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Sustainable Human Settlements through Pozzolan Concrete: Lessons from Ancient Roman concrete

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Abstract

Concrete in achieving sustainable human settlements, drawing insights from ancient Roman construction practices and examining modern applications, With the global cement industry contributing significantly to CO2 emissions, the adoption of supplementary cementitious materials like pozzolans offers a viable pathway to reduce environmental impact. The study highlights the historical use of pozzolans in Roman concrete, known for its exceptional durability and self-healing properties, and investigates the potential of natural pozzolanic resources in Libya, specifically within the Al Haruj Volcanic Province. Petrographic analysis of ancient Roman concrete from Sabratha ancient city provides valuable lessons for contemporary sustainable construction. The paper advocates for the integration of eco-friendly resources and sustainable practices within the cement industry to align with Sustainable Development Goals (SDGs) 9, 11, 12, 13, and 17.

Keywords: Sustainable Settlements, Pozzolan, ancient Roman Concrete, Al Haruj Libya.

1. Introduction

The rapid urbanization and expansion of human settlements globally necessitate a critical re-evaluation of construction materials and practices to ensure long-term sustainability. Concrete, as the second most consumed material globally after water (Gagg, 2017), plays a pivotal role in infrastructure development. However, the production of Ordinary Portland Cement (OPC), the primary binder in concrete, is a major contributor to global carbon dioxide (CO2) emissions, accounting for approximately 7% of the total (Brogan, 2022). This significant environmental footprint arises from both the calcination of limestone (50%) and the combustion of fossil fuels (40%) during clinker production, with an additional 10% attributed to raw material transportation and electricity generation (Brogan, 2022).

Addressing these environmental challenges is crucial for achieving several United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 17 (Partnerships for the Goals). One promising solution lies in the increased utilization of supplementary cementitious materials (SCMs), such as pozzolans, which can partially replace OPC, thereby reducing clinker content and associated CO_2 emissions (Müller & Harnisch, 2008). These materials are vital for creating a “climate-friendly” cement industry.

This paper aims to investigate the potential of pozzolan concrete as a sustainable building material. It draws parallels between the enduring legacy of ancient Roman concrete, which extensively utilized natural pozzolans, and contemporary efforts to develop eco-friendly construction solutions. The study will also focus on the specific context of Libya, a region rich in natural pozzolanic resources, exploring their potential for local cement production and sustainable development. By examining historical precedents, modern advancements, and regional opportunities, this research seeks to provide a comprehensive understanding of how pozzolan concrete can contribute to safer and more sustainable human settlements.

2. The Environmental Impact of Ordinary Portland Cement Production

The production of (OPC) is an energy-intensive process with substantial environmental consequences. The primary chemical reaction involved in clinker production, the decomposition of limestone ($CaCO_3$), releases CO_2:

$CaCO_3 \leftrightarrow CaO + CO_2$ (Brogan, 2022)

This calcination process alone accounts for a significant portion of the CO_2 emissions. Furthermore, the high temperatures required for clinkerization (typically 1400-1450°C) are achieved by burning fossil fuels, leading to additional greenhouse gas emissions (Kacimi *et al*., 2006; Telschow, 2012). The cumulative effect is that for every ton of OPC produced, approximately one ton of CO_2 is emitted into the atmosphere (Brogan, 2022).

The global demand for concrete, exceeding 12 billion tons annually (IEA, 2023), underscores the urgency of mitigating the environmental impact of its primary component. The cement industry’s contribution to global CO_2 emissions, estimated at around 7%, highlights the need for innovative and sustainable alternatives to conventional OPC. Reducing the carbon footprint of concrete is therefore a critical step towards achieving climate action goals and fostering responsible industrial practices.

3. Pozzolans: A Sustainable Alternative

3.1 What are Pozzolans?

The term “pozzolan” originates from Pozzuoli, Italy, a region historically rich in volcanic ash. Pozzolans are siliceous or aluminous materials that, in the presence of moisture, chemically react with calcium hydroxide ($Ca(OH)_2$) to form compounds with hydraulic cementitious properties (Efstathiadis, 2004). This reaction enhances the strength and durability of concrete while consuming the byproduct of cement hydration, $Ca(OH)_2$, which would otherwise contribute to porosity and weakness.

Pozzolans can be broadly classified into two categories based on their origin:

- **Natural Pozzolans:** These include volcanic ash, volcanic tuff, and pumicite. Their use dates back thousands of years.

- **Artificial Pozzolans:** These are byproducts of industrial processes, such as fly ash (from coal combustion), silica fume (from silicon and ferrosilicon alloy production), and granulated blast furnace slag (from iron manufacturing).

