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Great Pyramid Construction : In-Situ Casting of Composite Blocks

Ahmed H. Bakir [a], Rasha Bakir [b] and Reem A. Bakir*[c]
[a] Communication Engineer, Cairo University, Giza, Egypt.
E-mail: ahmed.h.bakir@hotmail.com
[b] Assistant Lecturer, Architectural Department, Cairo University, Giza, Egypt.
E-mail: r.bakir13@eng.cu.edu.eg
[c] Lecturer, Architectural Department, Cairo University, Giza, Egypt.
*Corresponding author: Reem Ahmed Bakir
E-mail: rbakir7@gmail.com
rbakir7@eng.cu.edu.eg
Tel.: +201224799711
Facebook: https://www.facebook.com/rabakir/
LinkedIn: Reem A.B.

Abstract
The construction of the Great Pyramid of Giza remains a fascinating mystery, captivating scholars well into the 21st century. This study investigates the hypothesis that the Ancient Egyptians employed an in-situ casting method using man-made composite blocks rather than relying on the traditional approach of transporting and assembling quarried stone blocks.
Through a two-phased methodology that combines material analysis and empirical research, this study offers new and significant insights into the construction techniques used by the Ancient Egyptians. The findings not only challenge long-standing assumptions about the construction of the Great Pyramid but also highlight the remarkable ingenuity, skill, and coordination necessary for building it.
Evidence indicates that casting composite blocks on-site was feasible, with the addition of sand significantly improving their mechanical properties. While the study presents compelling insights, it also emphasizes the need for further interdisciplinary research to fully validate this hypothesis. This call for further investigation invites scholars, historians, archaeologists, and engineers to contribute to the ongoing debate surrounding ancient construction methods.

Keywords
Great Pyramid of Giza; Ancient Egyptians; Construction; Blocks; Casting; Mould; Composite; Limestone.

Background
The construction of the Great Pyramids of Giza remains an enduring mystery, sparking debate among historians, archaeologists, and engineers for centuries (Brier, 1999; Verner, 2001). Understanding the techniques used in their construction is a significant challenge, as these structures have stood as symbols

of Ancient Egyptian civilization and human ingenuity for nearly five millennia (Edwards, 2003). Gaining insight into these techniques is essential for enhancing our knowledge of ancient civilizations and engineering practices and inspiring innovation across various fields (Verner, 2001). Despite having fragmented evidence that suggests possible construction methods, no single record or theory conclusively explains how these monumental structures were built, which adds to their mystique (Lehner, 1997; Shaw, 2003).

While widely accepted theories advocate using traditional tools and manual labour (Brier, 1999), there is a degree of scepticism within Egyptology and archaeology regarding considering more sophisticated approaches (Edwards, 2003). Nonetheless, one undeniable fact remains: the construction of the pyramids required immense time, knowledge, skill, coordination, and a substantial workforce, showcasing the enduring legacy of Ancient Egyptian ingenuity (Shaw, 2003; Verner, 2001; Verner & Hawass, 2001).

Recognizing the remarkable capabilities of the Ancient Egyptians, this study aims to provide a comprehensive analysis that considers the cultural, technological, and logistical complexities involved, thereby illuminating the puzzling aspects of pyramid construction. Understanding the techniques used in building the pyramids is crucial for historical knowledge and may also inspire innovations across various fields, including modern construction management.

This study investigates the construction method of the Great Pyramid of Giza, attributed to King Khufu. It challenges traditional construction theories and delves into the physical and chemical properties of the blocks used. Utilizing a two-phased approach, this research analyzes the composition and moulding sequence of the pyramid's blocks, questioning established theories (Brier, 1999; Verner, 2001) and exploring novel hypotheses such as in-situ block casting and the deliberate incorporation of materials to enhance implementation.

Revisiting Construction Theories

The Great Pyramid of Giza, built over 4,600 years ago during the Fourth Dynasty (2575–2465 BC), is a remarkable example of ancient engineering. It is the largest pyramid ever constructed and the only remaining structure from the Seven Wonders of the Ancient World (Brier, 1999). The pyramid features a perfectly square base on the Giza Plateau, each measuring 230 meters and aligned with true north. The pyramid stands approximately 137 meters tall, with its four faces sloping at about 51.28 degrees, inclined slightly toward the centre, which creates a stunning optical effect.

