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Echahid Cheikh Larbi Tebessi University

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Innovative Materials and Sustainability

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Author

Ismail LAYADI

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Abstract

The global construction industry is a primary contributor to resource depletion, energy consumption, and greenhouse gas emissions, necessitating a paradigm shift towards sustainable practices. This academic handout provides a comprehensive review of innovative materials and technologies designed to mitigate the environmental impact of the built environment. Grounded in a systematic analysis of contemporary scholarly literature, this document explores the foundational principles and practical applications of sustainable construction materials. The content is structured into four main chapters. **Chapter 1** introduces the concept of eco-materials, with a detailed examination of material valorization, which transforms waste streams and industrial by-products into valuable construction components, thereby fostering a circular economy. It also covers the properties and modern applications of natural materials like stone and earth, alongside activated materials such as metakaolin and rice husk ash. **Chapter 2** investigates a range of alternative binders and cementitious replacements, including organic binders, low-carbon belitic cements, glass-based binders, and alkali-activated geopolymers, all aimed at reducing the significant carbon footprint of ordinary Portland cement. **Chapter 3** delves into novel construction materials that offer enhanced performance and sustainability, such as self-compacting concrete, hemp concrete (hempcrete), and fiber-reinforced concrete. Finally, **Chapter 4** examines advanced materials and techniques at the forefront of construction technology, including high-performance, very-high-performance, and ultra-high-performance concretes (HPC, VHPC, UHPC), specialized low-pH concrete, and advanced injection grouts. By synthesizing multiple academic perspectives, this handout serves as a critical resource for understanding the scientific principles, performance characteristics, and sustainability credentials of the next generation of construction materials.

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General Introduction

The Imperative for Sustainability in the Construction Sector

The construction industry is a cornerstone of global economic development and societal progress, responsible for creating the built environment that underpins modern life. However, this progress comes at a significant environmental cost. The sector is one of the largest consumers of natural resources and energy, a major producer of waste, and a substantial contributor to global greenhouse gas emissions. Globally, the construction industry is responsible for approximately 40% of total energy and natural resource consumption, produces around 35% of total waste, and releases 40% of carbon dioxide into the atmosphere. The production of ordinary Portland cement (OPC) alone, the primary binder in concrete, accounts for an estimated 5-8% of total anthropogenic CO_2 emissions, making it a critical target for environmental mitigation strategies. These statistics underscore the urgent need for a fundamental transformation in how buildings and infrastructure are designed, constructed, operated, and deconstructed.

In response to these challenges, the concept of sustainable construction (also known as green building) has emerged as a critical framework. Sustainable construction is a multi-faceted approach that seeks to minimize the environmental, social, and economic footprints of construction projects throughout their entire lifecycle. It encompasses a wide range of practices, from energy-efficient building design and the integration of renewable energy sources to responsible water management and the reduction of construction and demolition waste. At the heart of this paradigm shift lies the development and application of innovative and sustainable materials. The selection of materials with lower embodied energy, minimal waste generation, and high potential for reuse or recycling can significantly reduce a project's environmental impact, thereby contributing to the preservation of natural resources and ecosystems.

Defining Eco-Materials and the Principles of Material Innovation

The transition towards sustainable construction is intrinsically linked to advancements in materials science. Traditional building materials like conventional concrete, steel, and fired bricks carry a significant environmental burden due to energy-intensive production processes and reliance on finite raw materials. In contrast, innovative materials offer more sustainable alternatives that can help reduce the environmental impact of construction. These materials are often referred to as “Green Building Materials” or “Eco-Materials”. An Eco-Material can be defined as an ecological, healthy, recycled, or high-performance material capable of minimizing its impacts on the environment and human health throughout its entire life cycle, from resource extraction and manufacturing to use, disposal, and recycling.

The innovation driving the development of eco-materials is guided by several core principles. A primary goal is the reduction of embodied energy (the total energy consumed during a material's lifecycle). This is often achieved by utilizing renewable resources, such as timber, bamboo, or hemp, or by incorporating recycled materials and industrial by-products, which diverts waste from landfills and reduces the demand for virgin resource extraction. Another key principle is enhancing material durability and extending the service life of structures, which mitigates the environmental impact over the building's lifecycle by reducing maintenance, repair, and replacement needs. Furthermore, modern material innovation is increasingly guided by the principles of the circular economy, which emphasizes designing materials and components for disassembly, reuse, and high-value recycling, thereby closing material loops and eliminating the concept of waste.

Overview of Key Themes

This academic handout is structured to provide a comprehensive exploration of the key domains within innovative materials and sustainability. The chapters are organized to build a foundational understanding and progress toward more advanced and specialized topics.

Chapter 1: Eco-Materials lays the groundwork by introducing the core concepts of sustainable material selection. It begins with a detailed examination of material valorization, a sophisticated approach to waste management that aims to transform industrial by-products and waste streams into high-value construction components, moving beyond simple recycling. The chapter then

explores a range of eco-materials, including traditional natural materials like stone and earth, which are being re-examined and enhanced for modern construction, and activated materials such as metakaolin and rice husk ash, whose cementitious properties are unlocked through thermal processing.

Chapter 2: Alternative Binders and Cementitious Replacements addresses one of the most significant challenges in sustainable construction: reducing the reliance on ordinary Portland cement. This chapter reviews a variety of low-carbon alternatives, from organic binders used to stabilize earth-based materials to advanced inorganic systems. It covers the science and performance of belitic binders, glass-based binders, and geopolymers, which are formed through the alkali activation of aluminosilicate precursors.

Chapter 3: Novel Materials focuses on innovative composite materials that offer unique performance characteristics and sustainability benefits. This includes: Self-Compacting Concrete, which enhances constructability and quality; Hemp Concrete (Hempcrete), a carbon-negative insulating material; and Fiber-Reinforced Concrete, which improves the ductility and crack resistance of concrete structures.

Chapter 4: Construction Materials explores the cutting edge of concrete technology. It details the progression from High-Performance Concrete (HPC) to Very-High-Performance (VHPC) and Ultra-High-Performance Concrete (UHPC), materials that offer unprecedented strength and durability. The chapter also covers specialized materials like Low-pH Concrete, designed for sensitive applications such as geological repositories for nuclear waste, and advanced Injection Grouts used for ground improvement and structural repair.

Together, these chapters provide a holistic overview of the field, demonstrating how innovations in materials science are paving the way for a more resilient, efficient, and environmentally responsible built environment.

Chapter 1

Eco-Materials

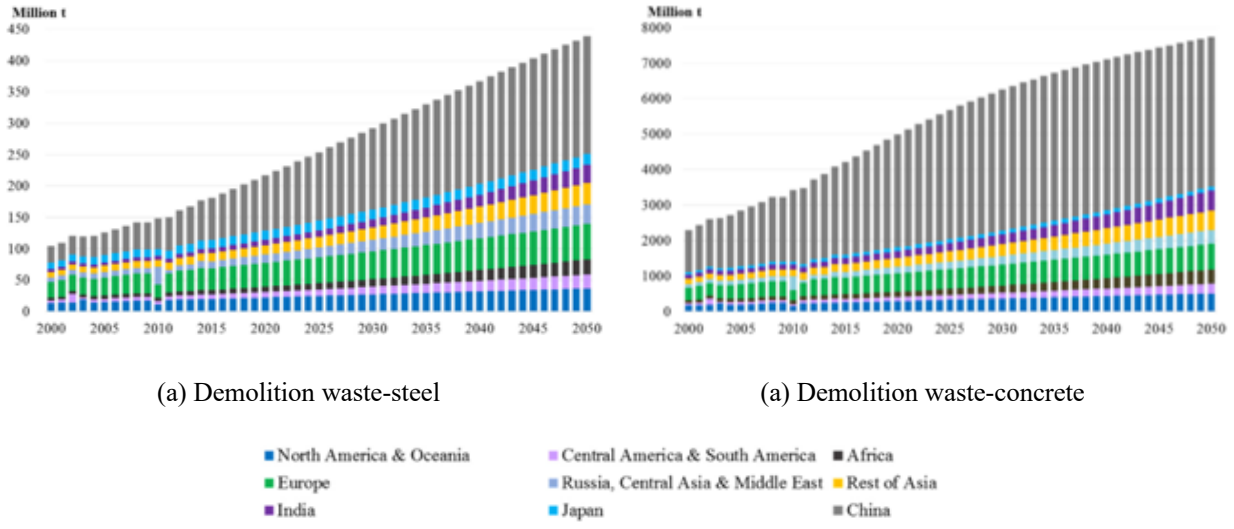
Introduction

The transition to a sustainable construction paradigm begins with a fundamental re-evaluation of the materials used to create the built environment. This chapter lays the groundwork by exploring the core principles of "eco-materials," which encompass a broad range of resources chosen for their reduced environmental impact. The focus is twofold: first, to establish the concept of material valorization, where waste is transformed into a resource; and second, to examine specific categories of materials that embody this principle, including natural, activated, and waste-derived resources. By understanding the properties and potential of these foundational materials, it becomes possible to design and engineer more sustainable and resilient structures.

1.1. Material Valorization: Principles and Applications

1.1.1. The Circular Economy and Waste Hierarchy in Construction

The traditional model of the construction industry has long been linear, following a “take-make-dispose” pattern where raw materials are extracted, manufactured into products, used, and then discarded as waste at the end of their service life. This linear approach is inherently unsustainable, leading to resource depletion and the generation of massive quantities of construction and demolition waste **(Figure 1)**.



(a) Demolition waste-steel (a) Demolition waste-concrete

Figure 1. *Global steel and concrete demolition waste estimation, 2000-2050.*

Source: *(Huang et al., 2020)*

The circular economy presents a transformative alternative to this model. It's an economic system designed to eliminate waste and pollution, circulate products and materials at their highest value, and regenerate natural systems. Materials are viewed, in this case, as valuable assets to be kept in use for as long as possible through processes like maintenance, reuse, repair, refurbishment, remanufacturing, and recycling **(Table 1)**, **(Figure 2)**.

Table 1. *Disposal potential of construction waste.*

Source: *(Yeheyis et al., 2013)*

Construction and demolition waste	Recycle/reuse potential	Biodegradable potential	Potential for landfilling	Potential for incineration
Concrete	Recycled aggregate for road base, and for concrete	No	Yes	No
Steel	Recyclable to steel	No	No	No
Brick and block	Backfill, recycled aggregate	No	Yes	No
Insulation	Insulate attic or as sound proofing on interior walls	No	No	Yes
Glass	Finer glass as pozzolans in cement	No	Yes	No
Ceramic	Possibly recyclable as filling material as a coarse aggregate for concrete	No	Yes	No
Aluminium	Recyclable to aluminium	No	No	No
Plastic	Recyclable to any form	Some are biodegradable	No	Yes
Paint	Reusable as paint/concrete admixture	Some are biodegradable	No	Yes
Wood	Recyclable to veneer board/paper pulp	Yes	Yes	Yes
Gypsum board	Recyclable to new board, crushed wall as clay and silt mixture and can be composed	Yes	No	No
Cardboard	Composting, fire kindling, paper production	Yes	Yes	Yes
Asbestos	No	No	If sealed properly	No

Central to the implementation of a circular economy is the concept of the waste hierarchy. This framework prioritizes waste management strategies in order of environmental preference, guiding decision-making to achieve the best possible environmental outcome. The hierarchy, as defined in frameworks like the European Union's Waste Framework Directive, typically follows this order of preference: (1) Prevention, (2) Minimization/Reuse, (3) Recycling/Valorization, (4) Energy Recovery, and (5) Disposal (e.g., landfilling) as the least desirable option.

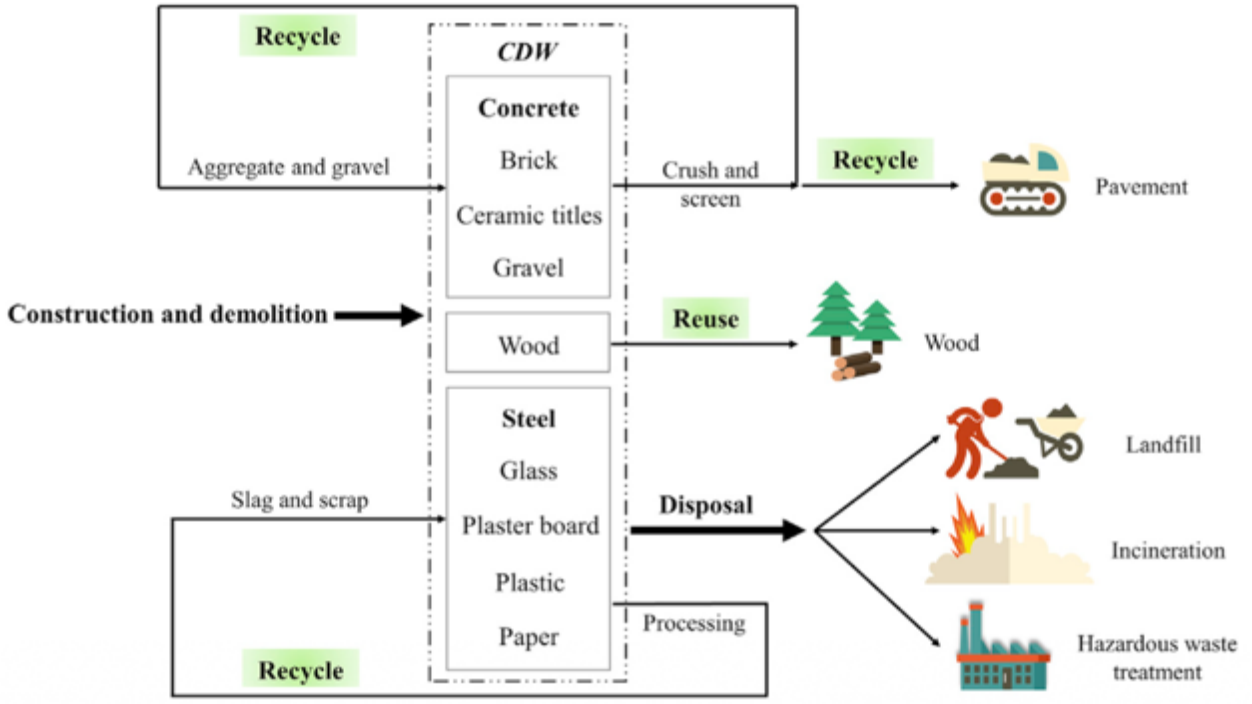


Figure 2. *Construction and demolition waste treatment and recycling.*

Source: *(Huang et al., 2020)*

Valorization is a key strategy situated high in this hierarchy. It is defined as a practice that adds economic value to waste while reducing the volume that ends up in landfills. This concept is crucial for the construction sector, as it reframes waste not as a problem to be disposed of, but as a resource with potential. To effectively implement a circular economy in construction, buildings must be designed with their entire lifecycle in mind. This involves designing for longevity, adaptability, and, critically, for disassembly, ensuring that components can be easily separated and recovered for reuse or high-value recycling at the end of the building's life.

1.1.2. Socio-Economic and Environmental Drivers for Valorization

The imperative to adopt valorization and circular economy principles is driven by the profound negative impacts of construction waste. The construction industry is one of the largest waste generators globally, accounting for an estimated 10-30% of all waste disposed of in landfills. These impacts can be categorized into environmental, economic, and social domains.

- **Environmental Impacts:** The most direct environmental impact is pollution. Waste generated on construction sites can release chemicals and other materials that contaminate

soil and water. Furthermore, the linear model drives the excessive consumption of raw materials, leading to the depletion of non-renewable natural resources and the degradation of ecosystems **(Figure 3)**.

- **Economic Impacts:** Construction waste has significant financial consequences. Project cost overrun is ranked as the most severe economic impact, as waste represents not only the loss of the initial material purchase cost but also incurs additional costs for collection, transportation, and disposal. This directly leads to a reduction in profit and can contribute to the financial failure of construction firms. The time required to manage waste, including cleaning, removing, and reworking, also causes project delays and time overruns.
- **Social Impacts:** The social consequences of construction waste include public health and safety risks from improperly managed waste sites, traffic congestion from disposal activities, and diseases associated with air pollutants released from waste.

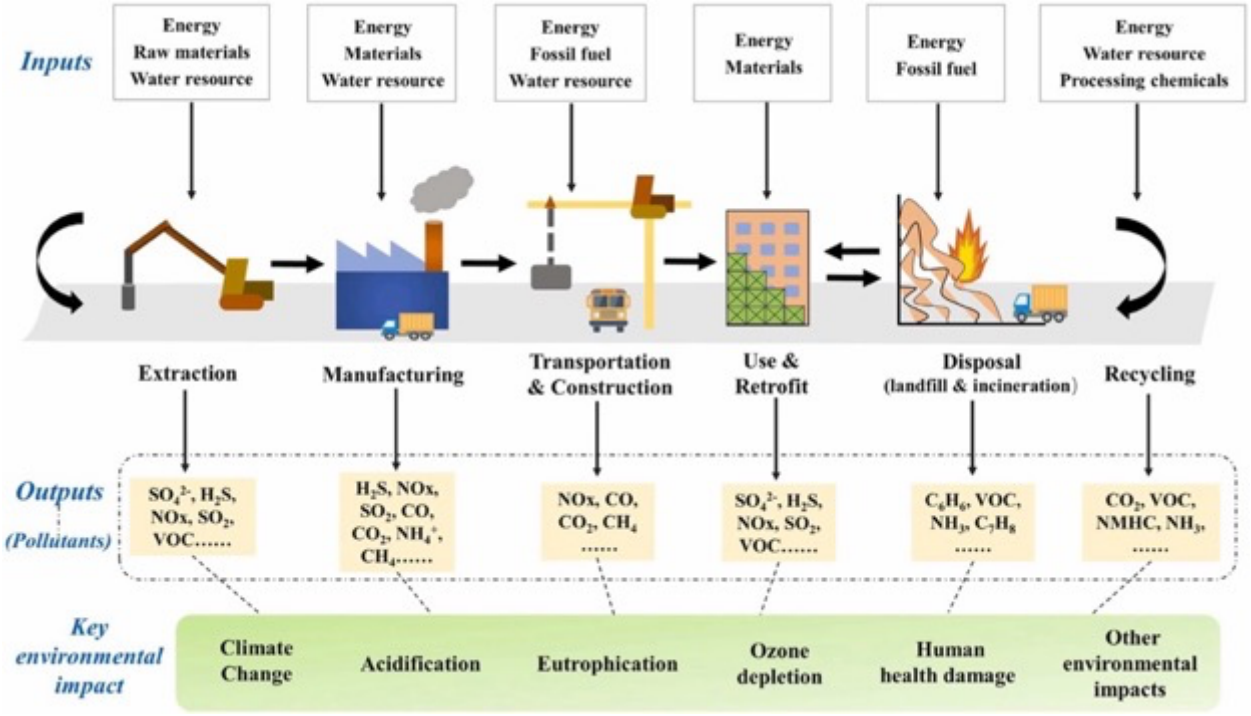


Figure 3. *Key environmental impacts during the life cycle of construction materials.*

Source: *(Barbhuiya & Das, 2023)*

In response to these drivers, a range of management strategies has been developed to mitigate waste. These include procedural changes, such as employing dedicated waste management officers and implementing strong on-site management practices, as well as technological solutions like the use of prefabricated components to reduce on-site waste generation. However, the most impactful strategies are those that directly address the material flows: the reuse and recycling of materials left over on-site, which are fundamental forms of valorization.

1.1.3. Principles of Valorization and Life Cycle Assessment

Valorization represents a strategic evolution from simple recycling **(Figure 4)**. While recycling can sometimes involve downcycling, where a material is reprocessed into a product of lower quality or value (e.g., crushing high-strength concrete into low-grade road base), valorization aims to convert waste materials and industrial by-products into new products of equal or higher value and functionality. This process is not merely about waste diversion, it is about value creation. It implies a more sophisticated, technology-driven approach that leverages materials science to unlock new potential in what was previously considered waste **(Figure 5)**.

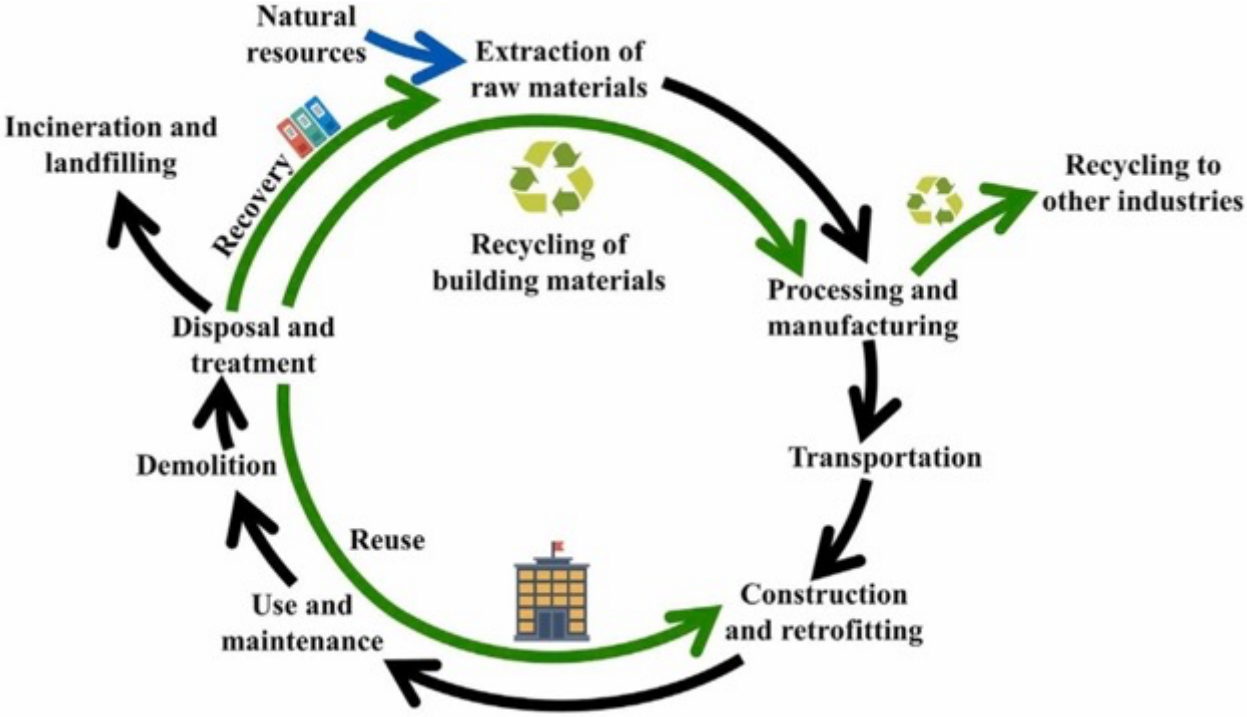


Figure 4. *Construction materials life cycle.*

Source: (Barbhuiya & Das, 2023; Huang et al., 2020)

Examples include the chemical transformation of plastic waste into high-value carbon nanostructures or the thermal activation of water treatment sludge to create a functional supplementary cementitious material. This strategic shift from volume reduction to value creation is fundamental to achieving a truly circular economy in construction, requiring investment in advanced processing technologies beyond simple mechanical reprocessing.

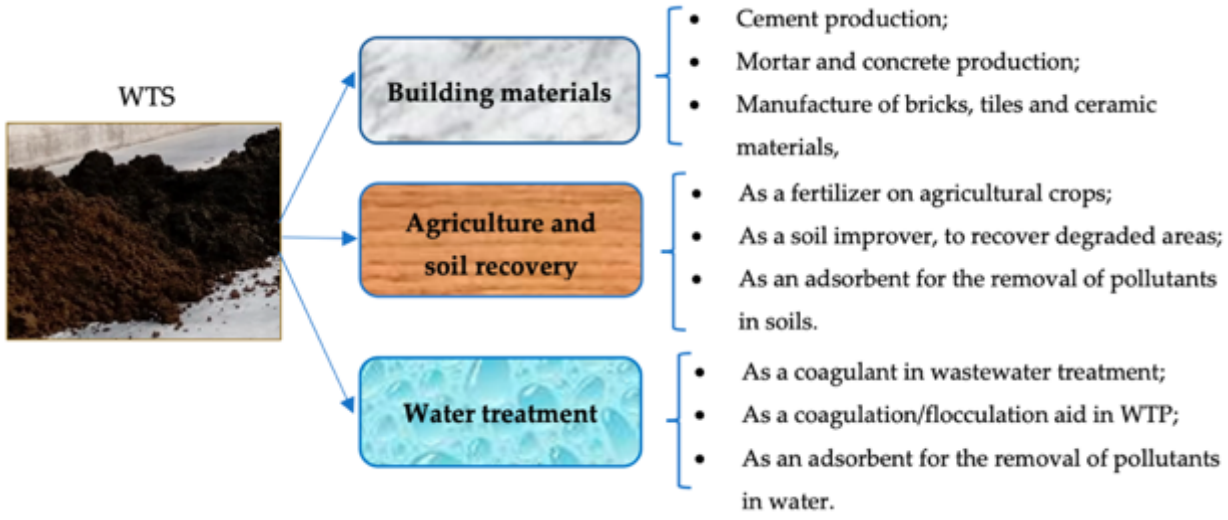


Figure 5. *Emerging applications for water treatment sludge (WTS).*

Source: *(Mattoso et al., 2024)*

To quantify the environmental benefits of such strategies, life cycle assessment is an indispensable tool. It's a systematic, methodological framework used to evaluate the potential environmental impacts of a product, process, or service throughout its entire life cycle, from "cradle to grave" (raw material extraction, manufacturing, use, and disposal) or "cradle to cradle" (incorporating recycling and reuse). The methodology is standardized under ISO 14040 and ISO 14044, which divide the life cycle assessment into four distinct phases :

1. **Goal and scope definition:** This phase establishes the purpose of the study, the system boundaries (i.e., which life cycle stages are included), the functional unit for comparison (e.g., one cubic meter of concrete with a specific strength), and key assumptions.
2. **Life cycle inventory analysis:** This involves the collection of data on all inputs (raw materials, energy, water) and outputs (emissions to air, water, and soil; waste generation) associated with the product system throughout its life cycle.

3. **Life cycle impact assessment:** The life cycle inventory data is translated into potential environmental impacts. This phase classifies emissions and resource use into impact categories (e.g., global warming potential, acidification, eutrophication, fossil fuel depletion) and characterizes their potential effects.
4. **Interpretation:** The results from the life cycle inventory and life cycle impact assessment phases are analyzed to draw conclusions, identify significant issues, and make recommendations in line with the study's goal.

