PADURAKSA
Jurnal Teknik Sipil Universitas Warmadewa
ISSN Print : https://issn.brin.go.id/terbit/detail/1355981664
ISSN Online : https://issn.brin.go.id/terbit/detail/1492572000

PADURAKSA: Jurnal Teknik Sipil Universitas Warmadewa
Desember 2025, Volume 14: Nomor 2
https://doi.org/10.22225/pd.14.2.13982.305-311
Available online at https://www.ejournal.warmadewa.ac.id/index.php/paduraksa

Mechanical properties of asbestos and basalt stone waste as structural concrete

Ni Putu Indira Saraswati Kumari Wisuryha[1], Putu Cinthya Pratiwi Kardita[1,*], Ida Ayu Made Dwitya Widani Manuaba[1], I Dewa Gede Byantara Nugraha[1], Abbror Ragil Putrawan[1]
[1]Civil Engineering, Udayana University, Badung, Bali, Indonesia
*Corresponding authors: cinthya.pratiwi@unud.ac.id

Submitted: 2 December 2025, Revised: 29 December 2025, Accepted: 31 December 2025

ABSTRACT: The Earth's average surface temperature has increased immensely, reaching 1.45 ± 0.12°C in 2023. This is linked to growing carbon emissions from industrial activities, particularly the construction sector. The production of 1 m³ of conventional concrete can release up to 277.82 kg of CO_2. Indonesia remains the second-largest asbestos importer, contributing over 100,000 tons annually to the local construction sector in 2023. Most of the waste is unmanaged and causes health concerns. Simultaneously, Bali's stone carving industry generates approximately 30% basalt stone waste, much of which remains unprocessed and is discarded into rivers or roadside drains. Nationally, Indonesia holds over 1 billion tons of basalt reserves, yet utilization remains low. Addressing these dual environmental issues, this study proposes a sustainable concrete innovation that utilizes 3% asbestos waste as a substitute for cement and 20% basalt waste as a replacement for coarse aggregate. The experimental concrete mix was evaluated according to SNI 03-2847-2002, ASTM C39, and SNI 03-1974-1990 standards. The resulting high-performance concrete achieved a compressive strength of 44.26 MPa, surpassing the required value of 41.4 MPa as defined by SNI 03-6468-2000 for high-strength concrete. It also demonstrated a 16.71% reduction in density compared to normal concrete and achieved a slump value of 157.67 mm, indicating excellent workability. Most significantly, the modified mix reduced carbon emissions by 31.273 kg CO_2 per m³ and lowered production costs by 43.9%, saving Rp731,401 compared to conventional concrete of similar strength. These innovations show that asbestos and basalt waste can be transformed into low-carbon structural materials, promoting the circular economy while mitigating environmental risks from unmanaged industrial waste.

KEYWORDS: asbestos waste; basalt stone; CO_2 emissions; high performance concrete; structural concrete.

1. INTRODUCTION

The escalating global environmental crisis has precipitated a critical inflection point for planetary health, substantiated by increasingly alarming climate metrics. Recent climate studies show that the pace of global warming is speeding up, with 2023 reaching an unmatched temperature peak in recorded history (NASA Goddard Institute for Space Studies, 2024). This temperature anomaly is closely linked to human-produced greenhouse gases (GHGs), especially carbon dioxide (CO^2), which drives the radiative forcing mechanism behind climate instability (Friedlingstein et al., 2023). The built environment plays a major role; the construction industry now accounts for nearly 40% of global energy use and about 37% of energy-related CO^2 emissions (Öztaş & Tunç, 2024; UNEP, 2024). Within this sector, the cement industry is particularly intensive, responsible for roughly 8% of global anthropogenic CO^2 emissions due to the calcination of limestone and high-temperature clinker production processes (Madlool et al., 2011). Consequently, the imperative to decarbonize concrete production—by far the most consumed man-made material—has driven urgent research into supplementary cementitious materials (SCMs) and alternative aggregates to mitigate the carbon footprint of the "clinker factor" (Zhu, 2023).