The Pyramid of Giza is constructed from over six million blocks, each weighing as much as two tons (Lehner, 1997; Verner, 2001). The construction is believed to have taken 20 years and required a workforce of more than 50,000 individuals (Edwards, 2003; Godley, 1920). Despite extensive studies, the methods of constructing the pyramid remain debated among scholars. Various theories have

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been proposed to explain the construction techniques used, including the use of ramps, sledges, ropes, and even water for transporting the massive stone blocks (Lehner, 1997; Shaw, 2003; Brier, 1999; Stocks, 2022; Verner, 2001; Houdin & Von Hagen, 2009; Varona & Vives) that were likely carved from nearby mountains (Brier, 2009; Godley, 1920). While ramps are widely accepted as a key method (Brier, 2009; Smith, 2004), Egyptologists acknowledge that this approach may need to be revised and integrated with other mechanisms, as the logistics of their construction and operation are still debated (Rigby, 2016).

A widely accepted theory suggests that the ancient Egyptians used natural limestone that was quarried and transported to the construction site (Lehner, 1997). In contrast, alternative proposals, such as cast concrete or geopolymer materials, lack substantial scientific support (Verner, 2001; Davidovits & Morris, 2009; Hemeda & Sonbol, 2020). While there is clear evidence that the ancient Egyptians had advanced skills in quarrying and stone-cutting, conclusive evidence supporting their ability to produce synthetic stone during that period still needs to be provided.

The French materials scientist Joseph Davidovits advocated for the geopolymer hypothesis, suggesting using artificial stone made from crushed limestone, water, and an alkaline solution (Davidovits, 2008). However, analytical studies have mainly supported using natural building materials (Lehner, 1997; Hemeda & Sonbol, 2020). These theories continue to stimulate scholarly discourse, highlighting the ongoing effort to gain a comprehensive understanding of Ancient Egyptian construction methods.

Methodology

This study adopted a comprehensive two-phased approach to investigate the composition and potential casting techniques used for the blocks in constructing the Great Pyramid of Giza. The first phase examined the theoretical framework and engineering feasibility of in-situ casting. This included a detailed material analysis to assess the suitability of identified raw materials as potential binding agents for large-scale casting. Through a series of experiments and trials, the study evaluated whether this method could achieve the structural integrity and precise geometry required for the pyramid while also addressing transportation, positioning, and alignment challenges.

Based on the findings from the first phase, the second phase focused on applying analytical techniques to the collected samples while adhering to strict ethical and preservation protocols. Carefully extracted stone samples were gathered from the ground near the pyramid's base, revealing the blocks' unique composition and potential origin. By identifying the presence and distribution of additional materials that aided the casting process, this study challenged the assumption that the blocks were made solely of natural limestone.

Phase 1: Composite Block

This study examined the construction methods of the Great Pyramid of Giza, focusing on using local limestone as the primary building material. The availability of limestone made it a sensible choice for the pyramid's construction (Lehner, 1997; Verner, 2014; Davidovits & Morris, 2009). The limestone was likely extracted from El-Mokattam Mountain in Wadi Hof, with evidence of extensive tunnel networks within the mountain (Lehner, 1997). Research by Klemm (1993) showed that most blocks—between 97% and 100%—were sourced from the softer limestone strata in Wadi Hof (Klemm, 1993). Evidence indicates that the Egyptians deliberately chose softer, friable limestone for construction, steering clear of denser varieties found near the pyramids (Lehner, 1985; Davidovits & Morris, 2009).

Material Logistics

The study suggested limestone blocks were mined in manageable sizes from El Mokattam Mountain. These blocks were transported to the construction site using boats or wagons (Verner, 2014). Once at the site, the limestone was roasted to produce calcium hydroxide, which is illustrated in the limestone cycle shown in Figure 1. Dry mixtures of calcium hydroxide powder and sand were packed into flexible reed bags (called Koffa) and lifted to the required casting level by teams of workers.