By applying life cycle assessment, it is possible to compare the environmental performance of a building material made from valorized waste against a conventional material performing the same function. This allows for evidence-based decision-making and demonstrates the tangible benefits of circular economy principles, such as reductions in CO_2 emissions, energy consumption, and natural resource usage **(Figure 6)**.

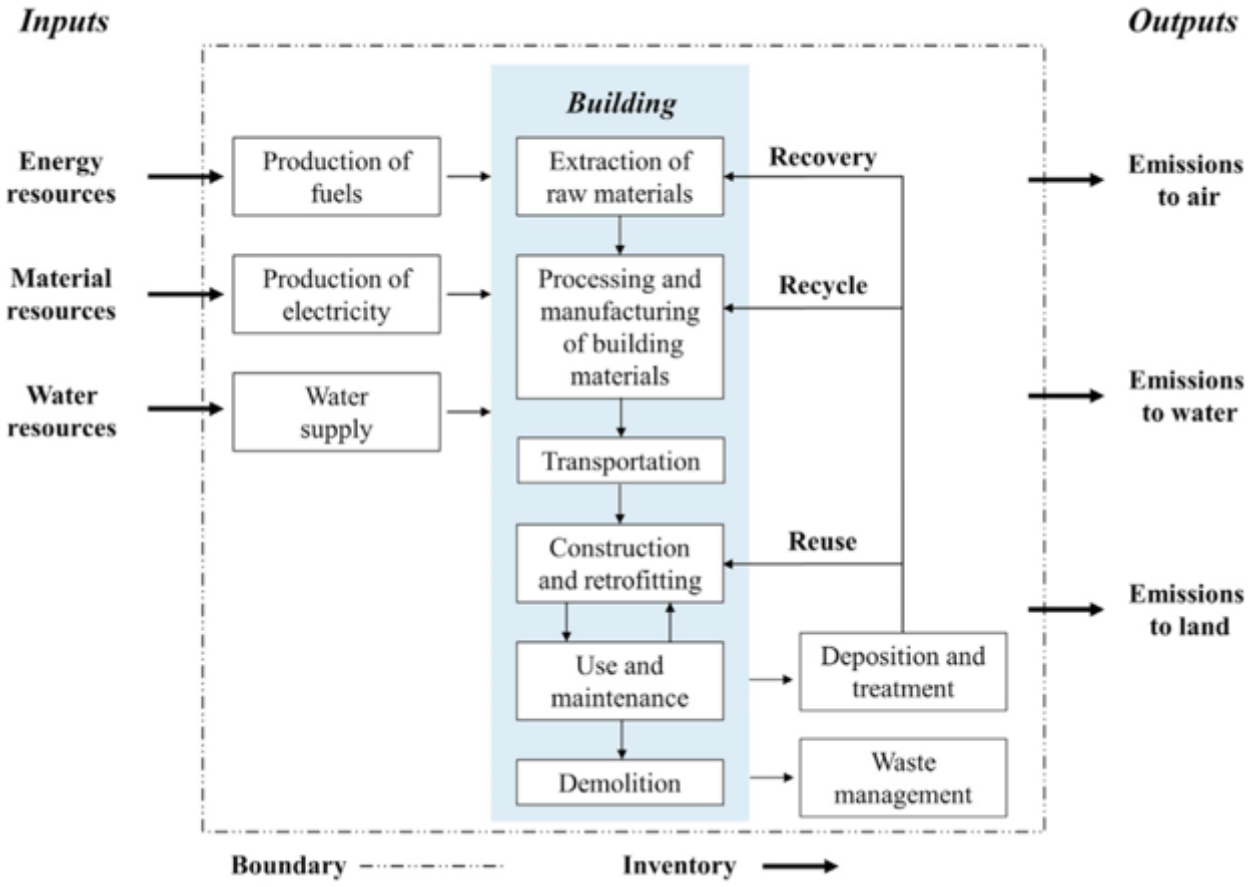


Figure 6. *Life cycle assessment application framework for building Materials.*

Source: *(Barbhuiya & Das, 2023)*

1.2. Natural Materials

1.2.1. Stone: Properties and Modern Applications

Natural stone is one of humanity's oldest building materials, valued for its inherent strength, exceptional durability, and timeless aesthetic appeal **(Figure 7)**. Formed over millions of years through geological processes, stone requires virtually no manufacturing, possesses a long service life, and can be salvaged and reused, making it an intrinsically sustainable material.



Figure 7. *Limestone quarries.*

Source: *(Ehrlich, 2013)*

Physical and Mechanical Properties

The suitability of a particular stone for a construction application depends on its specific physical and mechanical properties, which are determined by its mineralogical composition and internal fabric. Key properties include:

- **Compressive strength:** The ability to resist crushing loads. This is a critical property for structural applications like foundations, columns, and load-bearing walls. Values vary

significantly among stone types, with dense igneous rocks like granite and basalt typically exhibiting very high compressive strength.

- **Density and specific gravity:** These are indicators of a stone's compactness. Heavier stones are generally less porous and more durable.
- **Porosity and water absorption:** The volume of pore space within a stone affects its susceptibility to water ingress. Low porosity and absorption are desirable, as water penetration can lead to damage from freeze-thaw cycles and chemical attack **(Figure 8)**.
- **Flexural strength:** The ability to resist bending forces, which is important for applications like cladding panels, lintels, and flooring tiles.
- **Hardness and abrasion resistance:** These properties determine a stone's resistance to scratching and wear, crucial for flooring, paving, and countertops.

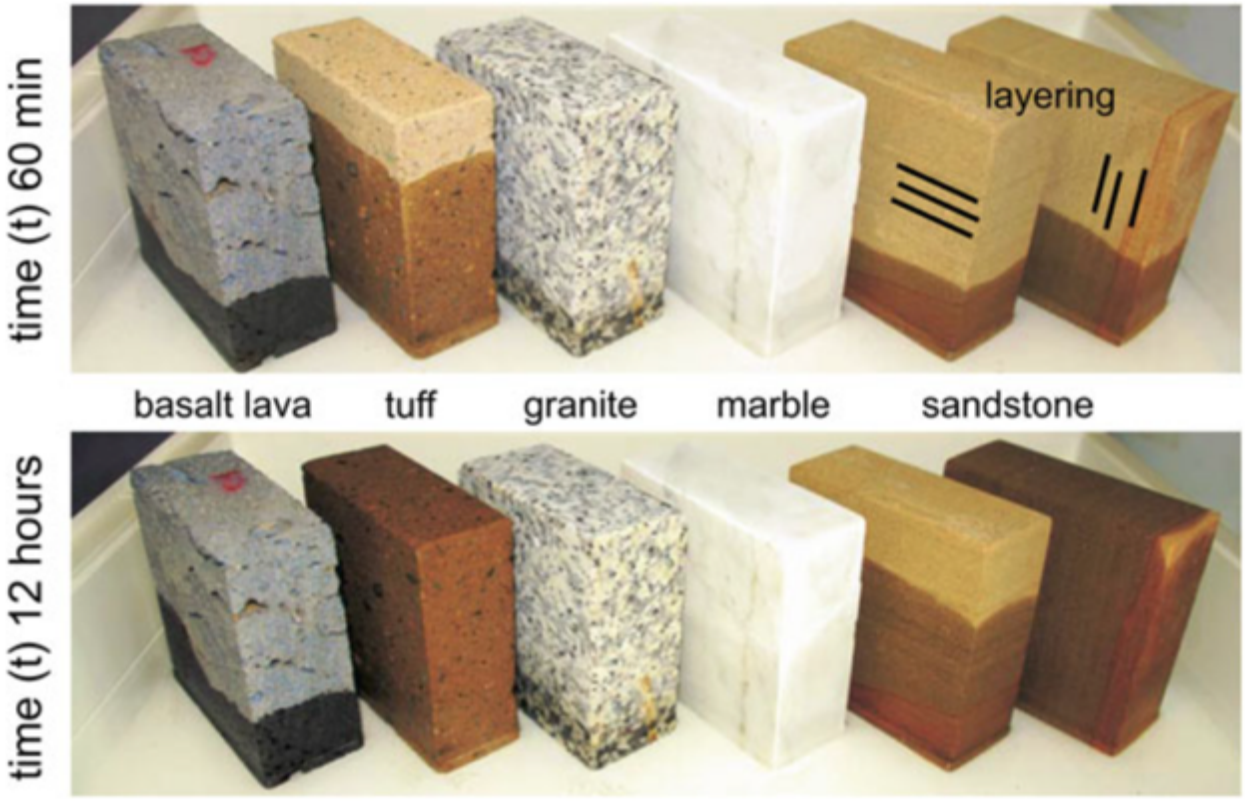


Figure 8. *Capillary water absorption of different stones.*

Source: *(Siegesmund & Snethlage, 2014)*

Table 2 provides a comparative overview of the typical properties for several common building stones from various academic and industry sources. It is important to note that these values can vary significantly based on the specific quarry and geological formation.

Table 2. *Physical and Mechanical Properties of Common Building Stones.*

Source: *(Klemm & Wiggins, 2016)*

Characteristic	Sandstone	Limestone	Granite	Slate
Density (bulk specific gravity) (Mg/m3)	2.00-2.35	1.95-2.55	2.60-2.65	2.7-3.10
Water absorption (%)	3.0-20.0	3-15	0.10-0.40	0.05-0.40
Porosity (%)	10.0-35.0	5-30	0.20-1.00	0.15-1.00
Compressive strength (dry) (MPa)	25-100	30-60/25-55[a]	175-350	225-400[b]
Compressive strength (wet) (MPa)	15-90	20-50/20-45[a]	150-300	200-350[b]
Flexural strength (dry) (MPa)	3-10	3-12/2-10[a]	10-30	50-90
Flexural strength (wet)	2-8	2-10/1-8[a]	8-25	50-90

[a] *Normal/parallel, relative to loading direction.*
[b] *Small data pool, representivity not certain.*

Modern Architectural Applications

While stone continues to be used for traditional structural purposes like foundations and walls, modern architecture leverages its properties in advanced and aesthetically driven applications. These include:

- **Interior and exterior finishes:** Polished granite and marble are widely used for high-end interior surfaces such as countertops, flooring, and wall panels, prized for their beauty and durability **(Figures 9-12)**. Limestone and sandstone offer warmer tones and are used for both interior and exterior cladding **(Figure 13)**.

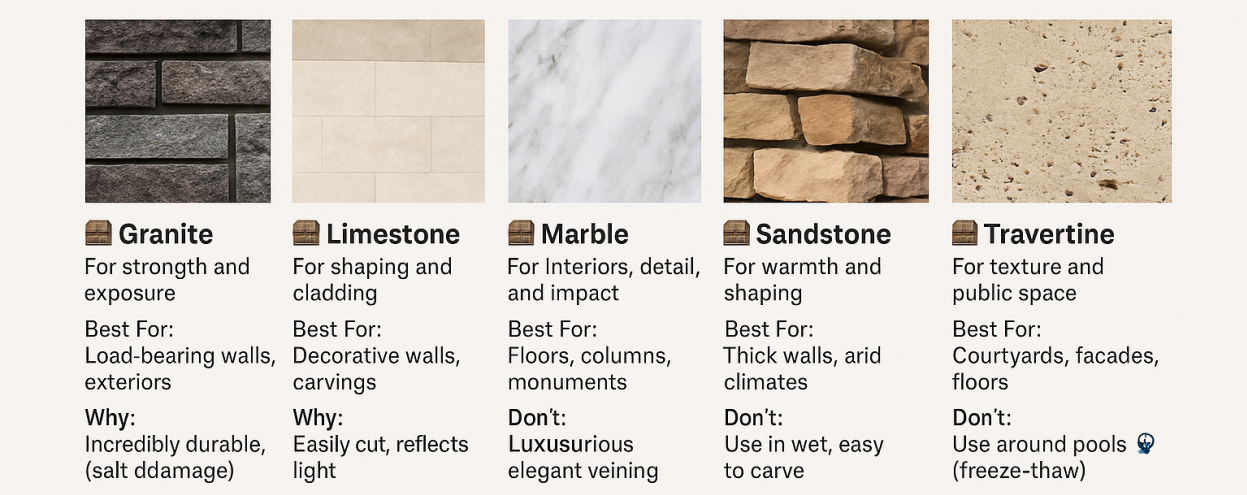


Figure 9. *Types of stone used in construction.*

Source: (*Stone in Architecture: Modern Uses and Importance*, 2025)



Figure 10. *The Dome of the Rock in Al-Quds, Palestine (Stone).*

Source: (*Stone in Architecture: Modern Uses and Importance*, 2025)



Figure 11. *Rashtrapati Bhavan in Delhi, India (Granite).*

Source: (*Stone in Architecture: Modern Uses and Importance*, 2025)



Figure 12. *The Great Mosque of Córdoba (Marble).*

Source: (*Stone in Architecture: Modern Uses and Importance*, 2025)



Figure 13. *Al-Azhar Mosque, Cairo (Limestone).*

Source: (*Stone in Architecture: Modern Uses and Importance*, 2025)

- **Ventilated facades and curtain walls:** A significant modern application is in high performance facade systems. A ventilated facade (or rainscreen) consists of an outer layer of stone panels mechanically fixed to a building's structural wall, with an air cavity in between. This system offers numerous benefits, including improved thermal insulation, moisture management (the “chimney effect” in the cavity helps remove moisture), and protection of the primary structure **(Figure 14)**. Studies indicate that ventilated facades can lead to energy savings of 25% to 40%. Stone curtain walls are non-structural exterior cladding systems where thin stone panels are integrated into a frame (typically aluminum) that is hung from the building's structure. These systems allow for the aesthetic of a stone building without the immense weight and structural requirements of traditional masonry.

Sustainability and Life Cycle

Natural stone possesses strong sustainability credentials. Its production requires minimal processing (primarily cutting and finishing) resulting in lower embodied energy compared to manufactured materials like concrete or steel. A life cycle assessment comparing various cladding materials found that granite had the least detrimental environmental profile, outperforming precast concrete and aluminum.

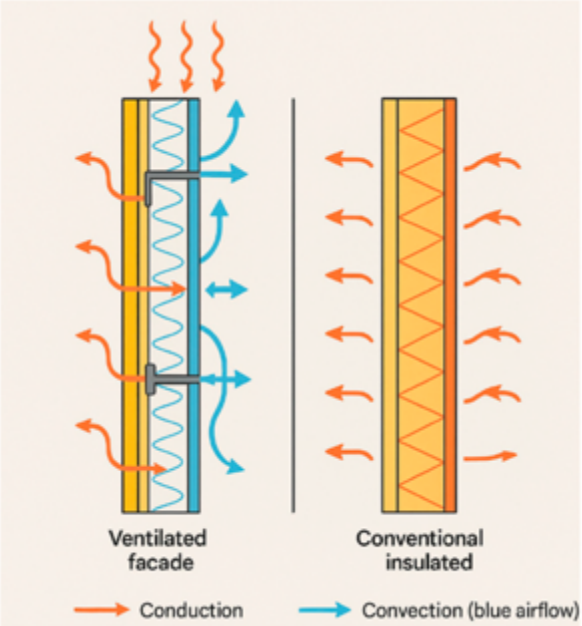


Figure 14. *Heat transfer in ventilated (left) vs. conventional (right) facades.*

Source: *(Cuce & Cuce, 2025)*

The durability of stone ensures an exceptionally long service life, reducing the need for replacement and associated resource consumption. At the end of a building's life, stone is fully recyclable. It can be salvaged and reused in new constructions, a practice known as reclamation, which is a key strategy in a circular economy **(Figure 15)**. Reclaimed stone can be recut for new applications, used as paving, or crushed for use as aggregate, thus diverting it entirely from the waste stream.



Figure 15. *The Parliament Building of Budapest constructed from soft, porous limestone (gray) and a successive restoration where this limestone is replaced by travertine (white).*

Source: *(Siegesmund & Snethlage, 2014)*

1.2.2. Earth-Based Materials: Stabilized Compressed Earth Bricks (CEBs) and Raw Earth Construction

Earth is, alongside stone and wood, one of the most ancient construction materials, with an estimated 30% of the world's population still living in earth-based homes **(Figure 16)**. In the context of modern sustainable construction, there is a renewed interest in both traditional raw earth techniques and their technologically enhanced derivatives. The minimal carbon footprint of earthen materials highlights their sustainability **(Figure 17)**.



Figure 16. *Earth construction distribution map.*

Source: *(Zhang et al., 2024)*

Raw Earth Construction Techniques

Traditional raw earth construction utilizes local soil with a sufficient clay content to act as a binder. Classification of earth construction are usaly based on the distinction between wet and dry compaction methods **(Figure 18)**.

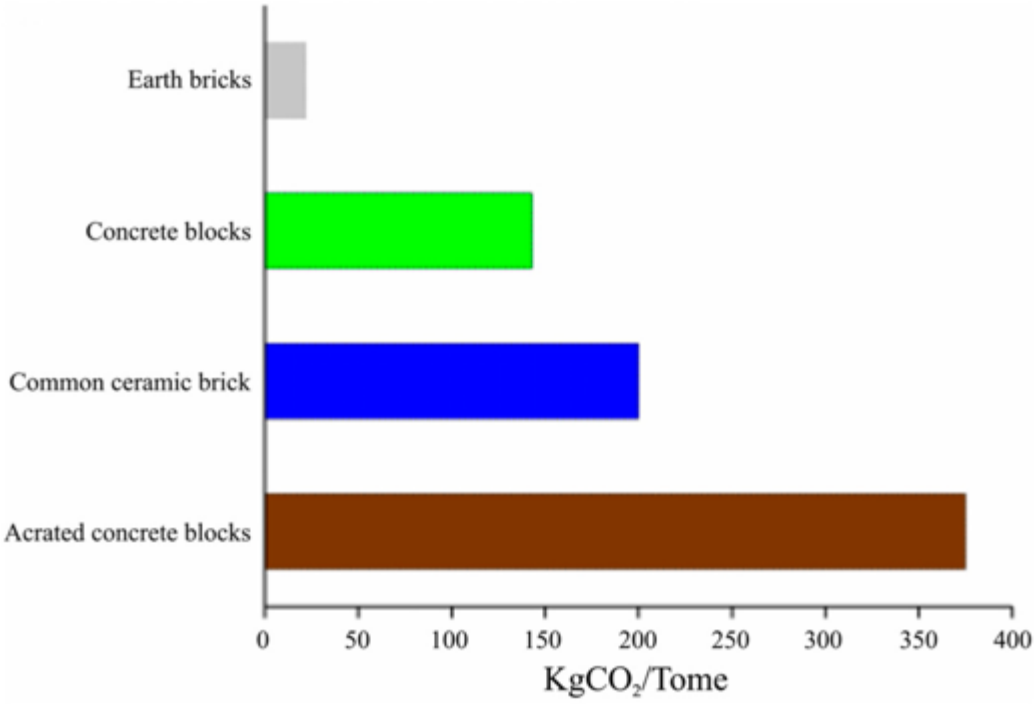


Figure 17. *Carbon emissions of different masonry materials.*

Source: *(Zhang et al., 2024)*

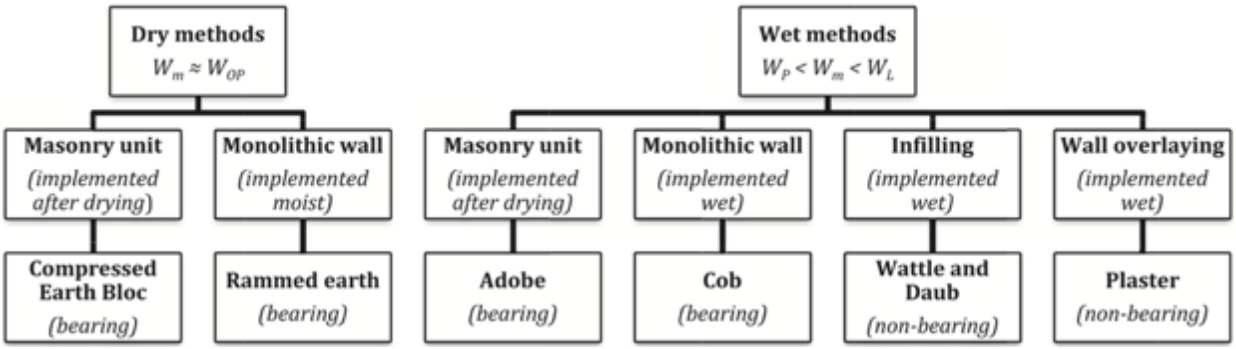


Figure 18. *Earth construction processes classification (W_m = manufacture water content, W_{OP} = optimum Proctor water content; W_P = water content at plastic limit; W_L = water content at liquid limit).*

Source: *(Hamard et al., 2016)*

The primary earth construction techniques include:

- **Adobe:** Mud is mixed with water and often a fibrous material like straw, placed into molds, and then sun-dried to form bricks. These bricks are then laid with a mud mortar to construct walls **(Figure 19)**.

- **Cob:** A monolithic technique where lumps of a plastic mixture of earth, water, and long-straw fibers are stacked and sculpted by hand to form walls without the use of formwork **(Figure 20)**.
- **Rammed Earth:** A damp, low-plasticity earth mixture is compacted in layers between temporary, removable formwork. The process creates dense, strong, monolithic walls with a characteristic stratified appearance **(Figure 21-22)**.



Figure 19. *Adobes from southern France.*

Source: *(Fabbri et al., 2022)*



Figure 20. *Cob technique.*

Source: *(Fabbri et al., 2022)*

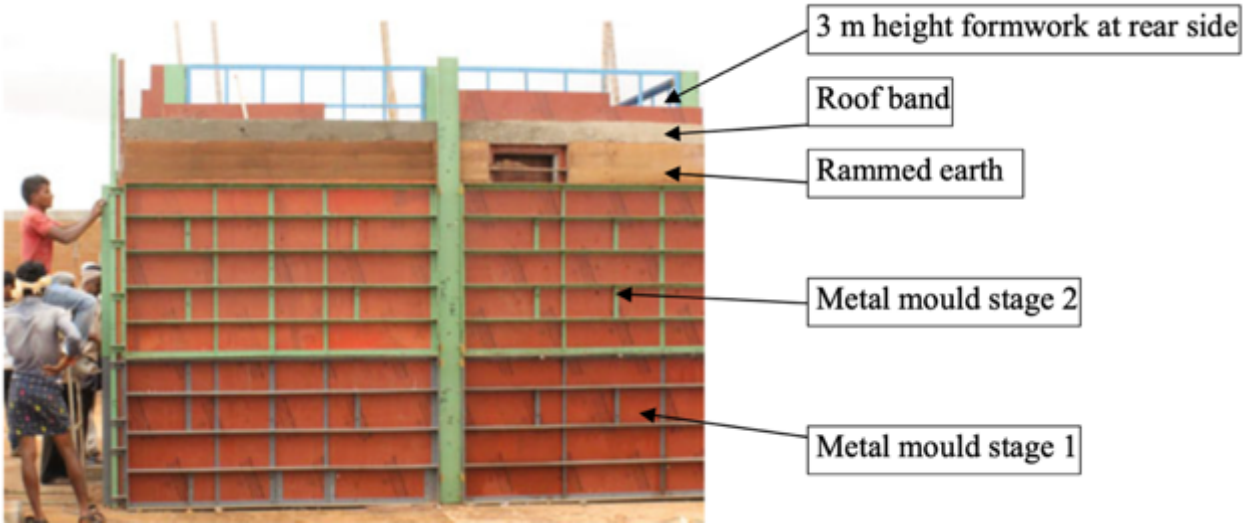


Figure 21. *Metal formwork for rammed earth wall construction.*

Source: *(Reddy, 2022)*



Figure 22. *Rammed earth wall.*

Source: *(Reddy, 2022)*

While these techniques are low-cost and have very low embodied energy, raw earth has inherent weaknesses, including low mechanical strength, poor durability, and high susceptibility to water erosion and damage, which have limited its widespread modern adoption.

Stabilized Compressed Earth Bricks

Compressed Earth Bricks (CEBs), also known as Compressed Stabilized Earth Bricks (CSEBs), represent a modern evolution of traditional earth blocks that addresses many of their shortcomings. CEBs are manufactured by compacting a soil mixture under high pressure (typically with a manual or hydraulic press), which results in a denser, stronger, and more uniform block than traditional adobe **(Figures 23 and 24)**.



Figure 23. *Manual CEB production system.*

Source: *(Zhang et al., 2024)*

To further enhance their performance, particularly their strength and water resistance, a stabilizing agent is typically added to the soil mixture. The most common stabilizers are:

- **Cement:** Portland cement is a highly effective stabilizer. Through hydration, it forms a cementitious matrix that binds the soil particles together, significantly increasing compressive strength and durability while reducing water absorption. An optimal cement content is often found to be in the range of 5% to 10% by weight; amounts above this can

sometimes have diminishing or even negative effects on strength while increasing cost and embodied energy.

- **Lime:** Lime works through a two-stage pozzolanic reaction with the clay minerals in the soil, forming calcium silicate and aluminate hydrates. This process is slower than cement hydration but results in a durable and more vapor-permeable material.



Figure 24. *CEB making process in a mechanised machine.*

Source: *(Zhang et al., 2024)*

Properties and Performance of Compressed Earth Bricks (CEBs)

The combination of high-pressure compaction and stabilization gives CEBs a set of properties that make them a viable sustainable alternative to conventional masonry units like fired bricks or concrete blocks :

- **Mechanical Properties:** Stabilized CEBs can achieve significant compressive strengths, often exceeding the requirements for load-bearing masonry in low-rise construction. While unstabilized blocks may have strengths around 2-3 MPa, cement-stabilized blocks can

readily achieve strengths in the range of 5-12 MPa, and in some cases, up to 24 MPa, which is comparable to some conventional materials.

- **Durability:** Stabilization dramatically improves the durability of earth blocks, particularly their resistance to water erosion and weathering, increasing the lifespan of the structure.
- **Thermal Performance:** Like other earth constructions, CEBs possess excellent thermal mass, helping to regulate indoor temperatures and reduce energy consumption for heating and cooling. Their thermal insulation properties are superior to those of dense concrete or fired brick.
- **Sustainability:** CEBs have a very low embodied energy compared to fired bricks or concrete blocks, as they are typically cured at ambient temperature rather than fired in a kiln. The use of local soil also minimizes transportation-related emissions and costs. The production of a CEB emits only around 22 kg CO_2/tonne, compared to 200 kg CO_2/tonne for fired clay bricks.

