Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 624

DOI: 10.34910/MCE.137.3

Thermal conductivity reduction and acoustic insulation enhancement in nanosilica-modified lightweight porcelanite concrete

***S.I. Ahmed*[1], *M.M. Sabri*[2] ✉ , *A.I. Saleh*[3], *A.Sh. Al Adili*[4]**

[1] *Scientific Research Commission, Baghdad, Iraq*

[2] *Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation*

[3] *Iraqi Atomic Energy Commission, Directorate of Nuclear Applications, Baghdad, Iraq*

[4] *Civil Engineering Department, University of Technology, Baghdad, Iraq*

✉ *mohanad.m.sabri@gmail.com*

Keywords: porcelanite, nanosilica, thermal conductivity, acoustic insulation, scanning electron microscope

Abstract. This study investigates the thermal and acoustic insulation properties of lightweight concrete modified with nanosilica and porcelanite aggregates. Eight lightweight concrete formulations with varying nanosilica content (0%, 1%, 1.5%, and 2%) and aggregate sizes (4 mm and 5 mm) were developed and tested. The results indicate that incorporating nanosilica significantly enhances both thermal conductivity and acoustic impedance. Concrete samples with 4 mm porcelanite and 1 % nanosilica achieved a thermal conductivity reduction of 24.85 %, while samples with 5 mm porcelanite and 2 % nanosilica demonstrated an 8.42 % increase in acoustic impedance. These findings underline the synergistic effects of nanosilica and aggregate size, providing insights for optimizing lightweight concrete performance in thermal and acoustic insulation applications.

Funding: This research was supported by a grant from the Russian Science Foundation No. 22-79-10021, https://rscf.ru/project/22-79-10021/

Citation: Ahmed, S. I., Sabri, M.M., Saleh, A. I., Al Adili, Sh. Thermal Conductivity Reduction and Acoustic Insulation Enhancement in Nanosilica-Modified Lightweight Porcelanite Concrete. Magazine of Civil Engineering. 2025. 18(5). Article no. 13703. DOI: 10.34910/MCE.137.3

1. Introduction

Lightweight concrete (LWC) is recognized for its low density and thermal conductivity, offering enhanced thermal and acoustic insulation compared to conventional concrete [1-5]. These characteristics, attributed to LWC's porous structure – formed by both aggregate and cement matrix pores – make it advantageous in energy-efficient construction, where high thermal resistance is essential [6,7]. Despite its benefits, optimization of LWC's thermal and acoustic properties remains limited in existing studies.

In recent decades, nanotechnology has introduced nanoscale admixtures, such as nanosilica, known for their high reactivity and minimal additive requirements, to improve cementitious composites [8-11]. Recent research has increasingly focused on the effects of nanomaterials, such as graphene nanoplatelets (GNPs), on the performance of cementitious composites, with parallels in the study of nanoscale admixtures in LWC. For instance, studies have examined the mechanical properties and durability of GNP-reinforced concrete, revealing improvements in structural performance through advanced dispersion and hydration techniques and microstructural optimization. In a similar vein, investigations into the anticorrosion performance of nanomaterial-modified epoxy coatings indicate promising applications for enhancing concrete resilience in challenging environmental conditions. These studies underscore the potential of nanomaterials to transform cement-based materials, motivating further exploration of nanosilica's role in optimizing LWC for enhanced thermal and acoustic properties [10,12-16].

Research on nanosilica primarily focuses on normal-weight concrete, which has demonstrated enhanced hydration, microstructural integrity, and mechanical properties through nucleation, filling, and pozzolanic effects [17-21]. However, investigations targeting the simultaneous improvement of thermal and acoustic insulation in lightweight aggregate concrete through nanosilica modification are limited, particularly concerning porcelanite aggregates [22].

This study addresses the aforementioned research gaps by examining the effects of nanosilica at varying cement replacement ratios on the thermal and acoustic properties of lightweight porcelanite aggregate concrete. Field Emission Scanning Electron Microscopy (FESEM) was employed for microstructural analysis. This research evaluates the impact of nanosilica content on thermal conductivity and acoustic impedance, aiming to optimize LWC formulations for enhanced insulation performance.

2. Materials and Methods

2.1. Materials

For the experimental series, Portland cement Type I from Krista (Mass Factory) was utilized across all mix designs, in accordance with the ASTM C150/C150M-16e1 [23].

