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Research Article

Optimization of mechanical properties in lime-based composites using the Taguchi method

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ABSTRACT

Global warming is widely recognized as one of the most pressing issues of our time. One of the primary contributors to this phenomenon is the emission of CO_2, which significantly exacerbates global warming. Today, the production and industry of cement stand out as leading sources of carbon emissions. Consequently, the scientific community is actively researching solutions to reduce cement usage. Some of these efforts focus on alternative binders such as silica fumes and lime. In this study, the goal is to enhance silica fume and lime binder composites, optimizing them for both refractory and insulating properties using the Taguchi optimization method. The results indicate significant improvements in compressive and flexural strengths, which were further validated through testing. The highest compressive strength achieved was 11.97 MPa, while the maximum flexural strength reached 0.34 MPa. This research underscores the potential of alternative binders in mitigating the environmental impact of cement production while enhancing material performance in various applications.

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1. Introduction

Today, climate change occurring as a result of both anthropogenic and natural effects significantly worsens human and environmental security (Karanafti et al. 2022). People spend most of their time in buildings, both in their daily and working lives. These buildings are expected to have comfort features that will not threaten human health and safety. Especially as a result of anthropogenic effects, a large amount of various waste products is released into the environment in industrial sectors. These products cause global warming, which is a major environmental problem, by releasing greenhouse gases such as carbon dioxide, especially disposal problems. The construction industry is one of them (Kosse et al. 2016).

It is estimated that buildings consume more than 45% of global energy consumption (Rashad et al. 2022a) and this figure is expected to rise in the coming years (Rashad et al. 2022b). Effectively managing scarce energy resources has become a top priority worldwide, particularly as energy demand continues to grow rapidly. Currently, achieving comfort in energy-efficient buildings involves using insulation materials that are not only environmentally friendly but also energy-saving, thanks to their thermal and mechanical properties. These modern materials are replacing traditional options, enabling buildings to maintain comfort while reducing energy consumption and environmental impact (Van Nguyen 2023).

Thermal insulation materials are crucial for maintaining comfortable indoor temperatures for both heating and cooling while preserving the natural state of living organisms and objects. These materials are broadly categorized into two main types: inorganic and organic. Inorganic insulation materials, such as silica fume (SF) based geopolymers, are extensively used in the construction industry. The use of mineral additives such as mi-

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crosilica, also known as silica fume, in cementitious systems has positive effects both environmentally and economically. It helps fill voids and exhibits a partial binding effect, enhancing the overall performance of the material (Yorulmaz et al. 2021; Oltulu and Şahin 2013). They are preferred due to their low flammability and non-toxic properties. Despite having higher thermal conductivity compared to organic insulation materials, inorganic options like geopolymers offer superior mechanical strength and environmental durability (Rashad et al. 2024). It has been stated that geopolymers offer numerous advantages, including superior mechanical properties (Mahmoodi et al. 2022), high resistance to elevated temperatures (Çelikten et al. 2020), and resistance to acid (Thokchom et al. 2009) and sulfate effects (Bhutta et al. 2013), along with environmentally friendly characteristics (Alakara et al. 2022). These characteristics make them highly suitable for applications where fire safety and longevity are critical considerations.

Alkaline liquid and pozzolanic materials are used to bond geopolymer material components. Inorganic mineral additive materials such as SF, metakaolin, slag and fly ash, rich in silica (Si) and aluminum (Al), are preferred as pozzolanic materials (Duxson et al. 2007; Tho-In et al. 2012). Aluminum silicates in pozzolanic materials enable the production of high-performance geopolymer materials in terms of their physical and mechanical properties through polymerization reaction (Zakka et al. 2021). Additionally, calcium hydroxide (lime), a weak alkali with a high calcium content, can be incorporated into components to improve the setting time and early strength of such geopolymers (Das et al. 2020). Additionally, by adding waste materials such as SF, additional silicate is included in the geopolymer system (Bajpai et al. 2020). The increase in the silicate/aluminate ratio in geopolymers increases the strength of the produced composite materials (Jena et al. 2019; Okoye et al. 2016).