1.2.3. Natural Pozzolans: Volcanic Ash and Other Naturally Occurring Cementitious Materials

Natural pozzolans are materials found in nature that, while not necessarily cementitious on their own, contain reactive silica and/or alumina that can react with calcium hydroxide (CH) (a by-product of Portland cement hydration) in the presence of water to form additional calcium silicate hydrate (C-S-H) gel **(Figure 25)**. This is the same compound that gives concrete its strength, so this “pozzolanic reaction” effectively densifies the concrete matrix, enhancing its long-term properties. These materials are classified by ASTM C618 as Class N pozzolans.

Natural pozzolans can be broadly categorized into two groups :

- **Materials of volcanic origin:** These include volcanic ashes, pumicites, tuffs, and shales. They are often reactive in their natural state and only require grinding to a sufficient fineness to be used as a supplementary cementitious material.
- **Clays and other soils:** Materials like kaolinite clay require a thermal activation process (calcination) to break down their crystalline structure and render them amorphous and reactive.



Figure 25. *Natural Pozzolan.*

Source: *(Boukachabia et al., 2025)*

Volcanic Ash as a Supplementary Cementitious Material

Volcanic ash, a product of explosive volcanic eruptions, is an abundant and often low-cost natural pozzolan that has been used in construction since Roman times **(Figure 26)**.

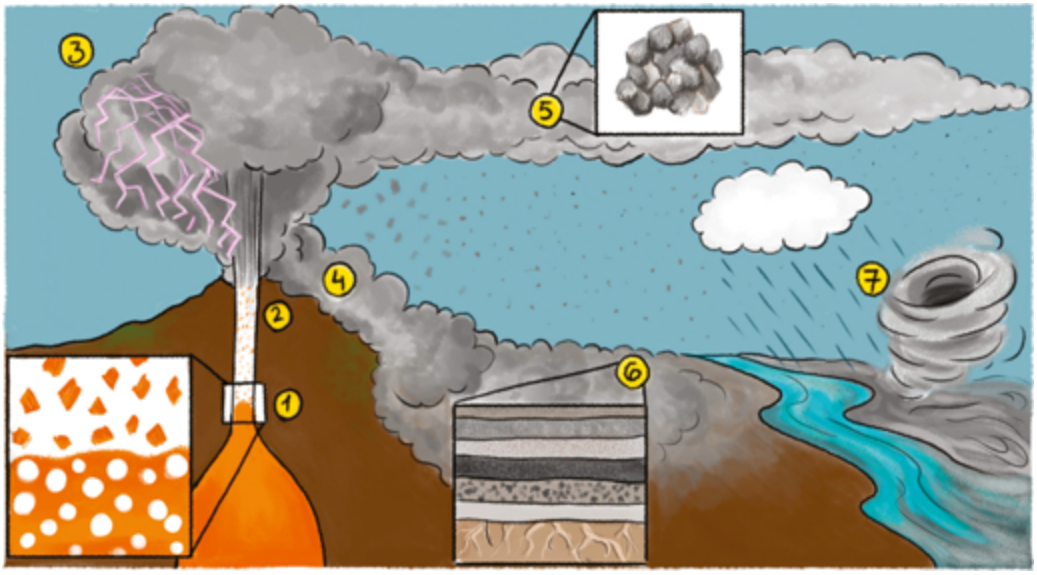


Figure 26. *Volcanic ash lifecycle: (1) magma fragmentation, (2) secondary ash generation within volcanic conduit, (3) volcanic lightning in the eruptive column, (4) volcanic ash transport by pyroclastic density current, (5) ash aggregation in the volcanic plume (umbrella section), (6) ash deposition blanketing the landscape and (7) ash remobilization by wind and water.*

Source: (Paredes-Mariño et al., 2022)

It is rich in amorphous (glassy) aluminosilicates, making it highly suitable for use as an supplementary cementitious material to partially replace Portland cement **(Figure 27)**.

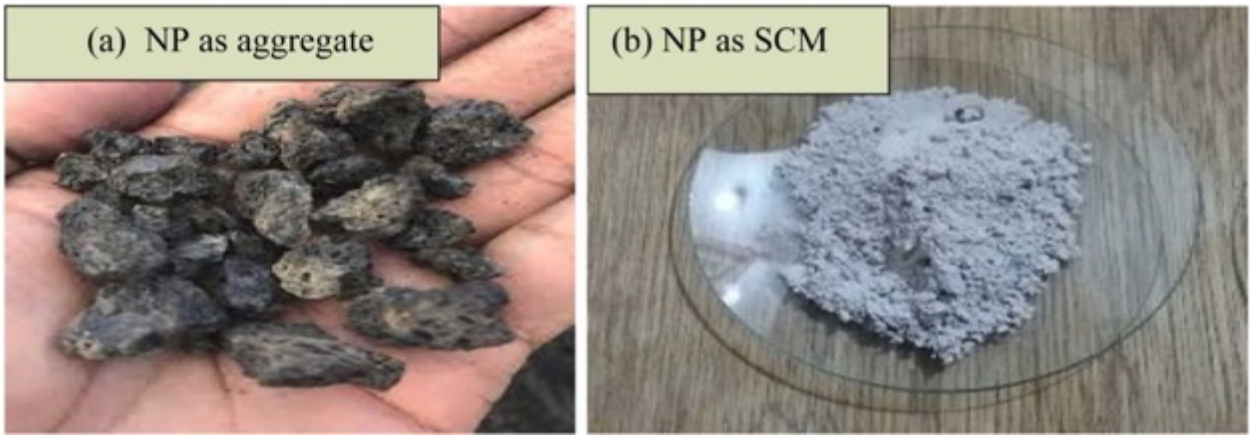


Figure 27. *Particles of Natural Pozzolan (NP) (a) as aggregate and (b) as Supplementary Cementitious Material (SCM).*

Source: *(Hamada et al., 2023)*

The use of Volcanic ash in concrete offers several performance and sustainability benefits:

- **Sustainability:** Replacing a portion of cement clinker with Volcanic ash directly reduces the CO_2 emissions associated with cement production, contributing to the development of low-carbon concrete.
- **Effect on Fresh Concrete:** The fine, often glassy particles of Volcanic ash can improve the workability and cohesiveness of fresh concrete, reducing bleeding.
- **Effect on Hardened Concrete:**

- **Strength:** The pozzolanic reaction of Volcanic ash is slower than cement hydration, which typically results in lower early-age strength. However, as the reaction progresses, it contributes to significant strength gain at later ages (28 days and beyond).
- **Durability:** The formation of additional calcium silicate hydrate (C-S-H) gel from the pozzolanic reaction refines the pore structure of the concrete, making it denser and less permeable. This leads to substantial improvements in durability, including enhanced resistance to chloride ion penetration (improving corrosion resistance of steel reinforcement) and mitigation of the harmful alkali-silica reaction.

- **Challenges and Enhancements:** The reactivity of Volcanic ash can vary significantly depending on its geological source and mineralogy. Some ashes may require activation to enhance their performance. Mechanical activation through fine grinding has been shown to significantly increase the pozzolanic reactivity of Volcanic ash, allowing it to meet the performance standards required for cementitious additives. However, the use of natural pozzolans can sometimes increase autogenous and drying shrinkage, a challenge that may require mitigation strategies like internal curing.

1.3. Activated Materials

While some natural materials are pozzolanic in their raw state, others require an activation process (typically thermal) to unlock their cementitious potential. This process transforms stable, crystalline minerals into reactive, amorphous phases, creating highly effective supplementary cementitious materials. The energy invested in this activation must be carefully balanced against the environmental savings from replacing cement, a trade-off that is often evaluated using life cycle assessment. The performance of these materials is critically dependent on the precise control of the activation process. For instance, the temperature and duration of calcination directly determine the degree of amorphization, which in turn dictates the pozzolanic reactivity that drives strength and durability improvements in concrete.

1.3.1. Calcined Clays: Focus on Metakaolin

Clays are abundant globally, but most are not pozzolanic in their natural state. However, certain clays, particularly those rich in the mineral kaolinite, can be transformed into a highly reactive pozzolan through thermal activation.

Production and Activation of Metakaolin

Metakaolin is a dehydroxylated aluminosilicate produced by heating high-purity kaolinite clay within a controlled temperature range, typically 650°C to 800°C **(Figure 28)**. This process, known as calcination, drives off the chemically bound water from the kaolinite's crystalline structure, causing it to collapse into a highly disordered, amorphous, and highly reactive state. If the temperature is too low, the dehydroxylation is incomplete, whereas, if it is too high (above ~900°C), the material recrystallizes into non-reactive phases like mullite, destroying its pozzolanic

potential. The resulting Metakaolin is then ground to an ultrafine powder, typically with a particle size smaller than cement (< 2 μm), which further enhances its reactivity.



Figure 28. *Kaolin clay (Left) and metakaolin (Right).*

Source: *(Al-Hashem et al., 2022)*

Properties and Performance in Concrete

Metakaolin is considered a high-reactivity pozzolan, with performance characteristics often comparable to or exceeding those of other supplementary cementitious materials like silica fume **(Table 3)**.

Metakaolin primary effects on concrete include:

- **Pozzolanic Reactivity:** Metakaolin reacts rapidly with calcium hydroxide produced during cement hydration. This consumption of calcium hydroxide and the formation of additional calcium silicate hydrates and calcium aluminosilicate hydrates significantly refines the microstructure of the cement paste.
- **Effect on Fresh Concrete:** Due to its high fineness, Metakaolin can increase the water demand of a concrete mix, potentially reducing workability. This is typically managed with the use of high-range water-reducing admixtures (superplasticizers).

Table 3. Chemical composition of Metakaolin compared to Ordinary Portland Cement.

Source: (Al-Hashem et al., 2022)

Chemical composition	% by Mass	
	Metakaolin	Ordinary Portland Cement
Al_2O_3	38.9	21.5
SiO_2	43.4	6.00
Fe_2O_3	2.67	3.75
CaO	2.74	62.0
MgO	0.20	2.80
SO_3	0.28	2.75
Na_2O	0.30	1.00
TiO_2	0.79	0.20
Mn_2O_3	0.027	0.64

- **Effect on Hardened Concrete:**

- **Strength:** The rapid pozzolanic reaction contributes to high early-age strength development, and its filler effect and continued reaction lead to significant increases in later-age compressive and flexural strength **(Figure 29)**. Optimal cement replacement levels are often found to be between 10% and 15%.
- **Durability:** The refinement of the pore structure and reduction in pore connectivity makes the concrete significantly less permeable. This leads to a dramatic improvement in durability, including enhanced resistance to chloride ion penetration, sulfate attack, and alkali-silica reaction. The improved density also enhances the bond strength between the paste and aggregates.

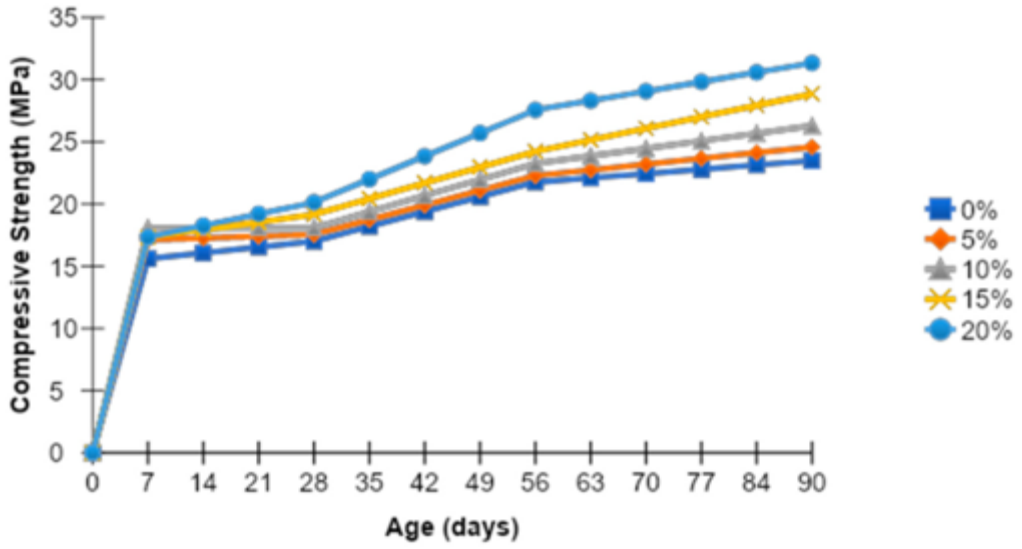


Figure 29. *Compressive strength of conrete for different Metakaolin percentages.*

Source: *(Al-Hashem et al., 2022)*

1.3.2. Rice Husk Ash: Production, Properties, and Use

Rice husk ash is a by-product of the agricultural industry, derived from the combustion of rice husks, the outer shells of rice grains **(Figure 30)**. It represents a valuable resource derived from a waste material, with global production of rice husks estimated in the millions of tons annually **(Figure 31)**.

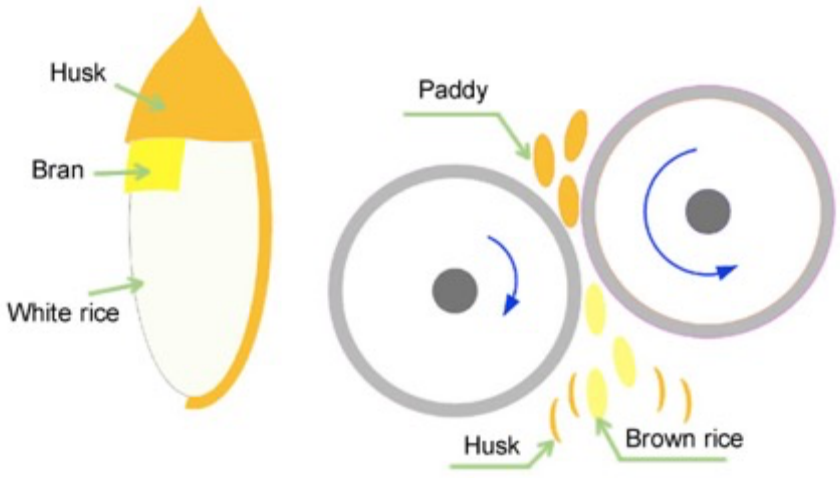


Figure 30. *Source of the by-product material and pretreatment of the rice husk and rice husk ash (RHA).*

Source: (*International Rice Research Institute (IRRI). Rice Husk.*, 2025)

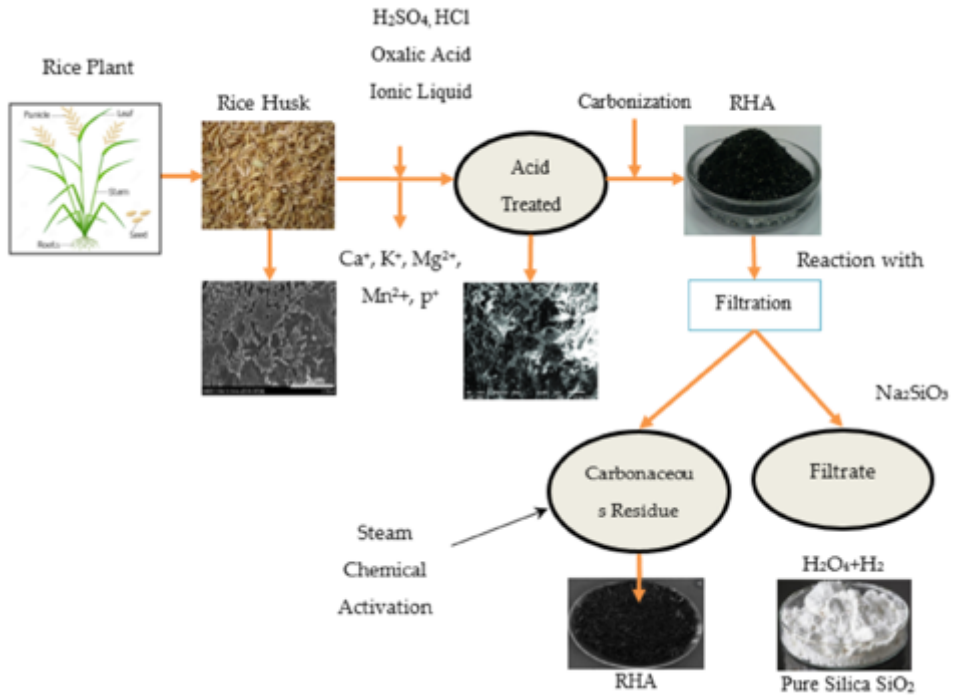


Figure 31. *Source of the by-product material and pretreatment of the rice husk and rice husk ash (RHA).*

Source: *(Amran et al., 2021)*

Production and Characterization

The properties of Rice husk ash as a supplementary cementitious materials are critically dependent on the combustion process **(Figure 32 and 33)**. Rice husks are naturally high in silica (around 20% by weight), which exists in a hydrated, amorphous form.

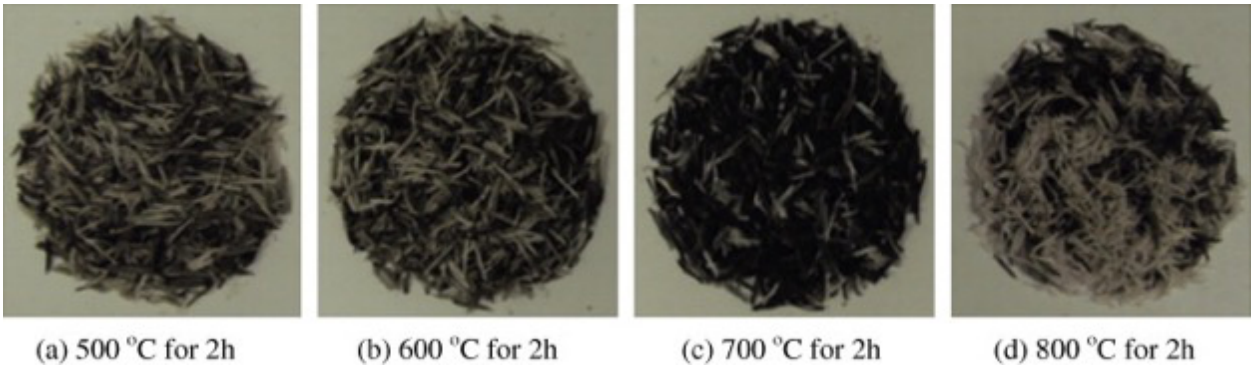


Figure 32. *Changes in the Rice husk ash color at different calcination temperatures.*

Source: *(Xu et al., 2012)*

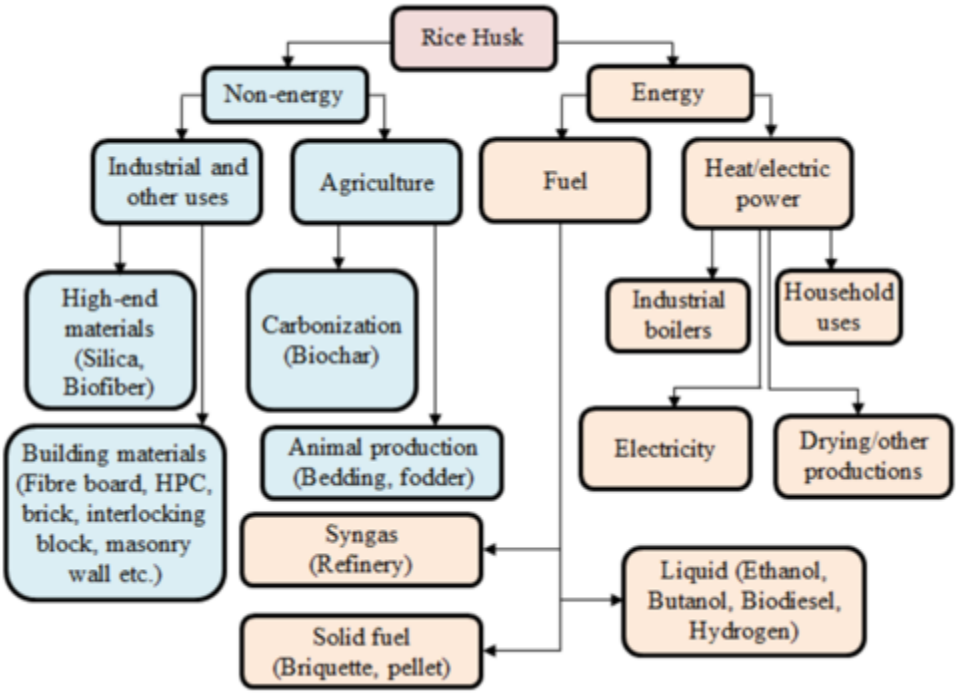


Figure 33. *The potential applications of RHA.*

Source: *(Mofijur et al., 2019)*

- **Controlled Combustion:** To produce highly reactive, amorphous Rice husk ash, the husks must be incinerated under controlled temperature and atmospheric conditions, typically between 500°C and 700°C. This process burns off the organic components while preserving the amorphous structure of the silica **(Table 4)**.
- **Uncontrolled Combustion:** If burned at higher temperatures or for prolonged periods, the amorphous silica will convert into crystalline forms like cristobalite and tridymite, which are largely non-reactive and thus have little to no pozzolanic value. The color of the ash is a good indicator of quality: a white or grey ash suggests amorphous silica and low residual carbon, while a dark or black ash indicates incomplete combustion and high carbon content, which can negatively affect concrete performance. After combustion, the Rice husk ash is often ground to increase its fineness and reactivity.

Table 4. *Influence of the temperature of burning on the RHA structure.*

Source: *(Amran et al., 2021)*

Temperature	Structure of RHA	Specific Surface Area (m2/g)
Up to 500	Particles are globular spherical or in form with permeable structure	0.5 to 2.1
500 to 600	Particles are partially crystalline and non-crystalline. It has a fine porous crystalline grain, not more than 1 μm, perhaps establishing the transition between the crystalline and the amorphous state	76 to 122
600 to 700	Diameter of pores, and amorphous particles is uppermost	100 to 150 at a lower temperature
700 to 800	Partially crystalline, formulation of coral formed crystals	6 to 10
800 to 900	Crystalline	Not more than 5
900 to 1000	The formulation of coral formed crystals augmented, and increasingly finer and molted significantly	-

Properties and Performance as an supplementary cementitious materials

High-quality Rice husk ash is an excellent pozzolanic material with several beneficial characteristics **(Table 5)**:

- **Chemical Composition:** Rice husk ash is predominantly composed of amorphous silicon dioxide, often in concentrations of 87-97%. This high silica content gives it strong pozzolanic activity.
- **Physical Properties:** Rice husk ash particles are typically very fine and have a porous microstructure and high specific surface area. This contributes to both its pozzolanic reactivity and a "micro-filling" effect, where the fine particles pack into the voids between cement grains, creating a denser paste matrix.
- **Effect on Fresh Concrete:** The high surface area and porous nature of Rice husk ash particles lead to a significant increase in water demand, which can reduce the workability

(slump) of fresh concrete. This effect must be compensated for with the use of superplasticizers.

Table 5. *Physical and chemical properties of Rice husk ash at 600 °C.*

Source: *(Xu et al., 2012)*

Physical and chemical characteristics	**Rice husk**
Physical properties	
Average size (nm)	150
Specific surface area (m^2/g)	77.42
Loose bulk density (g/cm^3)	-
Chemical composition (%)	
Loss on ignition	3.13
Silicon dioxide (SiO_2)	91.71
Calcium oxide (CaO)	0.86
Aluminum oxide (Al_2O_3)	0.36
Ferric oxide (Fe_2O_3)	0.9
Magnesium oxide (MgO)	0.31
Potassium oxide (K_2O)	1.67
Sodium oxide (Na_2O)	0.12

- **Effect on Hardened Concrete:**

- **Strength:** Rice husk ash contributes to both early and long-term strength development. The micro-filling effect provides early strength, while the pozzolanic reaction contributes to significant strength gain over time. Studies have shown that replacing 5% to 20% of cement

with Rice husk ash can lead to compressive strengths equal to or greater than that of conventional concrete **(Table 6)**.

- **Durability:** The combination of pore refinement from the micro-filling effect and the denser C-S-H gel from the pozzolanic reaction makes Rice husk ash concrete highly impermeable. This results in excellent durability performance, including high resistance to chloride penetration and chemical attack.

Table 6. *Mix proportion and compressive strength of RHA blended cement mortars (water/binder = 0.4).*

Source: *(Xu et al., 2012)*

Mix designation (calcination)	RHA (%)	Compressive strength (MPa)		
		3 days	7 days	28 days
M0 (control)	0	30.50	46.52	49.83
M1 (500 °C)	10	30.19	40.78	49.82
M2 (600 °C)	10	37.54	53.36	59.87
M3 (700 °C)	10	28.9	32.61	47.40
M4 (800 °C)	10	27.28	32.41	46.49

1.4. Industrial By-products and Waste

The valorization of industrial by-products and waste materials as resources for construction is a cornerstone of the circular economy. This approach not only diverts vast quantities of material from landfills but also reduces the demand for virgin raw materials, thereby lowering the environmental footprint of the construction sector.

1.4.1. Rubber Aggregates from Recycled Tires

The disposal of end-of-life tires represents a significant environmental challenge. Incorporating shredded or crumbed rubber from these tires into concrete as a partial replacement for natural aggregates is a promising valorization pathway **(Table 7)**, **(Figure 34)**.

Table 7. *Classification of the rubber particles.*

Source: *(Li et al., 2022)*

Term Name	Particle Size Range	Replacement Type
Shredded tyre	100-230 mm in width 300-460 mm in length	Coarse aggregate
Chipped tyre	13-76 mm	Coarse aggregate
Fibre rubber	2-5 mm in width 10-22 mm in length	Fine aggregate
Granulated crumb rubber	0.5-9.5 mm	Coarse aggregate or Fine aggregate
Crumb rubber	0.425-4.75 mm	Fine aggregate or cement
Rubber powder/Rubber ash	≤0.425 mm	Cement



Figure 34. *Waste rubber tire crumbs preparation process.*

Source: *(M. Mhaya et al., 2021)*

- **Application and Form:** Recycled tire rubber can be processed into various sizes and used to replace either fine aggregate (crumb rubber) or coarse aggregate (rubber chips or shreds) in concrete mixtures.
- **Effects on Concrete Properties:**

- **Mechanical Properties:** The inclusion of rubber aggregates generally leads to a reduction in compressive strength, tensile strength, and modulus of elasticity **(Figure 35)**. This is primarily due to the low stiffness of rubber compared to mineral aggregates and the weak, hydrophobic nature of the rubber-cement paste interface, which hinders stress transfer.
- **Positive Performance Attributes:** Despite the reduction in strength, rubberized concrete exhibits several beneficial properties. It has significantly enhanced ductility, energy absorption capacity, and impact resistance, making it more resilient under dynamic loading. It also demonstrates improved sound absorption and thermal insulation properties.
- **Durability:** Research indicates that rubberized concrete can offer improved durability in certain aspects, such as enhanced resistance to freeze-thaw cycles, acid attack, and sulfate attack. However, it may show increased water absorption and carbonation rates.