The experiments incorporated natural sands from AL-Ukhaidir, conforming to a grade-confined zone II with a maximum particle size of 4.75 mm. The fine aggregate's particle size distribution was methodically analyzed, with the results and grading curves detailed in Tables 1 and 2 and illustrated in Fig. 1. In accordance with IQS No. 45/1984 [24], the classification for the fine aggregates, along with their sulfate content, was meticulously determined, ensuring compliance with established standards.

Table 1. Analyzing the sand sieve.

Sieve size (mm)	Percentage of passing %	Limited of IQS No. 45/1984 zone 2
10	100	100
4.75	95	90–100
2.36	84	75–100
1.18	60	55–90
0.60	49	35–59
0.30	18	8–30
0.15	6	0–10

Table 2. Sand's physical characteristics.

Physical properties	Results	Limit of IQS No. 45/1984
Specific gravity	2.6	–
Bulk density (kg/m^3)	1729	–
Sulfate content (%)	0.343	≤ 0.5 %
Fineness modulus (mm)	2.69	–
Water absorbing (%)	2	–

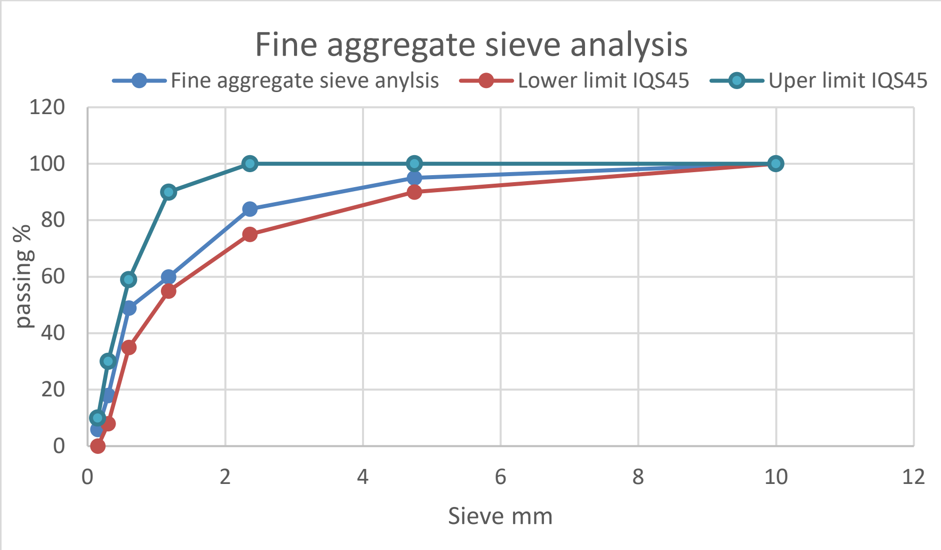

Figure 1. Grading curve of sand.

In this project, natural porcelanite lightweight aggregate rock, sourced from the Trefawi region near Rutba in the Al-Anbar province of the western Iraqi desert, was selected as the coarse aggregate [16]. Porcelanite, a sedimentary rock vital for industrial applications, is primarily characterized by its opal-CT (cristobalite-tridymite) composition, as initially defined by Kastner et al. [25]. Fig. 2 represents porcelanite aggregate.

The experimental work also incorporated nanopowder (nanosilica) (SiO_2) with a particle size of 20 nm and a surface area of 160 m^2/g, produced by Sky Spring Nanomaterials, USA.

Additionally, a synthetic superplasticizer, EUCOBET SUPER VZ, conforming to SIA, BS 5075 1/1974 ASTM-C494 Category G, and DIN standards, was employed to enhance the concrete's workability and physical properties.

Figure 2. Poreclanite rock.

2.2. Methods

2.2.1. Porcelanite aggregate's crush, sieve, and wash processes

The porcelanite aggregate underwent a thorough preparation process to ensure optimal performance in concrete applications. Initially, it was mechanically crushed to reduce it to smaller, more manageable sizes. Subsequently, mechanical sieving was employed to categorize porcelanite particles into two distinct particle-size groups, facilitating precise control over the aggregate's characteristics in the concrete mix. The lightweight aggregate was soaked in water for several hours to achieve saturated surface dry conditions. This pre-soaking process was critical for ensuring the aggregate's moisture content was at an ideal level, enhancing the batching of lightweight aggregates by allowing more accurate water-cement ratios and improving the concrete's overall performance.