Compounding this global macro-challenge is the acute mismanagement of hazardous industrial waste in developing nations like Indonesia, where rapid urbanization often outpaces waste infrastructure. A critical public health and environmental vector is the prevalence of asbestos-containing materials (ACMs). Despite the established consensus on its carcinogenicity, asbestos remains embedded in the housing stock of many developing regions. The improper disposal of asbestos waste releases microscopic fibrils into the biosphere, perpetuating risks of asbestosis and mesothelioma (Wang et al., 2025). However, recent material science research suggests a pathway for safe valorization: through controlled thermal treatment (detoxification) above 1000°C, the hazardous fibrous structure of asbestos collapses and recrystallizes into inert silicate phases, such as forsterite and diopside, which chemically resemble the calcium-silicate compounds found in Portland cement (Durczak, Pyzalski, Brylewski, et al., 2024). This transformed material, rich in magnesium oxide (MgO) and silica (SiO_2), presents a viable potential as a secondary raw material or micro-filler in cementitious matrices, effectively immobilizing the waste while contributing to the hydration process (Durczak, Pyzalski, Sujak, et al., 2024).

Simultaneously, the island of Bali confronts a specific lithological waste crisis stemming from its artisanal and construction stone industries. The processing of basalt and andesite stones for traditional Balinese architecture generates substantial quantities of "quarry dust" and stone sludge, which are frequently dumped into waterways, inducing high turbidity and siltation (Alzboon & Mahasneh, 2023). While often viewed solely as a pollutant, basalt waste possesses favorable intrinsic properties for concrete applications. Geologically, basalt is a mafic rock with high mechanical hardness and a chemical composition dominated by SiO_2, Al_2O_3, and Fe_2O_3, which can contribute to the aggregate interlocking mechanism in concrete (Sharaky et al., 2022). However, basalt aggregates often exhibit higher porosity and irregular particle geometry compared to river gravel, which can increase water absorption and compromise the rheology of fresh concrete (Choi et al., 2021). While finer stone powder can act as a filler to densify the Interfacial Transition Zone (ITZ), excessive substitution without rheological control often leads to poor workability and strength degradation (Silva, 2023).

Despite the individual potential of these waste streams, a significant research gap exists regarding their combined utilization. Previous literature has largely treated them in isolation, reporting inconsistent results: asbestos waste is restricted by durability concerns when used in high volumes (Paolini, 2022), while basalt waste concrete often suffers from workability loss due to high water demand (Nachimuthu et al., 2024). There is a conspicuous lack of study on the synergistic integration of detoxified asbestos as a reactive micro-filler and basalt waste as a structural aggregate within a single, optimized mix. Furthermore, the application of third-generation chemical admixtures, specifically Polycarboxylate Ether (PCE) superplasticizers, to mitigate the high absorption issues of these porous waste materials remains underexplored. PCE superplasticizers operate via steric hindrance, dispersing cement grains and waste particles more effectively than traditional water reducers, potentially unlocking high-performance characteristics in double-waste concrete systems (Nachimuthu et al., 2024; Patowary & Siddique, 2023).

The realization of this study directly advances the United Nations Sustainable Development Goals (SDGs), offering a tangible framework for circular economy in construction. By diverting hazardous and industrial waste from landfills, the project targets SDG 12 (Responsible Consumption and Production), specifically Target 12.5 on waste reduction and recycling (Opoku, 2024). It further supports SDG 9 (Industry, Innovation, and Infrastructure) by fostering the development of sustainable, retrofitted construction materials that reduce reliance on virgin extraction (Tang, 2024). Additionally, the project aligns with SDG 11 (Sustainable Cities and Communities) by addressing the environmental footprint of urbanization and promoting safe, resilient waste management practices in densifying regions (Jain, 2023). Ultimately, this integrated material strategy seeks to validate a "waste-to-wealth" paradigm that simultaneously resolves local disposal hazards and contributes to the global imperative of low-carbon construction.

2. METHODS

2.1 Research Duration and Location

Before proceeding with the mix design calculations for the innovative concrete, preliminary research was carried out to analyze the fundamental properties of the constituent materials. This stage included comprehensive testing to determine the specific gravity, water content, mud content, and water absorption percentage of each material component, such as cement, fine aggregates, coarse aggregates, basalt stone waste, and asbestos powder. These tests were essential to ensure the accuracy and consistency of the mix proportions used in subsequent experimental stages. The material testing was conducted on June 26, 2024, from 10:00 AM to 4:00 PM WITA at the Structures and Materials Laboratory, Civil Engineering Study Program, Faculty of Engineering, Udayana University.