SF is a refractory material that is a by-product with a high level of pozzolanic properties, consisting of glassy silica (SiO_2) particles with an amorphous crystalline structure, micrometric dimensions, during the manufacturing of silicon or iron ferrosilicon alloys (Al-Amoudi et al. 2007; Koca 1996; Liu et al. 2009). In the production process, it is obtained by reducing high purity quartzite with coal in electric arc furnaces at a temperature of approximately 2000 °C (Golafshani and Behnood 2019).

When SF, lime and water are mixed in certain proportions, a hydration reaction occurs. The reason why SF shows high pozzolanic activity is attributed to its very large surface area and amorphous character (Abo-El-Enein et al. 1996). The molecular calcium silicate hydration (C-S-H) reaction caused by SF and water depending on the CaO/SiO_2 ratio may differ (Cohen and Bentur 1988).

Basic hydration occurs in the process of dissolution of alite (C_3S) and belite (C_2S) in the formation of C-S-H and calcium hydroxide (CH) precipitation. While CH is a known crystalline phase (Petch 1961), C-S-H gel is a natural nanostructured material (Wang et al. 2024). C-S-H precipitates as a filling material and shows a pozzolanic effect. Thanks to this feature, the voids of the geopolymer material decrease and its stability improves (Muller et al. 2015). The highly pozzolanic nature of SF increases its capacity to react with free lime during hydration. SF forms C-S-H gels that provide density, strength, impermeability and durability in the geopolymer produced as a result of the CH reaction (Guleria and Salhotra 2016; Rodrigues et al. 2013). It also provides early strength and durability by being activated through a highly alkaline solution and thermal curing (Koca 1996). Thermal and mechanical properties can be further improved by selecting the most optimum ratios of SF, free lime and water (Al Zaidi et al. 2019).

Thermal insulation materials have different advantages. These include thermal conductivity, perforation gap, site adaptability, workability, mechanical strength, fire protection, smoke emission during fire, durability, resistance to climate variations, resistance to freeze/thaw cycles, water resistance, costs, biocompatibility, toxicity and environmental impacts (Güney 2019). In addition, high thermal protection, comfortable insulation and low operating costs are expected from these materials. Although there are many studies in the literature on improving concrete and its properties, there is limited information on the combined use of silica fume, free lime and water and its optimization with the Taguchi method.

Considering the diminishing material resources and the environmental damage caused by waste, the conversion of valuable materials such as silica fume into economic value is of great importance on a global scale. In this study, it was aimed to recycle silica fume, which is abundant in Türkiye as ferrosilicon and silicon ferrochrome production flue dust waste, into the economy in an environmentally friendly way. In the present study, the mechanical, physical and microstructural properties of the samples produced from different amounts of high temperature resistant silica fume, water and free lime mixture were investigated. The effects on sound permeability, thermal conductivity and water absorption of all samples produced were investigated. These materials were experimentally characterized using standard methods according to the relevant standards. It is clear that the insulation material produced using waste silica fume and lime shows promising results in terms of microstructure, physical and chemical properties. However, considering the constraints of limited resources and the imperative of sustainability, the importance of studying inorganic waste materials such as SF and lime greatly increases. In the present study, the effect of design variables on the physical and mechanical properties of SF with lime was optimized by Taguchi method and the relationships between the design variables were determined. Since this study is a first in this respect, it is believed that it will shed light on future optimization studies.

2. Materials and Method

2.1. Experimental studies

Within the scope of this study, detailed results of the experimental studies to be designed and optimized with Taguchi can be obtained from the previous study (Güney

2019). Compressive tests were performed on 28-day specimens according to TS EN 12390-3 (2019) and flexural tests were performed according to TS EN 12390-5 (2009). Three specimens were produced for each test and the arithmetic averages of the test results were considered.

2.2. Experimental design and optimization studies

Experimental design and optimization studies were carried out with the Taguchi method. Comprehensive results can be obtained with a small number of experiments using this technique (Calis et al. 2021; Gao et al. 2021). Silica fume content (SD), lime content (LM), and water binder ratio (WB) were taken as input parameters and compressive and flexural strengths were designed and optimized. Signal-to-noise (S/N) ratios were applied as 'bigger is better' for flexural and compressive strength evaluations. In addition, the contribution of each factor to the strengths was determined by ANOVA. During the experimental design, the number of experiments was reduced to 27 by Taguchi optimization. The flow diagram of the applied method is presented in Fig. 1. The experimental design proposed by Taguchi method is as shown in Table 1.

