowledge.	Technical	[53, 54]
12	Geopolymer concrete has several benefits, but there may be little market demand for it, particularly if standard Portland cement concrete remains the default material for many building projects. This may make creating sufficient interest and funding for geopolymer concrete difficult.	Social	Interview
13	Testing standards and procedures for geopolymer concrete are still in the process of being established and may need to be widely accepted or acknowledged by regulatory authorities. This may make it difficult to demonstrate the performance and durability of geopolymer concrete constructions to stakeholders and regulators.	Regulatory	[55, 56]
14	Absence of design guidelines Geopolymer concrete constructions may need different design rules and specifications than standard Portland cement concrete structures. Unfortunately, these parameters may need to be well-established, making it challenging to design and build geopolymer concrete structures in a manner that maximizes their performance.	Regulatory	[57-59]
15	The geopolymer concrete basic ingredients, such as fly ash, slag, and other industrial wastes, may not be easily accessible in all places. This may make it challenging to create geopolymer concrete locally and increase shipping expenses.	Economic	[60-62]
16	Owing to geopolymer concrete's relative novelty, its construction usage may relate to a perception of danger. This might make it challenging to persuade building owners, developers, and other stakeholders of its safety and dependability.	Social	[63, 64]
17	While geopolymer concrete has shown high performance in laboratory testing, its long-term performance and resilience to environmental conditions such as freeze-thaw cycles and chemical degradation still need to be investigated. This ambiguity might make it difficult for geopolymer concrete constructions to gain regulatory permission and finance.	Regulatory	Interview
18	Due to the expense of raw ingredients and the specialized equipment and knowledge necessary for its manufacturing, the initial cost of making geopolymer concrete might be greater than that of conventional concrete. Its expense may hinder the widespread use of geopolymer concrete.	Economic	[65, 66]

Table 3. Success factors of geopolymer implementation

Constructs	Code	Success Factors	References
Environmental	E1	Reduces waste	[67, 68]
	E2	Increases durability	[69, 70]
	E3	Provide weather resistance	[71-73]
Fire Resistance	F1	Increase fire resistance	[54, 65, 66]
	F2	Develop an efficient thermal concrete	[67, 69, 71]
	F3	Increases ductile failure chances during the fire	[74-76]
Improved Strength	S1	Increase mechanical properties	[75, 76]
	S2	Increase bond strength	[77, 78]
	S3	Add tensile strength	[79, 80]

3. Methodology

This research aims to simulate the link between overcoming hurdles to geopolymer concrete and its success in building projects, considering its fire resistance, environmental friendliness, and increased strength. The research used a structural equation modeling (SEM) technique, and Smart PLS 4 software was used to analyze the data. The research used a non-probability sampling strategy, especially a purposive sampling technique. The participants were chosen based on their civil engineering and construction knowledge, namely geopolymer concrete [55, 57]. An online structured questionnaire was used to collect data on the hurdles to the adoption and success of geopolymer concrete and its fire resistance, environmental protection, and enhanced strength features. Experts vetted and pretested the questionnaire to verify its validity and reliability. The acquired data was examined using the Smart PLS 4 program, a potent and robust instrument for evaluating complex data in structural equation modeling (SEM). Using a two-step methodology, the analysis was conducted: the measurement model and the structural model. The measurement model was used to evaluate the validity and reliability of the study's constructs, while the structural model was utilized to explore the links between the variables.

Many statistical tests, including reliability analysis, convergent validity, and discriminant validity, were used to evaluate the measurement model. Path coefficients, R-square values, and significance tests were used to examine the structural model [57, 58]. The research was conducted following ethical principles and standards, and all individuals gave informed permission before participation. The privacy and confidentiality of the participants were protected, and the gathered data were utilized only for research reasons. In addition, the research did not compare geopolymer concrete to other alternative materials. The study relied on self-reported data susceptible to bias and inaccuracy. The research offers valuable insights into the obstacles that impede the acceptance and success of geopolymer concrete and gives ways to overcome these obstacles. The method is indicated in Figure 2.

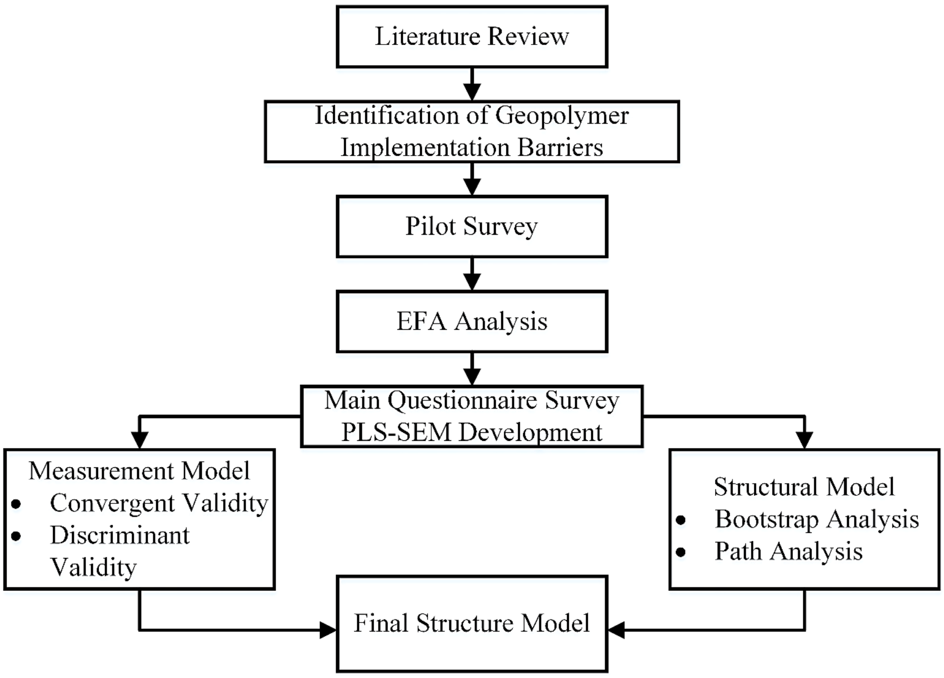

Figure 2. Research flowchart

3.1. Exploratory Factor Analysis (EFA)

The online pilot survey questionnaire included 150 people from the Malaysian construction sector randomly chosen for participation. The survey was meant to be a proof-of-concept to collect preliminary data on the perceived hurdles to the effective use of geopolymer concrete in building projects. After the pilot survey, the data were analyzed using EFA to tease out the contributing causes to the perceived roadblocks [65, 66]. It is a statistical approach used to examine a data set's interrelationships to isolate the relevant latent components. Using principal component analysis (PCA) and varimax rotation, this research performed EFA. The research strategy used here was developed to fill in the gaps in our knowledge about the factors affecting the success of building projects that utilize geopolymer concrete. The study's findings may be used to remove these roadblocks and increase geopolymer concrete's usage in building construction [55, 56].

3.2. Structural Equation Modelling (SEM)

After the pilot survey, 210 professionals working in the Malaysian construction business completed the final online main survey questionnaire. Structural Equation Modeling (SEM) was used to evaluate the gathered data to examine the connections between the formative and reflective structures and the obstacles preventing the widespread use of geopolymer concrete in buildings. Convergent and discriminant validity were computed to evaluate the survey's accuracy and precision [81-83]. The model fit indices were also examined to guarantee a satisfactory match to the data. Next, a path analysis was carried out to determine how the formative and reflective constructions are related to the challenges that geopolymer concrete faces in the building industry [81, 84]. The final model was achieved by iterative model refinement guided by the findings of a route analysis. As the influence of many constructs on a dependent variable may be evaluated in this research, the SEM method was used. This strategy is useful in social science research for testing theoretical models and illuminating connections between concepts [60, 62]. In conclusion, SEM was used in this research to better understand the interplay between the formative and reflective constructions and, therefore, the main factors that work against the widespread adoption of geopolymer concrete in the building industry. By understanding these challenges, we may better devise solutions to encourage the widespread usage of geopolymer concrete in building projects [58, 59].

3.3. Model Validation Analysis

A brief survey questionnaire was used to verify the generated structural model. The validation survey was administered to the major stakeholder of this study, who holds a PhD in civil engineering materials and has more than ten years of experience in construction projects. The purpose of validation was to verify the practical applicability of the developed structural model so that appropriate measures could be taken to manage the obstacles and their impact on the deployment of geopolymer concrete for ecofriendly success in the construction industry. Authors believe that the validation method is essential to the success of this research. Five essential questions were devised to determine the model's validity, and 17 experts were requested to participate in the validation survey.

- Considering environmental protection, fire resistance, and strength elements of modest building projects, are the model's proposed criteria applicable to hurdles associated with the usage of geopolymer concrete for the success of geopolymer concrete in overcoming these barriers?
- Is the model appropriate for identifying the principal barriers preventing the use of geopolymer concrete in the eco-friendly advancement of modest building projects?
- Are the success metrics outlined in the structural model a realistic depiction of the removal of obstacles associated with the usage of geopolymer concrete in building projects?
- Do you believe the conclusions of the research to be credible?
- Can the structural model suggested by the research be generalized?

