Development of High-Performance Concrete with Advanced Materials for Sustainable Building Applications

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ABSTRACT

Developing High-Performance Concrete (HPC) with advanced materials is crucial for achieving superior concrete that aligns with sustainable building practices. The use of innovative materials enhances both fresh and hardened properties, offering improved workability and strength. This study explores the impact of incorporating advanced materials into concrete mixtures by evaluating the performance of different compositions. Three mix variations were prepared by adjusting the types and dosages of admixtures. The first mix used a conventional Type F superplasticizer, while the other two applied advanced materials at varying dosages. Slump tests were conducted on fresh concrete and cylindrical specimens (10x20 cm) were tested to measure unit weight and compressive strength after 7, 14, and 28 days. Results indicate that the use of advanced materials significantly improves concrete performance, even at lower dosages compared to traditional superplasticizers. This research confirms that incorporating advanced materials improves both workability and compressive strength of concrete. The findings suggest that these materials offer a sustainable solution for developing high-performance concrete with enhanced durability and reduced material consumption. Consequently, their integration in construction can contribute to more sustainable, efficient, and resilient building structures. Further research is recommended to explore the long-term effects of advanced materials on concrete performance under various environmental conditions. The study highlights the potential of advanced material technologies as a transformative approach in concrete quality management within the construction industry.

Keywords-compressive strength; volume weight; advanced materials; superplasticizer

I. INTRODUCTION

The use of advanced materials in the development of high-performance concrete provides a sustainable approach to building construction by improving material efficiency and durability. Incorporating silica-rich substances, such as fly ash or rice husk ash, into modified concrete formulations reduces reliance on conventional cement, leading to lower carbon emissions. This strategy not only addresses pollution by utilizing industrial waste but also results in environmentally friendly concrete with enhanced strength and decreased permeability. By adopting advanced materials, the construction sector can reduce its environmental impact while supporting the creation of sustainable and resilient infrastructure [1].

The construction of infrastructure today primarily depends on concrete as a key building material [2, 3]. Concrete is valued for its ability to resist compression and its relatively low cost.

Additionally, there is considerable potential for enhancing its properties and performance [4]. Recent advancements in materials science have introduced innovative methods to develop construction materials with improved characteristics [5, 6]. These advanced materials have demonstrated a transformative impact across various scientific and engineering disciplines [7]. Among these materials, carbon-based structures have emerged as highly promising components in construction, offering unique properties and versatile applications [8, 9]. By refining conventional materials to a finer scale, they significantly enhance functionality, characteristics, and overall performance [10, 11].

A carbon-based cylindrical structure is composed of a single chain of carbon atoms arranged in a hexagonal pattern, with an extremely small diameter measured in nanometers. There are two main types of carbon-based tubes: single-walled tubes and multi-walled tubes [12, 13]. Single-walled carbon tubes are created by manipulating a curved sheet of graphite. Each single-walled tube consists of two distinct parts, each with its own physical and chemical properties: the cylindrical sidewall and the capped ends of the tube [14]. Multi-walled tubes form through the aggregation of multiple single-walled tubes with varying diameters. Due to the considerable differences in length and diameter between the two types, their physical and chemical characteristics vary significantly. The electrical, chemical, and structural properties of carbon-based tubes are largely influenced by their one-dimensional structure [15, 16]. The incorporation of carbon-based tubes in cement products has the potential to transform the construction industry by facilitating the production of cost-effective, high-performance, and long-lasting materials [17, 18]. The mechanical properties of cement-based materials are influenced by their structure and by processes occurring at the micro- and small-scale levels. Advanced materials can enhance the properties of various substances by altering their molecular structure. Furthermore, carbon-based tubes can improve the structural sustainability, volumetric stability, durability, and mechanical performance of these materials [19, 20].

Calcium silicate hydrate (C-S-H), a complex network of cohesive particles, is a key component of concrete, which is a composite material made from cement. The addition of carbon-based tubes can enhance the mechanical properties of concrete. The fine characteristics of these tubes lead to strong interactions with C-S-H, thereby improving the overall performance of the material [21]. These carbon-based tubes have the potential to fill voids in traditional concrete. These voids allow water to seep through cracks, weakening the concrete and making it brittle. By effectively blocking the flow of water through these gaps, carbon-based tubes can enhance the impermeability and durability of concrete [22].