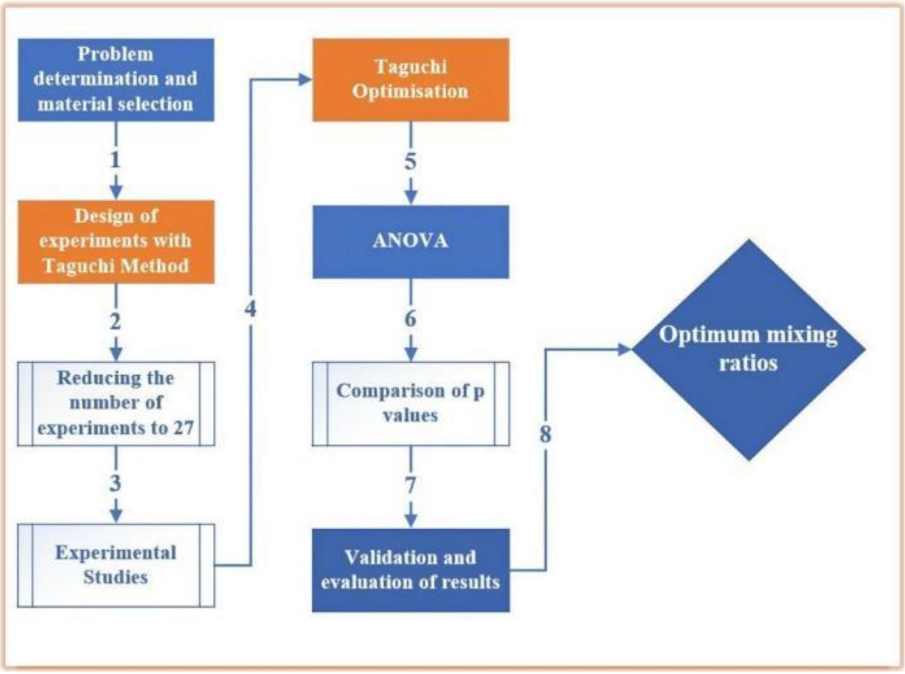

Fig. 1. Flow diagram of design and optimization studies.

Table 1. Mixing proportions of composites.

Mixture code	SD (%)	KM (%)	WB	BD (MPa)	ED (MPa)
K_1	59.14	40.86	0.80	9.21	0.25
K_2	59.14	40.86	0.80	9.18	0.25
K_3	59.14	40.86	0.80	9.23	0.25
K_4	59.14	48.22	0.82	9.32	0.25
K_5	59.14	48.22	0.82	9.28	0.25
K_6	59.14	48.22	0.82	9.34	0.25
K_7	59.14	55.76	0.90	8.47	0.23
K_8	59.14	55.76	0.90	8.42	0.23
K_9	59.14	55.76	0.90	8.45	0.23
K_{10}	51.68	40.86	0.82	11.54	0.31
K_{11}	51.68	40.86	0.82	11.47	0.31
K_{12}	51.68	40.86	0.82	11.51	0.31
K_{13}	51.68	48.22	0.90	11.79	0.32
K_{14}	51.68	48.22	0.90	11.81	0.32
K_{15}	51.68	48.22	0.90	11.74	0.31
K_{16}	51.68	55.76	0.80	8.81	0.24
K_{17}	51.68	55.76	0.80	8.79	0.24
K_{18}	51.68	55.76	0.80	8.85	0.24
K_{19}	44.24	40.86	0.90	8.54	0.23

Table 1. (continued)

Mixture code	SD (%)	KM (%)	WB	BD (MPa)	ED (MPa)
K_{20}	44.24	40.86	0.90	8.47	0.23
K_{21}	44.24	40.86	0.90	8.43	0.23
K_{22}	44.24	48.22	0.80	8.91	0.24
K_{23}	44.24	48.22	0.80	8.83	0.24
K_{24}	44.24	48.22	0.80	8.87	0.24
K_{25}	44.24	55.76	0.82	9.21	0.25
K_{26}	44.24	55.76	0.82	9.11	0.24
K_{27}	44.24	55.76	0.82	9.17	0.25

3. Results and Discussion

The Taguchi design and optimization results that will maximize the compressive strength are as given in Fig. 2. According to the optimization results, the recommended values for SD, KM and S/B are 51.68, 48.22 and 0.82, respectively. These results are in line with similar studies (Al-Waked et al. 2023; Ayasgil et al. 2022; Kang et al. 2019).

