How were the pyramids built?

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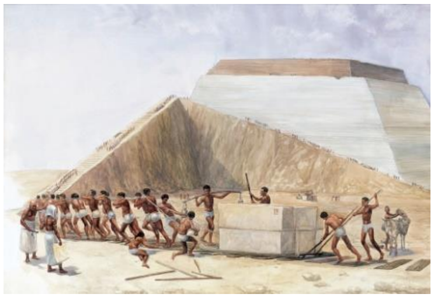
Spoiler alert: We may be wrong about how the ancient Egyptians built the Great Pyramids. Decades of schoolchildren are taught the prevailing theory: The pyramids were constructed from enormous blocks of solid stone, cut by hand from far away quarries, and hauled across the searing desert sands. We imagine—thanks in large part to Cecil B. DeMille—thousands of shirtless, sweating slaves harnessed to thick hemp ropes, dragging enormous square blocks of stone up steep ramps. The feat seems so incredible that some wonder whether the Egyptians had help from other planets. Always a rational voice in the room, Neil deGrasse Tyson counters, "Just because you can't figure out how ancient civilizations built stuff, doesn't mean they got help from aliens."

Figuring out how the pyramids were built has interesting applications beyond Egyptology. Today's building materials do not have an expected lifespan anywhere near 4,000 years. And many of our modern construction processes consume so much energy and emit so much CO2 that we're quickly destroying the very world we're working to build. The Egyptians seemed to know something we don't about using locally sourced materials to construct extraordinarily durable buildings without the huge environmental footprint so common today. Did the Egyptians use their minds as much as their muscle, and if so, what can we learn from them?



A common image in many of our minds explaining the construction of the pyramids.

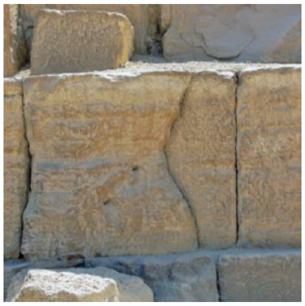
The skepticism Tyson addresses comes from a logical place. Despite the common teachings of the building of the pyramids at Giza, the feat of construction seems almost implausible. The Great Pyramid of Khufu was the tallest man-made structure on earth for over 3,800 years—16 times as long as our country has existed—until the construction of the Lincoln Cathedral in England. When built, the pyramid was 756 feet long on each side, 481 feet high, and composed of 2.3 million stones weighing on average nearly three tons each. Many of the joints between the blocks are so accurate that a human hair cannot be passed between adjoining blocks.

According to what we've been taught, quarried stone blocks weighing several tons were hauled to the pyramids, before the invention of the wheel. They were quarried out of the hillside with tools made of copper. And a city's worth of laborers were housed and worked in a cramped area for decades. It's difficult to imagine and little evidence exists to support this idea—no copper tools have been found around the site, no evidence remains of housing laborers, and no clear hieroglyphs exist documenting the quarrying, transportation, or ramp-lifting of these blocks.

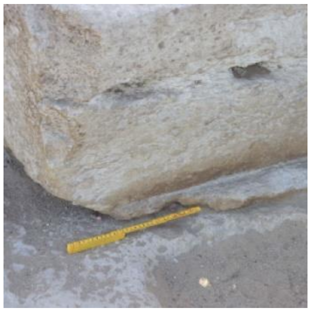
In the 1980s, a French materials scientist named Joseph Davidovits proposed a different theory—the Egyptians didn't haul the blocks to the pyramids but rather made the blocks one at a time in place on the pyramids. Davidovits suggested that the blocks were formed by pouring an ancient concrete—he called it geopolymer—into wooden molds. A fraction of the laborers would be needed to haul sacks of moist geopolymer concrete to wooden forms placed exactly where each block was needed. Joints between poured concrete blocks would always be perfectly accurate as a compacted moist mixture hardens against neighboring blocks. Davidovits suggested that the geopolymer concrete was made from crushed limestone, clay, water, and lime, a highly alkaline activator that caused the crushed limestone mixture to reconstitute into a man-made stone.

Davidovits's theory caused quite a stir among Egyptologists, historians, materials science researchers, and anyone who cared that a well-established explanation for the construction of something as iconic as an Egyptian pyramid was being turned on its head. Not only that, but if the Egyptians cast block in place from an early form of concrete, many established theories assigning the invention of mass-produced concrete to the Romans would be off by a few thousand years.

One would imagine that modern scientists with electron microscopes could prove in short order whether Davidovits was correct. Michel Barsoum, professor of materials science at Drexel University and a native of Egypt, never meant to get into the study of the pyramids but was amazed to hear Davidovits's theory. Barsoum was more amazed to find that no one had proved—or disproved—the idea.