4. Results

4.1. Exploratory Factor Analysis

The findings of an exploratory factor analysis (EFA) that suggests three main reasons preventing the widespread use of geopolymer concrete in the building industry. Three components with eigenvalues larger than 1 account for 58.015% of the total variance. With factor loadings between 0.604 and 0.793, barriers Bar9, Bar5, Bar12, Bar11, Bar6, and Bar8 comprise Component 1. These issues stem from engineers, contractors, and clients needing to be more familiar with and knowledgeable about geopolymer concrete technology. Barriers Bar2, Bar16, Bar17, Bar3, Bar14, and Bar18 comprise Component 2, with factor loadings from 0.602 to 0.771. The technical difficulties of making geopolymer concrete, such as deciding which ingredients to use in the mix, how to cure it, and so on, pose significant obstacles. Barriers Bar15, Bar 4, and Bar 13 comprise Component 3, with factor loadings of 0.615 to 0.703. The high manufacturing cost, the scarcity of raw materials, and the lack of demand in the building industry are all examples of geopolymer concrete's economic and market-related issues. As a result of their low factor loadings (0.6) or their cross-loading with numerous factors, the factors for the obstacles numbered Bar1, Bar7, and Bar10 were eliminated from the factor analysis. These roadblocks aren't neatly categorized by the three identified characteristics, indicating that further research is needed. High internal consistency and reliability levels may be inferred from the factors' Cronbach's alpha scores of 0.877, 0.823, and 0.811, respectively. The EFA findings show that stakeholders need to solve a variety of barriers to encourage the widespread implementation of geopolymer concrete in the building industry.

According to the EFA findings, the following structures were discovered, and particular obstacles have been allocated to each construct and listed in Table 4. Standardization and knowledge, novelty and creativity, and economics and strategy are the major categories the constructions fall into, as shown in Figure 3.

Table 4. Constructs with barriers generated after EFA analysis

Constructs	Variables
Standardization and Knowledge	Bar9
	Bar5
	Bar12
	Bar11
	Bar6
	Bar8
Novelty and Complexity	Bar2
	Bar16
	Bar17
	Bar3
	Bar14
Economic & Strategical	Bar18
	Bar15
	Bar4
	Bar13

Barriers associated with the absence of industry norms or rules governing the use of geopolymer concrete are included in the first construct, Standardization and Knowledge, as are difficulties in predicting the performance of geopolymer concrete due to the use of varying raw ingredients and binder solutions. The low market demand for geopolymer concrete and the lack of expertise in its production and use further contribute to this framework's limitations [10-12].

The absence of long-term performance data and the impression of risk connected with employing a relatively new material in the building are two challenges under the second component, Novelty and Creativity. The lack of geopolymer concrete-specific design rules and the construction industry's reluctance to embrace new technologies and materials also figure prominently here [15, 16].

The high initial cost of creating geopolymer concrete owing to the expensive raw materials and specialized equipment, as well as the restricted accessibility of essential components in particular regions, falls under the Economic and Strategical category. Incompatibility with preexisting facilities and a lack of standardized testing methods for geopolymer concrete additionally pose challenges to this structure's implementation [14, 17].

Overall, the obstacles uncovered in this research shed light on the difficulties inherent in removing roadblocks to the widespread use of geopolymer concrete in the building industry. According to the results, increasing the use of geopolymer concrete in building projects requires removing roadblocks associated with a lack of information and standards, a lack of experience with the material, and concerns about cost and strategy [17, 18].

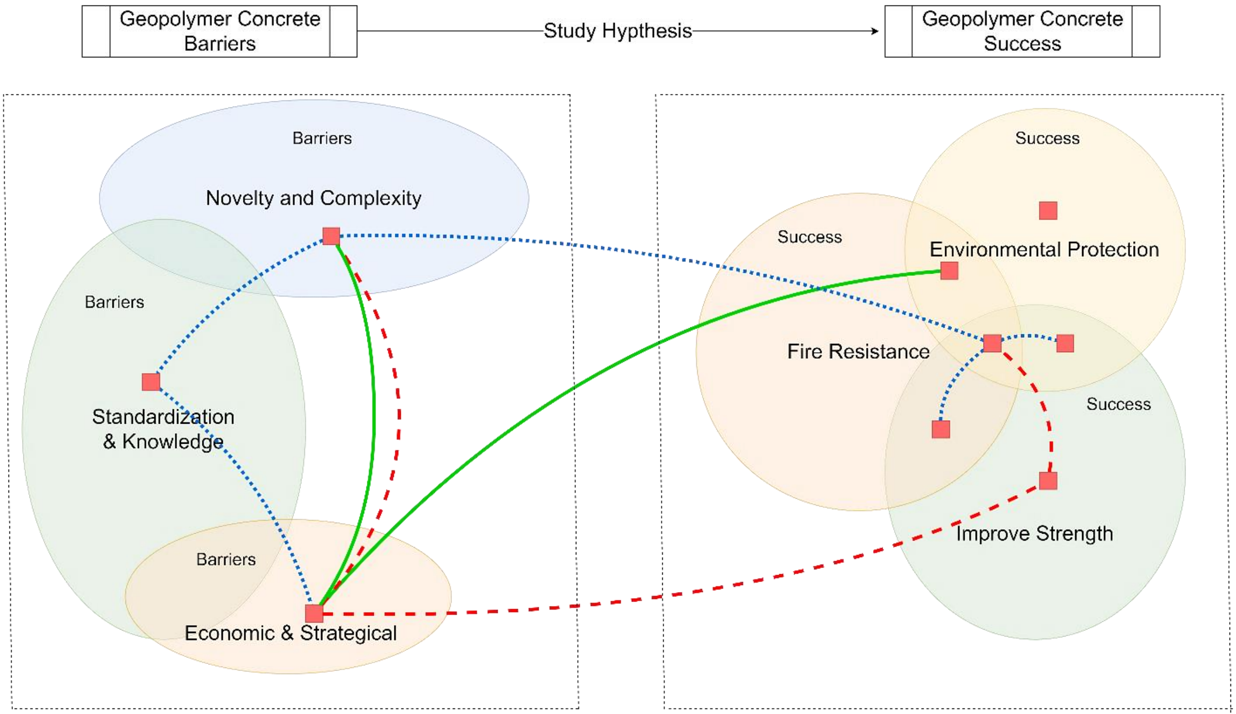

Figure 3. Categories designed after EFA analysis

4.2. Demographics

Participants' demographic information is shown in Table 5. The table shows the number of respondents at each level of the variables and the proportion of those that answered the survey. The first factor is the level of education, which may be either a bachelor's, master's, or doctorate. Sixty-eight percent of respondents have a master's degree; the next largest educational attainment percentage comprises those with a bachelor's degree (16 percent), followed by those with a doctorate (16 percent). Geopolymer Concrete Knowledge is the second variable, and it assesses how well-versed a responder is in geopolymer concrete. The categories used to classify the replies were no knowledge, uncertain, and yes. Sixty-five percent of respondents said they were familiar with geopolymer concrete; 21 percent said they were not; and 14 percent said they weren't sure (maybe). The third factor is years of job experience, broken into five distinct categories. Among the respondents, 31% said they had 16-20 years of experience in the workforce, 26% said they had 11-15 years, 21% said they had 5-10 years, 17% said they had more than 20 years, and 5% said they had fewer than 5 years. Most survey takers in this research had at least a master's degree. Most respondents also claim familiarity with geopolymer concrete, suggesting their understanding is rather deep. The respondents have a broad variety of experience, with those with 16-20 years in the workforce making up the biggest group. Results may be extrapolated to the general population with a comparable educational and occupational profile, as indicated by the sample's demographics.

Table 5. Demographic profile of respondents

Variable	Level	Frequency	Percent
Academic Qualification	Bachelor	34	16%
	Masters	143	68%
	PhD	33	16%
Geopolymer Concrete Knowledge	No	45	21%
	Maybe	29	14%
	Yes	136	65%
Work Experience	Less than 5	11	5%
	5 to 10 years	44	21%
	11 to 15 Years	55	26%
	16 to 20 Years	65	31%
	Above 20 Years	35	17%

4.3. Structure Equation Modelling

4.3.1. Measurement Model

Structural equation modeling's measurement model's reliability and validity data are summarized in the table below. Reliability statistics seek to quantify the internal consistency of a group of items or variables inside a concept, as indicated in Table 6. For this analysis, reliability was calculated using Cronbach's alpha coefficient. The Cronbach's alpha coefficients for all of the constructs are over 0.7, indicating high levels of dependability. The composite reliability quantifies the degree to which an attribute is reliably assessed. In the table, we can see the composite reliability measures of rho-a and rho-c. For all constructions, rho-a and rho-c are above 0.8, indicating high dependability. The amount to which a concept measures what it is intended to measure is quantified by validity statistics. As a metric of convergent validity, the average variance extracted (AVE) shows how well a concept accounts for the differences between its constituent parts.