The optimum flexural strength achieved by the Taguchi design is shown in Fig. 3. Hence, the suggested values for SD, KM, and S/B are 51, 68, 48, 22, and 0.82, respectively. The achieved limitations fall within the range of values consistently reported in previous similar research. (Kaya et al. 2023; Malathy et al. 2022).

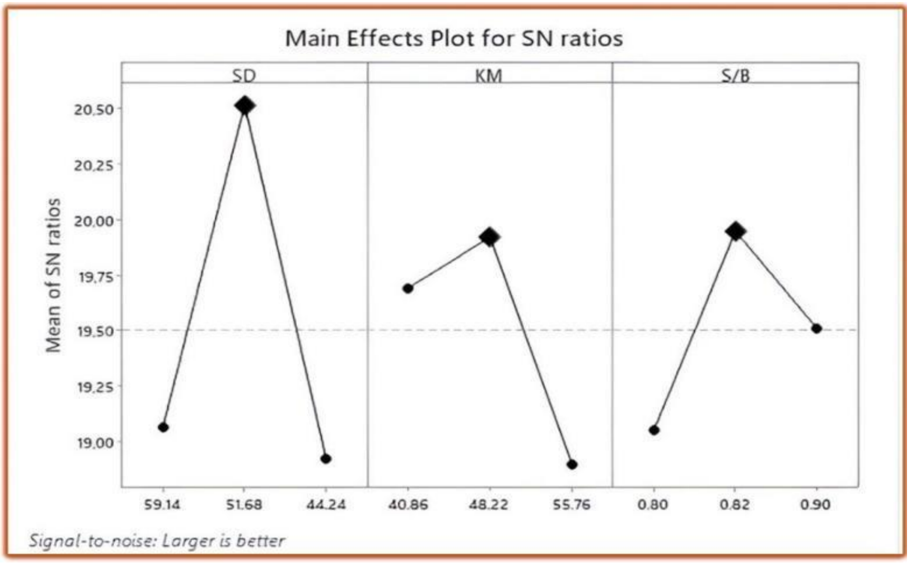

Fig. 2. Taguchi design results for compressive strength.

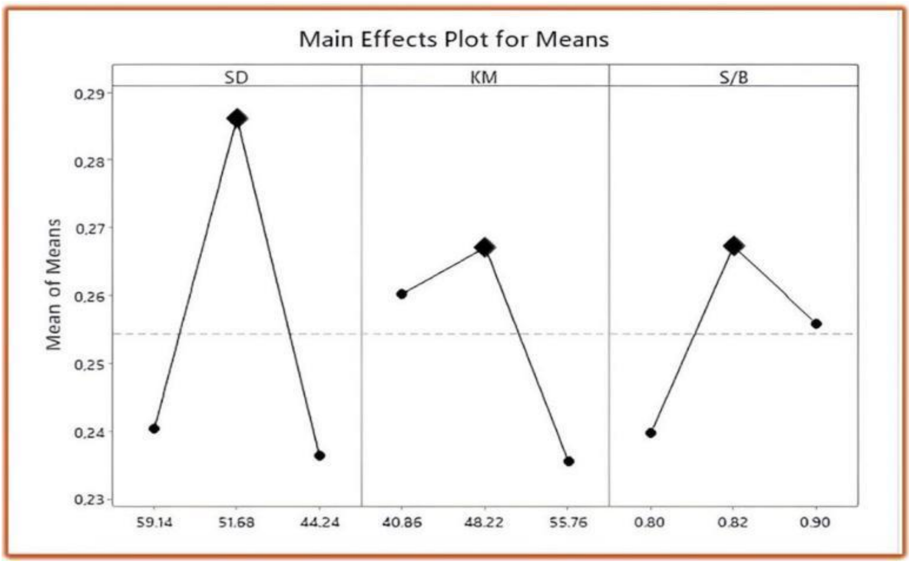

Fig. 3. Taguchi design results for flexural strength.