This integrated approach does not directly focus on sustainability, but it ensures that sustainability is properly considered. The design method takes environmental factors into account, striving to balance the components of concrete to maintain high performance while improving the sustainability of the manufacturing process. Achieving a concrete mixture that meets sustainability standards requires applying the right mix design strategy, selecting the most appropriate parameters, and determining optimal material quantities. The properties of the materials, among other factors, can influence the specifications of the concrete mixture [23, 24].

The aim of this study is to develop an optimal concrete mixture by incorporating advanced carbon-based materials. Three different mixtures were prepared by varying the types and quantities of admixtures used in the concrete. Two mixtures included carbon-based materials in different amounts, while the third contained a type F admixture, specifically a superplasticizer. Both fresh and cured concrete samples were tested. The fresh concrete underwent a slump test, and cylindrical specimens measuring 100 × 200 mm were tested for density and compressive strength after being cured in water. The hardened concrete samples were evaluated for compressive strength after 7, 14, and 28 days.

II. RESEARCH GAP

The literature review clearly demonstrates the wide range of applications of advanced materials in the construction industry, facilitating the integration of sustainability into various construction engineering processes and management systems. This study promotes the use of advanced materials in the development of high-performance concrete for managing sustainable concrete quality. It suggests potential design approaches and combination variables that incorporate environmental and socio-economic sustainability into the multi-criteria decision-making process during the concrete design stage. This characteristic makes these materials ideal for ensuring the quality of environmentally sustainable concrete.

III. MATERIALS AND METHODS

A. Portland Cement and Fly Ash

This study uses both physical and chemical analyses to assess the properties of fly ash and Portland cement as binding agents. The results from these tests form the foundation for the design, guiding the concrete mix design process. The chemical compositions of Portland cement and fly ash were analyzed through XRF (X-Ray Fluorescence) testing, which aims to identify the chemical makeup of the main ingredients used in concrete production. Tables I and II display the findings from the evaluation of the physical and chemical properties of fly ash and Portland cement. Additionally, analyses of the physical and chemical characteristics of cement were conducted to evaluate its suitability as a binding agent for this research. The strength of cement has a direct impact on the strength of the resulting concrete.

The fly ash for this project was obtained from the PLTU in Jeneponto, South Sulawesi, while the Portland cement was provided by a cement plant in Maros, also in South Sulawesi. The results in Tables I and II indicate that the Portland cement complies with the standards set by ASTM C150. The fly ash used is classified as category F according to ASTM C618-12 [25].

TABLE I. PHYSICAL PROPERTIES OF PORTLAND CEMENT AND FLY ASH

Properties	Unit	Portland cement	Fly ash
Autoclave expansion	%	0.13	0.12
Fineness	m^2/kg	346	379
Compressive strength a. 3 days b. 7 days c. 28 days	 kg/cm^2 kg/cm^2 kg/cm^2	 188 266 359	 98 105 125
Time of setting a. Initial Set b. Final Set	 minute minute	 125 260	 60 136
False set, final penetration	%	83.66	65.78
Air content	% volume	4.53	2.89
Specific gravity		3.15	2.2
Sieve analysis		-	90% pass no.200

TABLE II. CHEMICAL CHARACTERISTICS OF PORTLAND CEMENT AND FLY ASH

Compound	Portland cement (%)	Fly ash (%)
MgO	1.54	1.29
SO_3	2.36	1.18
SiO_2	34.89	45.56
Al_2SO_3	12.79	14.55
Fe_2O_3	10.78	11.83
$SiO_2 + Al_2SO_3 + Fe_2O_3$	58.46	70.94
CaO	9.78	12.74
Loss on ignition	2.47	0.30
Insoluble residue	1.24	1.07
Alkalis	0.38	0.19

B. Aggregate

Raw materials from the BiliBili River by a stone crushing factory in Gowa Regency, South Sulawesi, were utilized for producing crushed stone. The physical properties of the coarse aggregate meet the requirements of ASTM C33 [26]. The fine aggregate used in this study was obtained from silica sand taken from the BiliBili River in Gowa, South Sulawesi. Table III presents the physical properties of the fine aggregate, which comply with the specifications set by ASTM C33 [26].