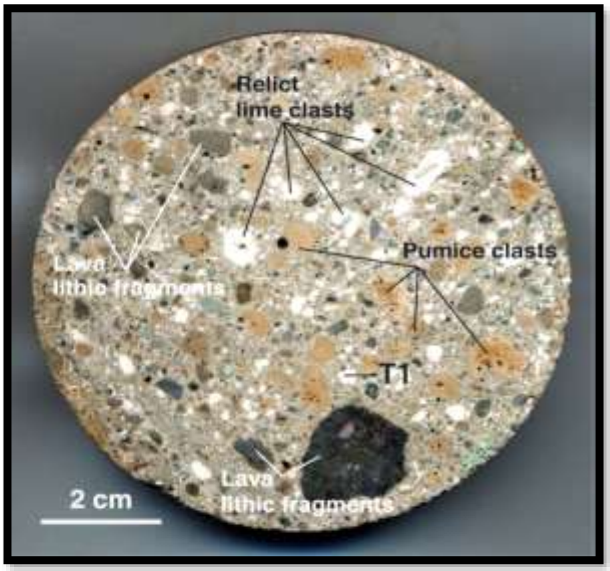


Fig (1) ancient Roman pozzolan concrete

3.2 Historical Significance: Roman Pozzolan Concrete

The ancient Romans were pioneers in the use of pozzolanic materials, recognizing their superior binding properties. Around 3000 years ago, pozzolans were the first cementing materials employed for the production of artificial stones, ancient mortars and concretes (Dedeloudis *et al*., 2017). Roman engineers, particularly during the 3rd century BC, utilized volcanic tuffs (pozzolans) in combination with lime to create hydraulic binders for monumental constructions like bridges, masonry, and brickwork. A common mixture involved two parts pozzolan to one part lime by weight (Efstathiadis, 2004).

Roman concrete (Fig1) incorporating these natural pozzolans, is renowned for its exceptional longevity and resilience, with many structures still standing today. Notable examples include the Pantheon and the Colosseum in Rome, and the Pont-du-Gard aqueduct in Nimes (Luiso, 2020). The science behind this durable material was largely lost after the fall of the Roman Empire, only to be rediscovered much later (Tellis & Tellis, 2014).

The sustainability of Roman concrete can be attributed to several characteristics (Seymour *et al*., 2023; Martinez, 2025):

- **Durability:** Its long-lasting nature minimizes the need for frequent maintenance and repairs, reducing the overall carbon footprint of buildings.
- **Low Porosity:** Resistance to water and other fluids prevents weathering and erosion, extending its lifespan.
- **Self-healing Properties:** The presence of aluminous silicate allows the concrete to self-repair minor cracks over time, further reducing maintenance requirements.

- **Low Energy Consumption in Production:** Made from natural, locally sourced materials like volcanic ash, lime, and seawater, its production required significantly less energy compared to modern concrete.
- **Relevance to Local Resources:** The ability to use local resources reduced transportation costs and emissions.

3.3 Petrographic Analysis of Roman Concrete in Sabratha Libya.

Historical evidence of pozzolan used in Libya was found in ancient Roman sites such as Leptis Magna,Oya and Sabratha including the Nile Villa, Wadi Lebda Villa (Leptis magna) , Nereides Villa (east Oya), sea baths, oil presses (Sabratha), reveals the composition of these ancient materials (Turki, 2012; El-Tawab, 2012).

Concrete samples and mortar were carefully selected to avoid the damage to evaluate the petrographic analysis from sea baths, oil presses (Sabratha) typically involve preparing polished thin sections (30µm thick slices) for examination under a polarizing microscope, often with a 35mm camera for detailed documentation. The petrographic examination of these Sabratha Sea paths and oil pressing Roman concretes shows a composition dominated by micrite, pellets, fossils, and shell fragments, along with intraclasts of non-crystalline igneous grains. These are characterized by medium to coarse, rounded, and moderately sorted particles, including subrounded quartz grains and crushed bricks (Fig 2). This composition is consistent with the use of local natural aggregates and pozzolanic materials, highlighting the ingenuity of Roman engineers in utilizing available resources for durable construction.