The ANOVA results within the compressive strength optimization studies are as shown in Table 2. According to the relevant table, since the "p" values of all components are less than 0.005, it is concluded that they have an effect on compressive strength (Yıldızel and Çalış 2019; Yildizel et al. 2022).

The ANOVA results of flexural strength are presented in Table 3. Accordingly, the p values for SD, KM and WB are 0.000, 0.001 and 0.004, respectively, and since all of them are less than 0.005, it is concluded that there is an effect on flexural strength.

The material quantities recommended by Taguchi design for SD, KM and S/B (51.68, 48.22 and 0.82) were used in the verification casting and the results obtained are as presented in Table 4. According to these results, higher compressive and flexural strengths were obtained as expected.

Table 2. ANOVA results for compressive strength design.

Source	DF	Adj SS	Adj MS	F	p
SD	2	19.2797	9.63983	30.02	0.000
KM	2	6.9185	3.45923	10.77	0.001
S/B	2	4.8221	2.41103	7.51	0.004
Error	20	6.4226	0.32113		
Lack of fit	2	6.3968	3.19841	2231.45	0.000
Pure error	18	0.0258	0.00143		
Total	26	37.4428			

Table 3. Flexural strength design ANOVA results.

Source	DF	Adj SS	Adj MS	F	p
SD	2	0.01379	0.006895	30.02	0.000
KM	2	0.0049	0.002474	10.77	0.001
S/B	2	0.0035	0.001724	7.51	0.004
Error	20	0.0046	0.000230		
Lack of fit	2	0.0046	0.002288	2231.45	0.000
Pure error	18	0.000018	0.000001		
Total	26	0.026781			

Table 4. Validation test results.

Type of experiment	Average test result (MPa)
Compressive strength (28 days)	11.97
Flexural strength (28 days)	0.34

4. Conclusions

In this study, optimization of construction materials produced using silica fume and lime using Taguchi method and validation of the obtained results were carried out. SD, KM and S/B quantities were considered as input values, while compressive and flexural strengths were taken as output values. The evaluations made in the light of the results obtained can be summarized as follows:

- According to the ANOVA results, each of the parameter's SD, KM and S/B are of great importance in compressive and flexural strength optimization studies.
- The values that maximize the compressive and flexural strengths were suggested by Taguchi optimization as 51.68%, 48.22% and 0.82% for SD, KM and S/B, respectively.
- According to the validation test results, the maximum BD was increased to 11.97 MPa and the maximum ED was increased to 0.34.

In future studies, further enhancement of Bulk Density (BD) and Elasticity (ED) values could be pursued using alternative optimization techniques. Exploring these different approaches may yield more refined control over these properties, leading to improved material performance and broader applications. By employing advanced optimization methods, it is possible to achieve even greater precision in tuning the physical and mechanical characteristics of the composites, potentially unlocking new opportunities for innovation in this field.

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Author Contributions
All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

Data Availability
The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

REFERENCES

Abo-El-Enein S, Abou-Gamra Z, El-Hosiny F, El-Gamal S (1996). Characteristics of lime-silica fume mixtures. *Journal of Thermal Analysis,* 46, 275-284.

Al Zaidi AKA, Demirel B, Atis CD (2019). Effect of different storage methods on thermal and mechanical properties of mortar containing aerogel, fly ash and nano-silica. *Construction and Building Materials,* 199, 501-507.

Alakara E, Sevim Ö, Demir İ, Günel G (2022). Effect of waste concrete powder on slag-based sustainable geopolymer composite mortars. *Challenge Journal of Concrete Research Letters*, 13(3), 101-106.

Al-Amoudi O, Maslehuddin M, Shameem M, Ibrahim M (2007). Shrinkage of plain and silica fume cement concrete under hot weather. *Cement and Concrete Composites,* 29(9), 690-699.

Al-Waked Q, Kinuthia JM, Adeleke BO, Oti J, Khalifa A (2023). Effects of mellowing practice on the strength and swelling properties of road construction materials: Case of sulphate-bearing clay soils stabilised with lime-silica fume blended binder. *Materials,* 16(6), 2187.