TABLE III. PHYSICAL CHARACTERISTICS OF AGGREGATE

Properties	Coarse aggregate	Fine aggregate
Colloid content (%)	0.55	3.14
Fineness modulus	7.01	2.59
Water absorption (%)	0.78	2.97
Moisture content (%)	0.79	7.43
Specific gravity (SSD)	2.75	2.63

TABLE IV. ADMIXTURE CHARACTERISTICS

Properties	Celchem 75 RS	Edencrate Pz
Appearance	Dark brown	A black, opaque liquid
Chemical type	Mixture	Mixture
Physical state	Liquid	Liquid
Specific gravity	1.17 g/mL	1.13 g/mL
Identified use	Very high workability – high water reducing – low shrinkage and creep	Improved strength and durability in concrete that use pozzolans
Dosage	0.4-1.5 kg/100 kg cement	

C. Mixtures Design

The considered mix design consists of three variations, each incorporating different admixtures into the concrete mixture. MIX-1 utilized a conventional superplasticizer, specifically sulfonated naphthalene (adm-1), at a dosage of 2.00 L/m^3 of concrete, MIX-2 included a carbon-based additive at a dosage of 0.243 L, and MIX-3 incorporated a carbon-based additive at a dosage of 0.389 L.

TABLE V. MIXED DESIGN COMPOSITION (PER 1 m^3)

Materials	MIX-1	MIX-2	MIX-3
Cement (kg)	339		
Fly ash (kg)	136		
Coarse aggregate (kg)	1040		
Fine aggregate (kg)	650		
Water (kg)	185		
Admx-1 (L)	2.0	-	-
Adm-2 (L)	-	0.24	0.39

D. Concrete Test

Both fresh and hardened concrete were tested in this study. Figure 1 shows our compliance with ASTM C143 [27] standards by performing the slump test on the fresh concrete. At the same time, we assessed the compressive strength of 100 mm ×200 mm cylinders made of dense concrete, which were submerged in water for 3, 7, and 28 days after casting (Figure 2).

Fig. 1. Slump test.

Fig. 2. Water curing.

Fig. 3. Compressive strength test.

Compression tests were conducted on the specimens to measure their compressive strength, using the equipment shown in Figure 3. The testing procedures adhered to the guidelines specified in ASTM C39 standards [28].

IV. RESULTS AND DISCUSSION

A. *Fresh Concrete*

Table VI presents the results of the fresh concrete slump test for all mix combinations. The outcome highlights the effectiveness of the additive in reducing water usage. The data show that the use of the additive results in a greater reduction in viscosity with smaller amounts of admixture used in MIX-2 and MIX-3, compared to MIX-1. Visual inspection reveals that each freshly prepared concrete mixture has a sticky consistency, preventing separation or bleeding.

TABLE VI. SLUMP TEST

No.	Variation of concrete	Slump test (cm)
1	MIX-1	12
2	MIX-2	13
3	MIX-3	14

B. *Volume Weight*

The density of concrete ranges from 2331 to 2394 kg/m^3 (Figure 5). MIX-1 exhibits the lowest unit weight values (kg/m³) at 7, 14, and 28 days, measuring 2331, 2350, and 2376 kg/m^3, respectively. In contrast, the unit weight values for the MIX-2 specimens are 2,331, 2,368, and 2,390 kg/m^3. Meanwhile, the MIX-3 specimens show unit weight values of 2348, 2368, and 2391 kg/m^3. Based on the unit weight values, all test specimens can be classified as normal-weight concrete. According to ACI 318-11 [27, 28], normal-weight concrete is defined as having a density between 2155 kg/m^{3}and 2560 kg/m^3. As concrete matures, its unit weight generally increases, improving its structural strength.

C. *Compressive Strength*

The results of the compressive strength tests performed on dense concrete after 7, 14, and 28 days for each specimen can be seen in Table VII. It can be seen that, among the specimens tested, MIX-1 exhibits the lowest average compressive strength at all curing ages, while MIX-3 demonstrates the highest average value.

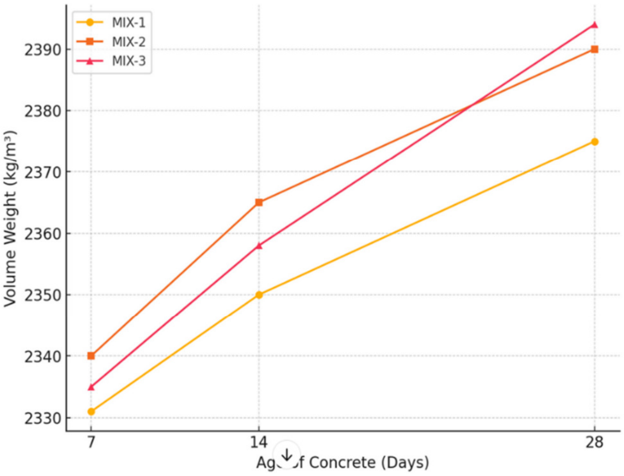

Fig. 4. Volume weight value of the test object.