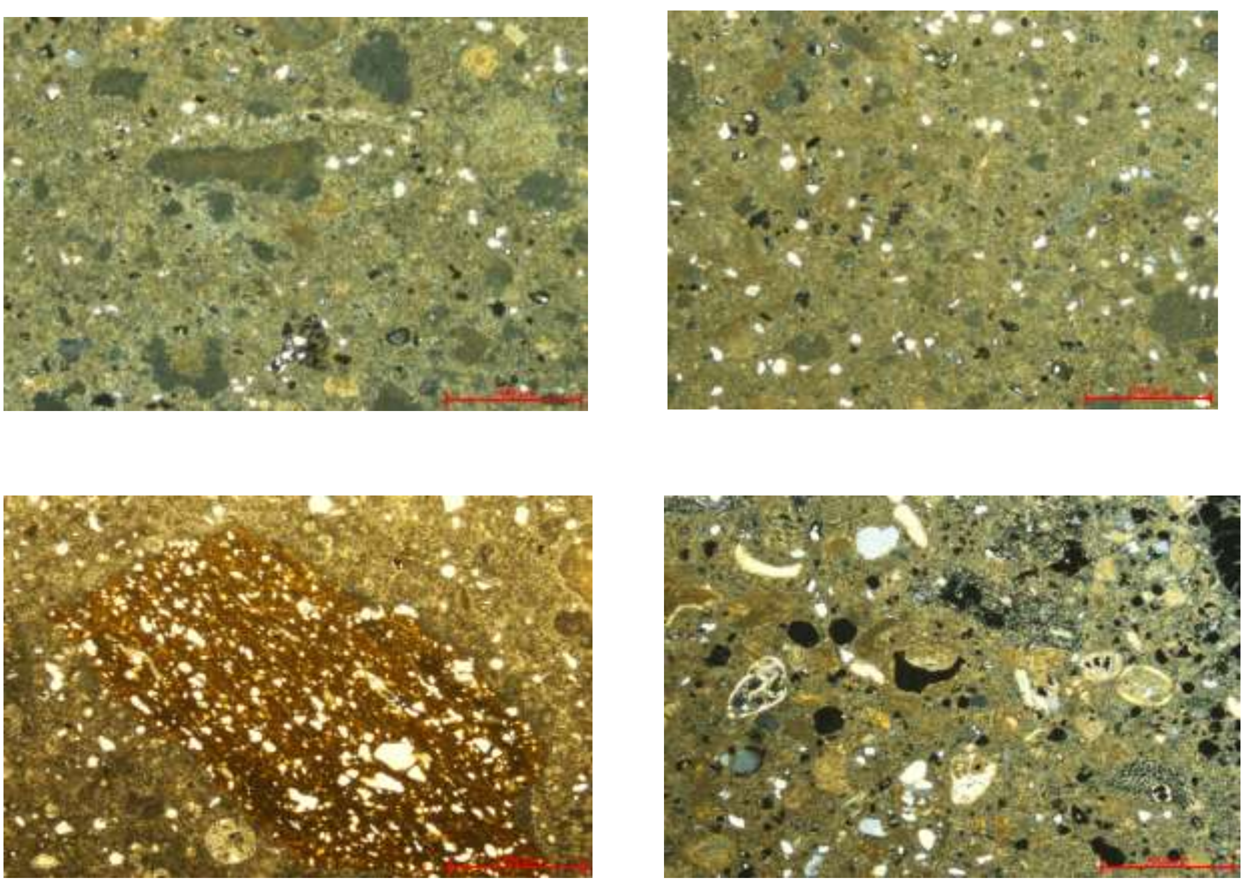


Fig (2): Photomicrograph showing ancient Concrete samples and mortar selected from Sabratha

3.4 Modern Applications and Environmental Benefits

The re-emergence of pozzolan use in modern construction is driven by the imperative to reduce the environmental impact of cement production. The substitution of OPC with pozzolans can lead to a significant reduction in CO_2 emissions, both by decreasing the amount of clinker required and by lowering the energy demand for kiln operation. It is estimated that the substitution of pozzolan alone could achieve a 5-8% reduction in total CO_2 by 2050, representing a 30% decrease in the carbon footprint of OPC (Miller *et al*., 2018).

CO_2 reduction, pozzolans offer some other benefits (Al-chaar, 2011; Malaiškienė *et al*., 2025)

- **Reduced Heat of Hydration:** This minimizes the risk of thermal cracking in mass concrete structures.
- **Improved Workability:** Pozzolans can enhance the plasticity and ease of placement of concrete mixtures.
- **Enhanced Durability:** They contribute to increased resistance against chemical attacks (e.g., sulfate attack, sulfuric, hydrochloric acid attacks) and alkali-silica reaction (Siad *et al*., 2010).