2.2.2. Dispersion of nanosilica in mixing water

Prior to the integration of nanosilica into the cement mix, it is essential to ensure its homogeneous distribution within the water. The homogeneous distribution is achieved through a manual process that effectively disperses the nanomaterial. Due to the potential health risks associated with handling nanomaterials, it is imperative to adopt safety measures, including wearing a face mask and gloves, before initiating dispersion. These precautions help mitigate any harmful effects and ensure a safe working environment during the preparation phase.

2.2.3. Samples preparation

As detailed in Table 3, eight distinct mixtures were prepared: A1 (Reference), A2, A3, and A4, which are porcelanite aggregate concretes with a particle size of 4 mm and varying ratios of nanosilica; and A5 (Reference), A6, A7, and A8, representing porcelanite aggregate concretes with a particle size of 5 mm and varying nanosilica ratios.

A proportion of 1:1:1 for (cement: sand: porcelanite coarse aggregate) that would be appropriate after 28 days was created using a water-to-cement mix of w/c = 0.35 plus a superplasticizer with 0.4 percent of cement weighting. The concrete mix proportions are listed in Table 3.

The mixtures followed a 1:1:1 ratio of cement, sand, and coarse porcelanite aggregate, with a water-to-cement ratio (w/c) of 0.35 and a superplasticizer content of 0.4 % by cement weight. Special molds with a 40 mm diameter and 10 mm thickness were used for casting, in accordance with BS 874-73 [26]. For thermal conductivity measurements, Lee's disc method was employed, and for acoustic insulation testing, cube samples measuring 10×10×10 cm were prepared in accordance with ASTM C 597-02 [27] using porcelanite particles with a size of 4,5 mm.

On the 28th day, thermal conductivity tests were conducted, along with FESEM testing on selected samples.

Table 3. Mixed design of the experiment

Mixture kind	Cement Kg/m^3	Sand Kg/m^3	Porcelanite Kg/m^3	Water-to-cement ratio	Nanosilica (NS), Kg/m^3	Superplasticizer wt.%
A1 Ref.	550	550	550	0.35	0	0.4
A2	544.5	550	550	0.38	5.5	0.4
A3	541.75	550	550	0.38	8.25	0.4
A4	531	550	550	0.38	11	0.4
A5 Ref.	590	590	590	0.35	0	0.4
A6	584.1	590	590	0.38	5.9	0.4
A7	581.15	590	590	0.38	8.85	0.4
A8	578.2	590	590	0.38	11.8	0.4

3. Results and Discussion

3.1. Thermal Conductivity

In Table 4, the thermal conductivity outcomes for the eight concrete mixes reveal a decrease in thermal conductivity across all nanosilica ratios A2, A3, A4, A6, A7, A8 as illustrated in Figs. 3 and 4. This reduction is attributed to the altered balance between the concrete's pore volume and its solid structural volume [28], indicating that while pore shape and size distribution have a marginal impact, the presence of nanosilica significantly enhances the concrete's thermal performance. The comparison in Table 4 underscores the superiority of nanosilica-enhanced porcelanite concrete over mixes without nanosilica, particularly highlighting that a porcelanite particle size of 5 mm results in lower thermal conductivity, demonstrating the critical role of nanosilica in reinforcing concrete's thermal insulation properties.

Table 4. Thermal conductivity.

Mix type	Specimen dishes	Conductivity (w/m. c°)	Reduction rang (%)	Time (μsec)	Velocity Ultrasonic Pulse Velocity (UPV) (Km/sec)	Acoustic impedance (Rayl) *106	Enhanced rang (%)
A1 Ref.	A	0.806	0	39.0	2.69	4.48	0
	B	0.610	0	40	2.60	4.29	0
A2	A	0.550	22.3	37.9	2.71	4.44	1.2
	B	0.514	27.4	38.9	2.69	4.38	–0.1
A3	A	0.625	11.7	36.7	2.72	4.30	–1.9
	B	0.589	16.8	36.4	2.85	4.60	4.9
A4	A	0.584	17.5	36.0	2.77	4.55	3.7
	B	0.537	24.1	35.9	2.78	4.55	3.7
A5 Ref.	A	0.616	0	36.3	2.75	4.81	0
	B	0.616	0	37.6	2.65	4.74	0
A6	A	0.497	29.8	35.3	2.94	5.11	16.5
	B	0.553	21.8	37.9	2.63	4.64	5.8
A7	A	0.429	39.4	36.9	2.84	4.95	12.8
	B	0.582	17.7	36.2	2.87	4.96	13.1
A8	A	0.550	22.3	34.3	3.03	5.30	20.8
	B	0.496	29.9	35.1	2.93	5.18	18.1