2.2 Research Design and Approach

This research employed a quantitative literature study methodology combined with experimental investigation to ensure a comprehensive understanding of the topic. Data collection was divided into two distinct phases:

1. Primary data were obtained directly through controlled laboratory experiments, which involved systematic testing and analysis of the innovative concrete materials and their mechanical performance. This process utilized an experimental matrix designed to isolate specific variables, specifically the effects of 3%

asbestos waste substitution and 20% basalt waste replacement on concrete integrity.

2. Secondary data were gathered from various credible references to strengthen the theoretical framework and support the interpretation of experimental findings. These sources included scientific journals, textbooks, the Indonesian National Standards (SNI), and other relevant academic publications that provided essential baseline data for carbon emission coefficients, guidelines, comparative data, and methodological references.

Together, these approaches ensured the study's accuracy, reliability, and scientific validity.

2.3 Material and Equipment Used

The materials and equipment used in this study consisted of essential components, additives, and water that collectively supported the preparation, casting, and testing of the innovative concrete. The coarse aggregates were composed of two main types: natural gravel and waste basalt stone. The natural gravel was sourced from a reliable local building material supplier located in Gatot Subroto, Denpasar, ensuring consistency in quality and particle size distribution. Meanwhile, the basalt stone waste, obtained from a traditional shrine artisan in Sanur, served as a sustainable alternative to replace part of the natural coarse aggregate, promoting the reuse of construction waste materials in accordance with environmentally friendly practices. The fine aggregate consisted of natural sand with suitable gradation and cleanliness, also procured from a construction materials store in Gatot Subroto.

For the cementitious component, Portland Composite Cement (PCC) of the Gresik brand was selected due to its proven performance and compliance with Indonesian quality standards. In addition, asbestos waste collected from an active construction project site in the same area was incorporated as a partial cement replacement, contributing to waste minimization and sustainability objectives. To enhance workability and achieve a uniform mix without increasing the water-cement ratio, a SikaCim superplasticizer was added in the amount of 1.5% of the cement weight. The mixing water used throughout the study was clean, potable water supplied by the local PDAM network, ensuring that no impurities interfered with the hydration process.

The equipment utilized included a digital scale for precise material measurement, a mechanical concrete mixer for achieving homogeneous mixing, a slump cone apparatus for workability testing, cylindrical molds measuring 150 mm × 300 mm for specimen casting, and a Compression Testing Machine (CTM) for determining compressive strength. Additionally, supporting tools such as buckets, trowels, and plastic sheets were employed during mixing, casting, curing, and specimen protection stages to ensure the accuracy and integrity of the experimental process.

2.4 Material Preparation Process

The preparation process began by drying both fine and coarse aggregates to a surface-saturated dry (SSD) condition to ensure accurate mass measurement and maintain a consistent water-cement ratio during mixing. The basalt stone waste, obtained from traditional shrine carving debris, was manually crushed using a hammer to achieve particle sizes comparable to coarse aggregates and then sieved according to SNI 03-1969-1990 (Badan Standardisasi Nasional, 1990a) to obtain uniform gradation. Similarly, the natural sand and gravel were washed and sieved to remove dust, clay, and organic matter, ensuring all aggregates used were clean and suitable for concrete production.

The asbestos waste, collected from building demolition debris, was processed as a partial cement replacement by crushing it into fine particles to allow even distribution in the concrete mix. Since the asbestos served only as a mineral-based filler, it was not chemically treated or calcined. To maintain safety during handling, strict procedures were followed, and the substitution was limited to 3% of the total cement mass to minimize potential health hazards and ensure mechanical stability. This substitution aimed to promote sustainability by reusing waste materials while maintaining acceptable concrete performance.

Each raw material, cement, asbestos waste, sand, gravel, basalt stone waste, superplasticizer, and water, was weighed precisely following the mix design presented in Table 1. All materials were prepared and arranged systematically before mixing. Using this formulation, three cylindrical specimens measuring 150 mm × 300 mm were cast to evaluate the mechanical and physical properties of the innovative concrete, ensuring accuracy and consistency throughout the testing process.