The results for MIX-2 and MIX-3 indicate that adding an advanced material-based admixture can improve the compressive strength of the concrete specimens, as shown in Table VII. After 28 days, concrete with advanced materials dosage of 0.243–0.389 L/m³ reaches a compressive strength of 37.5–37.9 MPa. In contrast, the use of a conventional superplasticizer at a dosage of 2 L/m³ in MIX-1 results in a compressive strength of 36.0 MPa.

The compressive strength of all three mixes increases as the curing time progresses, which is consistent with general concrete behavior. This phenomenon can be attributed to the continued hydration of cement particles over time, resulting in the gradual formation of stronger bonds within the concrete matrix. Research has shown that the hydration process is most rapid within the first few days of curing, contributing to a significant increase in strength by 14 days, and continuing to increase at a slower rate after 28 days.

TABLE VII. COMPRESSIVE STRENGTH

Concrete age (days)	Compressive strength (MPa)		
	MIX-1	MIX-2	MIX-3
7	23.8	24.5	25.0
14	30.1	31.2	32.5
28	35.4	36.0	37.9

MIX-3 consistently demonstrates the highest compressive strength at each curing stage, followed by MIX-2 and MIX-1. This could be due to differences in the proportions of cement, aggregate, and additives used in each mix. Previous studies have highlighted the importance of optimizing the mix design to achieve higher strength. For instance, the inclusion of supplementary cementitious materials or specific types of aggregates can enhance hydration and microstructure, leading to stronger concrete. These differences in mix design might explain why MIX-3 outperforms the other mixes in terms of compressive strength.

The increase in compressive strength over time is a well-established phenomenon in concrete science. Studies have consistently shown that concrete strength continues to grow beyond 28 days, albeit at a much slower rate. This suggests that while the data in Table VII provide a snapshot of early-age strength, the concrete may still continue to strengthen beyond 28 days, depending on environmental conditions and curing practices. In practical applications, the early strength (7 and 14 days) is critical for determining the concrete's suitability for construction, but the full-strength potential is realized at later stages.

D. Sustainable Quality Concrete Production

The DOE method also takes into account the water-to-cement ratio and the variation in fine aggregate proportions relative to the maximum size of the coarse aggregate. The Fineness Modulus (FM) technique for designing concrete mixes is based on the idea that the water-to-cement ratio, along with the proportions of fine and coarse aggregates, plays a crucial role in determining the strength of concrete. It ensures that the minimum amount of cement paste is used to fully compact the aggregate mix. While this approach considers environmental factors, it does not specifically focus on sustainability.

Concrete mix parameters such as density, water-to-cement ratios, fine aggregate-to-cement ratios (FA/c), coarse aggregate-to-cement ratios (CA/c), and the cost of concrete can be adjusted to align with the socioeconomic aspects of sustainable concrete. To meet environmental sustainability goals, factors like density, water-to-cement ratio (w/c), fine aggregate-to-total aggregate ratio (FA/T), total aggregate-to-cement ratio (T/c), and FA/c can be applied. Proper concrete mix design not only improves structural durability but also addresses both socioeconomic and environmental issues.

The factors involved in producing high-quality concrete highlight that an optimal concrete mix is essential for ensuring superior concrete quality. The mix proportions reflect the importance of achieving an ideal balance between the FA/c and the FA/T to enhance the overall performance of the concrete.

Density plays a vital role in the concrete mix, significantly affecting the quality of sustainable concrete. This is understandable, as the density of concrete directly influences its performance and durability. On the other hand, FA/T and FA/c typically have a negligible impact on the quality of concrete mixtures. This aligns with findings that show no strong correlation between the amount of fine aggregate and the overall volume of aggregate.

V. CONCLUSION

The results of the volume-weight tests indicate that all specimens meet the criteria for normal-weight concrete as outlined in ACI 318-11. This study reveals that an advanced materials-based admixture (MIX-2) is more effective than a naphthalene-based admixture (MIX-1) in enhancing both workability and compressive strength. Even with a relatively low dosage of MIX-2 (0.06–0.09% of the cementitious material, compared to 0.49% for MIX-1), the specimens demonstrate higher slump values and compressive strength. Furthermore, the compressive strength and slump values show a proportional increase with increasing dosage of the advanced material-based admixture.