3.2. Acoustic Insulation

The acoustic insulation effectiveness is significantly enhanced by adding nanosilica as demonstrated on day 28 (referenced in Figs. 4, 5, and Table 4 and in line with ASTM C 597–02 standards [27]). The improvement in acoustic insulation was notably sequential, with A4, A6, A7, and A8 showing increased effectiveness. The study highlights the dependency of LWC's insulation properties on its density and the elapsed time in microseconds. Notably, specimens A2 and A3 did not show an improvement in acoustic insulation by day 28, suggesting that the optimal nanosilica concentration for reinforcing concrete under the current dispersion conditions is between 1 % and 2 % by cement weight.

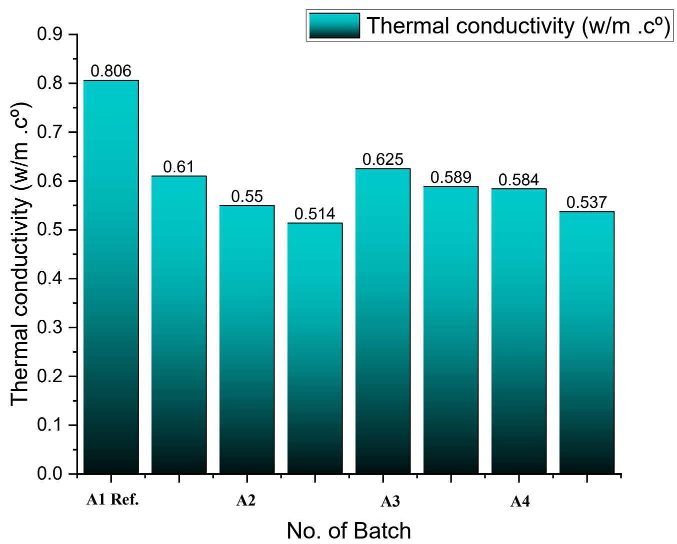

Figure 3. Porcelanite concrete's thermal conductivity with 4 mm particle size using various nanosilica ratios.

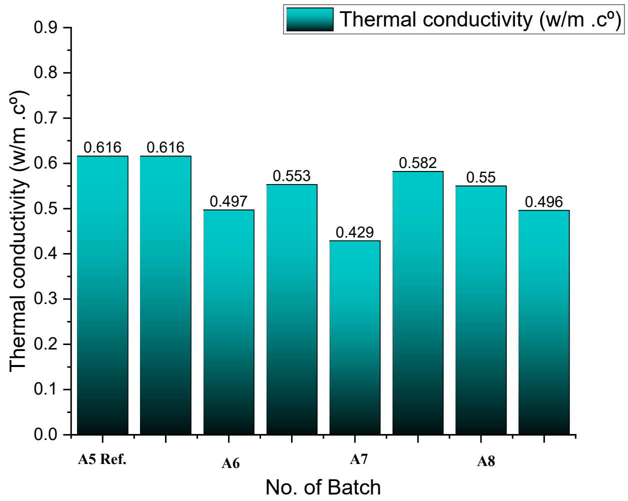

Figure 4. Porcelanite concrete's thermal conductivity with 5 mm particle size using various nanosilica ratios.