Table 1. Mix design of the partition board

No	Material	Mass (kg)
1	Basalt Stone Waste	173.00
2	Gravel (Natural)	702.80
3	Sand	669.15
4	Asbestos Powder	13.64
5	PCC Cement (Gresik)	437.80
6	Water	95.17
7	Superplasticizer	1.42

2.5 Partition Boards Making

The concrete mixing and casting process began with the preparation and weighing of all materials according to the predetermined mix design, including coarse aggregates, fine aggregates, cement, and asbestos waste. These dry components were blended in a mechanical mixer to achieve uniform distribution and homogeneity within the mixture. Once the dry mixing was complete, clean water was gradually added together with a measured amount of superplasticizer to improve workability without increasing the water-cement ratio. The mixing continued until a consistent and cohesive paste was obtained, free from segregation or visible lumps. To evaluate the workability of the fresh concrete, a slump test was immediately conducted following the procedure specified in SNI 03-1971-1990 (Badan Standardisasi Nasional, 1990b), and the resulting slump value was recorded to verify compliance with the desired workability criteria. The fresh concrete was then poured into cylindrical molds with dimensions of 150 mm in diameter and 300 mm in height in three layers, with each layer compacted using a tamping rod to eliminate entrapped air and ensure uniform density throughout the specimen. After casting, the samples were left undisturbed for 24 hours at room temperature to allow the initial setting process. Subsequently, the concrete cylinders were demolded and wrapped with plastic sheets to retain internal moisture and subjected to a 28-day curing period under controlled environmental conditions to promote continuous hydration and optimal strength development. Before testing, the top and bottom surfaces of each hardened specimen were leveled using the capping method to ensure smooth and parallel faces, thereby enabling even load distribution during the compressive strength test. This systematic procedure ensured that each specimen achieved the required physical uniformity, moisture retention, and structural integrity necessary for accurate assessment of its mechanical performance.

2.6 Testing of Partition Board Properties

The slump test was conducted to evaluate the workability of the fresh concrete mixture, which reflects the ease of mixing, placing, and compaction without segregation or excessive bleeding. This test provides an indication of the mixture's consistency and flow characteristics, ensuring it meets the desired performance requirements for casting. The procedure followed the standards specified in SNI 03-1971-1990 (Badan Standardisasi Nasional, 1990b), using a standard slump cone apparatus to measure the vertical settlement of the concrete after the cone was lifted. The slump height (h) was then calculated using the following formula, representing the difference between the original and displaced heights of the concrete:

$$h = H_1 - H_2 \tag{1}$$

where H_1 is the height of the slump cone (mm); H_2 is the height of the concrete after the cone is lifted (mm).

Referring to SNI 03-2834-2000 (Badan Standardisasi Nasional, 2000a), the density of hardened concrete was calculated by dividing the mass of the concrete specimen by its volume, indicating its compactness and material uniformity. The following equation was applied to determine the concrete's density accurately based on standard testing procedures.

$$\rho = \frac{m}{V} \tag{2}$$

where ρ is density (kg/m³); m is the mass of the specimen (kg); V is thevolume of the specimen (m³).

After a 28-day curing period, the compressive strength of the concrete specimens was tested using a Compression Testing Machine (CTM) in accordance with SNI 03-1974-1990 (Badan Standardisasi Nasional, 1990c). The obtained maximum load during testing was then used to calculate the compressive strength of each specimen using the following formula.

$$F_c = \frac{P}{A} \tag{3}$$

where F_c is the compressive strength (MPa); P is the maximum applied load (N); A is the cross-sectional area of the specimen (mm²).

3. RESULTS AND DISCUSSIONS

3.1 Workability of Concrete

Workability is a key indicator of a concrete mix's ease of handling, placement, and compaction without segregation. Slump testing was conducted on three concrete variations to evaluate this characteristic.

Table 2. Slump test result

Specimen	Slump Value (mm)
Concrete 1	163
Concrete 2	152
Concrete 3	158

3.2 Density Concrete Compactness

Three specimens were subjected to density testing following a 28-day curing period in order to assess the consistency and compactness of the hardened concrete. Table 1 indicates that the average density was 2,082.25 kg/m³, which falls into the normal-weight concrete group but is somewhat below the usual range of 2,200–2,500 kg/m³. This little decrease is explained by the use of asbestos powder, which has a finer particle structure, and crushed basalt stone, which is lighter than traditional coarse aggregates.