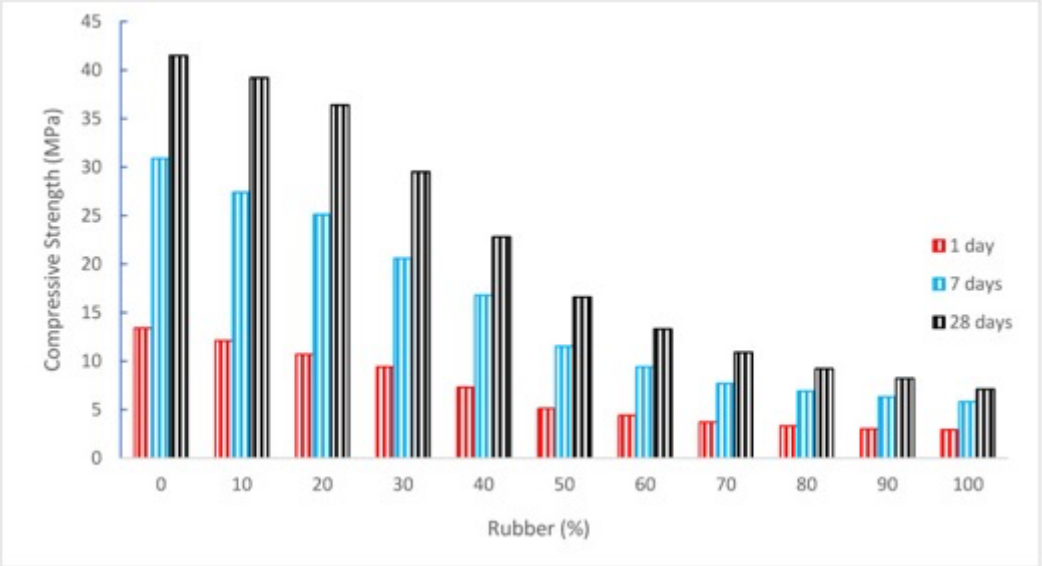


Figure 35. *Compressive strength of concrete with the substitution of rubber as aggregate.*

Source: *(Ahmad, Zhou, Majdi, et al., 2022)*

- **Mitigation Strategies:** The primary challenge of poor bonding can be addressed through various pre-treatment methods for the rubber particles. Surface treatments with chemical solutions, such as sodium hydroxide (NaOH), or coating the particles with materials like

silica fume can modify the rubber surface to be more hydrophilic and create a stronger bond with the cement matrix, thereby partially recovering the loss in mechanical strength.

1.4.2. Slags: High-Furnace (HF) and Linz-Donawitz (LD) Converter Slags

Slags are non-metallic by-products generated during the production of iron and steel. Their chemical and physical properties make them highly suitable for various applications in construction **(Figure 36)**.

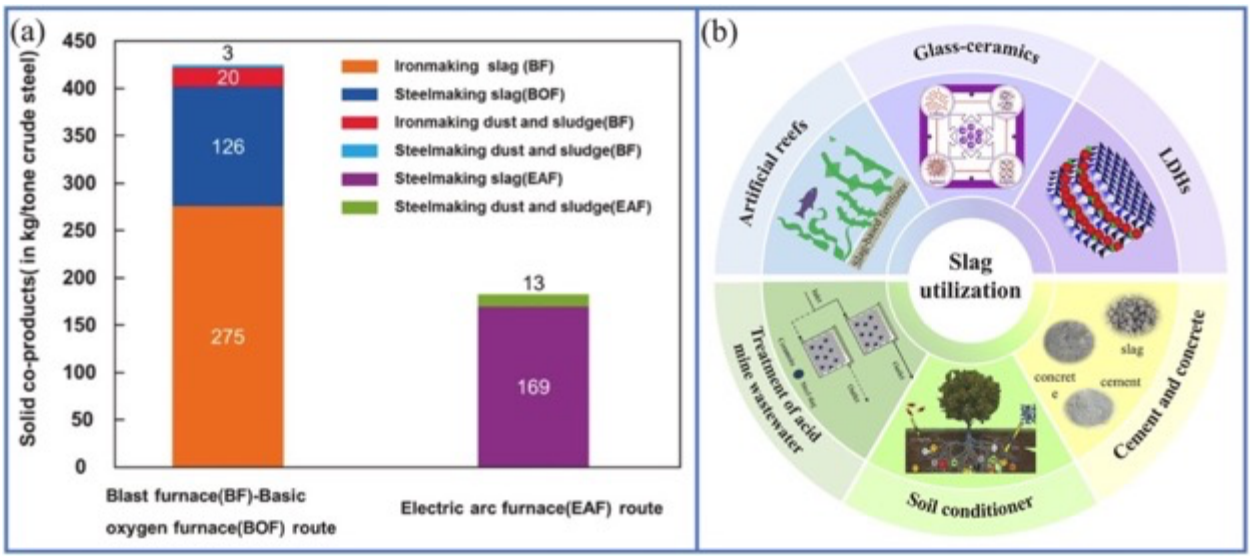


Figure 36. *Slag productions and their utilization for various application: (a) Main solid waste per steelmaking route, (b) Slag utilization for various application.*

Source: *(Duan et al., 2025)*

- **Blast Furnace Slag:** A by-product of iron manufacturing in a blast furnace. Its properties and applications depend on the cooling process :

- **Air-Cooled Blast Furnace Slag:** Produced by slow cooling, resulting in a crystalline, rock-like material. When crushed and screened, it is used as a high-quality construction aggregate in granular bases, asphalt, and concrete.
- **Ground Granulated Blast Furnace Slag:** Produced by rapid quenching of molten slag with water, which creates a glassy, amorphous granular material. When finely ground, Ground Granulated Blast Furnace Slag exhibits latent hydraulic and pozzolanic properties, making it an excellent supplementary cementitious materials. Replacing 30-70% of Portland cement with Ground Granulated Blast Furnace Slag in concrete improves workability, reduces heat of

hydration, and significantly enhances long-term strength and durability, particularly resistance to chloride and sulfate attack.

- **Steel Slag:** This is a by-product of converting iron into steel, for example, in a Basic Oxygen Furnace (also known as a Linz-Donawitz converter).

- **Properties and Applications:** Steel slag is harder, denser, and more angular than most natural aggregates, giving it excellent abrasion resistance and mechanical stability. It is widely used as a high-quality aggregate in road construction, particularly in asphalt surface courses where it provides superior skid resistance and durability.
- **Challenges:** A key challenge with steel slag is its potential for volumetric instability. The presence of unhydrated free lime (CaO) and magnesium oxide (MgO) can lead to expansive hydration reactions over time, which can cause cracking and damage. For this reason, steel slag is typically not used as an aggregate in Portland cement concrete unless it has been properly weathered (aged) or treated to ensure its dimensional stability.

1.4.3. Dredged Sediments

Dredging is essential for maintaining the navigability of harbors, rivers, and reservoirs, but it generates enormous quantities of sediment that require management. Valorizing these sediments as a construction material offers a sustainable alternative to landfilling or sea disposal **(Figure 37)**.

- **Characteristics and Challenges:** Dredged sediments are typically fine-grained (silt and clay), have very high water content, and can be contaminated with organic matter, heavy metals, and other pollutants depending on their source. These characteristics necessitate pre-treatment before they can be used in construction **(Table 8)**. Common treatments include dewatering (mechanical or natural), separation of contaminants, and thermal treatment (calcination) to burn off organics and activate pozzolanic properties.

- **Applications:** Once treated, dredged sediments have a wide range of potential applications:

- **Fired Bricks and Ceramics:** The clay and silt-rich fractions of sediments can be used as a raw material in the manufacturing of fired bricks and tiles.
- **Lightweight Aggregates:** Through a process of pelletizing and sintering, sediments can be converted into lightweight aggregates for use in concrete.
- **Road Construction:** Stabilized sediments can be used as a material for road sub-bases and embankments.

- **Cement and Concrete:** Calcined sediments can exhibit pozzolanic properties and be used as an supplementary cementitious materials. Untreated sediments can also be used as a fine aggregate or filler in concrete and mortar, provided their physical properties and contaminant levels are acceptable.

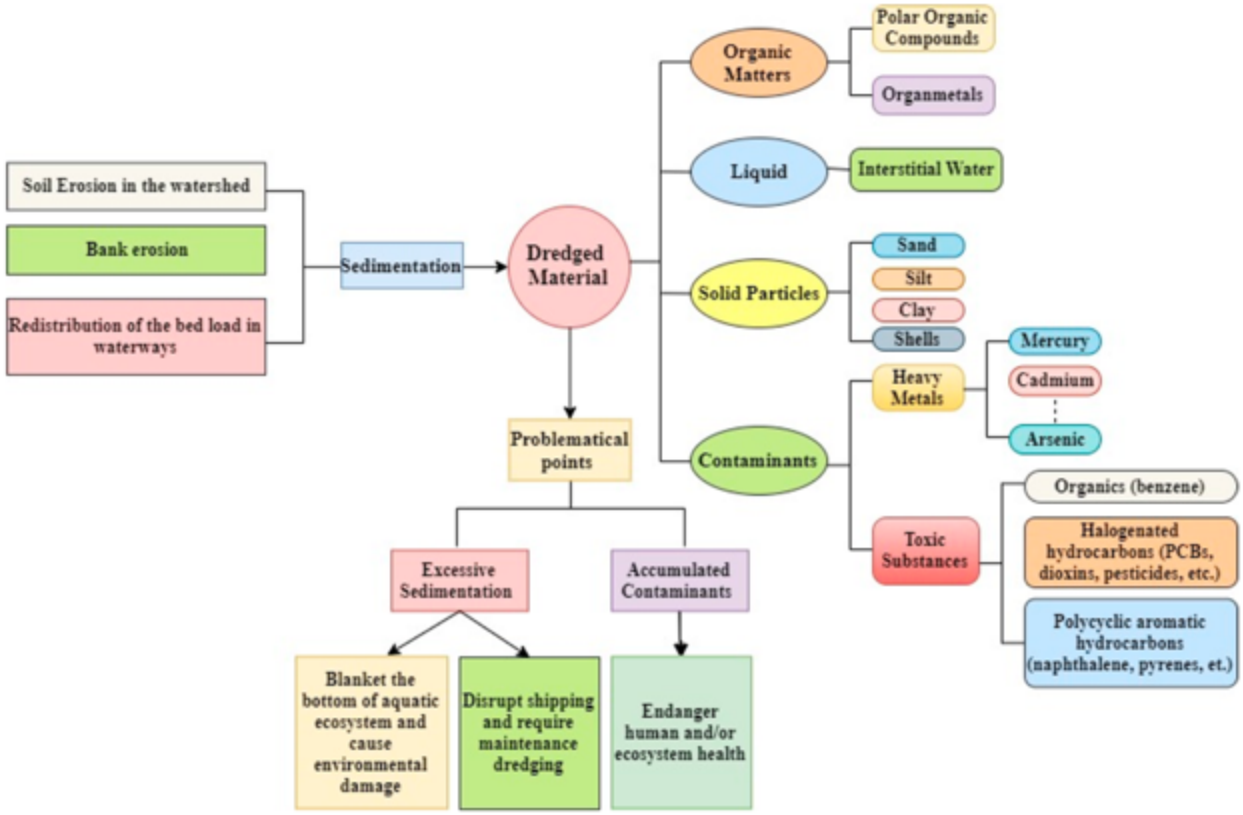


Figure 37. *Dredged material sources, characteristics, and social/ecological problems.*

Source: *(Solanki et al., 2023)*

Table 8. *Summary of treatment methods.*

Source: *(Afolayan et al., 2025)*

Resource Recovery Process	Treatment Techniques	Purpose

Physical	Separation using centrifuge, screening, hydrocyclone.	Separation of small and fine contaminated particles.
	Dewatering using filter presses, draining screens, natural evaporation and drainage.	Removal of free and interstitial water. Treatment of contaminated fraction.
Chemical	Washing with water or chemicals-acids, bases, surfactants.	Neutralization of toxic contaminants and salts.
	Oxidation, uses hydrogen peroxide, Fenton reagent, ozone, potassium permanganate.	Neutralization of organic contaminants.
	Immobilization, uses cement, lime.	Reduction in heavy-metal mobility.
Thermal	Thermal desorption, operates at 100 to 600 °C with a boundary temperature of 300 °C.	Removal of volatile organic compounds (VOCs) and metals.
	Pyrolysis, operates at low temperatures of 200 to 500 °C.	Burning off of organic contaminants and reductions in heavy metals in the absence of oxygen
	Thermal vitrification, operates at high temperatures of 1000 to 1500 °C.	Contaminants immobilized by transforming the DS into stable or crystalline materials.
Biological	Bioremediation, uses living microorganisms-bacteria, fungi, algae, cyanobacteria.	Degradation of organic contaminants and heavy metals by microbial activity.
	Natural attenuation, contaminants are reduced over time in natural state using native microbial population.	Self-amendment of contaminated DS.

1.4.4. Biomass Ash: From wastewater treatment plants and Animal Meal Combustion

The increasing use of biomass for energy generation produces a growing stream of biomass ash. This ash, which includes residues from the combustion of materials like wood, agricultural waste,

sewage sludge from wastewater treatment plants, and animal meal, presents both a disposal challenge and a valorization opportunity **(Figure 38)**.

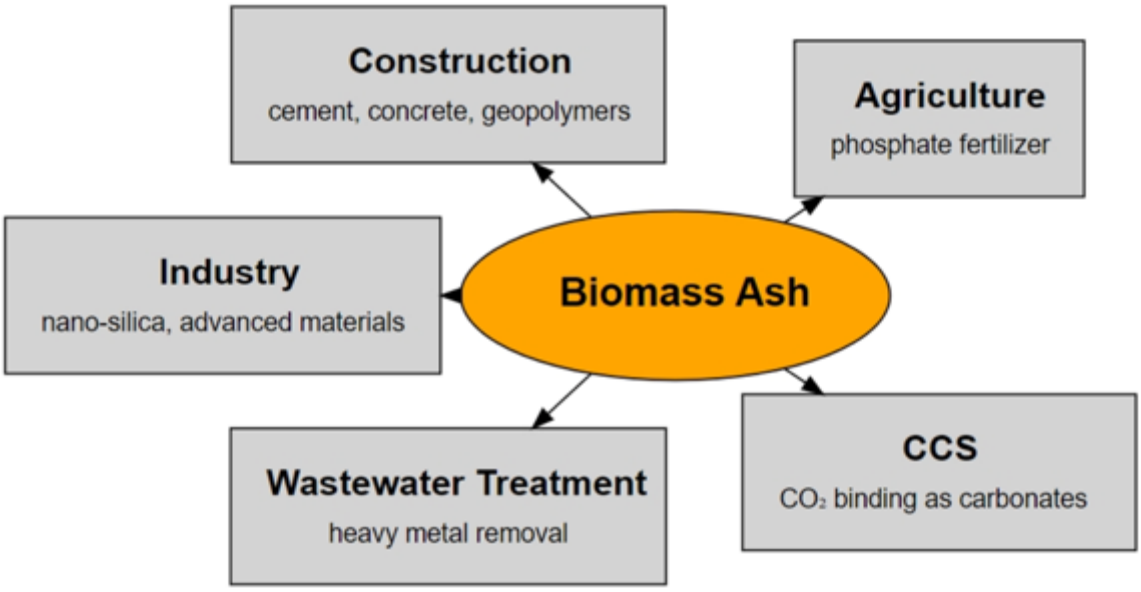


Figure 38. *Paths of biomass ash utilization.*

Source: *(Maj et al., 2025)*

- **Characteristics:** Biomass ash is highly heterogeneous, with its chemical and physical properties varying widely depending on the fuel source and combustion technology. Ashes can be rich in silica (Si), calcium (Ca), potassium (K), or phosphorus (P). However, they can also concentrate heavy metals and other contaminants, which must be carefully managed **(Figure 39)**.
- **Potential Applications:** The high silica content in some biomass ashes (e.g., from agricultural residues like rice husk ash) makes them suitable for use as pozzolanic supplementary cementitious materials in concrete. Calcium-rich ashes may have some cementitious properties. However, the high variability and potential for contaminants often require pre-treatment and rigorous testing before they can be safely and effectively used in construction materials. The use of these ashes in concrete is an active area of research aimed at developing greener construction materials and aligning with circular economy principles.

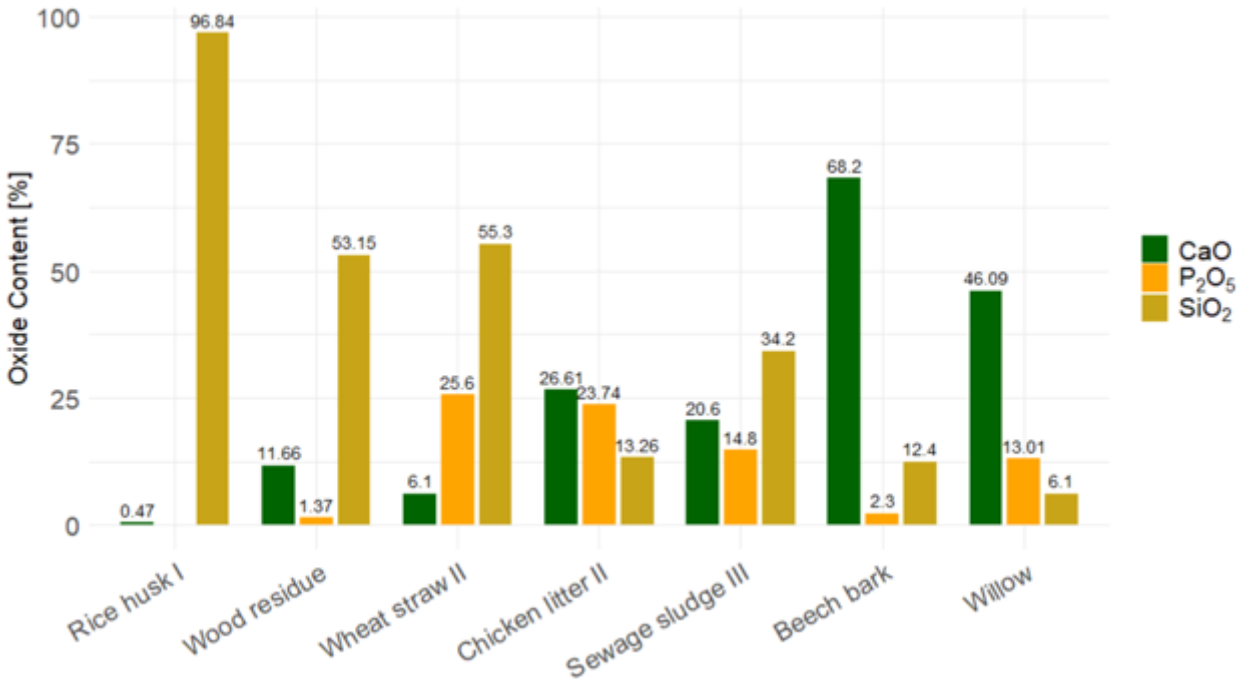


Figure 39. *Main components of biomass ashes.*

Source: *(Maj et al., 2025)*

1.4.5. Recycled Glass

Waste glass that cannot be recycled in a closed loop (e.g., mixed-color or contaminated glass) is often sent to landfills. Incorporating this waste into concrete is a viable valorization route with multiple primary approaches **(Table 9)**, **(Figure 40)**.

- **Use as Aggregate:** Crushed glass can be used as a replacement for fine or coarse aggregate. However, a major challenge with this application is the Alkali-Silica Reaction. The amorphous silica in the glass reacts with the high-alkali pore solution in concrete, forming an expansive gel that can cause severe cracking and deterioration of the structure. This risk has historically limited the use of glass as an aggregate.
- **Use as a Supplementary Cementitious Material:** A more effective approach involves finely grinding the waste glass into a powder with a particle size typically less than 75 µm. This process has two significant benefits:

- **Alkali-Silica Reaction Mitigation:** Reducing the particle size of the glass to a fine powder effectively mitigates the destructive Alkali-Silica Reaction expansion. The increased surface

area allows the pozzolanic reaction to consume the reactive silica before the expansive gel can form and cause damage.

- **Pozzolanic Activity:** The fine grinding activates the pozzolanic potential of the amorphous silica in the glass. The glass powder reacts with calcium hydroxide in the same way as other pozzolans, forming additional C-S-H, which densifies the microstructure and improves the strength and durability of the concrete **(Figure 41)**.

This transformation of a deleterious reaction (Alkali-Silica Reaction) into a beneficial one (pozzolanic reaction) through controlled processing is a prime example of advanced material valorization. Studies suggest that an optimal replacement of cement with glass powder is around 20%, which can enhance mechanical properties and durability, such as resistance to chloride penetration.

Table 9. *Chemical composition of waste glass and other pozzolans.*

Source: *(Federico & Chidiac, 2009)*

Compound	Waste glass	Volcanic ash	Volcanic pumice	Slag	Silica fume	High Ca fly ash	OPC
SiO_2	63.79	73.68	65.74	35	90.9	39.21	20.33
Al_2O_3	3.02	12.25	16.72	12	1.12	16.22	4.65
Fe_2O_3	1.57	2.2	3.58	1	1.46	6.58	3.04
CaO	13.01	1.13	3.33	40	0.69	22.78	61.78
MgO	0.89	0.23	0.95	-	0.77	2.35	3.29
K_2O	0.54	3.95	3.05	-	-	-	0.59
Na_2O	11.72	3.6	4.48	0.3	-	-	0.24
SO_3	0.165	0.32	0.65	9	0.38	4.3	3.63
LOI	4.55	3.05	2.4	1	3	2.1	-

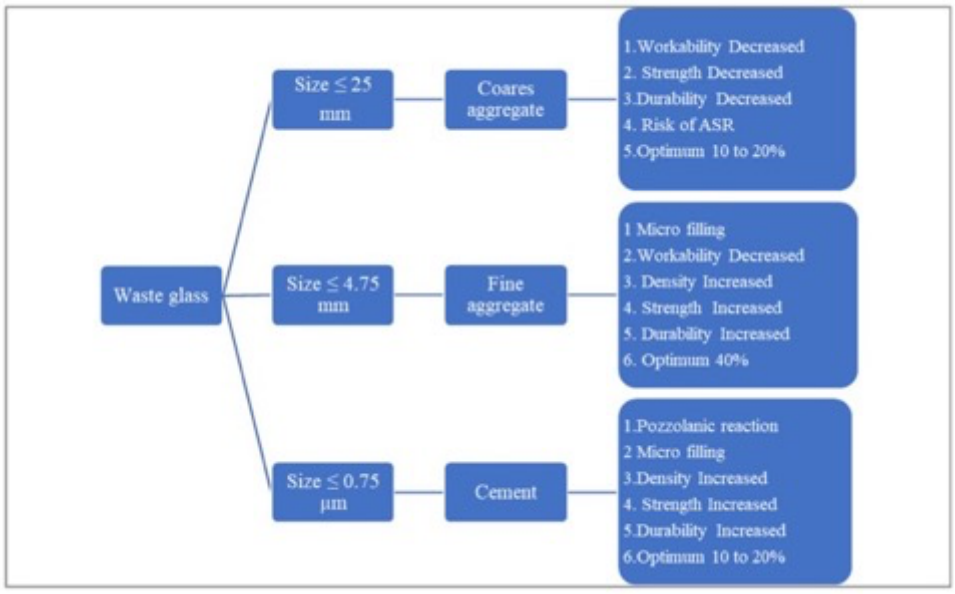


Figure 40. *Role of waste glass in concrete.*

Source: *(Ahmad, Zhou, Usanova, et al., 2022)*

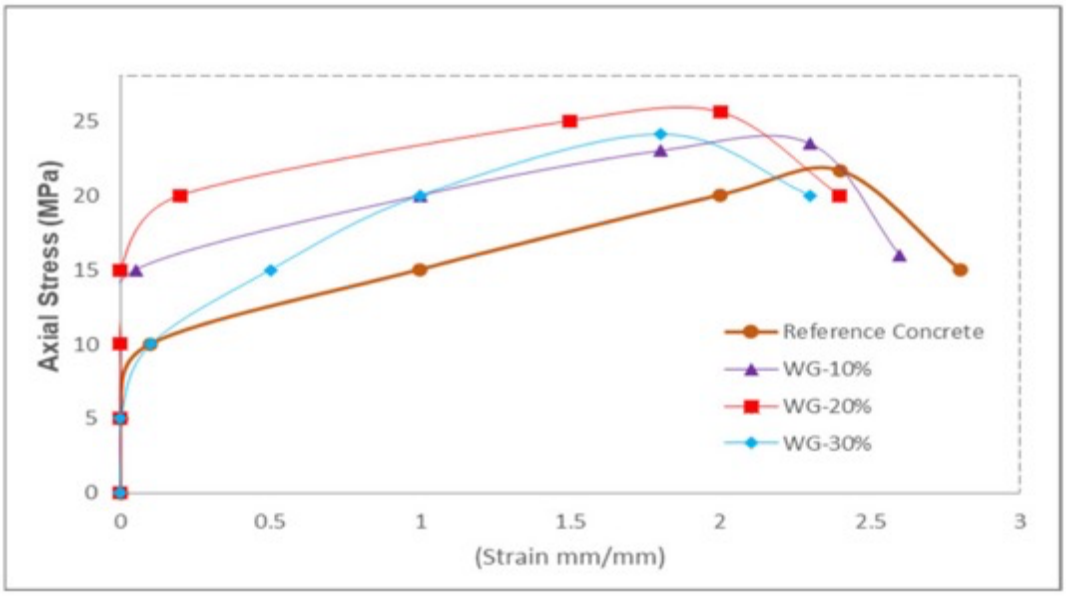


Figure 41. *Stress–strain curve of compression test for different replacement ratios of waste glass (WG).*

Source: *(Ahmad, Zhou, Usanova, et al., 2022)*

Chapter 2

Alternative Binders and Cementitious Replacements

Introduction

The production of ordinary Portland cement is a primary source of CO_2 emissions in the construction industry. Consequently, a major focus of sustainable materials research is the development of alternative binders and supplementary cementitious materials that can partially or fully replace ordinary Portland cement, thereby reducing the environmental footprint of concrete and other cement-based materials.