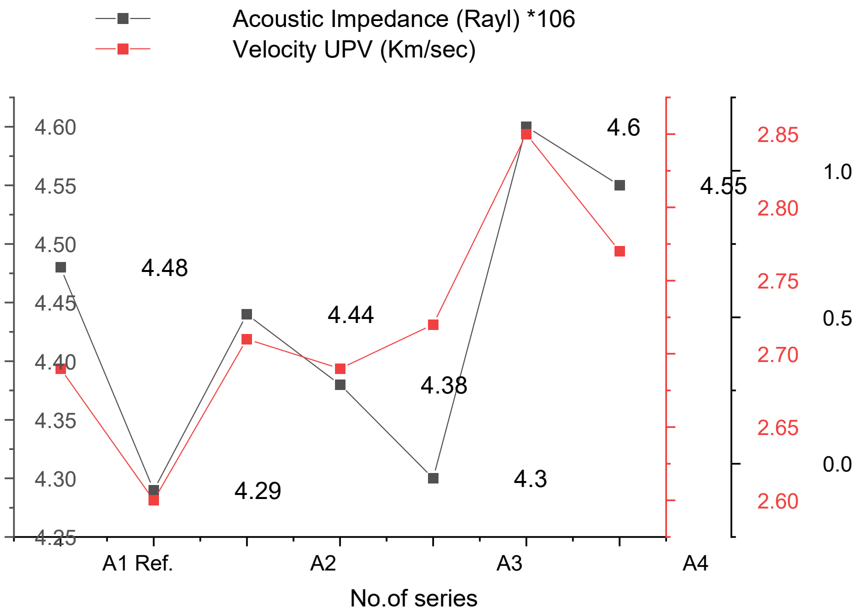

Figure 5. Acoustic impedance and velocity UPV of porcelanite aggregate concrete at 4 mm porcelanite particle size with various nanosilica ratios.

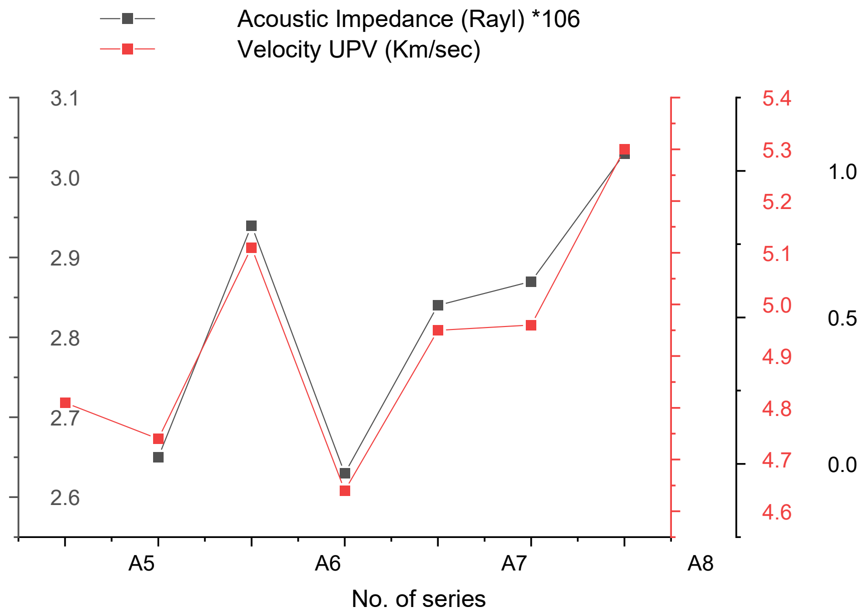

Figure 6. Acoustic impedance and velocity UPV of porcelanite aggregate concrete at 5 mm porcelanite particle size with various nanosilica ratios.

3.3. Microstructure by FESEM

The FESEM analysis reveals that porcelanite concrete incorporating nanosilica, specifically in mixture A7 with a 5 mm porcelanite particle size and 1.5 % nanosilica, exhibits the lowest thermal conductivity, as shown in Fig. 7.

This microstructure is characterized by its uniformity, compactness, and absence of cracks. Further examination of the acoustic impedance in plain concrete, particularly in mixture A8 (containing 5 mm porcelanite particles and 2 % nanosilica), corroborates these findings, showing a consistent, crack-free microstructure, which implies enhanced performance in both thermal insulation and acoustic impedance, as shown in Fig. 8.