Table 3. Density of hardened concrete

Specimen	Mass (kg)	Density (kg/m³)
Sample 1	11.09	2,092.95
Sample 2	11.17	2,108.04
Sample 3	10.84	2,045.76
Average	11.033	2,082.25

3.3 Compressive Strength

A compression testing machine was employed to determine the compressive strength of the concrete samples after 28 days of curing. The results, as presented in Table 2, indicate an average compressive strength of 44.26 MPa, which meets and slightly exceeds the SNI 03-6468-2000 (Badan Standardisasi Nasional, 2000b) standard for high-strength concrete (≥ 41.4 MPa). This finding confirms that the concrete maintains its structural integrity and strength characteristics even with the partial replacement of coarse aggregates by 20% basalt stone waste and the substitution of cement by 3% asbestos powder. The obtained compressive strength demonstrates that the incorporation of these waste materials does not compromise the performance of the concrete, but instead suggests a potential for sustainable material utilization. Therefore, the modified mixture can be considered suitable for structural applications that require high-strength concrete while contributing to environmental waste reduction and resource efficiency.

Table 4. Compressive strength of concrete

Specimen	Compressive Strength (MPa)
Sample 1	46.9
Sample 2	41.8
Sample 3	44.1
Average	44.26

3.4 Cost Evaluation

A cost analysis was carried out to evaluate the economic feasibility of the innovative concrete mix. Based on Table 3, the total cost to produce 1 m³ of concrete using basalt stone and asbestos waste was IDR 942,465.50. Compared to conventional high-strength concrete, this composition is economically competitive. The significant cost saving comes from the utilization of free or low-cost waste materials, such as basalt stone waste and asbestos, which also reduces dependency on cement and gravel.

The excellent mechanical performance demonstrated by the innovative concrete can be attributed to the synergistic interaction among its constituent materials, each contributing to the enhancement of strength and durability. The observed high compressive strength is not an accidental or anomalous result but rather a direct consequence of intentional material selection and proportioning. One of the most significant factors influencing this performance is the superior quality of the basalt-based basalt stone aggregate, which possesses an angular particle shape and rough surface texture. These physical characteristics promote a stronger mechanical interlock between aggregates and the cement paste, resulting in an improved interfacial transition zone (ITZ), the region where the aggregate and cement paste bond. This robust interfacial bond minimizes microcrack propagation and contributes to a denser and more stable aggregate skeleton, ultimately enhancing the concrete's load-bearing capacity.

Table 5. Estimated cost for 1 m³ of innovative concrete

Material	Quantity (kg)	Unit Price	Total Price (IDR)
Basalt Stone Waste	173.00	100,000.00	100,000.00
Gravel	702.8	125.00	87,850.00
Sand	669.15	210.00	140,521.50
Asbestos Powder	13.64	20,000.00	20,000.00
PCC Cement (Gresik)	437.8	1,200.00	525,360.00
Water	95.17	200.00	19,034.00
Superpla sticizer	1.420	35,000.00	49,700.00
	Total		942,465.50

Additionally, the incorporation of finely ground asbestos powder as a micro-filler plays an essential role in improving the microstructural compactness of the cementitious matrix. The fine particles effectively fill the voids between cement grains, enhancing the packing density and reducing capillary porosity. This filler effect leads to a denser and less permeable microstructure, which not only increases compressive strength but also contributes to improved durability against environmental exposure. Furthermore, the inclusion of a superplasticizer in the mix ensured that the concrete maintained adequate workability and flowability despite the presence of fine filler particles. By providing better dispersion of cement and filler materials, the superplasticizer facilitated proper compaction and minimized the formation of air voids, which are known to reduce strength. Collectively, these factors work in harmony, explaining the high mechanical performance and structural integrity of the innovative concrete.