Ayasgil D, Ince C, Derogar S, Ball RJ (2022). The long-term engineering properties and sustainability indices of dewatering hydrated lime mortars through Jacaranda seed pods. *Sustainable Materials and Technologies,* 32, e00435.

Bajpai R, Choudhary K, Srivastava A, Sangwan KS, Singh M (2020). Environmental impact assessment of fly ash and silica fume based geopolymer concrete. *Journal of Cleaner Production,* 254, 120147.

Bhutta MAR, Ariffin NF, Hussin MW, Lim NHAS (2013). Sulfate and sulfuric acid resistance of geopolymer mortars using waste blended ash. *Jurnal Teknologi*, 61(3), 1-5.

Calis G, Akpinar ME, Yildizel SA, Çöğürcü MT (2021). Evaluation and optimization Of PVA reinforced cementitious composite containing metakaolin and fly ash. *Revista Romana de Materiale,* 51(1), 53-66.

Çelikten S, Sarıdemir M, Akçaözoğlu K (2020). Effect of calcined perlite content on elevated temperature behaviour of alkali activated slag mortars. *Journal of Building Engineering*, 32, 101717.

Cohen MD, Bentur A (1988). Durability of portland cement-silica fume pastes in magnesium and sodium sulfate solutions. *Materials Journal,* 85(3), 148-157.

Das SK, Mustakim SM, Adesina A, Mishra J, Alomayri TS, Assaedi HS, Kaze CR (2020). Fresh, strength and microstructure properties of geopolymer concrete incorporating lime and silica fume as replacement of fly ash. *Journal of Building Engineering,* 32, 101780.

Duxson P, Provis JL, Lukey GC, Van Deventer JS (2007). The role of inorganic polymer technology in the development of 'green concrete'. *Cement and Concrete Research,* 37(12), 1590-1597.

Gao L, Adesina A, Das S (2021). Properties of eco-friendly basalt fibre reinforced concrete designed by Taguchi method. *Construction and Building Materials,* 302, 124161.

Golafshani EM, Behnood A (2019). Estimating the optimal mix design of silica fume concrete using biogeography-based programming. *Cement and Concrete Composites,* 96, 95-105.

Guleria AN, Salhotra S (2016). Effects of silica fume (micro silica or nano silica) on mechanical properties of concrete: A review. *International Journal of Civil Engineering and Technology,* 7(4), 345-357.

Güney B (2019). Refrakter yalıtım malzemesi üretiminin deneysel olarak araştırılması. *Journal of the Institute of Science and Technology,* 9(2), 880-889.

Jena S, Panigrahi R, Sahu P (2019). Effect of silica fume on the properties of fly ash geopolymer concrete. *Sustainable Construction and Building Materials*, Select Proceedings of ICSCBM 2018.

Kang S-H, Kwon Y-H, Moon J (2019). Quantitative analysis of CO_2 uptake and mechanical properties of air lime-based materials. *Energies,* 12(15), 2903.

Karanafti A, Theodosiou T, Tsikaloudaki K (2022). Assessment of buildings' dynamic thermal insulation technologies-A review. *Applied Energy,* 326, 119985.

Kaya M, Karahan O, Atiş CD (2023). Influence of silica fume additive and activator ratio on mechanical properties in slaked lime-based alkali-activated mortars. *Iranian Journal of Science and Technology, Transactions of Civil Engineering,* 47(2), 873-889.

Koca C (1996). Yüksek performanslı beton üretiminde mikrosilis, curuf, klinker karışımı çimento kullanımı. 4. *Ulusal Beton Kongresi Beton Teknolojisinde Mineral ve Kimyasal Katkılar Bildiri Kitabı,* TMMOB İnşaat Mühendisleri Odası, İstanbul, 381-394.

Kosse P, Blomberg K, Mikola A, Heinonen M, Kuokkanen A, Lange R-L, Lübken M, Wichern M (2016). Climate change and greenhouse gas emissions within the context of urban wastewater management. *Water Solutions,* 2, 89-94.

Liu XH, Lv XD, Fu JX, Peng P, Gai GS (2009). Application of silica fume in China. *Advanced Materials Research,* 58, 21-26.