Table 6. Reliability and validity statistics

Constructs	Cronbach's alpha	Composite reliability (rho-a)	Composite reliability (rho-c)	The average variance extracted (AVE)
Economic & Strategical	0.821	0.862	0.881	0.655
Environmental Protection	0.881	0.933	0.930	0.819
Fire Resistance	0.700	0.780	0.821	0.601
Improved Strength	0.767	0.821	0.851	0.662
Novelty & Complexity	0.800	0.803	0.862	0.551
Standardization & Knowledge	0.871	0.880	0.910	0.721

In most cases, convergent validity is excellent if the AVE is greater than 0.5. The AVE values for all constructs in this analysis are more than 0.5, demonstrating strong convergent validity [71, 73]. The findings indicate that the constructs are well-defined and sufficiently assessed by the variables used in the research and that the measurement model is valid and trustworthy.

Table 7 displays the results of an analysis of the discriminant validity of the constructs according to Fornell and Larcker's criteria. Discriminant validity describes the extent to which the constructs may be differentiated from one another and do not measure the same underlying idea. Fornell and Larcker's criteria compare the square root of the average variance extracted (AVE) for each construct by using the correlations between each construct and the others in the model. Discriminant validity is absent from a concept if the correlation between it and any of the others is smaller than the square root of the AVE for that construct. Each concept has discriminant validity, as shown in Table 6, when the square root of the AVE is bigger than the correlation between that construct and any of the other constructs. For instance, the square root AVE (0.808) for the Economic & Strategical construct is greater than the AVEs (0.189) for Environmental Protection, (0.194) for Fire Resistant, (0.1199) for Increased Strength, (0.162) for Novelty & Complexity, and (0.108) for Standardization & Knowledge (0.162). (0.15). This demonstrates the discriminant validity of the Economic and Strategical compared to the other model variables. Using the Fornell and Larcker criterion, the constructions accurately represent their intended categories of meaning [77, 78].

Table 7. Fornell and Larcker Criteria

Constructs	Economic & Strategical	Environmental Protection	Fire Resistance	Improved Strength	Novelty & Complexity	Standardization & Knowledge
Economic & Strategical	0.808					
Environmental Protection	0.189	0.904				
Fire Resistance	0.194	0.338	0.779			
Improved Strength	0.199	0.23	0.21	0.815		
Novelty & Complexity	0.162	0.4	0.143	0.188	0.747	
Standardization & Knowledge	0.15	0.142	0.315	0.194	0.389	0.851

Table 8 displays the HTMT ratio of correlation coefficients, which may be used to assess discriminant validity. The diagonal components show that the ideal HTMT ratio for the design is less than 1. The HTMT ratio, shown by the elements off the diagonal, should be less than the square root of the AVE of the two buildings under consideration. For the constructs to be convergent, it must be proven that all diagonal elements in the table have values smaller than 1. Excellent discriminant validity is shown by the fact that all off-diagonal component values are less than the square root of the AVE for their respective constructs [71, 73]. The HTMT analysis demonstrates that the measurement model's components have high discriminant validity, suggesting that they accurately measure separate things.

Table 8. HTMT statistics

Constructs	Economic & Strategical	Environmental Protection	Fire Resistance	Improved Strength	Novelty & Complexity	Standardization & Knowledge
Economic & Strategical						
Environmental Protection	0.22					
Fire Resistance	0.298	0.436				
Improved Strength	0.23	0.27	0.335			
Novelty & Complexity	0.245	0.477	0.14	0.256		
Standardization & Knowledge	0.211	0.072	0.407	0.236	0.467	

The model's cross-loadings are shown in Table 9. The degree to which items are developed to assess one construct and measure other constructs is called their cross-loading. Correlations between items and model constructs are shown in the table below. Each item in the table strongly connects with the construct it is designed to assess, indicating that the items have a high loading on their respective constructs. The Economic & Strategical construct correlates most strongly (0.86) with item Bar18.

Table 9. Cross loadings involved in model

	Economic & Strategical	Environmental Protection	Fire Resistance	Improved Strength	Novelty & Complexity	Standardization & Knowledge
Bar18	0.86	0.121	0.236	0.192	0.145	0.075
Bar13	0.746	0.147	-0.01	0.075	0.046	0.112
Bar4	0.796	-0.057	0.133	0.292	0.022	-0.107
Bar15	0.826	0.301	0.204	0.112	0.229	0.292
E1	0.236	0.911	0.324	0.192	0.371	0.86
E2	0.098	0.801	0.262	0.135	0.309	0.134
E3	0.153	0.926	0.325	0.191	0.401	0.178
F1	0.183	0.343	0.792	0.204	0.121	0.206
F2	0.233	0.256	0.761	0.252	0.218	0.244
F3	0.058	0.198	0.750	0.059	0.373	0.192
S1	0.286	0.121	0.236	0.861	0.145	0.075
S2	0.226	0.301	0.204	0.860	0.229	0.292
S3	0.046	0.147	-0.01	0.701	0.046	0.112
Bar2	0.118	0.291	0.192	0.153	0.826	0.226
Bar17	0.098	0.107	0.262	0.135	0.834	0.134
Bar3	0.153	0.046	0.325	0.191	0.878	0.078
Bar14	0.135	0.74	0.28	0.177	0.864	0.064
Bar12	0.233	0.256	0.362	0.252	0.244	0.818
Bar5	0.183	0.343	0.298	0.204	0.306	0.721
Bar6	-0.01	0.348	0.289	0.013	0.359	0.685
Bar8	0.197	0.234	0.114	0.208	0.227	0.804
Bar9	-0.049	0.328	0.016	-0.025	0.335	0.699

Similarly, there is a strong relationship (0.951) between item E1 and the concept of environmental protection. Whereas most objects have low loadings on structures other than the one they were designed to assess, a handful has quite high loadings. For instance, despite its intended use to gauge fire resistance, item Bar13 has a surprisingly high loading (0.746) on the Economic & Strategical construct. Similarly, despite its intended measurement of Novelty and Complexity, item F3 has a surprisingly high loading (0.776) on the Fire Resistance construct [76, 78, 80].

4.3.2. Structural Path Analysis

The following Tables 10 and 11 displays the findings from a path analysis that examined the connections between the three formative components and a dependent variable: Economic and Strategical, Novelty and Complexity, and Standardization and Knowledge (Barriers to Success of Geopolymers Concrete). The path analysis uses the coefficient alpha, standard error (SE), t-value, p-value, and variance inflation factor to measure the strength of the links between each formative component and the dependent variable (VIF). The findings show that these three formative structures are positively related to the success barriers of geopolymer concrete. An increase in Economic and Strategical Barriers to the Success of Geopolymers Concrete by one unit is correlated with an increase of 0.407 units in the coefficient. The novelty and complexity coefficient is 0.355, suggesting that a one-unit increase in this construct is correlated with a 0.355-unit rise in Geopolymers Concrete's barriers to success. The beta coefficient for Standardization & Knowledge is 0.611, suggesting a 0.611-unit rise in Barriers to the Success of Geopolymers Concrete for every 1-unit increase in this construct. The t-values and p-values for all three route coefficients are statistically significant, indicating that the observed correlations are probably not coincidental [57-59]. All of the VIF values are less than 1.5. Therefore, multicollinearity is not a major problem. This study's findings indicate that the Economic and Strategical, Novelty and Complexity, and Standardization and Knowledge antecedents to the Barriers to Success of Geopolymers Concrete are all positively correlated. This suggests that focusing on these frameworks may aid in lowering obstacles to the widespread use of geopolymer concrete.

Table 10. Formative constructs with path analysis results

Path	β	SE	t-values	p-values	VIF
Economic & Strategical → Barriers to Success of Geopolymers Concrete	0.407	0.087	5.39	<0.001	1.036
Novelty & complexity → Barriers to Success of Geopolymers Concrete	0.355	0.046	3.215	<0.001	1.194
Standardization & Knowledge → Barriers to Success of Geopolymers Concrete	0.611	0.058	12.195	<0.001	1.189

Table 11. Reflective constructs with path analysis results

Path	β	SE	t-values	p-values
The success of geopolymer Concrete → Environmental Protection	0.841	0.029	29.15	<0.001
The success of Geopolymer Concrete → Fire Resistance	0.541	0.06	8.379	<0.001
The success of Geopolymer Concrete → Improved Strength	0.544	0.085	6.644	<0.001

Path analysis results for the model reflecting constructs are shown in Table 12. The table displays the t-values, p-values, standard errors, and path coefficients (β) for the correlation between the various reflective constructs. Environmental protection (β = 0.841, p 0.001), fire resistance (β = 0.541, p 0.001), and enhanced strength (β = 0.544, p 0.001) all seem to benefit greatly from the use of geopolymer concrete. These results suggest that substantial enhancements to the characteristics of concrete may result from the widespread use of geopolymer concrete. The overall findings of the path analysis corroborate the hypothesized relationships between the model's constructs, demonstrating the significance of economic and strategic factors, novelty and complexity, and standardization and knowledge in removing the obstacles to geopolymer concrete's widespread adoption [55, 56, 66]. Environmental protection, fire resistance, and enhanced strength are just a few of the features that the studies show might benefit from the widespread use of geopolymer concrete. Figure 4 present the model with path significance, respectively.