This research tackles important issues, including escalating production costs, higher performance demands for concrete, and the necessity of promoting a safer environment and community, making it highly beneficial to the concrete manufacturing industry. Additionally, the proposed selection support framework offers a systematic approach for identifying key variables and adopting a sustainable perspective in concrete design. This framework serves as a valuable tool for modernizing concrete design practices and selecting the most effective strategies to develop concrete mixtures that ensure consistent long-term quality in both production and construction.

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REFERENCES

[1] F. Rachim, M. Tumpu, and M. Mansyur, "Research on Predicting Skilled Labor Availability to Enhance Sustainability Building Practices," *International Journal of Sustainable Development and Planning*, vol. 19, no. 11, pp. 4183–4192, 2024.

[2] Md. A. Uddin, M. Jameel, H. R. Sobuz, Md. S. Islam, and N. Md. S. Hasan, "Experimental study on strength gaining characteristics of concrete using Portland Composite Cement," *KSCE Journal of Civil Engineering*, vol. 17, no. 4, pp. 789–796, May 2013, https://doi.org/10.1007/s12205-013-0236-x.

[3] Y. I. A. Aisheh, D. S. Atrushi, M. H. Akeed, S. Qaidi, and B. A. Tayeh, "Influence of polypropylene and steel fibers on the mechanical properties of ultra-high-performance fiber-reinforced geopolymer concrete," *Case Studies in Construction Materials*, vol. 17, Dec. 2022, Art. no. e01234, https://doi.org/10.1016/j.cscm.2022.e01234.

[4] B. J. Olawuyi and W. P. Boshoff, "Influence of SAP content and curing age on air void distribution of high performance concrete using 3D volume analysis," *Construction and Building Materials*, vol. 135, pp. 580–589, Mar. 2017, https://doi.org/10.1016/j.conbuildmat.2016.12.128.

[5] A. S. Faried, S. A. Mostafa, B. A. Tayeh, and T. A. Tawfik, "The effect of using nano rice husk ash of different burning degrees on ultra-high-performance concrete properties," *Construction and Building Materials*, vol. 290, Jul. 2021, Art. no. 123279, https://doi.org/10.1016/j.conbuildmat.2021.123279.

[6] R. H. Faraj, H. U. Ahmed, S. Rafiq, N. H. Sor, D. F. Ibrahim, and S. M. A. Qaidi, "Performance of Self-Compacting mortars modified with Nanoparticles: A systematic review and modeling," *Cleaner Materials*, vol. 4, Jun. 2022, Art. no. 100086, https://doi.org/10.1016/j.clema.2022.100086.

[7] S. H. Lee, S. Kim, and D.-Y. Yoo, "Hybrid effects of steel fiber and carbon nanotube on self-sensing capability of ultra-high-performance concrete," *Construction and Building Materials*, vol. 185, pp. 530–544, Oct. 2018, https://doi.org/10.1016/j.conbuildmat.2018.07.071.

[8] K. P. Chong, "Nanoscience and engineering in mechanics and materials," *Journal of Physics and Chemistry of Solids*, vol. 65, no. 8, pp. 1501–1506, Aug. 2004, https://doi.org/10.1016/j.jpcs.2003.09.032.

[9] A. Hussain, Y. Xiang, T. Yu, and F. Zou, "Nanocarbon black-based ultra-high-performance concrete (UHPC) with self-strain sensing capability," *Construction and Building Materials*, vol. 359, Dec. 2022, Art. no. 129496, https://doi.org/10.1016/j.conbuildmat.2022.129496.

[10] C. Fava, L. Bergol, G. Fornasier, F. Giangrasso, and C. Rocco, "Fracture behaviour of self compacting concrete," in *3rd International RILEM*

Symposium on Self-Compacting Concrete, Reykjavik, Iceland, Aug. 2003, pp. 628–636.

[11] E. N. Ganesh, "Single Walled and Multi Walled Carbon Nanotube Structure, Synthesis and Applications," *International Journal of Innovative Technology and Exploring Engineering*, vol. 2, no. 4, pp. 311–320, 2013.

[12] M. S. Morsy, S. H. Alsayed, and M. Aqel, "Hybrid effect of carbon nanotube and nano-clay on physico-mechanical properties of cement mortar," *Construction and Building Materials*, vol. 25, no. 1, pp. 145–149, Jan. 2011, https://doi.org/10.1016/j.conbuildmat.2010.06.046.