Mahmoodi O, Siad H, Lachemi M, Dadsetan S, Şahmaran M (2022). Optimized application of ternary brick, ceramic and concrete wastes in sustainable high strength geopolymers. *Journal of Cleaner Production*, 338, 130650.

Malathy R, Shanmugam R, Chung I-M, Kim S-H, Prabakaran M (2022). Mechanical and microstructural properties of composite mortars with lime, silica fume and rice husk ash. *Processes,* 10(7), 1424.

Muller A, Scrivener K, Skibsted J, Gajewicz A, McDonald P (2015). Influence of silica fume on the microstructure of cement pastes: New insights from 1H NMR relaxometry. *Cement and Concrete Research,* 74, 116-125.

Okoye F, Durgaprasad J, Singh N (2016). Effect of silica fume on the mechanical properties of fly ash based-geopolymer concrete. *Ceramics International,* 42(2), 3000-3006.

Oltulu M, Şahin R (2013). Effect of nano-SiO_2, nano-Al_2O_3 and nano-Fe_2O_3 powders on compressive strengths and capillary water absorption of cement mortar containing fly ash: A comparative study. *Energy and Buildings*, 58, 292–301.

Petch H (1961). The hydrogen positions in portlandite, $Ca(OH)_2$, as indicated by the electron distribution. *Acta Crystallographica,* 14(9), 950-957.

Rashad AM, Abd El Fattah AM, Morsi W (2022). Aluminum dross for thermal insulation and acoustic absorption of alkali-activated slag mortars. *ACI Materials Journal,* 119(4), 151-164.

Rashad AM, Gharieb M, Shoukry H, Mokhtar M (2022). Valorization of sugar beet waste as a foaming agent for metakaolin geopolymer activated with phosphoric acid. *Construction and Building Materials,* 344, 128240.

Rashad AM, Mosleh YA, Mokhtar M (2024). Thermal insulation and durability of alkali-activated lightweight slag mortar modified with silica fume and fly ash. *Construction and Building Materials,* 411, 134255.

Rodrigues F, Evangelista L, Brito JD (2013). A new method to determine the density and water absorption of fine recycled aggregates. *Materials Research,* 16, 1045-1051.

Tho-In T, Sata V, Chindaprasirt P, Jaturapitakkul C (2012). Pervious high-calcium fly ash geopolymer concrete. *Construction and Building Materials,* 30, 366-371.

Thokchom S, Ghosh P, Ghosh S (2009). Acid resistance of fly ash based geopolymer mortars. International *Journal of Recent Trends in Engineering*, 1(6), 36.

TS EN 12390-3 (2019). Beton-Sertleşmiş Beton Deneyleri – Bölüm 3: Deney Numunelerinde Basınç Dayanımının Tayini. Turkish Standards Institution, Ankara, Türkiye

TS EN 12390-5 (2019). Beton-Sertleşmiş beton deneyleri – Bölüm 5: Deney Numunelerinde Eğilme Dayanımının Tayini. Turkish Standards Institution, Ankara, Türkiye.

Van Nguyen M (2023). Drivers of innovation towards sustainable construction: A study in a developing country. *Journal of Building Engineering,* 80, 107970.

Wang X, Ding S, Ashour A, Ye H, Thakur VK, Zhang L, Han B (2024). Back to basics: Nanomodulating calcium silicate hydrate gels to mitigate CO_2 footprint of concrete industry. *Journal of Cleaner Production,* 434, 139921.

Yıldızel SA, Çalış G (2019). Design and optimization of basalt fiber added lightweight pumice concrete using taguchi method. *Revista Romana De Materiale/ Romanian Journal of Materials,* 49(4), 544-553.

Yildizel SA, Tayeh B, Uzun M (2022). The evaluation of calcium carbonate added and basalt fiber reinforced roller compacted high performance concrete for pavement. *Case Studies in Construction Materials*, 17, e01293.

Yorulmaz H, Özuzun S, Uzal B, İlkentapar S, Durak U, Karahan O, Atiş C (2021). Effects of dry particle coating with nano- and microparticles on early compressive strength of portland cement pastes. *Challenge Journal of Concrete Research Letters*, 12(4), 125-130.

Zakka W P, Lim NHAS, Khun MC (2021). A scientometric review of geopolymer concrete. *Journal of Cleaner Production,* 280, 124353.