Water, essential for the casting process, was transported from the Nile River through a dedicated canal (Verner, 2001). It was then raised to the pyramid's ground level using buckets, likely facilitated by a large square hole on the eastern side of the pyramid (Manley & Abdel-Hakim, 2004; Lehner, 2007), as illustrated in Figure 2. After that, water was lifted to the necessary tier, where blocks were cast using Shadufs, as shown in Figure 3. These findings provide valuable insights into the advanced construction techniques employed by the Ancient Egyptians and highlight the logistical challenges they successfully addressed while building one of the world's most iconic structures.

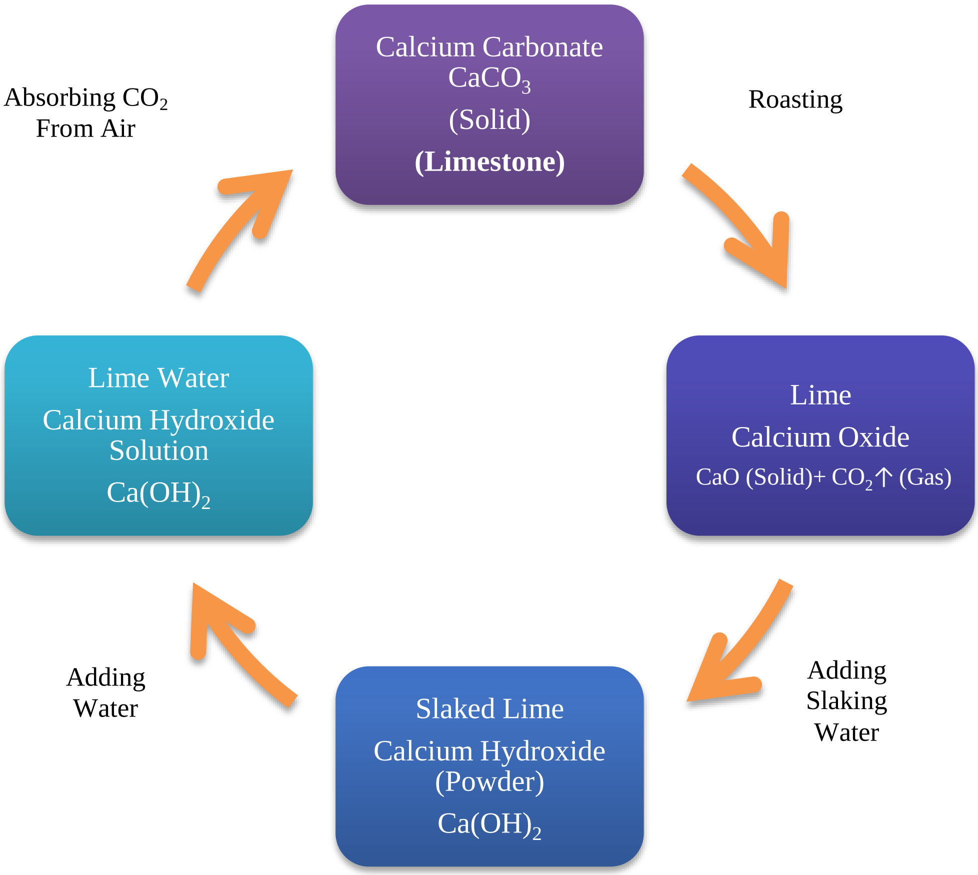

Figure 1 Limestone Cycle

Figure 2 An AI-generated image of water raised using a Shaduf, as suggested by Verner (2014)