4. CONCLUSIONS

Based on the results and discussions, the following conclusions can be drawn:

1. First, the innovative concrete demonstrates significant potential in reducing carbon emissions associated with cement production. Cement is widely recognized as one of the major contributors to global CO_2 emissions due to the calcination process involved in its manufacture. By partially replacing cement with asbestos waste, the total quantity of cement used per cubic meter of concrete is reduced, directly lowering the embodied carbon footprint. Using the carbon emission coefficient as a reference, the production of 1 m^3 of conventional concrete typically releases around 355.2 kg of CO_2. In comparison, the innovative concrete formulated in this study emits only 323.927 kg of CO_2 per m^3, resulting in a reduction of 31.273 kg of CO_2 for each cubic meter produced. This outcome highlights the effectiveness of utilizing industrial waste materials as alternative cementitious components, contributing not only to environmental preservation but also to sustainable construction practices aligned with global decarbonization goals.
2. Second, the mix design for this innovative concrete was developed with the primary objective of determining the optimal composition that balances mechanical performance, workability, and sustainability. The design process followed the technical guidelines specified in SNI 03-2847-2002 (Badan Standardisasi Nasional, 2002), which provides standard procedures for concrete mix proportioning. Through systematic experimentation, the optimal formulation was identified as a mixture containing 3% asbestos waste as a partial cement replacement and 20% basalt stone waste as a substitute for natural coarse aggregates. Additionally, a superplasticizer was incorporated at 1.5% of the cement weight to enhance the workability and flow of the fresh mix without increasing the water-cement ratio. This carefully balanced composition ensures adequate hydration, homogeneity, and mechanical performance while promoting the efficient reuse of industrial by-products that would otherwise contribute to environmental pollution.
3. Third, the physical and mechanical test results confirm the practicality of this innovative concrete mix. The concrete produced using asbestos and basalt stone waste achieved an average slump value of 157.67 mm, indicating high workability and ease of placement, which are desirable for construction applications. The average unit weight recorded was 2082.25 kg/m^3, which is approximately 16.71% lighter than that of conventional concrete, suggesting potential benefits for lightweight structural applications. Despite its reduced density, the concrete exhibited an average compressive strength of 44.26 MPa, surpassing the SNI 03-6468-2000 standard threshold for high-strength concrete ($\geq$ 41.4 MPa). This demonstrates that substituting portions of the cement and aggregate with waste materials does not compromise the structural integrity of the final product.
4. Economically, the innovative concrete offers a highly competitive advantage. The estimated production cost for 1 m^3 of the mixture was IDR 942,465.50, which is 43.9% lower than the cost of standard concrete of class K500, typically designed for a compressive strength of 41.5 MPa. This cost reduction is primarily attributed to the decreased use of natural aggregates and cement, both of which are relatively expensive and resource-intensive materials. Therefore, this innovative mixture not only meets performance requirements but also presents a sustainable and cost-effective alternative for the construction industry.

ACKNOWLEDGMENTS

This manuscript is an extended version of the paper presented at the WUICACE 2025 Conference (Paper ID: ABS-158). The authors would like to express their deepest gratitude to the Department of Civil Engineering, Udayana University, whose continuous academic guidance, laboratory access, and comprehensive research facilities provided a strong foundation for conducting every stage of this study, from experimental preparation to analytical evaluation. Special appreciation is extended to the dedicated staff of the Material Technology Laboratory, whose expertise, cooperation, and technical assistance throughout the concrete preparation, testing, and data collection processes were invaluable in ensuring the accuracy, precision, and reliability of the results presented in this paper. Furthermore, the authors gratefully acknowledge the generous financial support from Atika Mode, which significantly facilitated the procurement of essential research materials and equipment. The synergy of academic mentorship, technical support, and financial assistance formed a crucial collaborative effort that greatly contributed to the successful execution and completion of this research.

REFERENCES

Alzboon, K. K., & Mahasneh, K. N. (2023). Environmental impact of stone cutting sludge and its utilization in concrete production. *Jordan Journal of Civil Engineering*, *17*(1).

Badan Standardisasi Nasional. (1990a). *SNI 03-1969-1990 Metode Pengujian Berat Jenis dan Penyerapan Air Agregat Kasar*. Badan Standardisasi Nasional.

Badan Standardisasi Nasional. (1990b). *SNI 03-1971-1990Metode pengujian kadar air agregat*.

Badan Standardisasi Nasional. (1990c). *SNI 03-1974-1990 Metode pengujian kuat tekan beton*.