Table 12. Predictive relevance

Endogenous Latent Variable	R^2	Adjusted R^2	Explained Size
The success of Geopolymer Concrete	0.873	0.873	Highly Predictive

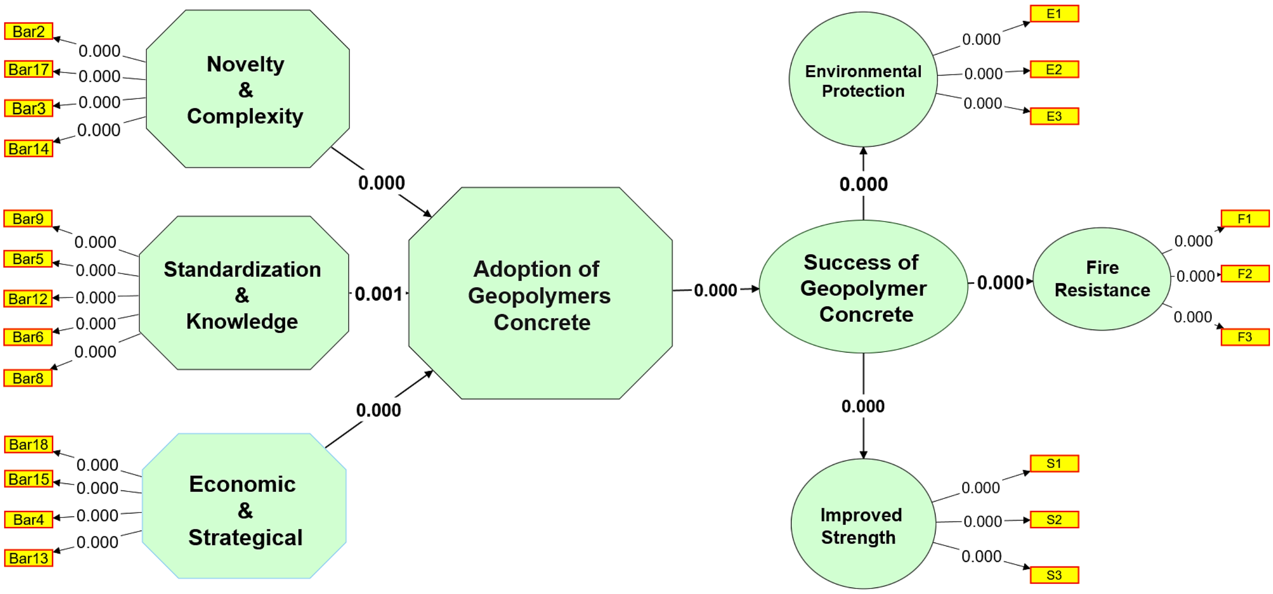

Figure 4. Model path significance

The success of Geopolymer Concrete" is an endogenous latent variable in the study model, and its predictive significance is shown in Table 13. The model's exogenous latent variables can explain 87.3% of the variation in the success of the Geopolymer Concrete construct, as shown by an R^2 value of 0.873. An adjusted R^2 of 0.873 indicates that the model fits the data well without overfitting. The large magnitude of the explanatory variable for "Highly Predictive" suggests that the predictions made by the endogenous construct are reliable. Thus, Table 12 suggests that the exogenous latent variables included in the model substantially influence the endogenous construct of "Success of Geopolymer Concrete" and may accurately predict the success of geopolymer concrete based on the constructs included in the model.

Table 13. Efficiency of prediction of the model

Endogenous Latent Variable	SS0	SSE	Predict-Q^2
The success of Geopolymer Concrete	849.000	537.255	0.367

The prediction model's efficacy is presented in Table 14. The success of Geopolymer Concrete is an endogenous latent variable, and the results comprise the sum of squares of the original data (SS0), the sum of squared errors (SSE), and the Predict- Q^2 value. The whole data variance (SS0) for the dependent variable (Success of Geopolymer Concrete) is compared with the variance (SSE) that the model does not capture. The model's predictive power is quantified by a metric called Predict- Q^2. Here, we get an SS0 of 849.000 and an SSE of 537.255. The model has a fair amount of predictive power, explaining about 37% (Predict-Q^2 = 0.367) of the variation in the data. While this is encouraging, it also shows that a large degree of mystery in the data remains, suggesting that further study is required to boost the model's predictive ability [53, 54].

Table 14. Importance and performance results

Predictor	Importance	Performance
Barriers to the Success of Geopolymers Concrete Implementation	1.341	55.116

The Predictor variable "Barriers to Success of Geopolymers Concrete Implementation" relevance and performance outcomes are shown in Table 15. This variable is a critical predictor of the endogenous latent variable "Success of Geopolymer Concrete," with a significance score of 1.341. With a performance score of 55.116, the model's ability to predict the outcome of "Success of Geopolymer Concrete" based on the predictor variable "Barriers to Success of Geopolymers Concrete Implementation" is moderate. This indicates that variables other than implementation hurdles may significantly influence geopolymer concrete's eventual success. Considering that this is just one of the predictor variables in the model, it is conceivable that other predictor variables have better relevance and performance ratings [56, 59]. Overall, Table 14's findings imply that removing implementation hurdles is crucial to increasing geopolymer concrete's likelihood of success; nevertheless, further study may be required to uncover other significant variables and boost the model's precision.

4.4. Model Validation Confirmation

Table 15 presents the results of an expert validation of a statistical model developed to evaluate the hurdles and success associated with the use of geopolymer concrete for the ecofriendly expansion of small building projects. The mean replies to the validation questions indicate that the recommended essential criteria can be applied, and the seventeen responses validate the model's concept, objective, and conclusions. This work is very credible, and the structural models it generates are both conventional and generic.

Table 15. Model validation survey result

Respondent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Mean
Q1	5	5	5	3	5	5	5	4	5	5	4	5	5	5	5	4	5	4.71
Q2	4	4	4	4	4	4	4	4	4	4	4	3	5	5	3	5	5	4.12
Q3	4	4	5	4	4	4	4	4	4	5	5	5	5	5	5	5	5	4.53
Q4	5	5	5	5	5	5	5	5	4	4	4	4	3	5	4	5	4	4.53
Q5	4	2	5	4	5	4	4	4	4	4	2	4	5	5	4	5	5	4.12

The geopolymer concrete adoption concept is crucial to the construction industry because it enables clients and contractors to conduct small building projects at a specified level of environmental friendliness while preserving their own benefits. Engineers, project managers, quantity surveyors, and companies may all benefit from the model's data. Furthermore, this technique assures that contractors will strive to maintain their competitive advantage. Many respondents agreed with the optimistic conclusions of the poll.

5. Discussion

The Standardization and Knowledge construct includes, Bar9 “The use of various raw ingredients and binder solutions in geopolymer concrete might result in differences in the concrete's physical qualities. This lack of uniformity might make predicting the performance of geopolymer concrete buildings challenging”, Bar5 “There are presently no industry norms or rules governing the use of geopolymer concrete in construction. This may make it challenging for architects, engineers, and contractors to integrate geopolymer concrete into their designs and maintain compliance with applicable building rules and regulations”, Bar12. “Geopolymer concrete has several benefits, but there may be little market demand for it, particularly if standard Portland cement concrete remains the default material for many building projects. This may make it difficult to create sufficient interest and funding for geopolymer concrete”, Bar6 “The manufacturing and use of geopolymer concrete need specific knowledge and skill that may not be commonly accessible. This might make it challenging for contractors and construction firms to use geopolymer concrete in their projects”, and Bar8 “The manufacture and delivery of geopolymer concrete sometimes need a specific supply chain that may not be well-established or broadly accessible. This might make it difficult to get supplies and equipment promptly and economically”. The inconsistency in geopolymer concrete makes it hard to anticipate how it will function in construction. Because of this lack of uniformity, architects, engineers, and contractors have more difficulty incorporating geopolymer concrete into their designs while still adhering to the code. Due to insufficient demand, it may be challenging to generate enough enthusiasm and resources for geopolymer concrete [1, 2]. Due to this obstacle, building companies and contractors need help to employ geopolymer concrete. This obstacle prevents the timely and cost-effective delivery of necessary materials and tools [3, 4]. Predicting the performance of geopolymer concrete buildings, integrating it into designs, generating enough interest and funding for geopolymer concrete, using it in projects, and obtaining supplies and equipment in a timely and cost-effective manner can all be difficult due to the five barriers discussed in the construct.

Novelty and creativity formative construct include Bar2 “Compared to conventional concrete, geopolymer concrete is a relatively new material, and research on its long-term performance and durability is still restricted. This lack of knowledge might make it difficult to establish the proper design and construction techniques for geopolymer concrete buildings”, Bar17. “While geopolymer concrete has shown high performance in laboratory testing, its long-term performance and resilience to environmental conditions such as freeze-thaw cycles and chemical degradation remain questionable. This ambiguity might make it difficult for geopolymer concrete constructions to gain regulatory permission and finance”, Bar3. “The building industry has a history of resistance to adopting new technology and materials. Change aversion may impede the broad adoption of geopolymer concrete, particularly if standard Portland cement concrete is seen as the default alternative”, and Bar14 “Absence of design guidelines Geopolymer concrete constructions may need different design rules and specifications than standard Portland cement concrete structures. Unfortunately, these parameters may need to be well-established, making it challenging to design and build geopolymer concrete structures in a manner that maximizes their performance. Overall, the novelty and creativity framework bring to light some of the major obstacles brought on by geopolymer concrete's relative newness [5, 6]. Uncertainties about its long-term performance and durability, reluctance to generally accept new materials and technology, and a need for recognized design standards for geopolymer concrete buildings are all potential obstacles. Geopolymer concrete may be difficult to overcome and obtain widespread acceptance in the building business, including gaining regulatory permission, attracting investors, and reducing costs.