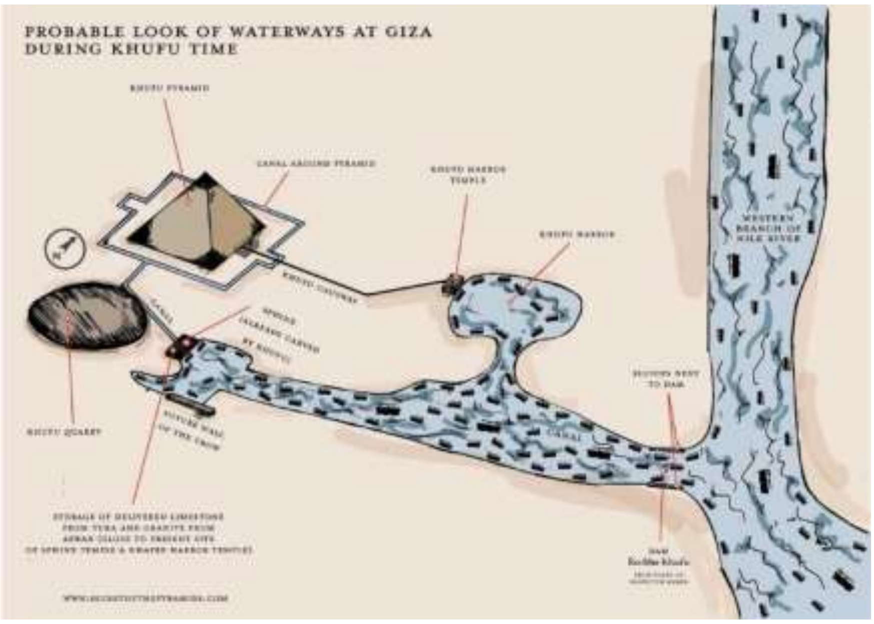

Figure 3 Potential establishment of a canal between the Nile and the Pyramid site, source: https://www.secretofthepyramids.com/projects/project-three-water-transportation-at-giza

Block Mould Types

This study introduces three types of wooden moulds for casting, as illustrated in Figure 4. The first type is a four-sided mould used at the beginning of the casting process. Its inner dimensions correspond to the outer dimensions of the desired block (Figure 4-A). The second mould consists of two long sides and is designed to overlap two consecutive blocks in the same row that have already been moulded (Figure 4-B). The third type features two short sides, which are meant to fit between two parallel rows of cast blocks (Figure 4-C). Pairs of wooden poles were anchored to the ground behind the moulds to secure these mould sides and tied together at the top to prevent outward movement during casting.

In preparation for casting, the Ancient Egyptians applied a greasy substance—likely oil or fat—to the inner surfaces of the moulds and blocks. This helped retain water within the moulds and facilitated the separation of the mould sides from the hardened blocks once the material solidified. After greasing, the moulds were filled with water, and a dry powder mixture of calcium hydroxide and sand was poured into the water. Due to its higher density, the mixture sank into the water, promoting compaction and ensuring the formation of dense, sturdy blocks.

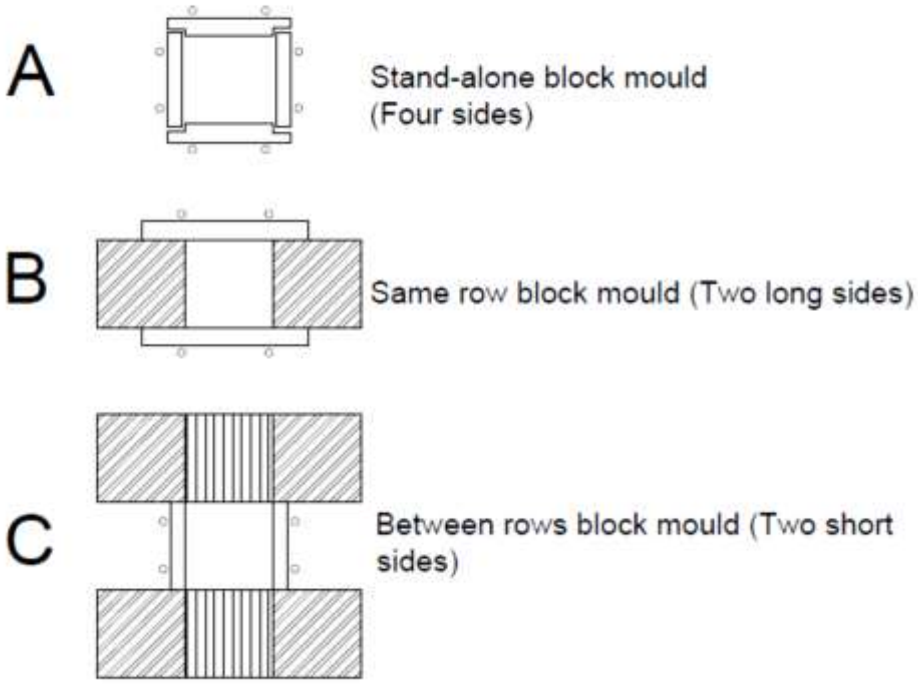

Figure 4 Various Block Mould types.