2.1. Organic Binders: Use as Stabilizers for Earth-Based Materials

While inorganic binders like cement and lime are effective for stabilizing earth-based materials, their production carries an environmental cost. This has spurred research into organic and bio-based binders as more sustainable alternatives, particularly for rammed earth and compressed earth blocks. These bio-binders are often derived from agricultural by-products or natural polymers.

A wide range of natural additives have been investigated for their soil-stabilizing potential, including gums, lignin, tannins, and proteins. These materials work by creating physical or chemical bonds between soil particles, improving cohesion and strength **(Figure 42)**.

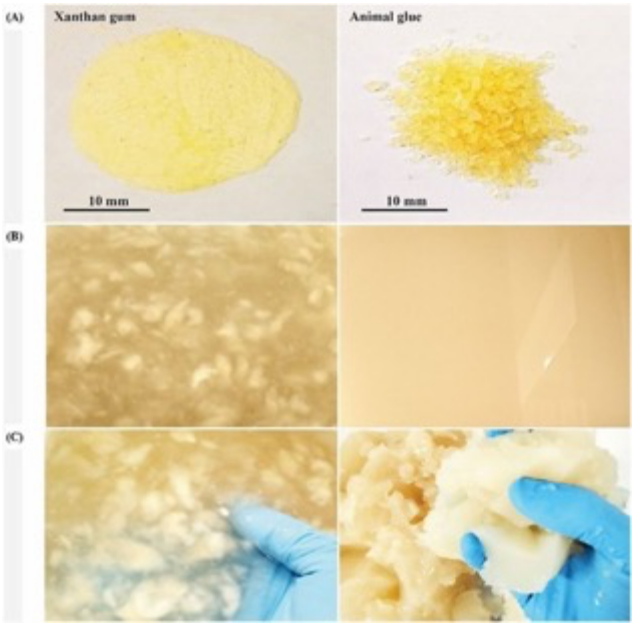


Figure 42. *Dissolution of Xanthan Gum (XG) (left) and Animal Glue (AG) (right): (A) before dissolution; (B) XG dissolved in 20°C water and AG dissolved in 70°C water; (C) dissolved XG and AG after 24 h desiccation time in 20°C.*

Source: *(Abdelaal et al., 2025)*

- **Xanthan Gum:** This biopolymer is produced by microbial fermentation of sugars, which can be derived from lignocellulosic biomass like agricultural waste. Xanthan Gum is known for its high viscosity and stability. Its addition on rammed earth has led to significant strength improvements, with one study reporting a 221% increase in compressive strength over unstabilized samples, reaching 5.58 MPa after 28 days. A notable challenge is its susceptibility to microbial proliferation, which could impact long-term durability **(Figure 43)**.

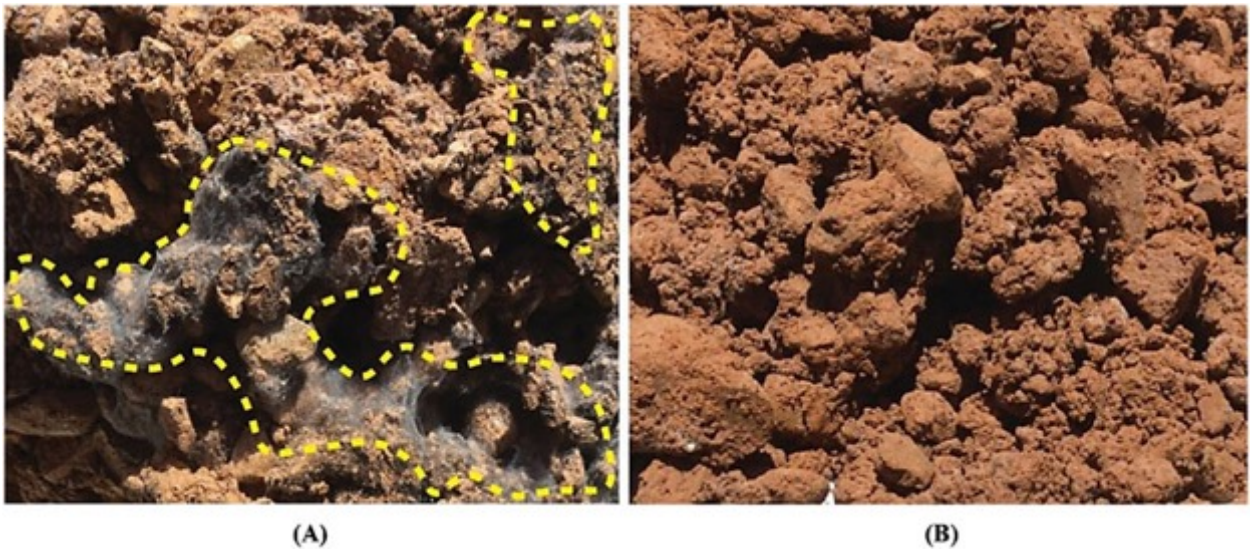


Figure 43. *Microbial growth: (A) fungus identified in soil mixed with XG, (B) no visible fungus can be identified in soil mixed with AG. Both soils from (A) and (B) are stored in 20°C with 50% humidity for 28 days.*

Source: *(Abdelaal et al., 2025)*

- **Animal Glue:** Traditionally made from animal by-products, it can now be produced from protein-rich agricultural wastes. The collagen in these materials is hydrolyzed to create effective binding agents. Animal Glue has shown excellent performance in stabilizing rammed earth, with one study demonstrating a 294% strength improvement over the control, achieving a compressive strength of 6.86 MPa at 28 days. Animal Glue-stabilized samples also showed better resistance to fungal growth compared to those stabilized with Xanthan Gum **(Figure 44)**.
- **Other Bio-Binders:** Other promising bio-binders include lignosulfonates (a by-product of the paper industry), which have been shown to increase the strength of clayey soils, and various plant-based gums like guar gum, which in some cases have provided compressive strengths comparable to cement stabilization.

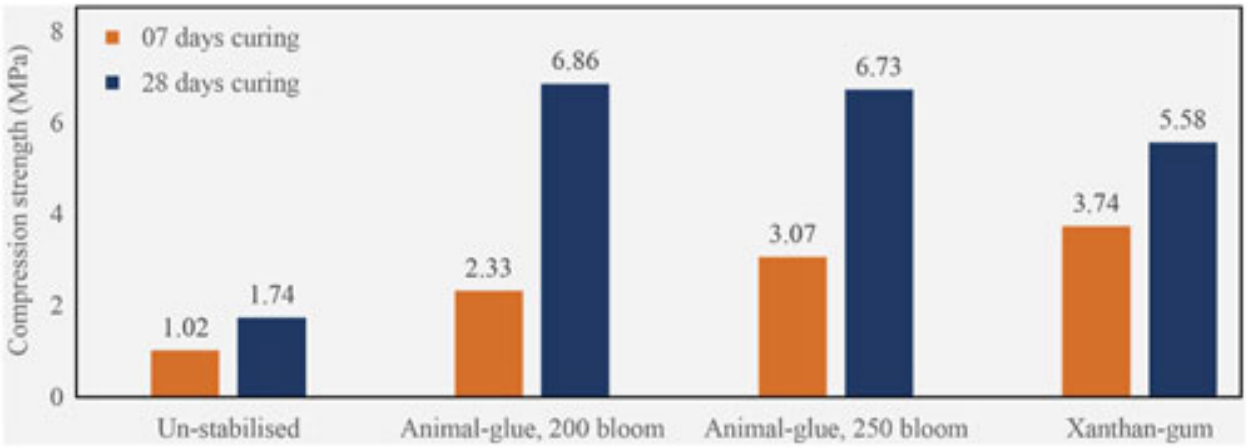


Figure 44. *Compressive strength of Rammed Earth samples stabilized by different settings over 7 and 28 days.*

Source: *(Abdelaal et al., 2025)*

These organic binders offer a pathway to producing stabilized earth materials with a significantly lower carbon footprint than those using conventional cementitious binders.

2.2. Belitic Binders: Low-Carbon Calcium Silicate Cements

Belitic binders, also known as belite-rich cements, are a class of hydraulic cements that offer a lower-carbon alternative to conventional ordinary Portland cement. Their chemistry is centered on maximizing the content of belite (dicalcium silicate) while minimizing alite (tricalcium silicate), the dominant mineral in ordinary Portland cement **(Figure 45)**.

The sustainability advantages of belitic binders stem from two key aspects of their production:

- **Lower Limestone Requirement:** The formation of belite requires a lower calcium-to-silica ratio than alite. This means that the raw meal for belitic clinker requires approximately 10% less limestone, which directly reduces the process-related CO_2 emissions from limestone decarbonation.
- **Lower Sintering Temperature:** Belitic clinker can be produced at lower kiln temperatures (around 1350°C) compared to the ~1450°C required for conventional ordinary Portland cement clinker, resulting in lower fuel consumption and reduced energy-related CO_2 emissions.

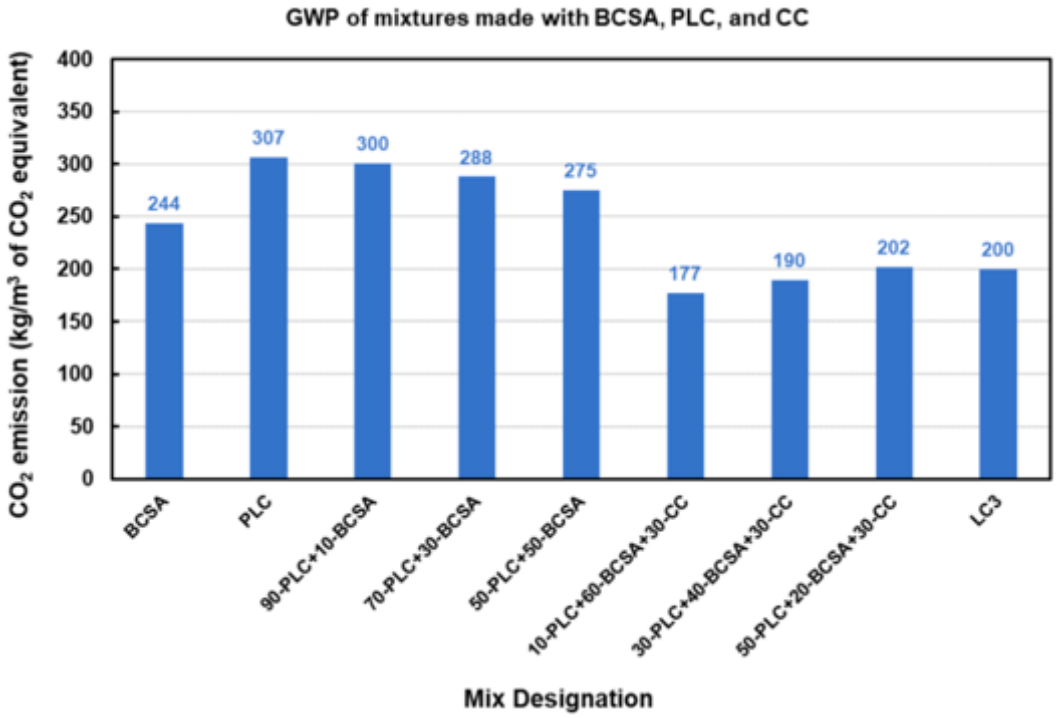


Figure 45. *Global Warming Potential of mixes made with either or in a combination of Belitic calcium sulfoaluminate (BCSA), Portland Limestone Cement (PLC), Calcined Clay (CC), and their blends.*

Source: *(Essolebe, 2023)*

In terms of performance, belitic binders exhibit distinct characteristics compared to ordinary Portland cement:

- **Hydration and Strength Development:** Belite hydrates much more slowly than alite. This results in low early-age strength, which is a primary drawback for many applications. However, the hydration continues over a longer period, leading to good or even superior long-term strength and durability **(Figure 46)**.
- **Heat of Hydration:** The slower hydration reaction generates significantly less heat, making belitic cements well-suited for mass concrete applications where thermal cracking is a concern.
- **Durability:** The hydration of belite produces a denser microstructure with a lower proportion of calcium hydroxide compared to ordinary Portland cement, which can lead to improved durability, particularly in aggressive chemical environments.

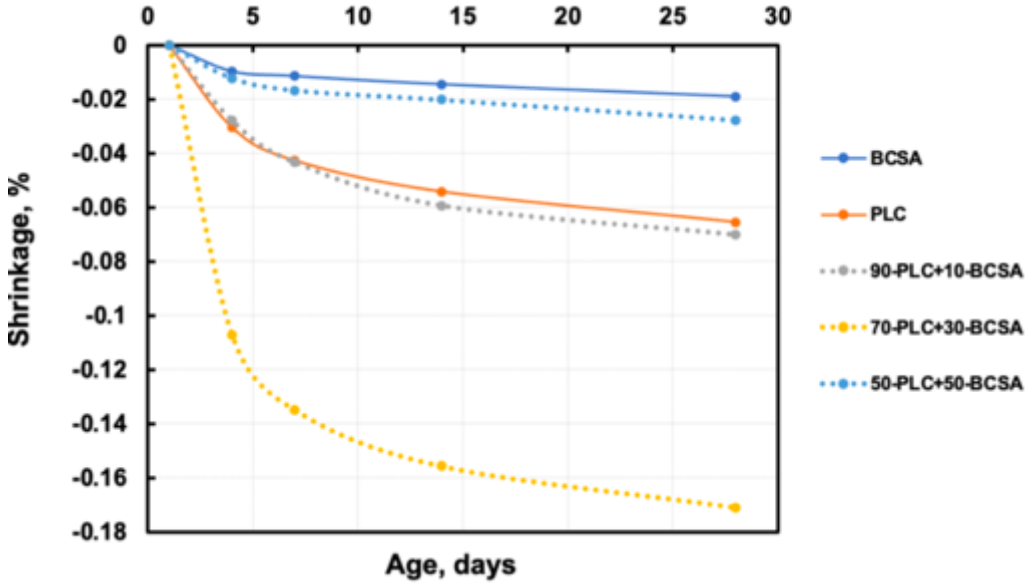


Figure 46. *Shrinkage results for Belitic calcium sulfoaluminate (BCSA), Portland Limestone Cement (PLC), and their blends.*

Source: *(Essolebe, 2023)*

Research is ongoing to improve the early-age reactivity of belitic cements, for example, by incorporating other reactive phases to create binders like belite calcium sulfoaluminate cements, which combine the low-carbon benefits of belite with the rapid strength gain of calcium sulfoaluminate phases.

2.3. Glass-Based Binders

As introduced in **Chapter 1**, finely ground waste glass powder can serve as an effective pozzolanic supplementary cementitious materials, or glass-based binder, in concrete. The high content of amorphous silica in common soda-lime glass makes it reactive in the high-alkali environment of cement paste **(Figure 47)**.

The mechanism of a glass-based binder relies on the pozzolanic reaction. The amorphous silica from the glass powder reacts with the calcium hydroxide produced during the hydration of Portland cement. This reaction forms additional calcium silicate hydrate (C-S-H), the primary binding phase in concrete.

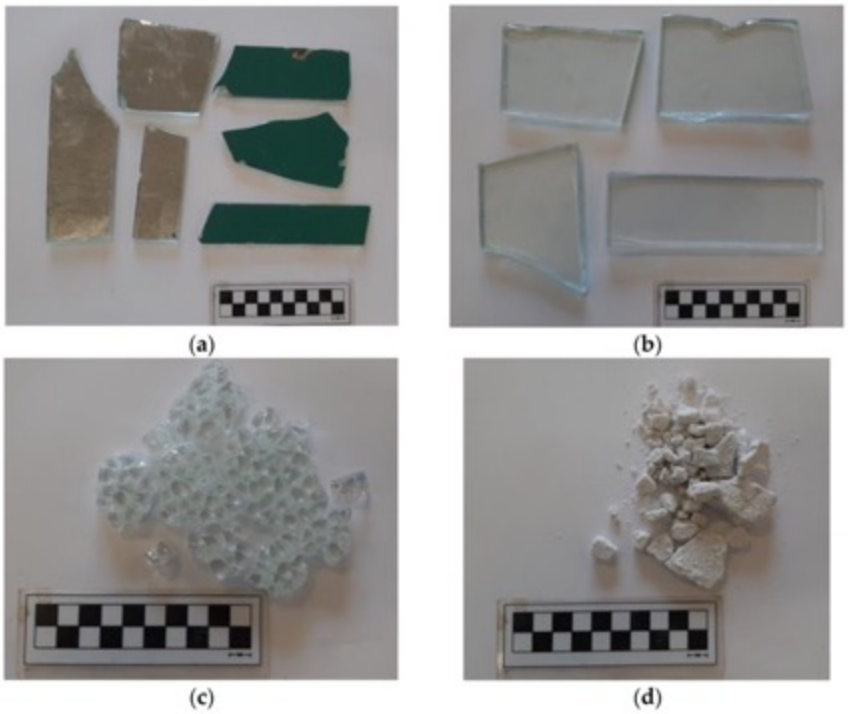


Figure 47. *Types of glass waste tested (a) mirror, (b) monolithic, (c) tempered, (d) sediment.*

Source: *(Stefanidou et al., 2023)*

The effectiveness of glass powder as a binder is critically dependent on its particle size. To exhibit significant pozzolanic activity and, crucially, to mitigate the risk of deleterious alkali-silica reaction, the glass must be ground to a fine powder, typically with particles smaller than 45 μm, and often finer than 20 μm for high reactivity.

The effects of using glass powder as a partial cement replacement include **(Table 10)**:

- **Fresh Properties:** The effect on workability can vary. The smooth, non-porous nature of glass particles can sometimes improve flowability, but very fine powders can increase water demand.
- **Hardened Properties:** At optimal replacement levels (typically 10-20%), glass powder can contribute to increased compressive and flexural strength at later ages due to the pozzolanic reaction. The densification of the microstructure also leads to reduced permeability and improved durability, such as enhanced resistance to chloride ion penetration **(Figure 48)**.

Table 10. *Composition of the mixtures containing glass waste as binder.*

Source: *(Stefanidou et al., 2023)*

Mixture	Cement	Glass Binder	Sand	Water	Workability
	g	g	g	ml	cm
C (Without)	450	-	1350	225	21.0
Mirror (75)	315	135	1350	225	20.5
Monolithic (75)	315	135	1350	225	21.0
Tempered (75)	315	135	1350	225	18.5
Mirror (45)	315	135	1350	225	18.8
Monolithic (45)	315	135	1350	225	19.5
Tempered (45)	315	135	1350	225	19.5
Sediment (45)	315	135	1350	225	18.0

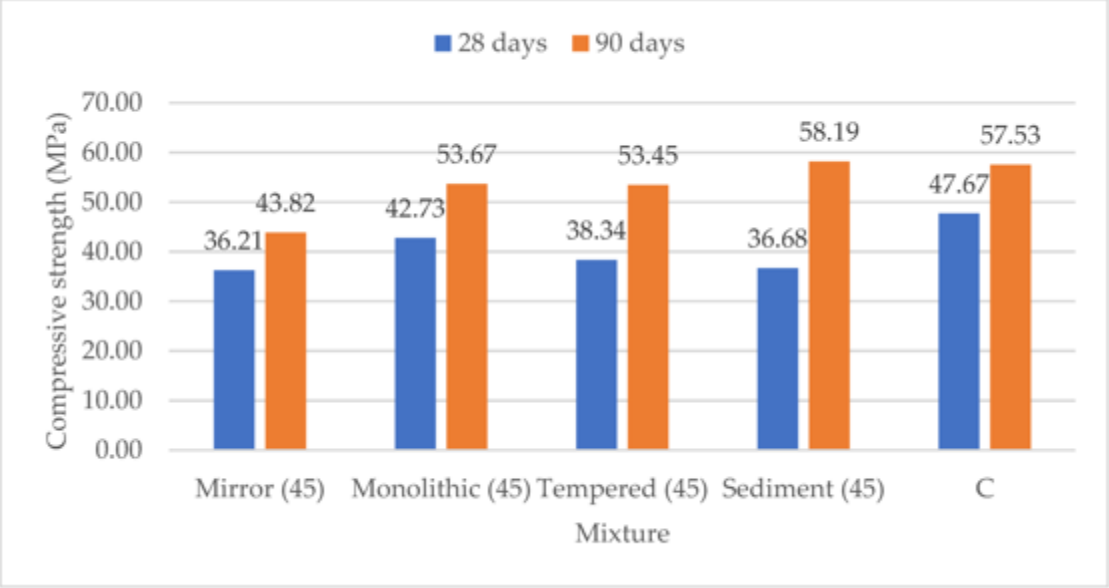


Figure 48. *Compressive strength of cement mortars containing glass waste as binder (under 45 μm).*

Source: *(Stefanidou et al., 2023)*

2.4. Geopolymers and Inorganic Polymers: Alkali-Activated Materials

Geopolymers, and the broader class of alkali-activated materials, represent a radical departure from traditional cement chemistry **(Figure 49)**. Instead of relying on the hydration of calcium silicates, these binders are formed through the chemical reaction of an aluminosilicate precursor with a highly alkaline activator solution **(Figure 50)**.

- **Precursors:** The aluminosilicate source materials are often industrial by-products or natural minerals rich in reactive silica and alumina. Common precursors include:

- Metakaolin (calcined kaolinite clay)
- Fly Ash (from coal combustion)
- Ground Granulated Blast Furnace Slag
- Natural pozzolans like volcanic ash.

- **Activators:** The alkaline activators are concentrated aqueous solutions that dissolve the precursor and facilitate the polymerization reaction. Common activators include:

- Sodium hydroxide (NaOH) or potassium hydroxide (KOH)
- Sodium silicate (Na_2SiO_3) or potassium silicate (K_2O_3Si)
- Alkali carbonates and sulfates.

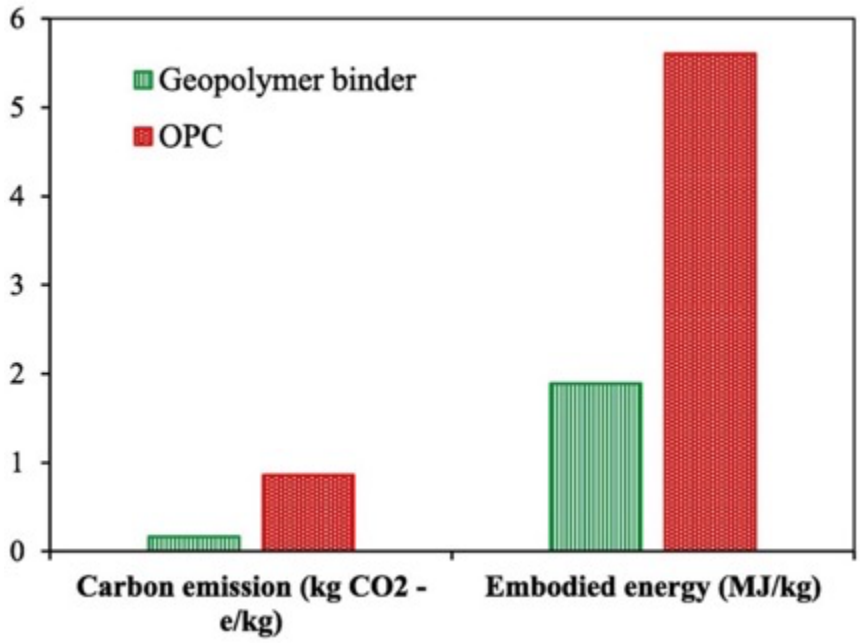


Figure 49. *Estimated Environmental impact: Geopolymer vs. ordinary Portland cement.*

Source: *(Neupane, 2022)*

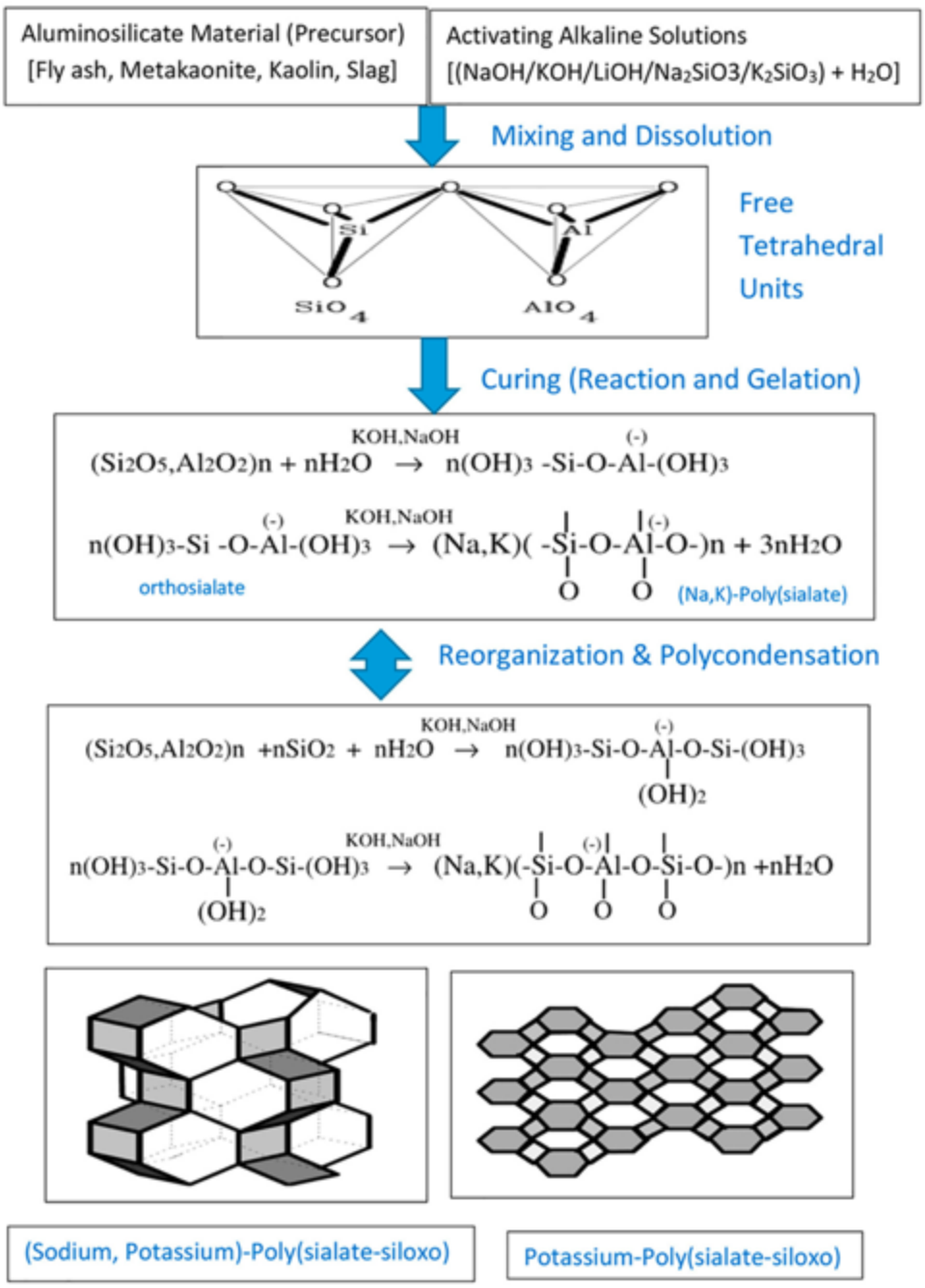


Figure 50. *Geopolymerization Process of Alkali Aluminosilicate Geopolymers: Mixing, Dissolution, and Polycondensation Pathways.*

Source: *(Mohan Kumar et al., 2025)*

The chemistry of the resulting binder depends heavily on the calcium content of the precursor **(Table 11)**:

- **Low-Calcium Systems (Geopolymers):** When precursors low in calcium, such as metakaolin or Class F fly ash, are used, the reaction forms a three-dimensional, amorphous aluminosilicate network structure, often described by the term "geopolymer". The primary binding phase is a sodium aluminosilicate hydrate (N-A-S-H) gel. These materials are known for their excellent high-temperature resistance, chemical and acid resistance, and rapid strength gain (especially when heat-cured).
- **High-Calcium Systems:** When precursors rich in calcium, such as Ground Granulated Blast Furnace Slag, are used, the primary reaction product is a calcium aluminosilicate hydrate (C-A-S-H) gel, which is structurally similar to the C-S-H in ordinary Portland cement but with more aluminum incorporated. These systems typically achieve very high early and final compressive strengths even at ambient curing temperatures.