[13] N. Sinha and J. T.-W. Yeow, "Carbon nanotubes for biomedical applications," *IEEE Transactions on NanoBioscience*, vol. 4, no. 2, pp. 180–195, Jun. 2005, https://doi.org/10.1109/TNB.2005.850478.

[14] M. Jung, Y.-S. Lee, and S.-G. Hong, "Effect of Incident Area Size on Estimation of EMI Shielding Effectiveness for Ultra-High Performance Concrete With Carbon Nanotubes," *IEEE Access*, vol. 7, pp. 183105–183117, 2019, https://doi.org/10.1109/ACCESS.2019.2958633.

[15] G. M. Kim, B. J. Yang, G. U. Ryu, and H. K. Lee, "The electrically conductive carbon nanotube (CNT)/cement composites for accelerated curing and thermal cracking reduction," *Composite Structures*, vol. 158, pp. 20–29, Dec. 2016, https://doi.org/10.1016/j.compstruct.2016.09.014.

[16] M. Jung, Y. Lee, S.-G. Hong, and J. Moon, "Carbon nanotubes (CNTs) in ultra-high performance concrete (UHPC): Dispersion, mechanical properties, and electromagnetic interference (EMI) shielding effectiveness (SE)," *Cement and Concrete Research*, vol. 131, May 2020, Art. no. 106017, https://doi.org/10.1016/j.cemconres.2020.106017.

[17] S. Wang, S. Wen, and D. D. L. Chung, "Resistance heating using electrically conductive cements," *Advances in Cement Research*, vol. 16, no. 4, pp. 161–166, Oct. 2004, https://doi.org/10.1680/adcr.2004.16.4.161.

[18] F. Reza, J. A. Yamamuro, and G. B. Batson, "Electrical resistance change in compact tension specimens of carbon fiber cement composites," *Cement and Concrete Composites*, vol. 26, no. 7, pp. 873–881, Oct. 2004, https://doi.org/10.1016/j.cemconcomp.2003.06.002.

[19] E. Najaf, M. Orouji, and S. M. Zahrai, "Improving nonlinear behavior and tensile and compressive strengths of sustainable lightweight concrete using waste glass powder, nanosilica, and recycled polypropylene fiber," *Nonlinear Engineering*, vol. 11, no. 1, pp. 58–70, Jan. 2022, https://doi.org/10.1515/nleng-2022-0008.

[20] D. Micheli *et al.*, "Electromagnetic characterization and shielding effectiveness of concrete composite reinforced with carbon nanotubes in the mobile phones frequency band," *Materials Science and Engineering: B*, vol. 188, pp. 119–129, Oct. 2014, https://doi.org/10.1016/j.mseb.2014.07.001.

[21] S. K. Adhikary, Z. Rudzionis, S. Tuckute, and D. K. Ashish, "Effects of carbon nanotubes on expanded glass and silica aerogel based lightweight concrete," Scientific Reports, vol. 11, no. 1, Jan. 2021, Art. no. 2104, https://doi.org/10.1038/s41598-021-81665-y.

[22] D. D. L. Chung, "Self-heating structural materials," *Self-heating structural materials*, vol. 13, no. 3, pp. 562–565, 2004, https://doi.org/10.1088/0964-1726/13/3/015.

[23] S. Kekez and J. Kubica, "Connecting concrete technology and machine learning: proposal for application of ANNs and CNT/concrete composites in structural health monitoring," *RSC Advances*, vol. 10, no. 39, pp. 23038–23048, 2020, https://doi.org/10.1039/D0RA03450A.

[24] M. Siahkouhi, G. Razaqpur, N. A. Hoult, M. Hajmohammadian Baghban, and G. Jing, "Utilization of carbon nanotubes (CNTs) in concrete for structural health monitoring (SHM) purposes: A review," *Construction and Building Materials*, vol. 309, Nov. 2021, Art. no. 125137, https://doi.org/10.1016/j.conbuildmat.2021.125137.

[25] *ASTM C33-07(2012), Standard Specification for Concrete Aggregates.* West Conshohocken, PA, USA: ASTM International, 2012.

[26] *ASTM C143/C143M-00 (2017), Standard Test Method for Slump of Hydraulic Cement Concrete*. West Conshohocken, PA, USA: ASTM International, 2017.

[27] *ASTM C39/C39M-18 (2020), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA, USA: ASTM International, 2020.

[28] *ACI 318-11 (2011), Building Code Requirements for Structural Concrete and Commentary*. Farmington Hills, MI, USA: American Concrete Institute, 2011.