Chessboard Method: Fitting and Precise Alignment of Blocks

The precise alignment and fitting of the blocks in the construction of the pyramids suggest that the Ancient Egyptians may have used a matrix method similar to a chessboard to achieve an exact block molding sequence. Each pyramid tier was likely divided into an odd number of rows and an equal number of columns. This study proposes that they began by placing and aligning the four-sided moulds (Type A) at the four outer corners of the tier to establish direction and outer dimensions.

The moulds were then positioned at the intersections of the odd-numbered rows and odd-numbered columns, where the blocks would be cast, as illustrated in Figure 5. The process likely started from the tier's central row(s) and progressed outward toward the opposite sides. This method ensured uniformity and precision in block placement throughout the pyramid's construction, as depicted in Figure 5.

After placing blocks with the four-sided moulds (Type A), the Ancient Egyptians employed two long-sided moulds (Type B) to fill the gaps between the blocks in the odd-numbered rows. This process involved casting blocks at the intersections of odd-numbered rows and even-numbered columns, allowing the new blocks to settle and interlock with the existing ones. As a result, a continuous row of blocks was formed, which provided longer sides for placing subsequent blocks.

Next, two short-sided moulds were used to cast blocks in the gaps between the previously cast rows, focusing on the intersections of even-numbered rows and odd-numbered columns. Finally, any remaining gaps at the intersections of even-numbered rows and even-numbered columns were filled, completing the surface area of the tier. This meticulous approach ensured precise jointing between the faces of the blocks, which contributed to the structural integrity and aesthetic quality of the pyramid's construction.

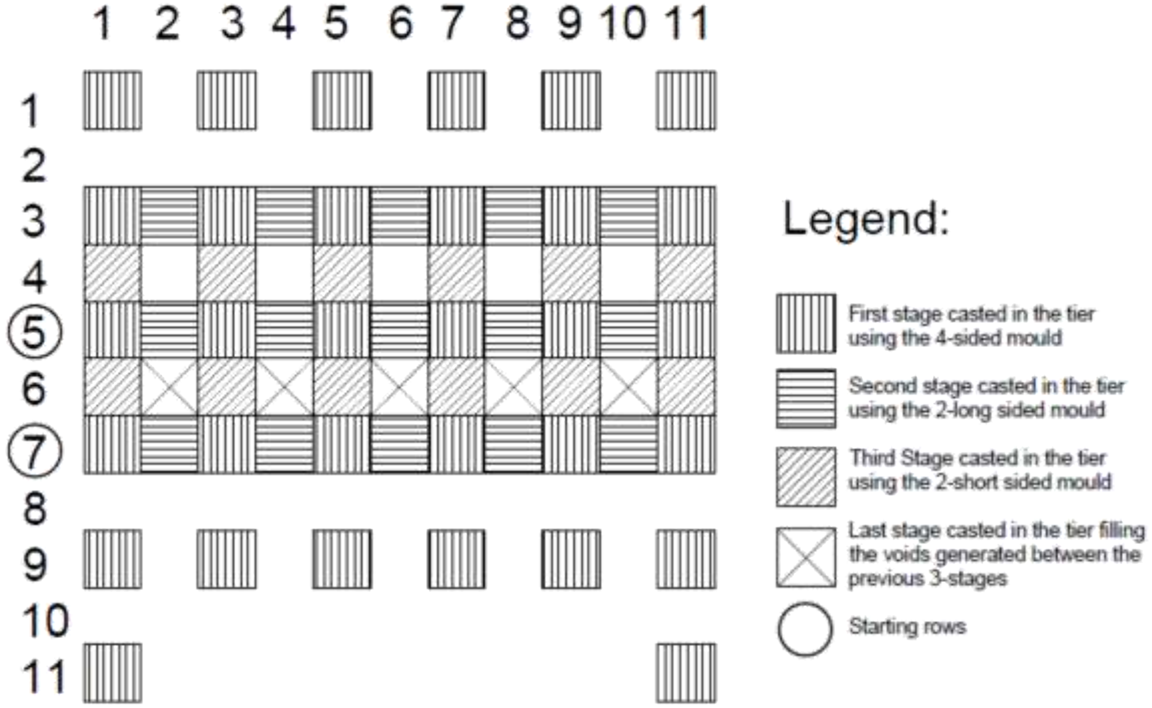

Figure 5 Chessboard 11x11 Block Matrix

Phase 2: Empirical Research

To investigate the hypothesis that blocks were molded in place, an experiment was conducted to construct a block using calcium hydroxide powder and water. A mold was assembled using two wooden planks measuring 10 cm x 30 cm x 2 cm and two wooden blocks measuring 10 cm x 10 cm x 10 cm, which were clamped together to form the sides. This mold was then positioned on a wooden board measuring 15 cm x 30 cm x 5 cm, serving as the base.