Table 11. *Chemical Composition of Precursors.*

Source: *(Mohan Kumar et al., 2025)*

Precursors	**Chemical Composition (%)**								
	SiO_2	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**TiO_2**	**SO_3**
Fly ash	52.4	25.8	8.4	6.42	2.27	-	1.47	1.31	0.86
Ground Granulated Blast Furnace Slag	32.19	13.89	0.35	40.45	6.67	0.28	0.32	0.74	4.74
Kaolinite	51.30	32.60	1.10	0.10	0.30	0.20	0.30	1.10	0.00
Rice Husk Ash	83.10	2.15	1.10	4.70	1.50	0.10	2.96	-	1.20
Silica Fume	96.9	0.15	0.06	0.53	1.1	-	0.78	-	0.12
Red Mud	29.18	30.01	8.71	15.96	0.89	8.22	0.80	2.70	2.73
Waste Glass	69.65	0.85	0.50	14.45	2.89	9.69	0.39	0.10	0.55
Gold Mine Tailings	74.50	6.98	7.03	0.53	5.16	0.27	1.26	0.44	3.05
Basalt Powder	45.00	15.00	15.00	7.50	5.20	3.00	1.00	2.00	-
Bamboo Leaf Ash	72.97	2.85	2.31	4.98	1.23	-	6.07	0.41	0.55
Rice straw ash	69.20	5.30	0.90	3.46	2.81	3.43	6.40	-	-
Granulated Phosphorus Slag	39.11	2.38	0.74	47.47	4.60	0.03	0.15	-	0.22

Geopolymers and alkali-activated materials offer a promising pathway to low-carbon concrete, as they can be produced using 100% industrial by-products, potentially reducing the carbon footprint by up to 80-90% compared to ordinary Portland cement.

2.5. Natural and Artificial Pozzolans

Pozzolans are a broad category of supplementary cementitious materials that are essential for producing durable and sustainable concrete. They can be broadly classified as natural or artificial **(Table 12)**. This section provides a comparative summary of the key pozzolanic materials discussed throughout this handout **(Table 13)**.

Table 12. *General classification of pozzolans.*

Source: *(Jhonatan A. Becerra-Duitama & Rojas-Avellaneda, 2022)*

Pozzolans	
Natural pozzolans	**Artificial pozzolans**
Volcanic origin	Fly ash
Altered and unaltered pyroclasticmaterial	Blast furnace slag
Pumice stone and vitreous ashes	Silica fume
Zeolitic tuffs	Calcined organic matter residues
Sedimentary origin	Calcined clays and shales
Chemical sediments	Bottom ash from coal combustion
Diatomaceous earth	Steel industry slags
Detrital sediments	Municipal solid waste ashes
Naturally calcined clays	Glass wastes
Hydrothermal sintering of silicon	Fluid cracking catalyst residues

Table 13. *Summary of pozzolans in cement blends.*

Source: *(Jhonatan A. Becerra-Duitama & Rojas-Avellaneda, 2022)*

Pozzolan	High lights
Volcanic ash	The incorporation of volcanic slag in mortar and concrete increases properties such as durability, chloride permeability, and compressive strength. These properties increase with the age of curing and decrease with the content of volcanic slag in the mixture. This decrease is caused by the fact that pozzolanic reactions are retarded at room temperature.
Fly ash	Addition of fly ash in concrete improves workability, reduces runoff and linear shrinkage, decreases the amount of air in the mixture and the heat of hydration. Also, compressive strength increases with the age of curing.
Blast furnace slag	Increases the compressive and flexural strength at mature ages. This depends to a large extent, on the fineness and percentages used in the mix. Also, the porosity decreases, increasing the resistance to sulfate attack and improving durability. Blast furnace slag decreases the heat of hydration but increases the bulk density
Silica fume	Increases the compressive strength at mature ages, acid attack resistance, density, and durability of concrete.
Metakaolin	The recommended level of metakaolin as a cement substitute in concrete is between 10% and 20%. Within these percentages, higher flexural and compressive strengths in the mix are achieved. Similarly, the addition of metakaolin to this pozzolan reduces autogenous shrinkage and increases sulfate resistance and heat of hydration.
Rice husk ash	Improves compressive, tensile, and flexural strength. Moreover, rice husk ash reduces autogenous shrinkage. It also decreases the diffusion of acids in the mixture. The authors recommend a 20% substitution of cement for better results.
Sugarcane bagasse ash	Increases compressive strength at mature ages reduces permeability and increases resistance to acid attack. However, it has not yet been established how it affects concrete durability.
Wood ash	Workability and bulk density were not affected by this substitution. However, the mechanical performance was reduced by up to 45% compared to the reference samples. However, cement can be substituted with wood ash, up to 15%, without affecting the performance of mortars.

- **Natural Pozzolans:** These are materials of geological origin that possess pozzolanic properties. Examples include volcanic ash, pumicite, and certain diatomaceous earths. Some, like kaolinite clay, require thermal activation to become reactive (forming metakaolin) **(Figure 51)**.
- **Artificial Pozzolans:** These are primarily by-products of industrial or agricultural processes. Key examples include:

- **Fly Ash:** A by-product of coal combustion in power plants.
- **Silica Fume:** A by-product of silicon and ferrosilicon alloy production. It is an extremely fine and highly reactive pozzolan.
- **Ground Granulated Blast Furnace Slag:** While also having latent hydraulic properties, it acts as a pozzolan in blended systems.
- **Rice Husk Ash:** An agricultural by-product requiring controlled combustion.

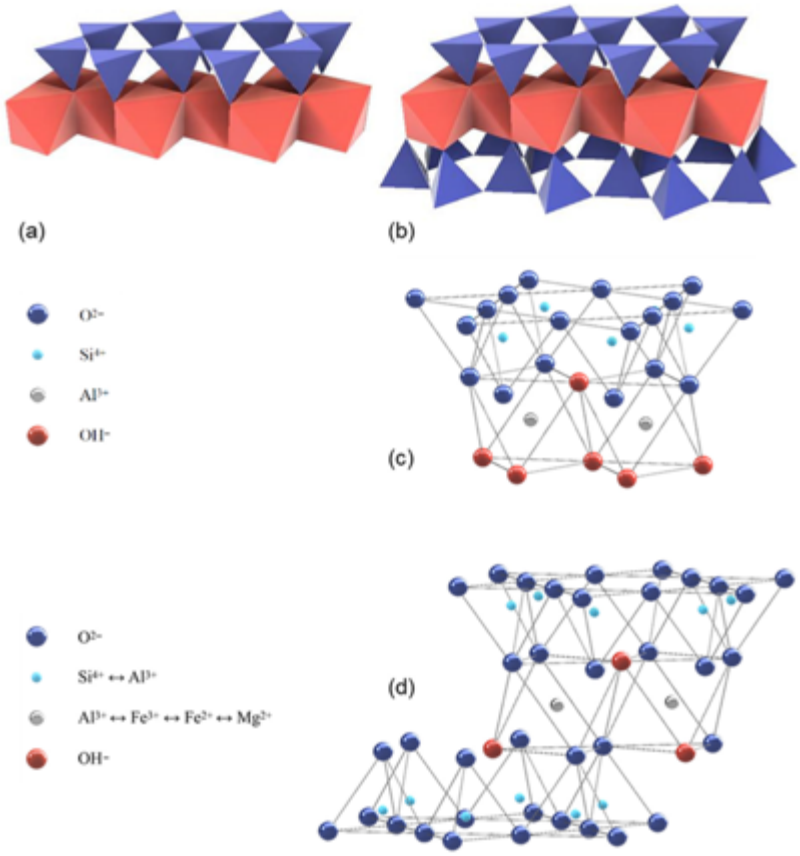


Figure 51. *1:1 layer structure e.g., kaolinite (a) and 2:1 layer structure e.g., montmorillonite (b) illustrated with tetrahedra and octahedra; 1:1 layer structure of kaolinite (c) and 2:1 layer structure of illite (d) illustrated with atom positions.*

Source: *(Overmann et al., 2024)*

Chapter 3

Novel Materials

Introduction

Building upon the foundation of eco-materials and alternative binders, this chapter explores novel composite materials that are engineered to provide unique combinations of performance, sustainability, and functionality. These materials often represent a departure from traditional concrete and masonry, offering specialized solutions for modern construction challenges.

3.1. Self-Compacting Concrete

Self-compacting concrete (SCC), also known as self-consolidating concrete, is a highly engineered, innovative concrete that flows under its own weight, completely filling formwork and encapsulating reinforcement without the need for any mechanical vibration or compaction. Developed in Japan in the late 1980s to address issues of poor compaction and improve the durability of concrete structures, it has since become a vital material in both precast and in-situ construction worldwide **(Figure 52)**.



Figure 52. *Smooth flow and self-levelling of SCC during casting.*

Source: *(Siddique, 2020)*

3.1.1. Mix Design and Fresh State Properties

The unique behavior of Self-compacting concrete is achieved through a carefully balanced mix design that is fundamentally different from that of conventional vibrated concrete **(Figure 53 and 54)**.

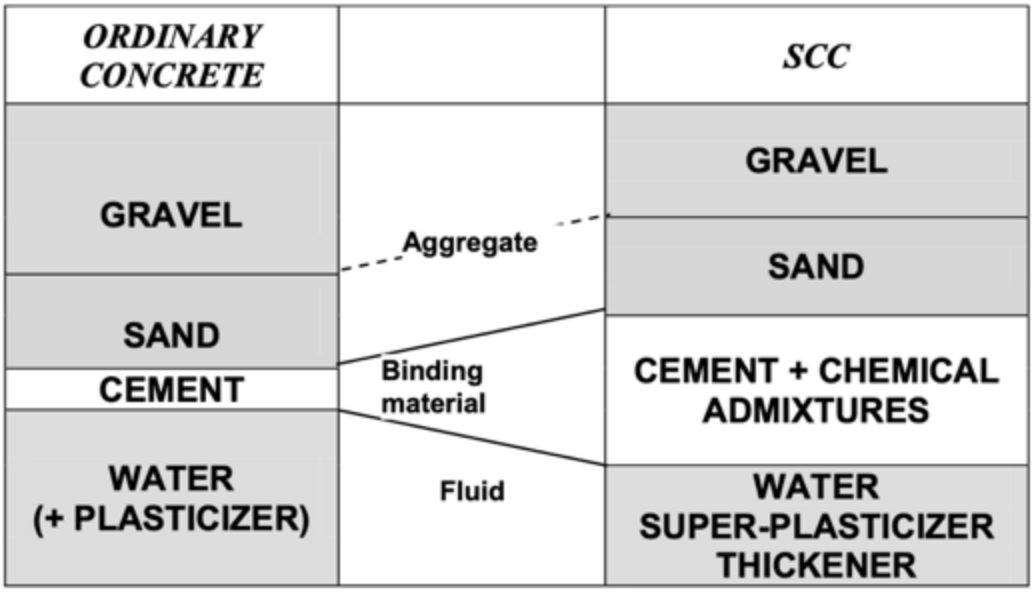


Figure 53. *Schematic comparison between compositions of Self-compacting concretes (SCCs) and conventional vibrated concretes.*

Source: *(Loukili, 2011)*

The key principles are:

- **High Powder Content:** SCC contains a higher volume of fine materials (powder), typically between 450 and 600 kg/m³. This powder fraction consists of cement plus fine fillers like limestone powder, fly ash, or ground granulated blast furnace slag. The high powder volume increases the viscosity of the paste, which is essential for preventing segregation.
- **Low Coarse Aggregate Content:** The volume of coarse aggregate is limited, typically to around 50% of the solid volume, to reduce internal friction and the risk of interlocking and blockage as the concrete flows through reinforcement.
- **Low Water-to-Powder Ratio:** The water-to-powder ratio (by volume) is kept low (e.g., 0.9 to 1.0) to ensure high strength and durability while maintaining cohesion.
- **Essential Chemical Admixtures:** The fluidity of Self-compacting concrete is made possible by the use of a new generation of high-range water-reducing admixtures, or

superplasticizers, typically based on polycarboxylate ethers (PCE). These admixtures provide high flowability at a low water content. In many cases, a Viscosity-Modifying Agent (VMA) is also added to enhance the stability and segregation resistance of the mixture, especially in mixes with lower powder contents.

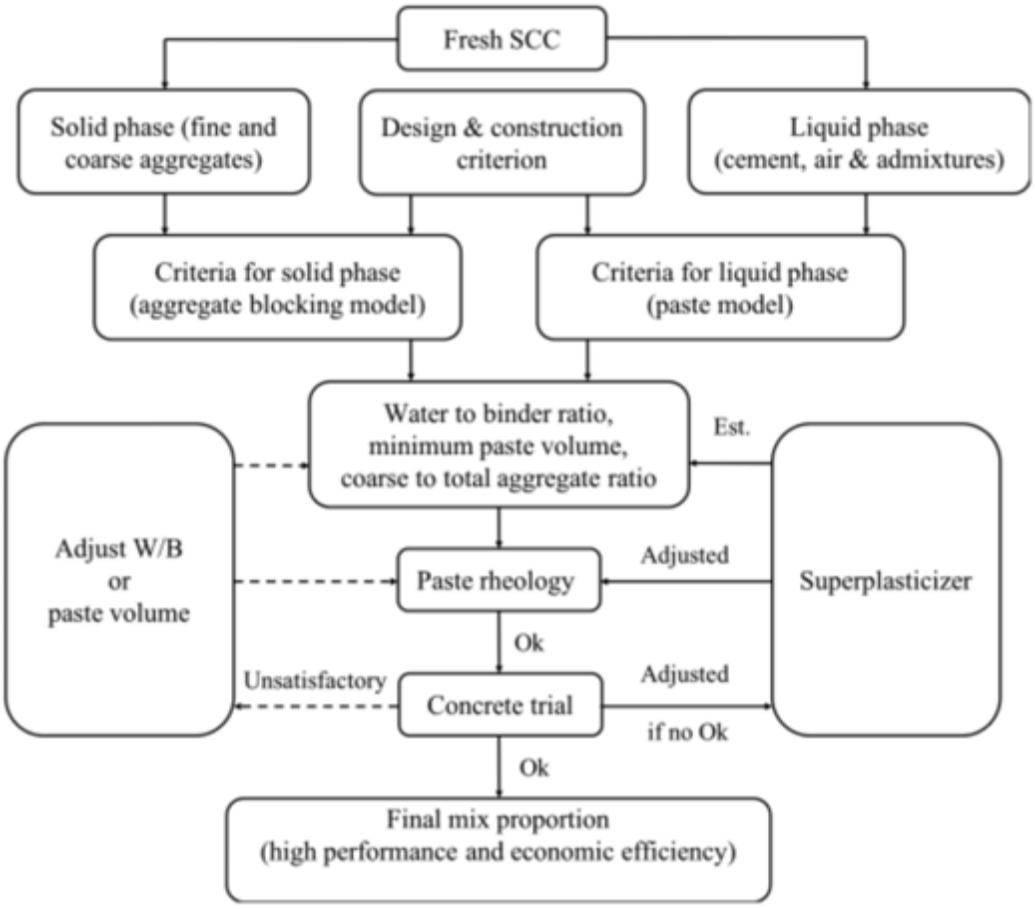


Figure 54. *Mix design procedure of Self-compacting concretes (SCC).*

Source: *(Nuha H. Al_jubory et al., 2020)*

The performance of Self-compacting concrete in its fresh state is characterized by three critical properties **(Figure 55-58)**:

- **Filling Ability:** The ability of the concrete to flow into and completely fill all spaces within the formwork under its own weight. This is typically assessed using the Slump-Flow Test.
- **Passing Ability:** The ability of the concrete to flow through tight spaces, such as congested reinforcement, without segregation or blockage. This is evaluated using tests like the L-box Test or J-ring Test.

- **Segregation Resistance:** The ability of the concrete to remain a stable and homogeneous mixture during transport and placement. This is assessed visually during the slump-flow test or more quantitatively with tests like the V-funnel Test.

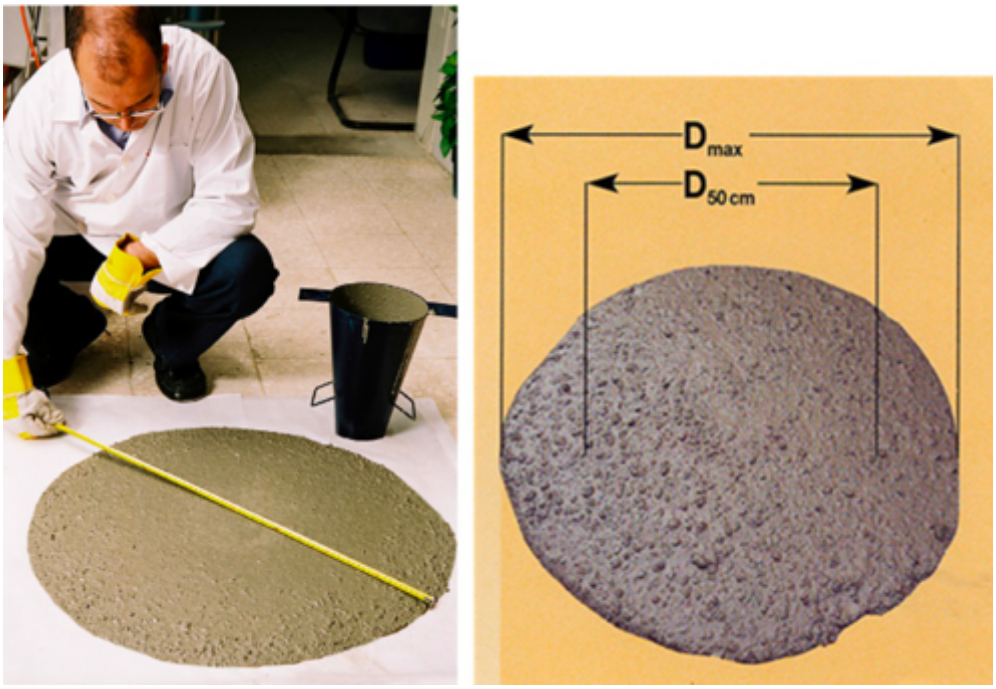


Figure 55. *Slump-flow test.*

Source: *(Siddique, 2020)*

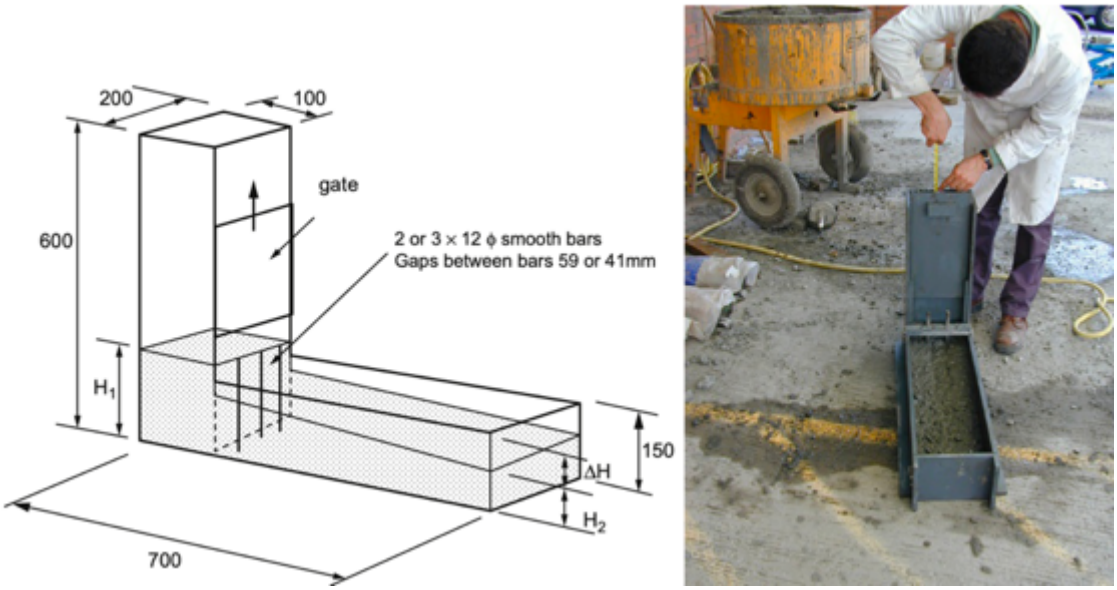


Figure 56. *L-box test.*

Source: *(Siddique, 2020)*

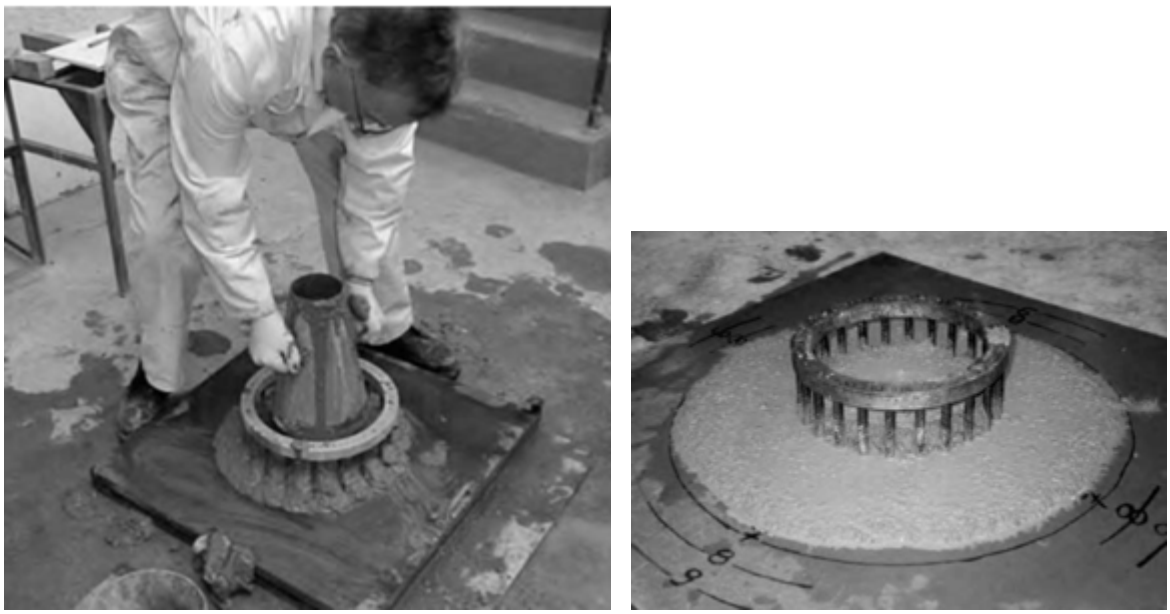


Figure 57. *J-Ring test.*

Source: *(De Schutter, 2008)*



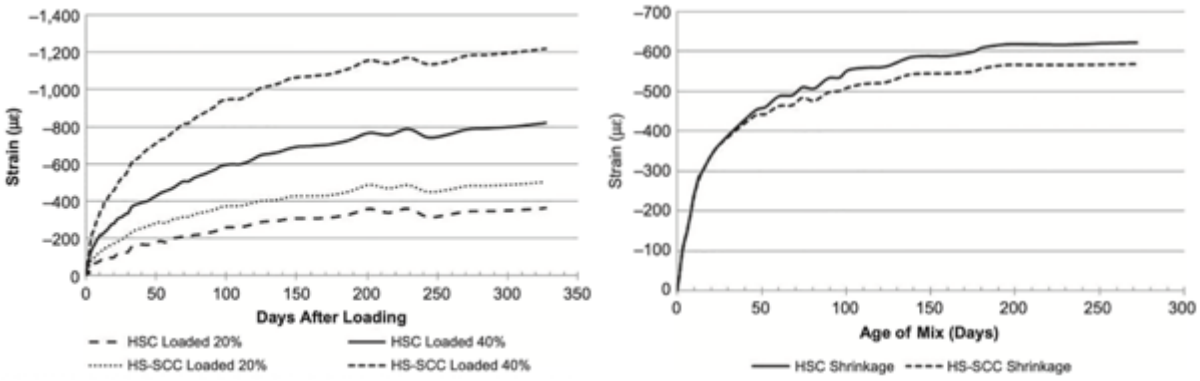
Figure 58. *V-funnel test.*

Source: *(De Schutter, 2008)*

3.1.2. Hardened State Properties and Durability

While the primary innovation of Self-compacting concrete lies in its fresh properties, its hardened properties are also of critical importance. In general, a well-designed Self-compacting concrete can achieve mechanical properties and durability that are comparable or superior to those of conventional concrete with the same water-binder ratio.