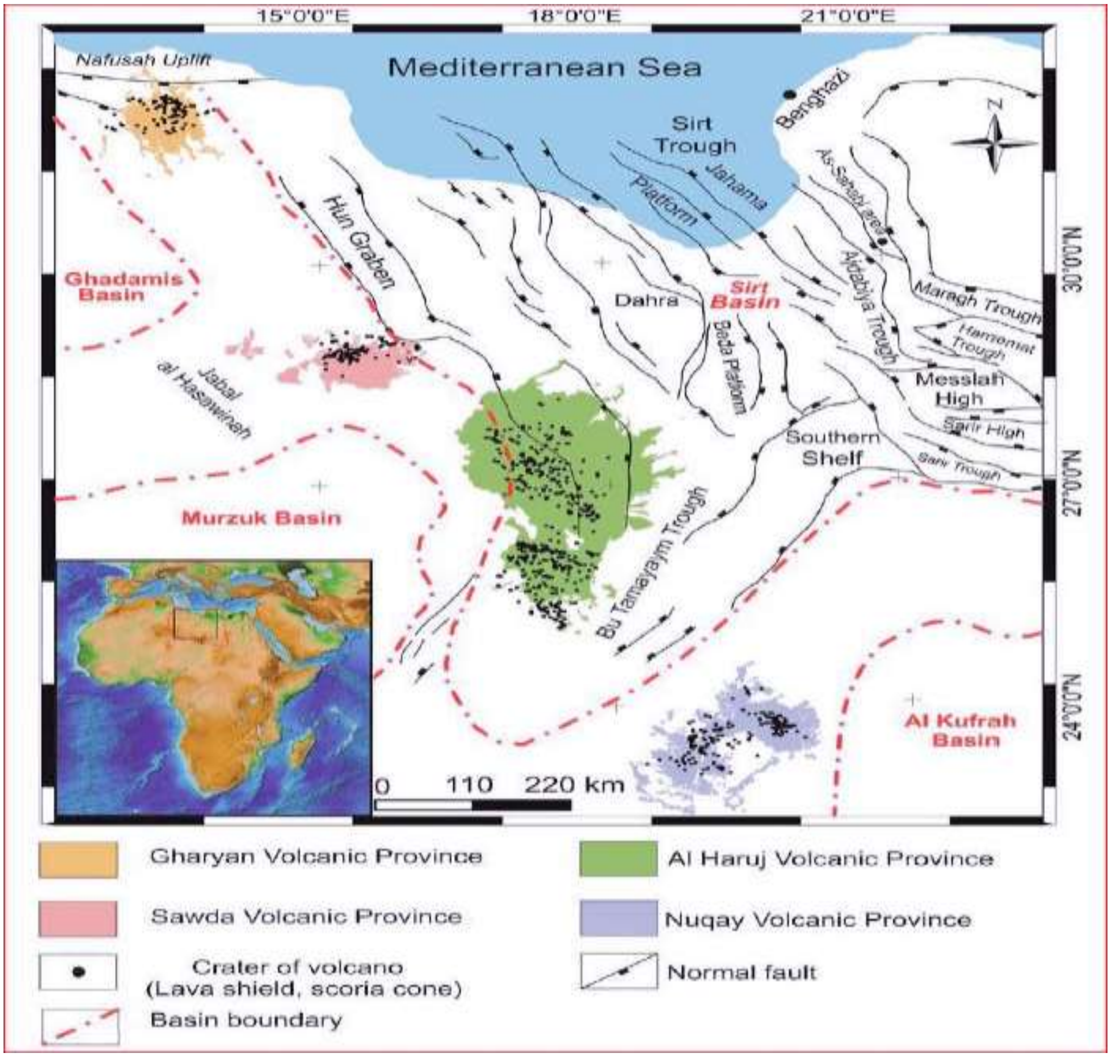
Modern examples of pozzolan use include the Golden Gate Bridge and Davis Dam in the USA, and more recently, the Burj Khalifa in the UAE, which utilized fly ash and silica fume as partial cement replacements (Aldred, 2007). The Japanese company Tekuto has also pioneered the use of volcanic ash (shirasu concrete) as a sand replacement in their sustainable housing projects (Tekuto, 2017). Furthermore, advancements in nanotechnology are being explored to further enhance the properties of concrete, offering even greater potential for performance improvements (Rathi & Modhera, 2014; Meshram *et al*., 2023). These examples demonstrate the versatility and effectiveness of pozzolans in diverse construction applications.