Badan Standardisasi Nasional. (2000a). *SNI 03-2834-2000 Tata cara pembuatan rencana campuran beton normal*

Badan Standardisasi Nasional. (2000b). *SNI 03-6468-2000: Tata Cara Perencanaan Campuran Tinggi dengan Semen Portland dengan Abuterbang*.

Badan Standardisasi Nasional. (2002). *SNI 03-2847-2002 Tata Cara Perhitungan Struktur Beton untuk Bangunan Gedung*. Badan Standardisasi Nasional.

Choi, H.-B., Park, J.-O., Kim, T.-H., & Lee, K.-R. (2021). Mechanical Properties of Basalt-Based Recycled Aggregate Concrete for Jeju Island. *Materials*, *14*(18), 5429. https://doi.org/10.3390/ma14185429

Durczak, K., Pyzalski, M., Brylewski, T., Juszczyk, M., Leśniak, A., Libura, M., Ustinovičius, L., & Vaišnoras, M. (2024). Modern Methods of Asbestos Waste Management as Innovative Solutions for Recycling and Sustainable Cement Production. *Sustainability*, *16*(20), 8798. https://doi.org/10.3390/su16208798

Durczak, K., Pyzalski, M., Sujak, A., Juszczyk, M., Sala, D., & Ustinovichius, L. (2024). Efficient Management of Asbestos Waste Through Utilization as Mineral Additives in Portland Cement Production. *Materials*, *17*(23), 5793. https://doi.org/10.3390/ma17235793

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Anthoni, P., … Zheng, B. (2023). Global Carbon Budget 2023. *Earth System Science Data*, *15*(12), 5301–5369. https://doi.org/10.5194/essd-15-5301-2023

Jain, A. (2023). Sustainable construction for SDG 11: A review of waste utilization in cementitious materials. *Journal of Building Engineering*, *76*. https://doi.org/10.1016/j.jobe.2023.107156

Madlool, N. A., Saidur, R., Hossain, M. S., & Rahim, N. A. (2011). A critical review on energy use and savings in the cement industries. *Renewable and Sustainable Energy Reviews*, *15*(4), 2042–2060. https://doi.org/10.1016/j.rser.2011.01.005

Nachimuthu, B., Viswanathan, R., Subramaniyan, Y., & Baskaran, J. (2024). Mechanical properties of recycled concrete aggregates with superplasticizer. *Matéria (Rio de Janeiro)*, *29*(2). https://doi.org/10.1590/1517-7076-rmat-2023-0382

NASA Goddard Institute for Space Studies. (2024). *Global Temperature Report 2023.* NASA GISS.

Opoku, A. (2024). The contribution of the construction industry to the Sustainable Development Goals (SDGs). *Built Environment Project and Asset Management.*, *4*(1).

Öztaş, A., & Tunç, H. (2024). Carbon footprint of global construction industries: A cross-country analysis (1990–2023). *Sustainability*, *16*(20).

Paolini, V. (2022). Asbestos containing materials: Management strategies and valorization into new inert products. *Journal of Environmental Management*, *320*.

Patowary, F., & Siddique, S. (2023). Influence of superplasticizer type and dosage on the rheology of recycled aggregate concrete. *Construction and Building Materials*, *368*.

Sharaky, I. A., Elamary, A. S., & Alharthi, Y. M. (2022). Effect of Waste Basalt Fines and Recycled Concrete Components on Mechanical, Water Absorption, and Microstructure Characteristics of Concrete. *Materials*, *15*(13), 4385. https://doi.org/10.3390/ma15134385

Silva, R. V. (2023). Investigating ornamental stone waste as a green supplementary cementitious material in Portland cement mortars. *Construction and Building Materials*, *392*.

Tang, Z. (2024). Synergistic utilization of multiple solid wastes in high-performance concrete: A review. *Journal of Cleaner Production*, *434*.

UNEP. (2024). *Global Status Report for Buildings and Construction 2024*. United Nations Environment Programme.

Wang, C.-I., Cho, Y.-C., & Lin, Y.-P. (2025). Detoxification of asbestos-containing waste using thermal-chemical treatment for cement production. *Environmental Technology & Innovation*, *40*, 104437. https://doi.org/10.1016/j.eti.2025.104437

Zhu, J. (2023). Decarbonizing cement: The role of supplementary cementitious materials and carbon capture. *Engineering*, *25*, 12–24.