Economic and Strategical formative construct includes Bar18 “Due to the expense of raw ingredients and the specialized equipment and knowledge necessary for its manufacturing, the initial cost of making geopolymer concrete might be greater than that of conventional concrete. Its expense may hinder the widespread use of geopolymer concrete”, Bar15 "The basic ingredients, such as fly ash, slag, and other industrial wastes, may not be easily accessible in all places. This may make it challenging to create geopolymer concrete locally and increase shipping expenses", Bar4 "Compatibility with existing infrastructure Geopolymer concrete may have different qualities than standard Portland cement concrete, making its application in retrofitting or repair projects hard. This may restrict the uses of geopolymer concrete and make its integration into existing infrastructure challenging”, and Bar13 “Testing standards and procedures for geopolymer concrete are still in the process of being established and may not be widely accepted or acknowledged by regulatory authorities. This may make it difficult to demonstrate to stakeholders and regulators the performance and durability of geopolymer concrete constructions”. The accumulation of these obstacles raises the possibility that the financial and strategic considerations around geopolymer concrete may hinder its widespread use. Spending much money on research and development, specialized tools and expertise, raw materials, and testing protocols are possible. It may also need a change in the traditional way of thinking prevalent in the construction industry, which has historically needed to be faster to embrace innovative methods and materials [7, 8]. Researchers, manufacturers, contractors, engineers, and regulatory authorities may work to remove these obstacles and speed up geopolymer concrete's acceptance and integration into the building sector.

The environmental reflective construct includes E1, "Reduces waste", E2 "Increases durability", and E3 “Provide weather resistance”. As a result, factories will produce less garbage, cutting down on the space required for landfills. Also, waste may be reduced since geopolymer concrete can be manufactured from recycled resources. This may lessen the environmental toll that building projects take on the planet by minimizing the frequency with which repairs and replacements are required. Geopolymer concrete's durability in bad weather may go longer between maintenance and repairs, lowering construction's environmental toll. The environmental reflective design indicates that geopolymer concrete may help cut down on trash, last longer, and withstand the elements [11, 12]. The building sector is essential to lowering humanity's environmental effects, and these characteristics may help it become more sustainable and ecologically benign.

Fire Resistance reflective construct includes F1, "Increase fire resistance", F2 "Develop an efficient thermal concrete", and F3 ", Increases ductile failure chances during fire". This may be especially useful in places with high temperatures or buildings with significant energy needs. Maintaining a building's structural integrity during a fire is crucial to occupant safety and limiting property loss [13, 14]. The overall significance of geopolymer concrete in enhancing the fire resistance of buildings is highlighted by the Fire Resistance reflective construct, as are the material's potential benefits in terms of thermal efficiency and ductile failure in the event of a fire.

Improved strength reflective construct includes S1 "Increase mechanical properties", S2 "Increase bond strength", and S3 "Add tensile strength". More structural capacity and longer-lasting structures and infrastructure may be possible because of geopolymer concrete's better mechanical qualities than traditional concrete. Strong and dependable connections between the reinforcement and the concrete are crucial for the structure's safety, which is especially significant in seismic zones [9, 10]. This is accomplished by adding materials, such as fibers, that strengthen the concrete matrix. Overall, the enhanced strength reflective construct demonstrates the promise of geopolymer concrete in raising the bar for the strength and longevity of concrete buildings, which may have far-reaching effects on construction safety, efficiency, and longevity.

By contrasting our findings with those of other studies, we shed light on the advantages and disadvantages of using geopolymer concrete in building projects, as well as the ways in which our findings are in line with and differ from the existing literature.

Our results corroborate those of previous research that has shown geopolymer concrete to have the ability to greatly decrease CO_2 emissions linked to the building sector. In comparison to conventional Portland cement, geopolymer concrete has better mechanical qualities and a smaller carbon footprint, as shown by studies by Lao et al. [26] and Kanagaraj et al. [31]. The relevance of geopolymer concrete in improving building sustainability and durability is highlighted by our study, which further supports these mechanical and environmental advantages. Beyond these contributions, however, our study provides an in-depth examination of the particular obstacles to the broad use of geopolymer concrete, including, but not limited to, the absence of standardized testing procedures and gaps in industry-wide knowledge.

In addition, our research fills a gap in the literature by providing a detailed analysis of the strategic and economic difficulties encountered by geopolymer concrete. Our research provides a more thorough view of the economic challenges associated with switching to geopolymer concrete by delving deeper into the initial cost barriers, supply chain issues, and the need for specialized knowledge. Previous work, such as that of Amin et al. [7], has touched on these topics, but our findings go even further.

We also found that our findings don't line up with previous predictions of how quickly geopolymer concrete would be used. Increasing knowledge of the advantages of geopolymer concrete will inevitably lead to its widespread adoption, according to study by Abdalla et al. [35]. On the other hand, our research shows that there are ongoing problems that need fixing before this shift can happen, such the lack of industry standards and a weak supply chain. Furthermore, our study adds to the existing body of knowledge by statistically evaluating the connections between different obstacles and the effective application of geopolymer concrete via the use of structural equation modeling (SEM). Since most prior research has depended on subjective evaluations or inadequate quantitative metrics, this methodology offers a more thorough examination. The study supports previous findings on the mechanical and environmental benefits of geopolymer concrete and offers a more thorough analysis of the obstacles to its widespread use. By comparing our findings to those of previous studies, we show how important it is to work together to remove these obstacles, and we recommend that researchers put their energies into finding workable solutions so that geopolymer concrete may be used more widely in building projects.

5.1. Empirical and Theoretical Contributions

Important contributions to both theory and practice may be drawn from this investigation. This research provides empirical evidence that helps us better understand what elements affect the success of using geopolymer concrete in building projects. Understanding the hurdles, opportunities, and results of using geopolymer concrete in building projects is made possible by this research. The research also used a route analysis to zero in on the most important factors that will determine whether or not geopolymer concrete, with its many benefits like fire resistance, greater strength, and preservation of the environment, is adopted widely. Theoretically, this research adds to the growing work on environmentally friendly building materials [17, 18]. The research provides insight into geopolymer concrete's viability and promises it as a cutting-edge green building material. The research shows how crucial it is to include economic, environmental, and social considerations when determining the success of geopolymer concrete use in building projects. The research also helps fill in the blanks of a theoretical model that would help expedite the widespread use of geopolymer concrete in building projects. This study's empirical and theoretical contributions are useful for academics, professionals, and policymakers investigating environmentally friendly building materials and methods. Insights into the aspects that may contribute to the success of geopolymer concrete's acceptance are provided, as well as a framework for comprehending the obstacles and possibilities related to its adoption.

5.2. Managerial Suggestions

There currently needs to be established standards or regulations for using geopolymer concrete in the building sector, which might slow its widespread usage. The usage of geopolymer concrete should be regulated. Hence it is suggested that relevant parties in the industry collaborate to create such standards and recommendations. Because of the specialized nature of geopolymer concrete production and application, these abilities may be in short supply. Consequently, seminars and courses should be created to instruct contractors, building companies, and other industry experts on geopolymer concrete's production, handling, and use. Geopolymer concrete's production and distribution might need a specialized supply chain that isn't widely available or well-established. Industry players should collaborate to build a strong and trustworthy supply chain to guarantee the timely and cost-effective delivery of geopolymer concrete supplies and equipment. It may be difficult to design and construct geopolymer concrete buildings in a way that optimizes their performance due to a lack of design rules and requirements.

Geopolymer concrete uses readily available industrial waste materials and dramatically reduces CO_2 emissions from typical concrete manufacture, solving environmental sustainability and resource consumption challenges. The material's fire resistance and structural strength provide safer and longer-lasting construction projects. Unfortunately, a lack of awareness, limited resources, and bad planning must be addressed before these benefits may be broadly enjoyed. The research emphasizes the necessity for established industrial procedures for geopolymer concrete applications to help practitioners assure quality and comply with laws. Supply chain infrastructure is essential to ensure raw material and geopolymer concrete mix availability. Educational programs for current and future construction workers are essential for strengthening technical skills and fostering innovation. These strategic interventions may help the construction industry adopt geopolymer concrete more widely as a vital component of sustainable and resilient building systems.

6. Conclusion

This study thoroughly examined the various advantages and disadvantages of geopolymer concrete in the construction industry. It highlighted how this material could change the game with its increased strength, fire resistance, and environmental friendliness. Our study highlights significant obstacles to the broad use of geopolymer concrete, which include industry-wide knowledge gaps, budgetary limitations, and strategic concerns, despite the material's apparent benefits. Not only do these results demonstrate the viability of geopolymer concrete as a greener substitute for Portland cement, but they also pinpoint the essential measures that must be taken to promote its wider adoption and use in building processes.