4. Pozzolanic Resources and Potential in Libya

Libya possesses significant natural pozzolanic resources, primarily within its extensive volcanic provinces. Al Haruj Volcanic Province (AHVP), along with Nuqay (NVP), Gharyan (GVP), and As Sawda (SVP), represent the main volcanic regions in the country Fig(3). The AHVP, located at the south-western margin of the Sirt Basin, is particularly notable for its extensive and recent volcanic activity, covering an area of approximately 42,000 km² (Elshaafi, 2018). This vast geological resource presents a substantial opportunity for sustainable cement production within Libya.

Petrochemical studies of the AHVP indicate that most volcanic rocks belong to the alkaline olivine basaltic ranging in composition from alkaline to mildly alkaline basalts (Farahat *et al*., 2006). These basalts, along with associated volcanic tuffs and ashes, can exhibit pozzolanic properties, making them suitable for use as SCMs in cement production. Research into the specific mineralogical and chemical characteristics of these materials is crucial to optimize their application in concrete.

Further detailed studies on the pozzolanic activity index of materials from AHVP are needed to quantify their effectiveness as cement replacements and to guide their industrial application. (Elshaafi, 2018)



Fig(3): Libya possesses significant natural pozzolanic resources

5. Results and Discussion

The petrographic and literature-based analysis of Roman concrete from Libyan archaeological sites such as Leptis Magna and Sabratha demonstrates the significant role of pozzolanic materials in enhancing long-term durability and structural performance. The observed microstructure, characterized by micrite, fossil fragments, shell debris, and subrounded quartz grains embedded within a heterogeneous cementitious matrix, reflects the intentional use of locally available natural aggregates and reactive pozzolanic materials. Similar compositional features have been reported in ancient Mediterranean concretes, where volcanic materials contributed to the development of durable hydraulic binders (Efstathiadis 2004)

The effectiveness of these materials is primarily attributed to the pozzolanic reaction, in which amorphous silica reacts with calcium hydroxide ($Ca(OH)_2$) to form calcium silicate hydrate (C–S–H), the principal phase responsible for strength and durability in cementitious systems . This reaction reduces free calcium hydroxide and enhances long-term chemical stability (Said etal2010).

From an environmental perspective, the integration of pozzolanic materials into concrete systems represents a critical strategy for reducing the carbon footprint of the construction sector. The production of Ordinary Portland Cement (OPC) contributes approximately 7% of global CO_2 emissions due to calcination and fuel combustion (Brogan 2022). Partial replacement with pozzolans reduces clinker demand and associated emissions. Studies indicate that such substitution may reduce emissions by up to 30% by 2050 (Miller2018).

In addition to environmental benefits, pozzolans improve concrete performance by reducing heat of hydration, enhancing durability, and increasing resistance to chemical attack such as sulfate exposure (Said2010). These findings are consistent with modern engineering practices where supplementary cementitious materials are widely applied (Aldred2017).

The Libyan geological context offers strong potential for pozzolan utilization. The Al Haruj Volcanic Province represents a major natural source of pozzolanic materials, characterized by alkaline basaltic compositions suitable for cement applications. Geological studies indicate that these materials may exhibit sufficient pozzolanic activity for industrial use (Elshaafi 2018).

However, further experimental validation is required, including compressive strength testing, durability analysis, and pozzolanic activity indices. Such testing is essential to confirm performance and optimize mix designs for practical applications (Said2010).

Overall, the results demonstrate that pozzolan-based concrete represents a sustainable and durable solution for modern construction, integrating historical knowledge with modern engineering practices and supporting environmentally responsible development strategies (Miller2018).

6. Conclusion

The integration of pozzolans into concrete technology offers a compelling pathway towards more sustainable human settlements, aligning with global efforts to mitigate climate change and achieve the SDGs. The lessons from ancient Roman construction, where pozzolan concrete demonstrated unparalleled durability and self-healing capabilities, underscore the long-term benefits of this material.

The global cement industry must embrace eco-friendly resources like pozzolans to significantly reduce its carbon footprint. The use of pozzolans not only decreases the demand for OPC, thereby lowering $CO2$ emissions, but also enhances the performance and longevity of concrete structures. Furthermore, it contributes to reducing the heat of hydration and improving workability, leading to more robust and sustainable built environments.

Libya, with its abundant natural pozzolanic resources, particularly in the Al Haruj Volcanic Province, is well-positioned to leverage these materials for sustainable development. Investment in research and development to characterize and optimize the use of Libyan pozzolans in cement production is crucial. This includes detailed petrographic and chemical analyses to determine their pozzolanic activity and suitability for various applications.

By adopting these recommendations, the construction industry can move towards a more sustainable future, creating resilient and environmentally responsible human settlements for generations to come.

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