The experiment involved filling the mold with a mixture of calcium hydroxide powder and water, filled to the top. However, the mixing process proved tedious and challenging due to air entrapment and significant shrinkage after setting. Molding large-scale blocks would have required substantial effort and time from the Ancient Egyptians, prompting consideration of alternative methods.

To address these challenges, multiple trials were conducted, with each trial building upon the previous one to explore more efficient methods. Additionally, a second hypothesis was tested, suggesting the inclusion of sand in the mixture. To verify this, a site visit was conducted, during which a few samples were ethically collected from the vicinity of the pyramid’s base. These samples were subjected to a chemical reaction with concentrated hydrochloric acid in a flask, leaving behind a sand residue, which supported the hypothesis.

The reaction formula: $HCl+ CaCO_3 \rightarrow CaCl_2+CO_2\uparrow+H_2O$

Subsequent experiments involved mixing sand with dry calcium hydroxide powder before pouring the mixture into the mould, which already contained sufficient water. This approach allowed for smoother air release and more consistent solidification. This empirical method offers valuable insights into the feasibility of moulding composite blocks in place, as practised by the Ancient Egyptians, and provides important considerations for understanding ancient construction techniques.

Results

The empirical investigation suggests that the Ancient Egyptians utilized in-situ casting techniques for constructing the blocks of the Pyramid of Giza, utilizing locally available materials such as sand, limestone, and water. Incorporating sand into the mixture contributed to the blocks' enhanced mechanical and physical properties, which likely resulted in the characteristic beige colour of the pyramid. These findings challenge previous beliefs attributing colouration to pollution, environmental factors, or the application of Tura limestone casing (Dodson & Hilton, 2004). Furthermore, analysis of actual pyramid blocks from collected samples revealed the presence of sand, indicating that the blocks were artificial cast composite blocks rather than naturally extracted ones.

Interestingly, two types of sand were identified in this investigation: The first is yellow-coloured sand particles with edges comprising more than 60% by weight of the sample, as shown in Figure 6, used in the building blocks. The second is white-coloured, very fine sand particles (silica flour) constituting 2% by sample weight, as shown in Figure 7, used for cladding the pyramid.

These results provide valuable insights into the construction methods employed by the Ancient Egyptians and shed light on the composition and properties of the pyramid blocks.

Figure 7 Yellow-coloured sand particles with edges.

Figure 6 White-coloured, very fine sand particles.

Discussion

Ramp and boat transportation theories are widely accepted among scholars due to their alignment with available evidence, ancient depictions, and practical feasibility. Scholars like Jean-Pierre Houdin and Mark Lehner have proposed various theories involving ramp types and boat transportation. Although spiral external ramps and internal ramps suggested by Bob Brier and Gilles Dormion could have facilitated the movement of builders and materials (Varona & Vives), they likely were not used for transporting the blocks (Brier, 1999; Brier, 2009). Casing and cladding required scaffolding or other attachments to the pyramid's facade.

The boat transportation theory supports the discovery of boat pits near the pyramids and reflects the cultural significance of boats in Ancient Egyptian art. However, the practicality of transporting large stone blocks along the Nile River to the pyramid construction site remains uncertain (Verner, 2014). The prevailing belief is that limestone blocks were quarried, shaped, and transported from mines on the east bank of the Nile River to the Giza Plateau using various methods, including wooden logs, sledges, carts, boats, and ramps.