Our work adds to the body of knowledge on the challenges of incorporating geopolymer concrete into conventional building practices by means of thorough empirical analysis, such as exploratory factor analysis and structural equation modeling. The creation of industry standards, the improvement of supply chains, and the promotion of information dissemination and skill development among industry players are some of the specific management solutions that we recommend overcoming the highlighted impediments. The limitations of our study, such as its small sample size and methodological dependence on exploratory methodologies, highlight the need for further exploration. Extending our results requires bigger and more varied investigations, as well as more investigation into the economic feasibility and long-term performance of geopolymer concrete in a wider variety of building applications. By the end of the day, our research does double duty: it confirms geopolymer concrete's contribution to green building practices and shows the way forward for removing the major obstacles to its widespread use. In order to make geopolymer concrete work as intended and create a building sector that is more durable, efficient, and environmentally friendly, these issues must be resolved.

6.1. Limitations and Future Implications

The sample size of this research, which was restricted to 150 people working in the construction business in a single location, needs to be improved. The findings can't be applied to different contexts. EFA is used to find the latent constructs with their problems. Although EFA is common, CFA might have been employed to verify the latent components. SEM also presupposes a causal connection between the latent components, which may not be justified given the presence of confounding factors. This work lays the groundwork for further inquiry into using geopolymer concrete in buildings. Future studies may use a bigger sample size and confirmatory factor analysis to build on this research to validate the latent structures. There is a need for more investigation into the varying perspectives and obstacles to adoption across geographic areas and professional sectors. Extensive field tests might verify geopolymer concrete's long-term performance and reliability. This study's use of exploratory methods and a small sample size limits the generalizability of its findings, potentially overlooking the full range of factors affecting geopolymer concrete adoption across the construction industry. To address these limitations, future research should adopt a broader methodological approach, expand the sample size to include a more diverse demographic, and combine quantitative and qualitative methods for a more comprehensive analysis. Longitudinal studies could further elucidate the long-term effects of interventions on geopolymer concrete adoption. Such efforts will enrich our understanding, offering more definitive strategies for promoting the widespread use of geopolymer concrete. Lastly, studies might investigate how geopolymer concrete could be used in environmentally friendly construction.

7. Declarations

7.1. Author Contributions

Conceptualization, M.S.A. and I.O.; methodology, A.W.; software, N.H.S.; validation, H.F.I., H.M.N., and O.B.; formal analysis, M.M.S.S.; investigation, M.M.S.S.; resources, M.M.S.S.; data curation, M.S.A.; writing—original draft preparation, M.S.A.; writing—review and editing, M.S.A. and N.H.S.; visualization, M.S.A.; supervision, I.O.; project administration, N.H.S.; funding acquisition, H.M.N. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

The research is partially funded by the Ministry of Science and Higher Education of the Russian Federation as part of the World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2022-311 dated 20.04.2022).

7.4. Conflicts of Interest

The authors declare no conflict of interest.

8. References

[1] Zakka, W. P., Abdul Shukor Lim, N. H., & Chau Khun, M. (2021). A scientometric review of geopolymer concrete. Journal of Cleaner Production, 280. doi:10.1016/j.jclepro.2020.124353.

[2] Ahmed, H. U., Mohammed, A. A., Rafiq, S., Mohammed, A. S., Mosavi, A., Sor, N. H., & Qaidi, S. M. A. (2021). Compressive strength of sustainable geopolymer concrete composites: A state-of-the-art review. Sustainability (Switzerland), 13(24), 13502. doi:10.3390/su132413502.

[3] Nodehi, M., & Taghvaee, V. M. (2022). Alkali-Activated Materials and Geopolymer: a Review of Common Precursors and Activators Addressing Circular Economy. Circular Economy and Sustainability, 2(1), 165–196. doi:10.1007/s43615-021-00029-w.

[4] Zaid, O., Abdulwahid S., N., Martínez-García, R., de Prado-Gil, J., Mohamed Elhadi, K., & Yosri, A. M. (2024). Sustainability evaluation, engineering properties and challenges relevant to geopolymer concrete modified with different nanomaterials: A systematic review. Ain Shams Engineering Journal, 15(2). doi:10.1016/j.asej.2023.102373.

[5] Part, W. K., Ramli, M., & Cheah, C. B. (2015). An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products. Construction and Building Materials, 77, 370–395. doi:10.1016/j.conbuildmat.2014.12.065.

[6] Ahmed, H. U., Mohammed, A. S., Faraj, R. H., Abdalla, A. A., Qaidi, S. M. A., Sor, N. H., & Mohammed, A. A. (2023). Innovative modeling techniques including MEP, ANN and FQ to forecast the compressive strength of geopolymer concrete modified with nanoparticles. Neural Computing and Applications, 35(17), 12453–12479. doi:10.1007/s00521-023-08378-3.

[7] Amin, M., Elsakhawy, Y., Abu el-hassan, K., & Abdelsalam, B. A. (2022). Behavior evaluation of sustainable high strength geopolymer concrete based on fly ash, metakaolin, and slag. Case Studies in Construction Materials, 16. doi:10.1016/j.cscm.2022.e00976.

[8] Taher, S. M. S., Saadullah, S. T., Haido, J. H., & Tayeh, B. A. (2021). Behavior of geopolymer concrete deep beams containing waste aggregate of glass and limestone as a partial replacement of natural sand. Case Studies in Construction Materials, 15. doi:10.1016/j.cscm.2021.e00744.

[9] Sonal, T., Urmil, D., & Darshan, B. (2022). Behaviour of ambient cured prestressed and non-prestressed geopolymer concrete beams. Case Studies in Construction Materials, 16. doi:10.1016/j.cscm.2021.e00798.

[10] Noushini, A., Castel, A., Aldred, J., & Rawal, A. (2020). Chloride diffusion resistance and chloride binding capacity of fly ash-based geopolymer concrete. Cement and Concrete Composites, 105. doi:10.1016/j.cemconcomp.2019.04.006.

[11] Amran, Y. H. M., Alyousef, R., Alabduljabbar, H., & El-Zeadani, M. (2020). Clean production and properties of geopolymer concrete; A review. Journal of Cleaner Production, 251. doi:10.1016/j.jclepro.2019.119679.

[12] Wangler, T., & Flatt, R.J. (2019). Correction to: First RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2018. First RILEM International Conference on Concrete and Digital Fabrication – Digital Concrete 2018, DC 2018, RILEM Bookseries, 19. Springer, Cham, Switzerland. doi:10.1007/978-3-319-99519-9_31.

[13] Morla, P., Gupta, R., Azarsa, P., & Sharma, A. (2021). Corrosion evaluation of geopolymer concrete made with fly ash and bottom ash. Sustainability (Switzerland), 13(1), 1–16. doi:10.3390/su13010398.

[14] Ahmed, H. U., Mohammed, A. S., Qaidi, S. M. A., Faraj, R. H., Hamah Sor, N., & Mohammed, A. A. (2022). Compressive strength of geopolymer concrete composites: a systematic comprehensive review, analysis and modeling. European Journal of Environmental and Civil Engineering, 27(3), 1383–1428. doi:10.1080/19648189.2022.2083022.

[15] Wong, L. S. (2022). Durability Performance of Geopolymer Concrete: A Review. Polymers, 14(5). doi:10.3390/polym14050868.

[16] Ali, I. M., Naje, A. S., & Nasr, M. S. (2020). Eco-friendly chopped tire rubber as reinforcements in fly ash based geopolymer concrete. Global Nest Journal, 22(3), 342–347. doi:10.30955/gnj.003192.

[17] Driouich, A., El Hassani, S. A., S., N., Zmirli, Z., El harfaoui, S., Mydin, M. A. O., Aziz, A., Deifalla, A. F., & Chaair, H. (2023). Mix design optimization of metakaolin-slag-based geopolymer concrete synthesis using RSM. Results in Engineering, 20, 101573. doi:10.1016/j.rineng.2023.101573.

[18] Ganesh, A. C., & Muthukannan, M. (2021). Development of high performance sustainable optimized fiber reinforced geopolymer concrete and prediction of compressive strength. Journal of Cleaner Production, 282. doi:10.1016/j.jclepro.2020.124543.

[19] Li, W., Shumuye, E. D., Shiying, T., Wang, Z., & Zerfu, K. (2022). Eco-friendly fibre reinforced geopolymer concrete: A critical review on the microstructure and long-term durability properties. Case Studies in Construction Materials, 16. doi:10.1016/j.cscm.2022.e00894.

[20] Ren, B., Zhao, Y., Bai, H., Kang, S., Zhang, T., & Song, S. (2021). Eco-friendly geopolymer prepared from solid wastes: A critical review. Chemosphere, 267. doi:10.1016/j.chemosphere.2020.128900.

[21] Tayeh, B. A., Zeyad, A. M., Agwa, I. S., & Amin, M. (2021). Effect of elevated temperatures on mechanical properties of lightweight geopolymer concrete. Case Studies in Construction Materials, 15. doi:10.1016/j.cscm.2021.e00673.