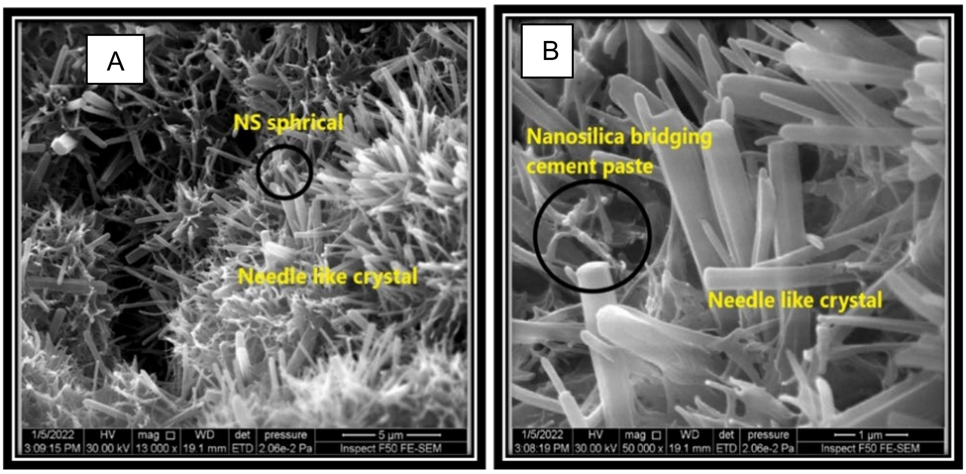

Figure 7 (A and B). Porcelanite concrete at 5 mm particle size has nanosilica 1.5 % at magnifications of 13000X and 50000X, respectively.

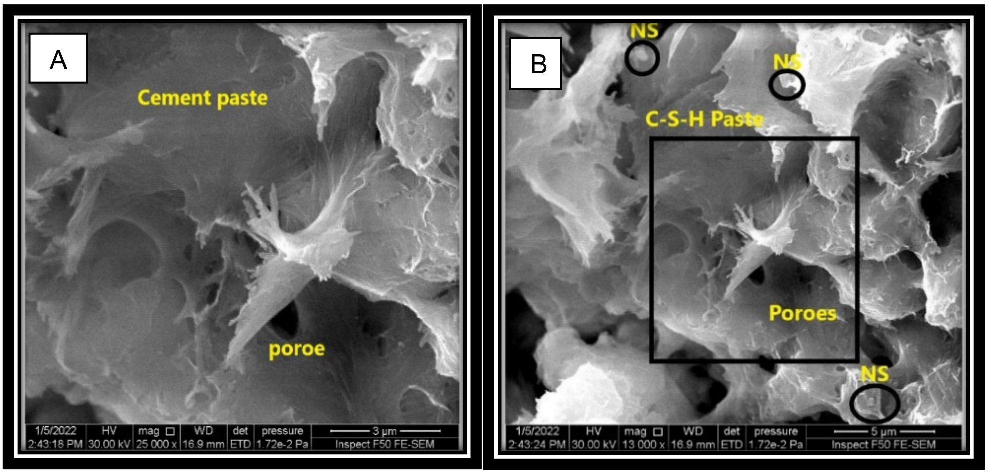

Figure 8 (A and B). The microstructure image of plain porcelanite concrete at 5 mm particle size using nanosilica 2 % at magnifications of 13000X and 25000X, respectively.

4. Conclusions

The study meticulously examines the influence of nanosilica incorporation on the thermal and acoustic properties of LWC, utilizing diverse ratios and particle sizes of porcelanite aggregates. Based on the results of this research, the derived conclusions are as follows:

1. Enhanced Thermal and Acoustic Properties: Incorporation of nanosilica into porcelanite aggregate concrete significantly reduces thermal conductivity and increases acoustic impedance compared to standard porcelanite aggregate concrete.
2. Microstructural Improvement: FESEM analyses reveal that nanosilica serves dual purposes: mitigating microcracks and acting as a hydration activator, thereby improving the microstructure when uniformly distributed.
3. Optimal Mix Proportions: The mixture containing 1.5 % nanosilica (specimen A7) demonstrated a remarkable 39.4% reduction in thermal conductivity. On the other hand, a 2 % nanosilica mixture (specimen A8) exhibited a 20.8% increase in acoustic impedance.
4. Catalytic Role of nanosilica: Beyond microcrack prevention, nanosilica accelerates hydration, optimizing concrete performance.
5. Future Implications: These findings suggest potential guidelines for designing concrete mixtures with improved thermal insulation and sound-dampening capabilities, highlighting the critical role of nanoparticle distribution and concentration.