- **Compressive Strength:** Self-compacting concrete can be designed to achieve a wide range of compressive strengths, from normal to very high strength. Due to the absence of vibration-induced voids and a more homogeneous microstructure, Self-compacting concrete often exhibits a slightly higher compressive strength than an equivalent vibrated concrete mix. The improved paste quality also leads to a stronger interfacial transition zone between the aggregate and the paste.
- **Modulus of Elasticity, Creep, and Shrinkage:** Due to its higher paste content and lower coarse aggregate volume compared to conventional concrete, Self-compacting concrete may exhibit a slightly lower modulus of elasticity and potentially higher creep and drying shrinkage. These factors must be considered in the structural design of elements where long-term deflection is a concern **(Figure 59)**.



(a) *(b)*

Figure 59. *Creep (a) and Shrinkage (b) results for High-strength concrete (HSC) and High strength Self-compacting concrete (HS-SCC).*

Source: *(Siddique, 2020)*

- **Durability:** The highly dense and homogeneous microstructure of Self-compacting concrete, free from voids and honeycombing, results in very low permeability. This leads to excellent durability performance, including high resistance to chloride ion penetration,

carbonation, and chemical attack. The superior surface finish and uniform quality also contribute to a longer service life for the structure.

3.2. Hemp Concrete (Hempcrete): Properties and Applications

Hempcrete is a bio-composite building material that has gained significant attention for its exceptional environmental credentials and unique performance characteristics. It is not a direct replacement for structural concrete but serves as a lightweight, insulating infill material.

- **Composition:** Hempcrete is created by mixing hemp hurds (also known as shivs), the chopped woody core of the industrial hemp plant, with a lime-based binder and water. The lime binder coats the hemp particles and, through a process of hydration and carbonation, binds them together into a rigid matrix **(Figure 60 and 61)**.



Figure 60. *Hemp Plant & Hemp Hurd.*

Source: *(Parmar & Babbar, 2023)*

- **Key Properties (Table 14):**

- **Low Density and Thermal Insulation:** Hempcrete is a lightweight material with a dry density typically ranging from 200 to 800 kg/m³, significantly lower than conventional concrete. Its high porosity, created by the voids between the hemp particles and the porous nature of the

hurds themselves, gives it excellent thermal insulation properties. Its thermal conductivity is very low, typically in the range of 0.06 to 0.18 W/(m·K), making it an effective insulator.

- **Hygrothermal Performance:** One of hempcrete's most notable properties is its ability to regulate moisture. It is highly vapor-permeable and hygroscopic, meaning it can absorb excess moisture from the indoor air when humidity is high and release it when humidity is low. This "breathing" capacity helps to passively regulate indoor humidity, preventing condensation and mold growth and contributing to a healthier indoor environment.



Figure 61. *Hemp fiber (left), hemp hurd (center) and hempcrete (right).*

Source: *(Asghari & Memari, 2024)*

- **Mechanical Properties:** Hempcrete has very low compressive strength, typically between 0.2 and 1.5 MPa, and is therefore not suitable for load-bearing applications. It must be used as an infill material within a structural frame, such as timber, steel, or concrete.
- **Fire Resistance:** The lime binder renders the organic hemp hurds highly resistant to fire. Hempcrete is non-combustible and does not release toxic fumes when exposed to high temperatures.

Table 14. *Hempcrete properties.*

Source: *(Tong & Memari, 2025b)*

Property	Typical Range
Dry Density	200 - 800 kg/m3
Thermal Conductivity	0.06 - 0.18 W/(m·K)
Compressive Strength	0.2 - 1.5 MPa
Tensile Strength (Splitting)	0.02 - 0.15 MPa
Specific Heat Capacity	1000 - 1590 J/(kg·K)
Water Absorption	20% to 325% by weight

- **Applications:** The primary application of hempcrete is in the construction of monolithic walls, floors, and roofs as an insulating infill. It can be cast in-situ using formwork, sprayed onto a substrate, or pre-manufactured as blocks or panels **(Figure 62)**.



Figure 62. *Hempcrete used in construction:Roof (left), floor (center) and wall (right).*

Source: *(Tong & Memari, 2025b)*

- **Sustainability:** Hempcrete's most significant advantage is its environmental performance. It is considered a carbon-negative material. The industrial hemp plant absorbs a large

amount of CO_2 from the atmosphere during its rapid growth. Additionally, the lime binder absorbs CO_2 over its lifetime as it carbonates. The total amount of CO_2 sequestered in the material is greater than the emissions produced during its cultivation, processing, and construction, resulting in a net removal of CO_2 from the atmosphere. At the end of its life, hempcrete is biodegradable and can be recycled as an aggregate or returned to the soil.

Table 15. *Life cycle assessment (LCA) comparison of hempcrete and conventional concrete.*

Source: *(Tong & Memari, 2025a)*

Property/Metric	**Hempcrete**	**Conventional Concrete**
Global warming potential (GWP)	–1.03 to –2.30 kg CO_2 eq per m^2 (0.25 m-thick wall) [after carbonation] −40 to −80 kg CO_2 eq per m^3 (varies by binder mix)	+300 to +400 kg CO_2 eq per m^3 (OPC concrete) +50 to +90 kg CO_2 eq per m^2 (masonry wall; 0.20–0.25 m thick)
Transport sensitivity	Transport within ~50–200 km adds 5–15% to total GWP; >200 km increases impacts	Cement and aggregates often transported >100 km; transport can contribute 10–20% of OPC GWP
Electricity source impact	Grid electricity for bio-binder production contributes up to 45% of hempcrete GWP; 100% solar reduces net CF by ~164%	Cement production energy (kiln fuel + electricity) >80% of OPC CF
Functional unit	1 m^2 hempcrete wall (0.25 m thick, U-value ≈ 0.27 W/m^2·K) or 1 m^3 hempcrete mix	1 m^2 concrete/masonry wall (0.20–0.25 m thick) or 1 m^3 concrete mix

3.3. Fiber-Reinforced Concrete

Concrete is inherently strong in compression but weak in tension and prone to brittle failure. Fiber reinforced concrete addresses these weaknesses by incorporating short, discrete, randomly oriented fibers into the concrete mixture. These fibers act as a form of micro-reinforcement, bridging cracks as they form and improving the overall toughness, ductility, and durability of the concrete **(Figure 63)**.

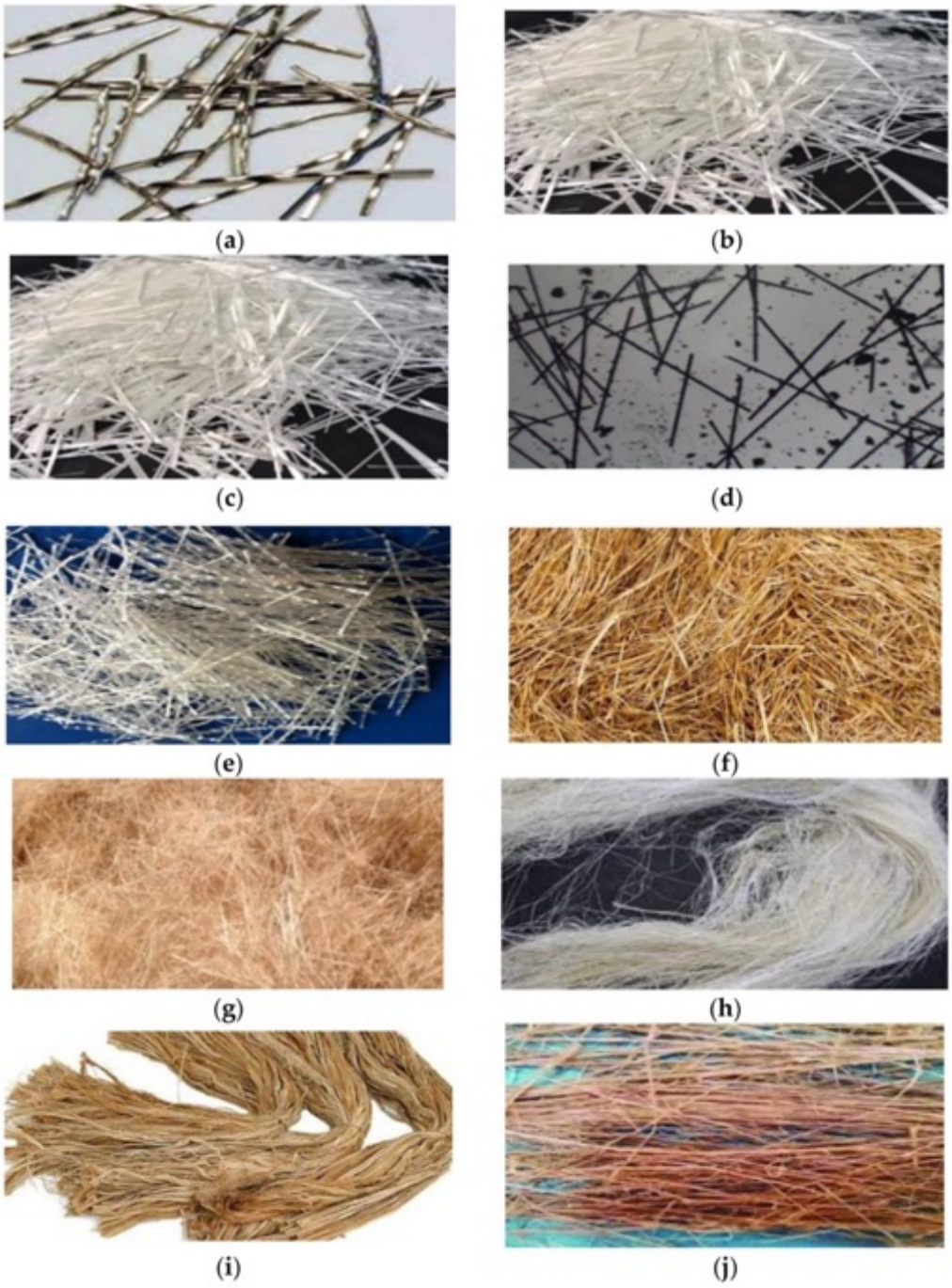


Figure 63. *Appearance of some fibers used in concrete: (a) Steel fibers, (b) Glass fibers (c), Polypropylene Fibers, (d) Carbon fibers, (e) Plastic fibers, (f) wheat straw, (g) Sugarcane fibers, (h) Sisal fibers, (i) Jute fiber and (j) Bamboo fibers.*

Source: *(Anas et al., 2022)*

- **Mechanism of Reinforcement:** When a microcrack initiates in the concrete matrix, it is intercepted by a fiber. To propagate further, the crack must either fracture the fiber or pull it out of the matrix. This process requires significant energy, which is the source of Fiber reinforced concrete's enhanced toughness and post-cracking residual strength. The fibers effectively transfer stress across the crack, allowing the material to sustain load even after initial cracking **(Figure 64-66)**.

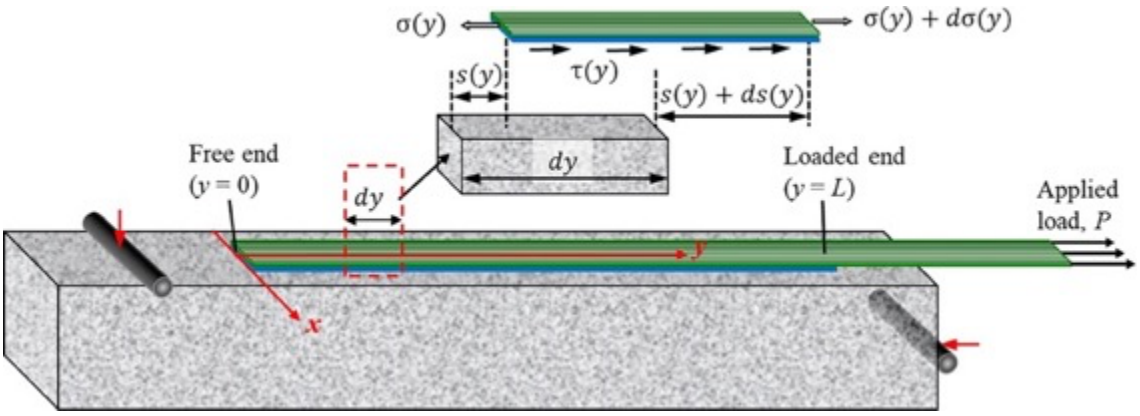


Figure 64. *Bond-slip in fiber-reinforced concrete.*

Source: *(Zou et al., 2021)*

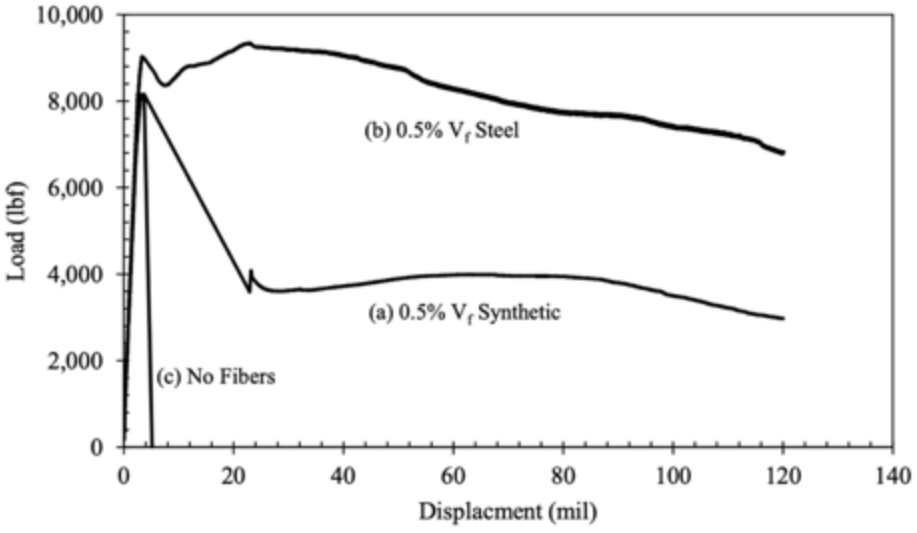


Figure 65. *Typical load-displacement curve for: (a) synthetic fiber, (b) steel fiber and (c) no fibers.*

Source: *(Barman, 2018)*



Figure 66. *Fibers bridging a crack and providing post-crack performance.*

Source: *(Barman, 2018)*

- **Types of Fibers and their Effects:** A variety of fiber types are used, each imparting different properties to the concrete **(Table 16)**:

- **Steel Fibers:** These are the most common type of structural fiber. Due to their high strength and stiffness, steel fibers significantly increase the flexural strength, shear resistance, and energy absorption capacity (toughness) of concrete. They are highly effective at controlling the widening of major structural cracks and transforming the brittle failure of plain concrete into a more ductile one.
- **Synthetic Fibers:**
    - ***Micro-synthetic Fibers (e.g., Polypropylene, Nylon):*** These are very fine, low-modulus fibers used at low dosages. Their primary function is to control plastic shrinkage cracking, which occurs in the first few hours after concrete placement. They do not provide significant structural reinforcement to the hardened concrete.
    - ***Macro-synthetic Fibers (e.g., Polyethylene):*** These are larger, stronger fibers designed to provide post-cracking residual strength, similar to steel fibers. They improve toughness and impact resistance and are often used as an alternative to light steel reinforcement for crack control in applications like slabs-on-ground and pavements.

Table 16. *Performance indicators of fibers for concrete reinforcement.*

Source: *(Jia et al., 2025)*

Classification	Fiber category	Tensile strength(MPa)	Elastic modulus(GPa)	Elongation at break(%)
Metal fibers	Steel fiber	345–1700	200–210	3.5–4.0
	Stainless steel fiber	1500–2500	180–210	1.0–2.0
Inorganic fiber	Basalt fiber	4100–4840	90–110	2.9–3.1
	E-Glass fiber	3400–3700	72–74	3.3–4.8
	S-Glass fiber	4020–4500	83–86	2.0–3.0
	Carbon fiber	3000–6500	230–600	1.0–2.0
Organic fiber	Polyethylene fiber	420–450	3.1–10	15
	Polypropylene fiber	300–520	3.5	15–18
	Polyvinyl alcohol fiber	550–745	4.0–5.8	10–18
	Aramid fiber	3000–3800	70–140	3.0–4.0
	Ultra-high molecular weight polyethylene fiber	1800–3900	40–150	2.0–5.0
	polyoxymethylene fiber	1030	8.5	15
Plant fiber	Sisal fiber	363–700	9.0–38.0	2.0–7.0
	Jute fiber	320–800	26–32	1.0–1.8
	Banana fiber	400–980	6.2–20.0	1.0–10
	Flax fiber	343–1500	27.6–70.0	1.2–3.3
	Bamboo fiber	140–800	11.0–32.0	2.5–3.7

- **Glass Fibers:** Due to the alkaline environment of concrete, standard glass fibers would degrade. Therefore, special Alkali-Resistant glass fibers are used. Glass fiber reinforced concrete is often produced as thin, lightweight panels for architectural cladding, where it provides high flexural and tensile strength.
- **Natural Fibers:** Fibers from natural sources like jute, sisal, or bamboo are being explored as low-cost, sustainable alternatives for reinforcement. They can improve toughness and crack control but may face challenges with long-term durability due to their organic nature.
    - **Hybrid Fiber Systems:** Modern advancements include the use of hybrid fiber reinforced concrete, which combines two or more different types of fibers (e.g., steel and polypropylene) in the same mix. The concept is that different fibers can control cracks at different scales: microfibers control microcracks, while macrofibers bridge larger, structural cracks. This synergistic approach can lead to superior performance across a wider range of loading conditions.

Chapter 4

Construction Materials

Introduction

This chapter explores the forefront of cementitious materials technology, focusing on advanced concretes that offer exceptional performance and specialized materials designed for unique and demanding engineering applications. These innovations are critical for building more resilient, durable, and efficient infrastructure.

4.1. Advancements in Precast Concrete

Precast concrete manufacturing provides a controlled environment ideal for producing high-quality, advanced concrete elements. The evolution of concrete technology has led to a spectrum of high-performance materials that push the boundaries of strength, durability, and design possibilities **(Figure 67)**.

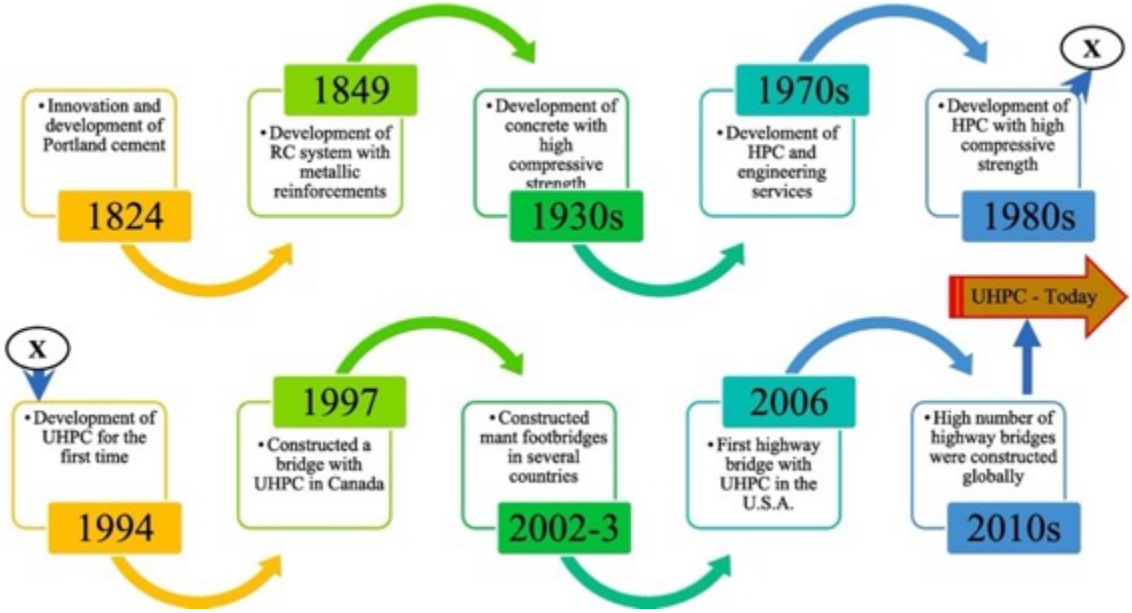


Figure 67. *Historical development trends of UHPC.*

Source: *(Amran et al., 2022)*

4.1.1. High-Performance Concrete (HPC)

High-Performance Concrete is not defined by compressive strength alone but by a combination of characteristics tailored to meet specific performance requirements that surpass those of conventional concrete. These requirements often include enhanced strength, long-term durability,

and excellent workability. The key to achieving these properties lies in the careful selection and proportioning of its constituents, typically involving:

- A low water-to-binder (w/b) ratio, often below 0.40.
- The use of supplementary cementitious materials such as silica fume, fly ash, or ground granulated blast furnace slag to densify the microstructure and improve durability.
- The application of high-range water-reducing admixtures (superplasticizers) to achieve the desired workability at a low w/b ratio.

High-Performance Concrete is widely used in precast applications where high strength and superior durability are paramount, such as in bridge girders, piles, and architectural panels.

4.1.2. Very-High-Performance Concrete (VHPC)

Very-High-Performance Concrete represents a category of concrete that bridges the gap between High-Performance Concrete (HPC) and Ultra-High-Performance Concrete (UHPC). While not a formally standardized term, it generally refers to concretes with compressive strengths in the range of 100 MPa to 150 MPa. Achieving this level of performance requires further refinement of the HPC mix design, typically involving higher dosages of supplementary cementitious materials (especially silica fume), a very low w/b ratio, and meticulous quality control. Very-High-Performance Concrete is used in applications demanding higher strength and lower permeability than what can be achieved with standard HPC, such as in columns for high-rise buildings or specialized industrial structures.

4.1.3. Ultra-High-Performance Concrete (UHPC)

Ultra-High-Performance Concrete is a revolutionary cementitious composite material characterized by exceptionally high compressive strength, significant tensile ductility, and outstanding durability. According to definitions such as that from the Federal Highway Administration (FHWA), Ultra-High-Performance Concrete-class materials exhibit compressive strengths above 150 MPa, sustained post-cracking tensile strength above 5 MPa, and a discontinuous pore structure that provides exceptional durability.

The extraordinary properties of UHPC are derived from its unique composition, which is based on the principle of optimized particle packing density **(Table 17)**, **(Figure 68)**:

- **Binder System:** A high content of Portland cement combined with significant amounts of supplementary cementitious materials, particularly silica fume, to fill voids between cement particles **(Figure 69)**.

Table 17. *Mechanical properties and durability of conventional concrete, HPC and UHPC.*

Source: *(Shi et al., 2024)*

Parameter	**Conventional concrete**	**HPC**	**UHPC**
w/b ratio	~0.5	0.25-0.35	0.14-0.24
Binder content (kg/ m^3)	≤450	400-700	800-1200
Chemical admixture	Superplasticizer not necessary	Superplasticizer necessary	Superplasticizer essential
Supplementary cementitious materials	Not necessary	Silica fume or fly ash	Silica fume or ultra-fine essential
Fibers	Beneficial	Beneficial	Essential
Compressive strength (MPa)	20-60	60-100	≥150
Flexural strength (MPa)	3-5	6-10	25-60
Tensile strength (MPa)	≤3	≤5	5-15
Elastic modulus (GPa)	20-30	30-40	40-60
Fracture energy (J/m^2)	30-100	120-500	20,000-40,000
Chloride- ion diffusion coefficient (steady state) ($\times 10^{-12}$ J/m^2)	1	0.6	0.02
Carbonation depth after 3 years (mm)	7	4	≤1.5
Salt-scaling resistance (g/m^2)	≤1500	150	20-50

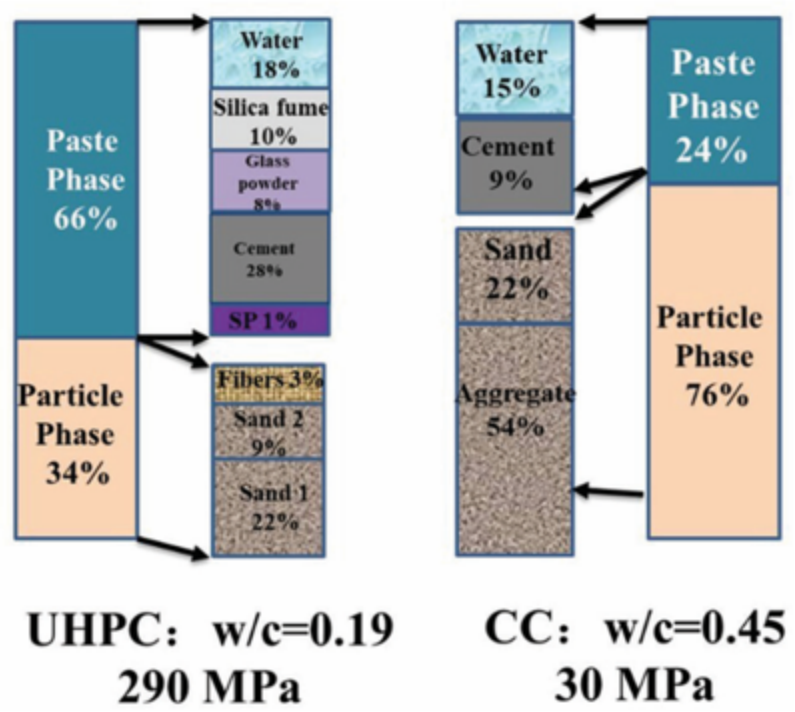


Figure 68. *Typical volumetric proportions of conventional concrete and UHPC.*

Source: *(Shi et al., 2024)*

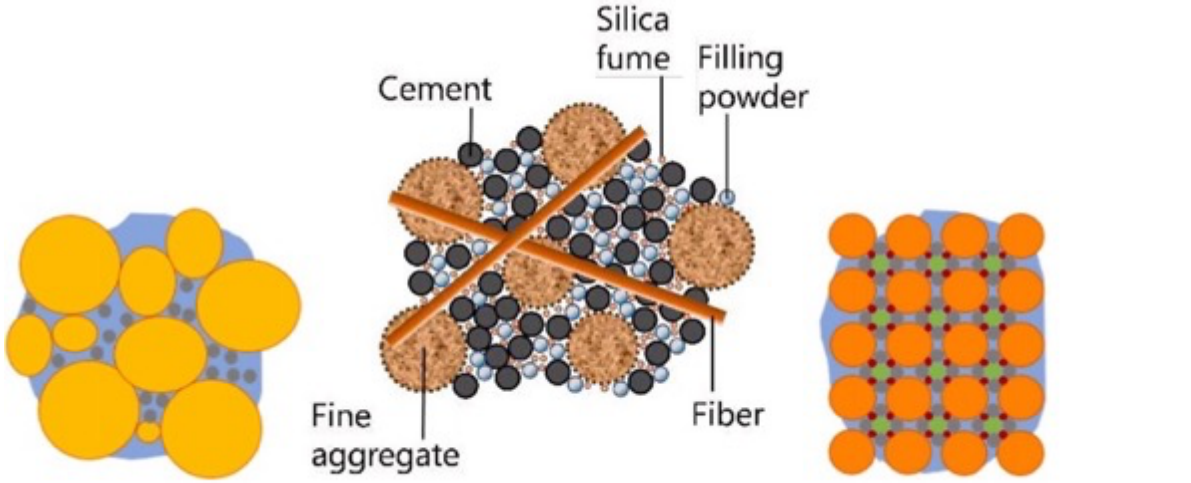


Figure 69. *Particle packing (composition) of Normal strength concrete (NSC) and UHPC.*

Source: *(Amran et al., 2022)*

- **Aggregates:** The elimination of coarse aggregates. Only fine aggregates, such as fine sand and ground quartz, are used to create a more homogeneous matrix.
- **Water-to-Binder Ratio:** An extremely low w/b ratio, typically below 0.20.
- **Fiber Reinforcement:** A high volume (typically 2% or more by volume) of short, high-strength steel fibers is essential. These fibers are critical for providing tensile strength and ductility, allowing the material to strain-harden in tension.
- **Admixtures:** High dosages of advanced superplasticizers are required to achieve a flowable consistency despite the very low water content.