[22] Sikder, A., & Saha, P. (2021). Effect of different types of Waste as Binder on Durability Properties of Geopolymer Concrete: A Review. IOP Conference Series: Earth and Environmental Science, 796(1). doi:10.1088/1755-1315/796/1/012018.

[23] Das, S. K., Singh, S. K., Mishra, J., & Mustakim, S. M. (2020). Effect of Rice Husk Ash and Silica Fume as Strength-Enhancing Materials on Properties of Modern Concrete—A Comprehensive Review. Emerging Trends in Civil Engineering. Lecture Notes in Civil Engineering, 61, Springer, Singapore. doi:10.1007/978-981-15-1404-3_21.

[24] Zhang, H. Y., Kodur, V., Wu, B., Yan, J., & Yuan, Z. S. (2018). Effect of temperature on bond characteristics of geopolymer concrete. Construction and Building Materials, 163, 277–285. doi:10.1016/j.conbuildmat.2017.12.043.

[25] Munir, Q., Abdulkareem, M., Horttanainen, M., & Kärki, T. (2023). A comparative cradle-to-gate life cycle assessment of geopolymer concrete produced from industrial side streams in comparison with traditional concrete. Science of the Total Environment, 865. doi:10.1016/j.scitotenv.2022.161230.

[26] Lao, J. C., Xu, L. Y., Huang, B. T., Zhu, J. X., Khan, M., & Dai, J. G. (2023). Utilization of sodium carbonate activator in strain-hardening ultra-high-performance geopolymer concrete (SH-UHPGC). Frontiers in Materials, 10. doi:10.3389/fmats.2023.1142237.

[27] Prasittisopin, L., & Sereewatthanawut, I. (2018). Effects of seeding nucleation agent on geopolymerization process of fly-ash geopolymer. Frontiers of Structural and Civil Engineering, 12(1), 16–25. doi:10.1007/s11709-016-0373-7.

[28] Tang, J., Liu, X., Chang, X., Ji, X., & Zhou, W. (2022). Elastic geopolymer based on nanotechnology: Synthesis, characterization, properties, and applications. Ceramics International, 48(5), 5965–5971. doi:10.1016/j.ceramint.2021.11.070.

[29] Kejkar, R. B., & Wanjari, S. P. (2021). Feasibility study of commercially viable sustainable aerated geopolymeric foam based block. Materials Today: Proceedings, 45, 4398–4404. doi:10.1016/j.matpr.2020.11.916.

[30] Kotop, M. A., El-Feky, M. S., Alharbi, Y. R., Abadel, A. A., & Binyahya, A. S. (2021). Engineering properties of geopolymer concrete incorporating hybrid nano-materials. Ain Shams Engineering Journal, 12(4), 3641–3647. doi:10.1016/j.asej.2021.04.022.

[31] Kanagaraj, B., Anand, N., Samuvel Raj, R., & Lubloy, E. (2023). Techno-socio-economic aspects of Portland cement, Geopolymer, and Limestone Calcined Clay Cement (LC3) composite systems: A-State-of-Art-Review. Construction and Building Materials, 398. doi:10.1016/j.conbuildmat.2023.132484.

[32] Jindal, B. B., Alomayri, T., Hasan, A., & Kaze, C. R. (2023). Geopolymer concrete with metakaolin for sustainability: a comprehensive review on raw material's properties, synthesis, performance, and potential application. Environmental Science and Pollution Research, 30(10), 25299–25324. doi:10.1007/s11356-021-17849-w.

[33] Hassan, A., Arif, M., Shariq, M., Alomayri, T., & Pereira, S. (2023). Fire resistance characteristics of geopolymer concrete for environmental sustainability: a review of thermal, mechanical and microstructure properties. Environment, Development and Sustainability, 25(9), 8975–9010. doi:10.1007/s10668-022-02495-0.

[34] Nagaraju, T. V., Bahrami, A., Azab, M., & Naskar, S. (2023). Development of sustainable high performance geopolymer concrete and mortar using agricultural biomass—A strength performance and sustainability analysis. Frontiers in Materials, 10. doi:10.3389/fmats.2023.1128095.

[35] Abdalla, J. A., Hawileh, R. A., Bahurudeen, A., Jyothsna, G., Sofi, A., Shanmugam, V., & Thomas, B. S. (2023). A comprehensive review on the use of natural fibers in cement/geopolymer concrete: A step towards sustainability. Case Studies in Construction Materials, 19. doi:10.1016/j.cscm.2023.e02244.

[36] Upshaw, M., & Cai, C. S. (2021). Feasibility study of MK-based geopolymer binder for RAC applications: Effects of silica fume and added CaO on compressive strength of mortar samples. Case Studies in Construction Materials, 14. doi:10.1016/j.cscm.2021.e00500.

[37] Luhar, S., Nicolaides, D., & Luhar, I. (2021). Fire resistance behaviour of geopolymer concrete: An overview. Buildings, 11(3), 1–30. doi:10.3390/buildings11030082.

[38] Guades, E. J., Stang, H., Schmidt, J. W., & Fischer, G. (2021). Flexural behavior of hybrid fibre-reinforced geopolymer composites (FRGC)-jacketed RC beams. Engineering Structures, 235. doi:10.1016/j.engstruct.2021.112053.

[39] Ojha, A., & Aggarwal, P. (2022). Fly Ash Based Geopolymer Concrete: a Comprehensive Review. Silicon, 14(6), 2453–2472. doi:10.1007/s12633-021-01044-0.

[40] Singh, N. B. (2018). Fly ash-based geopolymer binder: A future construction material. Minerals, 8(7). doi:10.3390/min8070299.

[41] Pandit, P., Prashanth, S., & Katpady, D. N. (2024). Durability of alkali-activated fly ash-slag concrete-state of art. Innovative Infrastructure Solutions, 9(6), 1-21. doi:10.1007/s41062-024-01530-5.

[42] Chen, K., Wu, D., Xia, L., Cai, Q., & Zhang, Z. (2021). Geopolymer concrete durability subjected to aggressive environments – A review of influence factors and comparison with ordinary Portland cement. Construction and Building Materials, 279. doi:10.1016/j.conbuildmat.2021.122496.

[43] Ye, G., Luković, M., Ghiassi, B., Aldin, Z., Prinsse, S., Liu, J., Nedeljković, M., Hordijk, D., Lagendijk, P., Bosman, A., Blom, T., van Leeuwen, M., Huang, Z., Celada, U., Du, C., van den Berg, J., Thijssen, A., & Wijte, S. (2019). Geocon bridge geopolymer concrete mixture for structural applications. Spool, 6(2), 21–26. doi:10.7480/spool.2019.2.4369.

[44] Pawluczuk, E., Kalinowska-Wichrowska, K., Jiménez, J. R., Fernández-Rodríguez, J. M., & Suescum-Morales, D. (2021). Geopolymer concrete with treated recycled aggregates: Macro and microstructural behavior. Journal of Building Engineering, 44. doi:10.1016/j.jobe.2021.103317.

[45] Ramesh, G. (2021). Geopolymer Concrete: A Review. Indian Journal of Structure Engineering, 1(2), 5–8. doi:10.35940/ijse.a1302.111221.

[46] Singh, B., Ishwarya, G., Gupta, M., & Bhattacharyya, S. K. (2015). Geopolymer concrete: A review of some recent developments. Construction and Building Materials, 85, 78–90. doi:10.1016/j.conbuildmat.2015.03.036.

[47] Neupane, K. (2018). High-Strength Geopolymer Concrete- Properties, Advantages and Challenges. Advances in Materials, 7(2), 15. doi:10.11648/j.am.20180702.11.

[48] Liew, K. M., Sojobi, A. O., & Zhang, L. W. (2017). Green concrete: Prospects and challenges. Construction and Building Materials, 156, 1063–1095. doi:10.1016/j.conbuildmat.2017.09.008.

[49] Zhang, Z., Provis, J. L., Reid, A., & Wang, H. (2014). Geopolymer foam concrete: An emerging material for sustainable construction. Construction and Building Materials, 56, 113–127. doi:10.1016/j.conbuildmat.2014.01.081.

[50] Biondi, L., Perry, M., McAlorum, J., Vlachakis, C., & Hamilton, A. (2020). Geopolymer-based moisture sensors for reinforced concrete health monitoring. Sensors and Actuators, B: Chemical, 309. doi:10.1016/j.snb.2020.127775.

[51] Ganeshan, M., & Venkataraman, S. (2022). Interface shear strength evaluation of self compacting geopolymer concrete using push-off test. Journal of King Saud University - Engineering Sciences, 34(2), 98–107. doi:10.1016/j.jksues.2020.08.005.

[52] Khedmati, M., Kim, Y. R., & Turner, J. A. (2019). Investigation of the interphase between recycled aggregates and cementitious binding materials using integrated microstructural-nanomechanical-chemical characterization. Composites Part B: Engineering, 158, 218–229. doi:10.1016/j.compositesb.2018.09.041.

[53] Karthik, A., Sudalaimani, K., & Vijaya Kumar, C. T. (2017). Investigation on mechanical properties of fly ash-ground granulated blast furnace slag based self-curing bio-geopolymer concrete. Construction and Building Materials, 149, 338–349. doi:10.1016/j.conbuildmat.2017.05.139.