References

1. Caiza, M., Gonzalez, C., Toulkeridis, T., Bonifaz García, H. Physical properties of pumice and its behavior as a coarse aggregate in concrete. Malaysian Construction Research Journal. 2018. 25(2). Pp. 85–95.
2. Chung, S.-Y., Sikora, P., Kim, D.J., El Madawy, M.E., Abd Elrahman, M. Effect of different expanded aggregates on durability-related characteristics of lightweight aggregate concrete. Materials Characterization. 2021. 173. Article no. 110907. DOI: 10.1016/j.matchar.2021.110907
3. Abd Elrahman, M., Chung, S.-Y., Stephan, D. Effect of different expanded aggregates on the properties of lightweight concrete. Magazine of Concrete Research. 2019. 71(2). Pp. 95–107. DOI: 10.1680/jmacr.17.00465
4. Ali, H.H., Awad, H.K. The Influence of Nano-Silica on Some Properties of Light Weight Self-Compacting Concrete Aggregate. E3S Web of Conferences. 2023. 427. Article no. 02008. DOI: 10.1051/e3sconf/202342702008
5. Al Zaidi, I.K., Demirel, B., Atis, C.D., Akkurt, F. Investigation of mechanical and thermal properties of nano SiO_2/hydrophobic silica aerogel co-doped concrete with thermal insulation properties. Structural Concrete. 2019. 21. Pp. 1123–1133. DOI: 10.1002/suco.201900324
6. Zeng, Q., Mao, T., Li, H., Peng, Y. Thermally insulating lightweight cement-based composites incorporating glass beads and nano-silica aerogels for sustainably energy-saving buildings. Energy and Buildings. 2018. 174. Pp. 97–110. DOI: 10.1016/j.enbuild.2018.06.031
7. Jiang, X., Zhang, S., Gu, Z., Wang, L., Zhao, Y. Study on Permanent Thermal Insulation Formwork of Mass Concrete Prepared by Different Types of Nano-modified Lightweight Aggregate. Journal of Physics: Conference Series. 2021. 2011. Article no. 012070. DOI: 10.1088/1742-6596/2011/1/012070
8. Utsev, T., Tiza, T.M., Mogbo, O., Kumar Singh, S., Chakravarti, A., Shaik, N., Pal Singh, S. Application of nanomaterials in civil engineering. Materials Today: Proceedings 2022. 62(8). Pp. 5140–5146. DOI: 10.1016/j.matpr.2022.02.480
9. Pongsopha, P., Sukontasukkul, P., Zhang, H., Limkatanyu, S. Thermal and acoustic properties of sustainable structural lightweight aggregate rubberized concrete. Results in Engineering. 2022. 13. Article no. 100333. DOI: 10.1016/j.rineng.2022.100333