The resulting material has a highly dense, nearly impermeable microstructure, which gives it unparalleled durability against chloride ingress, freeze-thaw cycles, and abrasion **(Figure 70)**. Its high strength and ductility allow for the design of more slender, lightweight, and elegant precast elements, such as long-span bridge girders, thin architectural shells, and durable connections between precast components **(Figure 71)**. While the high initial material cost is a challenge, the extended service life and reduced maintenance needs often make UHPC a cost-effective solution over the lifecycle of a structure.

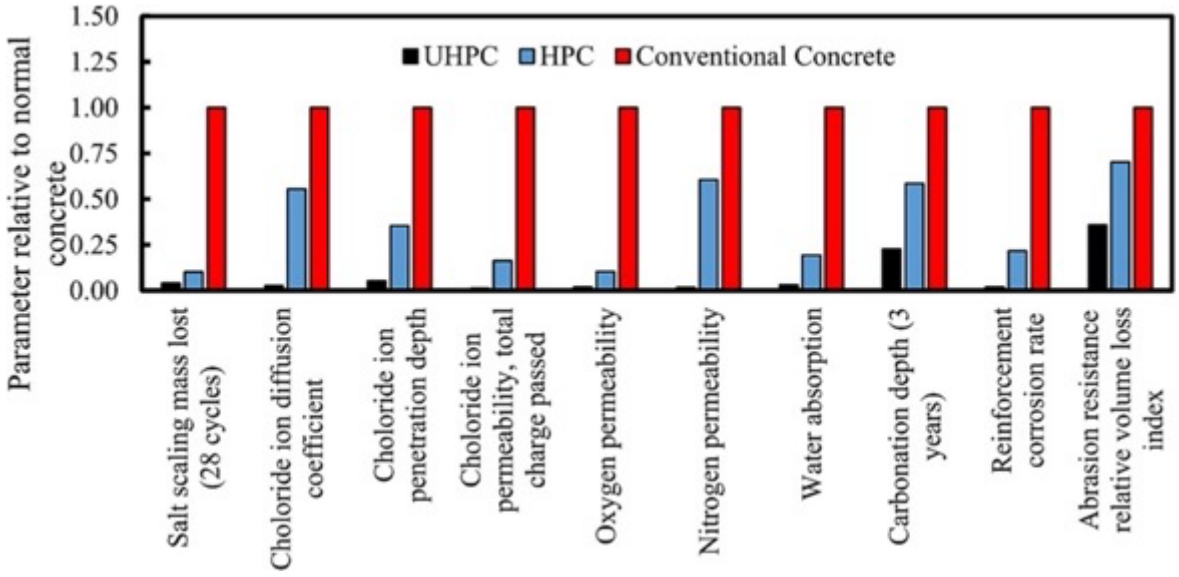


Figure 70. *Durability of UHPC compared with HPC and traditional concrete.*

Source: *(Du et al., 2021)*

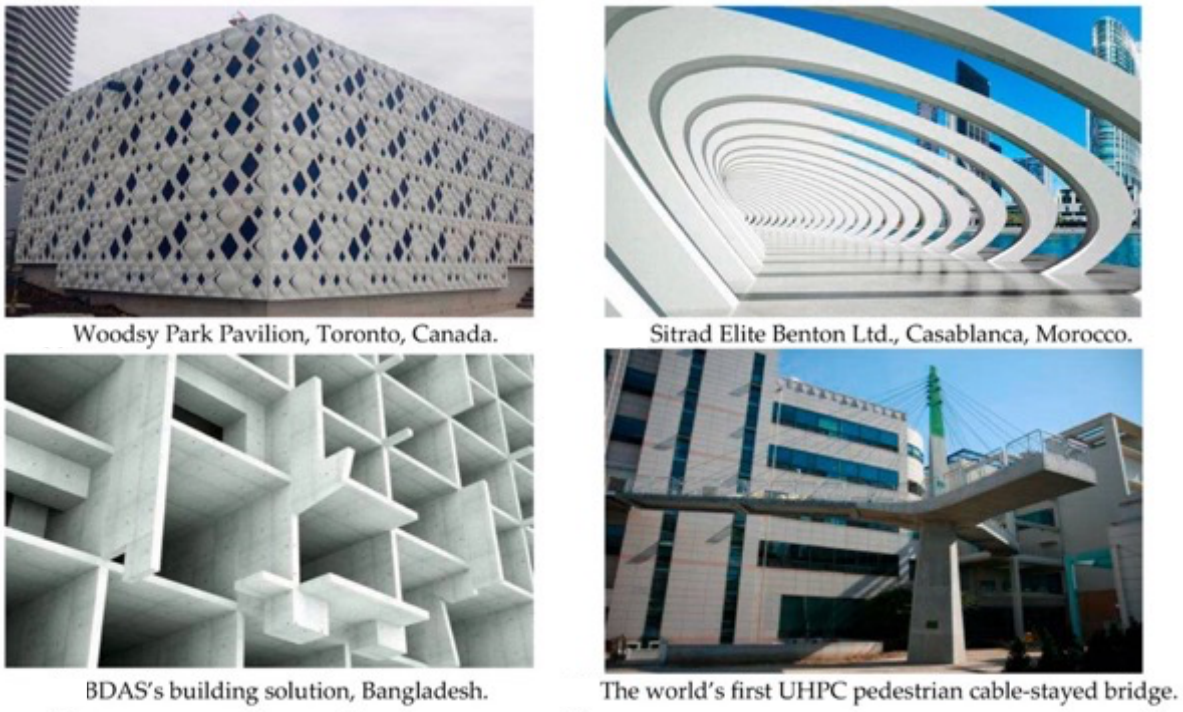


Figure 71. *Typical UHPC building structures.*

Source: *(Kravanja et al., 2024)*

4.2. Low-pH Concrete

Low-pH concrete, also referred to as low-alkalinity concrete, is a specialized binder system designed for use in environments where the high alkalinity of conventional Portland cement concrete (which has a pore solution pH of 12.5-13.5) could have detrimental effects. The primary application driving its development is the construction of deep geological repositories for the long-term disposal of high-level radioactive waste **(Figure 72)**.

In a deep geological repositorie, engineered barriers such as bentonite clay are used to encapsulate waste containers. The hyper-alkaline plume that leaches from conventional concrete can chemically alter and degrade the bentonite, compromising its swelling capacity and low permeability, which are critical for isolating the waste. Low-pH concrete is therefore designed to have a pore solution pH that is in a more stable equilibrium with the surrounding geological environment, with a target pH of around 11 or lower **(Table 18)**.



Figure 72. *Trials of the use of Low-pH concrete for tunnel plugs.*

Source: *(Radioactive Waste Management Committee, 2012)*

The formulation of Low-pH concrete involves a drastic reduction in the amount of Portland cement, which is the primary source of alkalinity (calcium hydroxide). The cement is replaced with very high volumes of supplementary cementitious materials, particularly those rich in silica **(Table 19)**, **(Figure 73 and 74)**:

- **Binder Composition:** A typical Low-pH concrete binder might consist of only 30-40% Portland cement, with the remainder being a blend of Supplementary Cementitious Materials such as microsilica (silica fume) and ground granulated blast furnace slag or fly ash. For example, one successful formulation used a binder composed of 40% cement, 51% microsilica, and 9% slag.
- **Mechanism:** The large quantity of reactive silica from the Supplementary Cementitious Materials consumes most of the calcium hydroxide produced during cement hydration through the pozzolanic reaction. This prevents the establishment of a high-pH environment buffered by Ca(OH)2, resulting in a pore solution with a stabilized, lower pH.

Table 18. *Functional requirements for low-pH concrete plugs.*

Source: *(Alonso et al., 2010)*

Requirement	Target
Hydraulic conductivity	$K < 10^{-10}$ m/s
Final mechanical properties	
Young modulus	> 20 000 MPa
Poisson ratio	0.2-0.3
Tensile strength	> 1 MPa
Friction angle	≥ 37°
Cohesion	≥ 2 MPa
Compressive strength	≥ 10 MPa
Workability	≥ 2 h
Pump ability	100-250 m
Peak of hydration temperature	≤ 40°C; ≤ 30°C
Thermal conductivity	1.2-1.75 W/m°C
Maximum pressure at the plug/buffer interface	3-15 MPa

While achieving the target pH is the primary goal, Low-pH concrete must also meet stringent long-term performance requirements, including mechanical properties comparable to conventional concrete, low permeability, and predictable chemical evolution over thousands of years.

Table 19. Composition of different mixtures.

Source: (Pernicova et al., 2023)

Material (kg)	REF	1A	1B	2A	2B	3
Sand 0–4	885	880	840	935	868	895
Aggregate 4/8	360	375	340	432	401	413
Aggregate 8/16	605	605	570	422	392	404
CEM I 42.5 R Cement	300	120	160	120	140	140
Microsilica	-	153	204	153	179	179
Slag	-	27	36	27	32	32
Water	130	130	170	170	180	200
Plasticizer	6	6	6	6	7	7
Defoamer	-	-	-	-	-	1.75

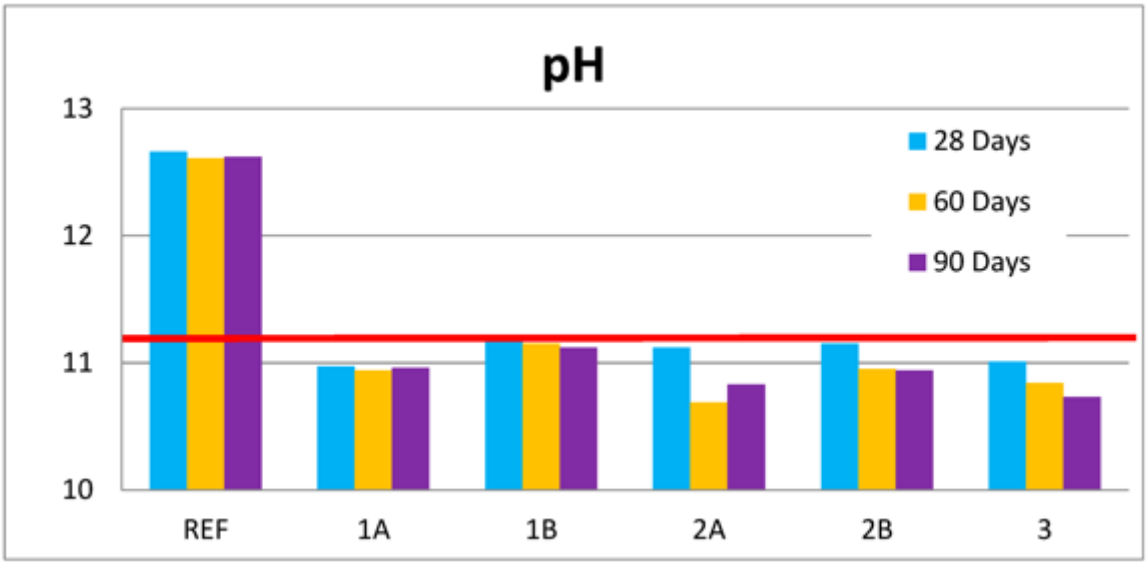


Figure 73. Decrease in pH in concretes dependent on time for the different mixtures.

Source: (Pernicova et al., 2023)

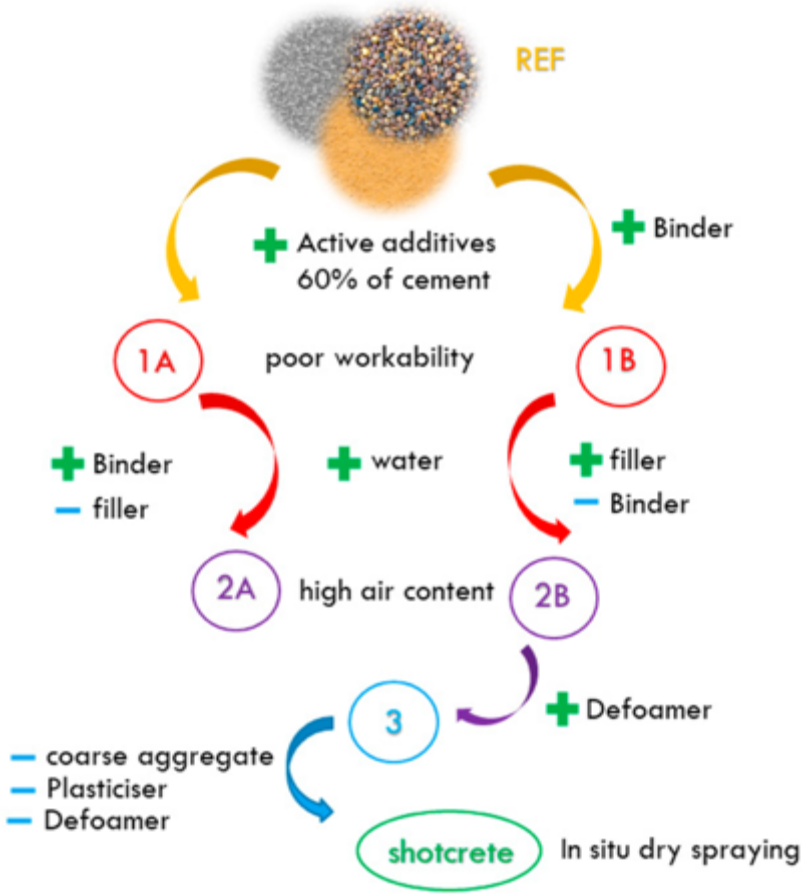


Figure 74. *Flow chart of Materials and Methods for design of the different mixtures.*

Source: *(Pernicova et al., 2023)*

4.3. Injection Grouts: Formulations and Applications

Injection grouting is a geotechnical and structural engineering technique used to inject a fluid-like material (grout) into voids in soil, rock, or concrete structures to improve their properties. The primary objectives of grouting are to reduce permeability (i.e., create a water barrier) and/or to increase strength and stability.

- **Formulations:** Grouting materials can be broadly classified into two categories:

- **Suspension Grouts:** These consist of solid particles suspended in a fluid, typically water. The most common type is cementitious grout, made from a mixture of cement and water, often with admixtures like bentonite (to reduce bleeding), superplasticizers (to improve flow), and

accelerators or retarders (to control setting time). Ultrafine cements can be used to penetrate smaller fissures.

- **Solution Grouts:** These are chemical-based liquids that react in-situ to form a solid or gel. They have very low viscosity and can penetrate much finer soil pores and rock fractures than suspension grouts. Common types include sodium silicates, polyurethanes, epoxies, and acrylamides. The choice of chemical grout depends on the required strength, setting time, and environmental considerations.
    - **Applications and Techniques:** Different grouting techniques are employed depending on the ground conditions and the desired outcome :
- **Permeation Grouting:** This involves injecting low-viscosity grout at low pressure to permeate the pore spaces of soil or fine fractures in rock without disturbing the ground structure. It is used to create cutoff walls under dams or to stabilize sandy soils for tunneling **(Figure 75)**.



Figure 75. *Rock grouting.*

Source:

- **Compaction Grouting:** A very stiff, low-mobility, mortar-like grout is injected at high pressure to displace and densify the surrounding loose soil. It is used to remediate settlement under existing structures or to improve ground bearing capacity **(Figure 76)**.

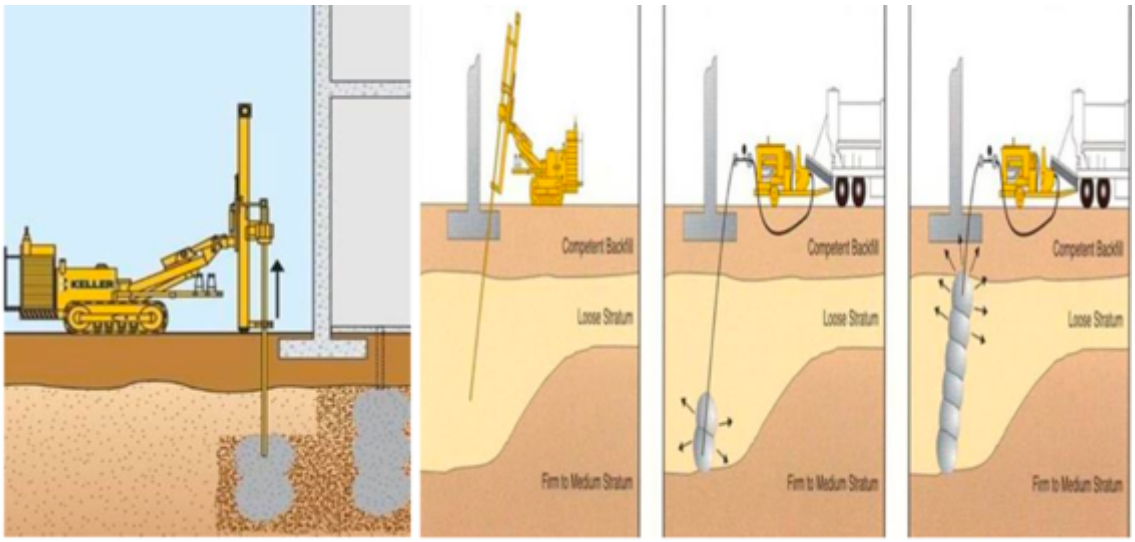


Figure 76. *Compaction grouting.*

Source: *(Zahra, 2024)*

- **Jet Grouting:** A high-pressure jet of grout (and sometimes water and air) is used to erode the soil in-situ and mix it with cement grout, forming hardened columns of "soilcrete". This technique can be used in a wide range of soil types to create structural elements, cutoff walls, or foundation underpinning **(Figure 77)**.

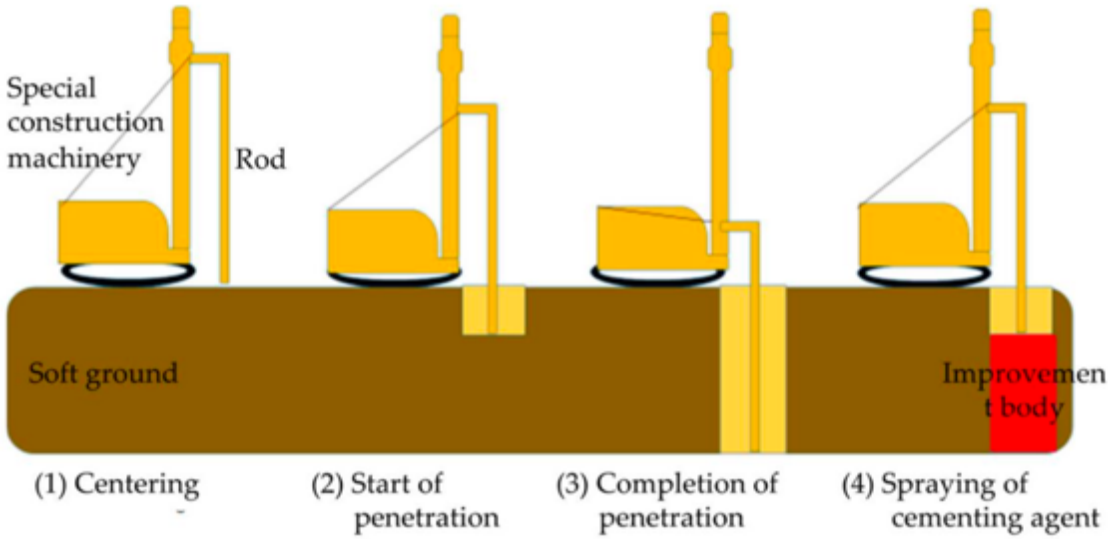


Figure 77. *Jet grouting system construction process.*

Source: *(Zahra, 2024)*

- **Hydrofracture Grouting:** Grout is injected at a pressure high enough to intentionally fracture the soil or rock, creating a network of interconnected grout lenses that increase the overall strength and reduce the permeability of the mass **(Figure 78)**.

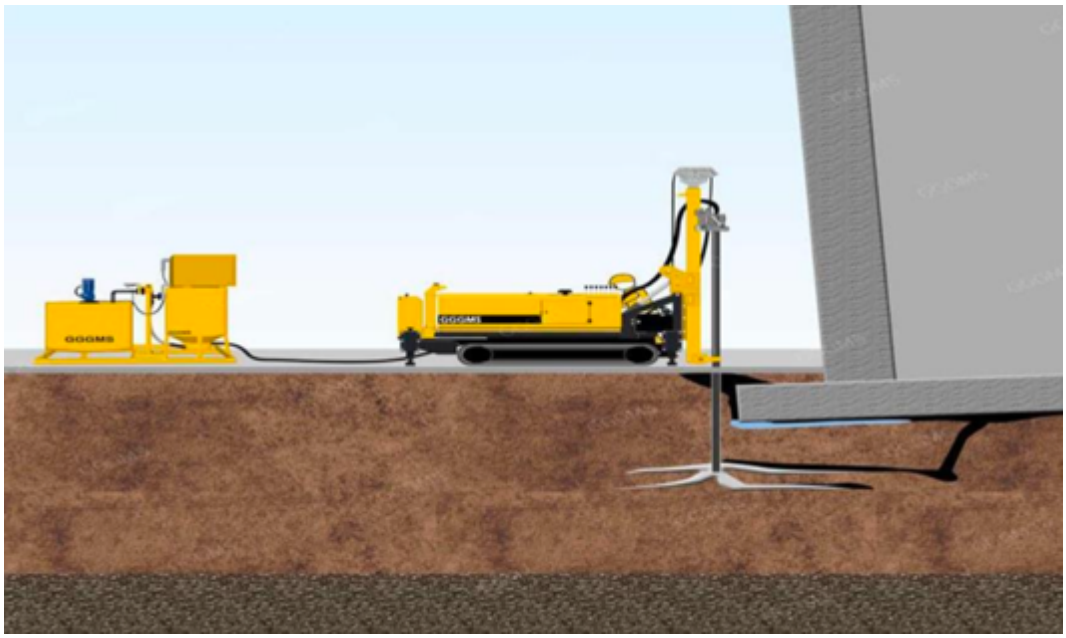


Figure 78. *Fracture grouting.*

Source: *(Zahra, 2024)*

The selection of the appropriate grout formulation and injection technique is a complex engineering decision that depends on a thorough understanding of the site geology, groundwater conditions, and project objectives.

General Conclusion

This review has traversed the expansive landscape of innovative and sustainable materials in construction, revealing a profound and accelerating shift away from traditional, resource-intensive practices. The journey from eco-materials to advanced concrete technologies underscores a unified goal: to create a built environment that is more durable, efficient, and in greater harmony with the planet's ecological limits.

The principle of material valorization has emerged as a foundational strategy, transforming the concept of waste into one of resource potential. By applying scientific principles to industrial and agricultural by-products (such as slags, ashes, recycled glass, and dredged sediments) the industry is moving beyond simple landfill diversion towards the creation of high-performance materials that actively contribute to a circular economy. This is complemented by a renewed appreciation for natural materials, where ancient resources like stone and earth are being re-engineered through modern techniques (such as ventilated facades and soil stabilization) to meet contemporary performance standards while retaining their inherent low-embodied-energy advantages.

The development of alternative binders directly confronts the most significant contributor to the industry's carbon footprint: Portland cement. Innovations ranging from low-carbon belitic cements and alkali-activated geopolymers to bio-binders demonstrate a multi-pronged approach to decarbonizing concrete. Simultaneously, the emergence of novel composites like self-compacting concrete, carbon-negative hempcrete, and ductile fiber-reinforced concrete showcases a move towards multifunctional materials that enhance not only sustainability but also constructability, building performance, and structural resilience. Finally, advancements in high-performance concretes, culminating in Ultra-High-Performance Concrete, illustrate the pinnacle of material science in construction, enabling structures with unprecedented strength and century-long service lives, the ultimate expression of material efficiency.

The trajectory of material innovation points towards a future where the principles of the circular economy are not an alternative but the default mode of operation for the construction industry. The materials and techniques presented in this handout are not isolated solutions but interconnected

components of a systemic transformation. The future of sustainable construction lies in the intelligent synthesis of these innovations and creating hybrid systems that combine the benefits of different materials. One can envision structures built with geopolymer concrete made from valorized fly ash, reinforced with recycled steel fibers, and insulated with carbon-negative hempcrete panels, all designed for easy disassembly and reuse at the end of their life.

Achieving this vision requires a collaborative effort among researchers, industry stakeholders, and policymakers. Continued research will refine material performance and reduce costs, industry adoption will drive economies of scale, and supportive government policies and regulations will create the market conditions necessary for widespread implementation. The ultimate goal is a built environment that is not only resilient, safe, and functional but also regenerative, one that minimizes its demand on finite resources, eliminates waste, and contributes positively to the health of our planet's ecosystems. The journey is complex, but the path forward, paved with the innovations detailed herein, is clear.

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