[54] Aravind, N., Nagajothi, S., & Elavenil, S. (2021). Machine learning model for predicting the crack detection and pattern recognition of geopolymer concrete beams. Construction and Building Materials, 297. doi:10.1016/j.conbuildmat.2021.123785.

[55] Ban, C. C., Khalaf, M. A., Ramli, M., Ahmed, N. M., Ahmad, M. S., Ahmed Ali, A. M., Dawood, E. T., & Ameri, F. (2021). Modern heavyweight concrete shielding: Principles, industrial applications and future challenges; review. Journal of Building Engineering, 39. doi:10.1016/j.jobe.2021.102290.

[56] Li, W., Luo, Z., Gan, Y., Wang, K., & Shah, S. P. (2021). Nanoscratch on mechanical properties of interfacial transition zones (ITZs) in fly ash-based geopolymer composites. Composites Science and Technology, 214. doi:10.1016/j.compscitech.2021.109001.

[57] Walbrück, K., Maeting, F., Witzleben, S., & Stephan, D. (2020). Natural fiber-stabilized geopolymer foams-A review. Materials, 13(14). doi:10.3390/ma13143198.

[58] Almutairi, A. L., Tayeh, B. A., Adesina, A., Isleem, H. F., & Zeyad, A. M. (2021). Potential applications of geopolymer concrete in construction: A review. Case Studies in Construction Materials, 15. doi:10.1016/j.cscm.2021.e00733.

[59] Aly, A. M., El-Feky, M. S., Kohail, M., & Nasr, E. S. A. R. (2019). Performance of geopolymer concrete containing recycled rubber. Construction and Building Materials, 207, 136–144. doi:10.1016/j.conbuildmat.2019.02.121.

[60] Dhasindrakrishna, K., Pasupathy, K., Ramakrishnan, S., & Sanjayan, J. (2021). Progress, current thinking and challenges in geopolymer foam concrete technology. Cement and Concrete Composites, 116. doi:10.1016/j.cemconcomp.2020.103886.

[61] Mohajerani, A., Suter, D., Jeffrey-Bailey, T., Song, T., Arulrajah, A., Horpibulsuk, S., & Law, D. (2019). Recycling waste materials in geopolymer concrete. Clean Technologies and Environmental Policy, 21(3), 493–515. doi:10.1007/s10098-018-01660-2.

[62] Mesgari, S., Akbarnezhad, A., & Xiao, J. Z. (2020). Recycled geopolymer aggregates as coarse aggregates for Portland cement concrete and geopolymer concrete: Effects on mechanical properties. Construction and Building Materials, 236. doi:10.1016/j.conbuildmat.2019.117571.

[63] Xu, Z., Huang, Z., Liu, C., Deng, H., Deng, X., Hui, D., Zhang, X., & Bai, Z. (2021). Research progress on key problems of nanomaterials-modified geopolymer concrete. Nanotechnology Reviews, 10(1), 779–792. doi:10.1515/ntrev-2021-0056.

[64] Luhar, S., Luhar, I., & Shaikh, F. U. A. (2021). Review on performance evaluation of autonomous healing of geopolymer composites. Infrastructures, 6(7). doi:10.3390/infrastructures6070094.

[65] Tempest, B., Snell, C., Gentry, T., Trejo, M., & Isherwood, K. (2015). Manufacture of full-scale geopolymer cement concrete components: A case study to highlight opportunities and challenges. PCI Journal, 60(6), 39–50. doi:10.15554/pcij.11012015.39.50.

[66] Liang, X., & Ji, Y. (2021). Mechanical properties and permeability of red mud-blast furnace slag-based geopolymer concrete. SN Applied Sciences, 3(1). doi:10.1007/s42452-020-03985-4.

[67] Liu, C., Huang, X., Wu, Y. Y., Deng, X., Liu, J., Zheng, Z., & Hui, D. (2020). Review on the research progress of cement-based and geopolymer materials modified by graphene and graphene oxide. Nanotechnology Reviews, 9(1), 155–169. doi:10.1515/ntrev-2020-0014.

[68] Siddika, A., Hajimohammadi, A., Ferdous, W., & Sahajwalla, V. (2021). Roles of waste glass and the effect of process parameters on the properties of sustainable cement and geopolymer concrete—a state-of-the-art review. Polymers, 13(22). doi:10.3390/polym13223935.

[69] Zhang, H. Y., Qiu, G. H., Kodur, V., & Yuan, Z. S. (2020). Spalling behavior of metakaolin-fly ash based geopolymer concrete under elevated temperature exposure. Cement and Concrete Composites, 106. doi:10.1016/j.cemconcomp.2019.103483.

[70] Figiela, B., Šimonová, H., & Korniejenko, K. (2022). State of the art, challenges, and emerging trends: Geopolymer composite reinforced by dispersed steel fibers. Reviews on Advanced Materials Science, 61(1), 1–15. doi:10.1515/rams-2021-0067.

[71] Ma, C. K., Awang, A. Z., & Omar, W. (2018). Structural and material performance of geopolymer concrete: A review. Construction and Building Materials, 186, 90–102. doi:10.1016/j.conbuildmat.2018.07.111.

[72] Hardjasaputra, H., Cornelia, M., Gunawan, Y., Surjaputra, I. V., Lie, H. A., Rachmansyah, & Pranata Ng, G. (2019). Study of mechanical properties of fly ash-based geopolymer concrete. IOP Conference Series: Materials Science and Engineering, 615(1), 012009. doi:10.1088/1757-899X/615/1/012009.

[73] Mo, K. H., Alengaram, U. J., & Jumaat, M. Z. (2016). Structural performance of reinforced geopolymer concrete members: A review. Construction and Building Materials, 120, 251–264. doi:10.1016/j.conbuildmat.2016.05.088.

[74] Siddika, A., Hajimohammadi, A., Mamun, M. A. Al, Alyousef, R., & Ferdous, W. (2021). Waste glass in cement and geopolymer concretes: A review on durability and challenges. Polymers, 13(13), 2071. doi:10.3390/polym13132071.

[75] Luhar, I., & Luhar, S. (2021). Valorization of geopolymer paste containing wastes glass. Research on Engineering Structures and Materials, 7(4), 481–504. doi:10.17515/resm2020.240st1213.

[76] Antoni, A., Shenjaya, S. D., Lupita, M., Santosa, S., Wiyono, D., & Hardjito, D. (2020). Utilization of low sulfur fly ash from circulating fluidized bed combustion burner as geopolymer binder. Civil Engineering Dimension, 22(2), 94–100. doi:10.9744/ced.22.2.93-97.

[77] Shi, J., Liu, Y., Xu, H., Peng, Y., Yuan, Q., & Gao, J. (2022). The roles of cenosphere in ultra-lightweight foamed geopolymer concrete (UFGC). Ceramics International, 48(9), 12884–12896. doi:10.1016/j.ceramint.2022.01.161.

[78] Hassan, A., Arif, M., & Shariq, M. (2019). Use of geopolymer concrete for a cleaner and sustainable environment – A review of mechanical properties and microstructure. Journal of Cleaner Production, 223, 704–728. doi:10.1016/j.jclepro.2019.03.051.

[79] Panda, B., Singh, G. B., Unluer, C., & Tan, M. J. (2019). Synthesis and characterization of one-part geopolymers for extrusion based 3D concrete printing. Journal of Cleaner Production, 220, 610–619. doi:10.1016/j.jclepro.2019.02.185.

[80] Beskopylny, A. N., Shcherban', E. M., Stel'makh, S. A., Mailyan, L. R., Meskhi, B., & El'shaeva, D. (2022). The Influence of Composition and Recipe Dosage on the Strength Characteristics of New Geopolymer Concrete with the Use of Stone Flour. Applied Sciences (Switzerland), 12(2), 613. doi:10.3390/app12020613.

[81] Sajjad, M., Hu, A., Waqar, A., Falqi, I. I., Alsulamy, S. H., Bageis, A. S., & Alshehri, A. M. (2023). Evaluation of the Success of Industry 4.0 Digitalization Practices for Sustainable Construction Management: Chinese Construction Industry. Buildings, 13(7), 1668. doi:10.3390/buildings13071668.

[82] Waqar, A., Skrzypkowski, K., Almujibah, H., Zagórski, K., Khan, M. B., Zagórska, A., & Benjeddou, O. (2023). Success of Implementing Cloud Computing for Smart Development in Small Construction Projects. Applied Sciences (Switzerland), 13(9), 5713. doi:10.3390/app13095713.

[83] Waqar, A., Othman, I., Skrzypkowski, K., & Ghumman, A. S. M. (2023). Evaluation of Success of Superhydrophobic Coatings in the Oil and Gas Construction Industry Using Structural Equation Modeling. Coatings, 13(3), 526. doi:10.3390/coatings13030526.

[84] Waqar, A., Othman, I., Falqi, I. I., Almujibah, H. R., Alshehri, A. M., Alsulamy, S. H., & Benjeddou, O. (2023). Assessment of Barriers to Robotics Process Automation (RPA) Implementation in Safety Management of Tall Buildings. Buildings, 13(7), 1663. doi:10.3390/buildings13071663.