Kurt Mendelssohn's hypothesis, which combines the use of ramps, sledges, and levers with large external ramps, offers a more precise explanation of the construction process. This aligns with various observations, calculations, and engineering principles (Weisend et al., 2021). While specific details and logistics may still be subject to debate, it is important to recognize that these theories are not mutually exclusive; different combinations of techniques may have been employed during various construction phases. Ongoing research and technological advancements continue to improve our understanding of Ancient Egyptian engineering capabilities.

This study presents an alternative perspective on the methods used for constructing the pyramids, countering the views of some researchers. Rather than sourcing the blocks from distant locations such as Arabia or using levees for transportation, as noted by Diodorus of Sicily, we suggest a construction method known as "pyramidal growth," previously proposed by Crozat (2004). This approach involves moulding each block in place using a matrix, allowing for the slope of the pyramids at 52° (Rossi, 2021) and aligning with the agglomeration concept introduced by Davidovits (2008).

Regarding the block’s composition, mainly consisting of limestone (Lehner, 2007), this study exclusively identified natural components in the block formation process, contradicting the use of artificial components (Davidovits, 2008). While earlier research investigated possible chemical reactions, adhesives, and synthetic materials—such as Davidovits' hypothesis of artificial stone blocks with added substances—this analysis discovered a composite mortar formula of limestone and sand. Including sand improves mechanical properties, reduces the amount of limestone required, prevents shrinkage, and facilitates mixing. This demonstrates the Ancient Egyptians' advanced understanding of material science and construction techniques. This study focuses on the composition of the blocks, which are primarily made of limestone (Lehner, 2007). It exclusively identified natural components in the block formation process, challenging the idea that artificial materials were used (Davidovits, 2008). While earlier research investigated possible chemical reactions, adhesives, and synthetic materials—such as Davidovits' hypothesis of artificial stone blocks with added substances—this analysis discovered a composite mortar formula of limestone and sand. Including sand improves mechanical properties, reduces the amount of limestone required, prevents shrinkage, and facilitates mixing. This demonstrates the Ancient Egyptians' advanced understanding of material science and construction techniques.

In-situ moulded composite blocks offer valuable insights into construction efficiency. They may streamline the building process by eliminating the need for extensive quarrying, transportation, and the fitting of sizeable individual stone blocks. This perspective challenges earlier construction time estimates (Edwards, 2003), suggesting that the actual duration might have been shorter than previously thought. Understanding this could have significant implications for modern construction projects, encouraging the adoption of alternative techniques that enhance efficiency and reduce resource consumption.

The findings of this study have important implications for our understanding of ancient construction methods. The in-situ casting hypothesis presents a practical solution to the challenges of transporting and assembling large stone blocks. Furthermore, the use of composite materials allowed the Ancient Egyptians to optimize their construction processes, thereby reducing the time and resources required. However, the study is limited by the availability of samples and the need for more research to validate this hypothesis fully. Future studies should focus on exploring the chemical composition of the stone blocks in greater detail and examine the potential applications of these techniques in modern construction.

Conclusion and Recommendations

This study offers new insights into constructing the Great Pyramid of Giza, challenging the traditional belief that the stone blocks were quarried. The evidence suggests that the blocks may have been cast on-site using a composite material, with sand playing a crucial role in enhancing their properties. These findings have significant implications for our understanding of ancient engineering and the evolution of modern construction techniques. However, further research is needed to investigate the potential of in-situ casting thoroughly and its applications in contemporary construction management.

Future research should broaden the empirical scope of the study by incorporating more detailed chemical analyses of the pyramid's blocks and investigating other potential composite materials used in ancient construction. Furthermore, collaboration among archaeologists, materials scientists, and construction engineers could lead to a deeper understanding of ancient building techniques. It would also be beneficial to explore the practical implications of this research, especially concerning sustainable construction practices that reduce material waste and enhance structural efficiency.

Limitations and Future Research

Ongoing research is crucial for enhancing our understanding of how pyramids were constructed and investigating the broader implications of in-situ casting for contemporary construction practices. Collaborating across disciplines—such as archaeology, materials science, and construction engineering—can yield a more thorough understanding of ancient building techniques and their potential applications in modern construction.

Conflict-of-interest statement

The authors declare no conflicts of interest. All co-authors have reviewed the manuscript and agree with its contents. This submission is original work and is not under review by any other publication.

Data Availability

The authors confirm that the data supporting this study's findings are available in the article and its supplementary materials.

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