10. Varghese, L., Rao, V.V.L.K., Parameswaran, L. Nanosilica-added concrete: strength and its correlation with time-dependent properties. Proceedings of the Institution of Civil Engineers – Construction Materials. 2019. 172(2). Pp. 85–94. DOI: 10.1680/jcoma.17.00031
11. Jia, H., Cui, B., Niu, G., Chen, J., Yang, Y., Wang, Q., Tang, C. Experimental and mechanism study on the impermeability and thermal insulation of foam concrete regulated by nano-silica and fluorine-free foam. Journal of Building Engineering. 2023. 64. Article no. 105675. DOI: 10.1016/j.jobe.2022.105675
12. Ismail, F.I., Shafiq, N., Abbas, Y.M., Bheel, N., Benjeddou, O., Ahmed, M., Sabri, M.M., Ateya, E.S. Behavioral assessment of graphene nanoplatelets reinforced concrete beams by experimental, statistical, and analytical methods. Case Studies in Construction Materials. 2022. 17. Article no. e01676. DOI: 10.1016/j.cscm.2022.e01676
13. Cui, K., Chang, J., Sabri, M.M.S., Huang, J. Study of Dispersion, Hydration, and Microstructure of Graphene Nanoplates-Modified Sulfoaluminate Cement Paste. Nanomaterials. 2022. 12(15). Article no. 2708. DOI: 10.3390/nano12152708
14. Lyu, K., Liu, X., Liu, R., Yang, H., Qiao, Y., Shah, S.P. Evaluation of the Anticorrosion Performance of CeO_2-Modified Graphene Oxide Nanocomposite Epoxy Coating Subjected to Simulated Saline-Alkali Solution. Polymers. 2022. 14(7). Article no. 1412. DOI: 10.3390/polym14071412
15. Cui, K., Chang, J., Sabri, M.M.S., Huang, J. Influence of Graphene Nanoplates on Dispersion, Hydration Behavior of Sulfoaluminate Cement Composites. Materials. 2022. 15(15). Article no. 5357. DOI: 10.3390/ma15155357
16. Bolhassani, M., Samani, M. Effect of Type, Size, and Dosage of Nanosilica and Microsilica on Properties of Cement Paste and Mortar. ACI Materials Journal. 2015. 112(2). Pp. 259–266. DOI: 10.14359/51686995
17. Shankar, A.N., Farouq, M.M., Bondinuba, F.K., Singh, V.K., Aliyu, D.S., Ganvir, V.Y. Critical Review on the Impact of Nanotechnology in Concrete Materials. Advances in Science and Technology. 2022. 117. Pp. 17–24. DOI: 10.4028/p-2o26jd
18. Hamada, H., Shi, J., Yousif, S.T., Al Jawahery, M., Tayeh, B., Jokhio, G. Use of nano-silica in cement-based materials – a comprehensive review. Journal of Sustainable Cement-Based Materials 2023. 12(10). Pp. 1286–1306. DOI: 10.1080/21650373.2023.2214146
19. Du, S., Wu, J., AlShareedah, O., Shi, X. Nanotechnology in Cement-Based Materials: A Review of Durability, Modeling, and Advanced Characterization. Nanomaterials. 2019. 9(9). Article no. 1213. DOI: 10.3390/nano9091213
20. Sikora, P., Abd Elrahman, M., Stephan, D. The Influence of Nanomaterials on the Thermal Resistance of Cement-Based Composites—A Review. Nanomaterials. 2018. 8(7). Article no. 465. DOI: 10.3390/nano8070465
21. Ahmed, S.I., Al-Adili, A.S., Hameed, A.M. The effect of dosage nanosilica and the particle size of porcelanite aggregate concrete on mechanical and microstructure properties. Journal of the Mechanical Behavior of Materials. 2022. 31(1). Pp. 573–579. DOI: 10.1515/jmbm-2022-0062
22. Lam, L.H., Lam, D.D. Application of Nano-Silica in Concrete Bridges in Vietnam for Sustainable Development. Advances and Challenges in Structural Engineering. GeoMEast 2018. Springer. Cham, 2018. Pp. 23–31. DOI: 10.1007/978-3-030-01932-7_3
23. ASTM C150/C150M-16e1, "Standard Specifications for Portland Cement," Developed by ASTM Subcommittee C01.10 on Concrete and Concrete Aggregates, Vol. 04.01, West Conshohocken, PA, USA, 2016, 10pp.
24. Central Organization for Standardization and Quality Control. Iraqi Specifications Number 45/1984. Aggregate from natural sources for concrete and construction. Baghdad, 1984.
25. Ahmed, S. I., Hameed, A. M., & Al-Adili, A. S. (2024). Effect of nanosilica on properties of porcelanite aggregate concrete. *Magazine of Civil Engineering*, *17*(5). https://doi.org/10.34910/MCE.129.5.
26. BS 874. Methods for determining thermal insulating properties. With definitions of thermal insulating terms. 1973. https://*codehub*.building.govt.nz/resources/bs-8741973.
27. ASTM C 597-02. Standard Test Method for Pulse Velocity through Concrete. 4.2. ASTM International. West Conshohocken, PA, 2002.
28. Chung, S.-Y., Abd Elrahman, M., Kim, J.-S., Han, T.-S., Stephan, D., Sikora, P. Comparison of lightweight aggregate and foamed concrete with the same density level using image-based characterizations. Construction and Building Materials. 2019. 211. Pp. 988–999. DOI: 10.1016/j.conbuildmat.2019.03.270

Information about the authors:

***Sahar Ahmed**, PhD*
E-mail: sahar.i.ahmed@src.edu.iq

***Mohanad Sabri**, PhD*
ORCID: https://orcid.org/0000-0003-3154-8207
E-mail: mohanad.m.sabri@gmail.com

***Anas Saleh**, PhD*
E-mail: anasdaf@yahoo.com

***Aqeel Al Adili**, PhD*
E-mail: Aqeeladili@hotmail.com

Received 26.03.2024. Approved after reviewing 30.04.2025. Accepted 13.07.2025.