Left: A gash in the side of one of the pyramids shows a combination of irregularly cut quarried limestone blocks surrounded by tight-jointed, cast-in-place geopolymer blocks. Right: Curved, perfectly aligned joints between these backing blocks are evidence of the blocks being cast in place rather than poured. Below: A ground level block in front of the Great Pyramid of Khufu includes an irregular lip at the bottom. This lip indicates that the block was cast in place. Images © Michel Barsoum, used with permission.



Barsoum, along with a graduate student named Adrish Ganguly, began studying samples from the inner and outer casings of the pyramids. What they thought would be a months-long study turned into a five-year odyssey. In the end, they disproved some of Davidovits's assumptions but proved his overall theory.

Barsoum believes that the Egyptians did cast a small but significant portion of the block in the pyramids. His electron microscope analysis indicates the Egyptians didn't use clay in the geopolymer mixture, as Davidovits proposed, but rather diatomaceous earth, a naturally occurring, commonly found soft sedimentary rock formed from the fossilized remains of algae.

And Barsoum importantly disagrees with Davidovits by suggesting that not all the blocks were cast-in-place geopolymer. Rather, Barsoum suggests that the Egyptians used both man-made cast block along with limestone block quarried and hauled to the site in the way our traditional explanation proposes. Barsoum believes that only the exterior casing blocks and the blocks at the higher levels of the pyramids were cast geopolymer blocks. This makes sense: The casing blocks were visible, so cast-in-place block with extremely accurate "joints" would be appropriate to exterior application. And the blocks at higher levels of the pyramids were harder to reach for quarried blocks hauled up ramps—replacing these with cast-in-place geopolymer blocks made the process easier.

Linn Hobbs, professor of materials science at the Massachusetts Institute of Technology, has also added to Davidovits's original theory and Barsoum's corroborating research. Hobbs's students have reverse engineered a geopolymer concrete made from crushed limestone, kaolinite, silica, and natron salts, a substance found in the evaporated remains of saline lake beds. The Egyptians used natron salts for mummification. When exposed to water, natron salts become alkaline, a perfect activator to make a geopolymer reaction.

As predicted, new theories that suggest that even a small portion of the stones in the pyramids at Giza were man-made blocks formed from an early form of concrete have erupted into a firestorm of resistance and vitriol, most notably from those with the most to lose when an established theory is pulled apart. As much as Barsoum assumed that solid materials analysis could indisputably prove how some of the pyramid's blocks were made, the debate still rages on.

Cement factory in China. The production of cement alone is responsible for 6 percent of the world's CO2 emissions.
Separating the debate from the historical discussion can shed important light on how we can improve today's construction materials by exploring what the Egyptians might have done. Just the idea of an ancient form of geopolymer concrete masonry that has lasted 4,000 years can forever change the way we build today.

Concrete is the most voluminous material made by all humankind. It's used all around the world in roads, bridges, dams, and buildings. The key binding ingredient in today's concrete is Portland cement, which alone is responsible for 6 percent of the world's CO2 output.

And concrete made with Portland cement isn't as durable as its environmental footprint might warrant. Concrete bridges are often taken out of service after only 50 years, due in part to harsh conditions like road salt, heavy truck traffic, and freeze-thaw cycles. While the relatively stable environment of the Giza pyramids avoids many of the harsh conditions of today's urban built environment, the 4,000-year durability of the structure indicates the expanded material lifespan possible with geopolymer concrete. When coupled with a much smaller carbon footprint—geopolymer concretes like those the Egyptians likely pioneered have a tenth the carbon footprint of Portland cement–based concretes—geopolymers offer a compelling alternative.

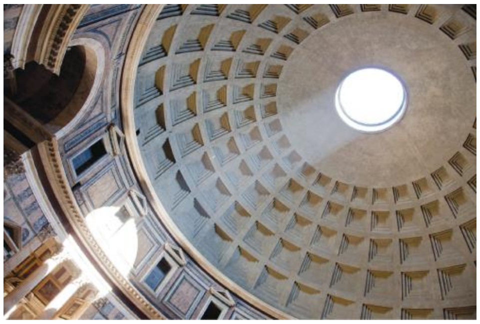
Geopolymer concrete is significantly different from Portland cement–based concrete. To simplify the science, Portland cement is akin to a strong glue whereas a geopolymer reaction is akin to a two-part epoxy. Portland cement binds together all kinds of aggregates to form relatively strong building materials. But that high reactivity comes at an environmental cost.

Geopolymer reactions, on the other hand, require two parts—a source of alumina silicates as well as an alkali activator. The former, the alumina silicates, is often found in volcanic ash. The latter, the alkali activator, is often found in lime. When the two are combined, a chemical reaction results in the creation of a strong concrete. Interestingly, while the process of creating the structural bonds in Portland cement is different from that of geopolymers, the final product can be near identical—something called calcium-silicate hydrate or CSH.

The Romans are often cited as inventing concrete, and they surely perfected its use. The Pantheon in Rome is to this day the largest unreinforced concrete dome, still standing 2,000 years later. The Romans couldn't have made a concrete of the type we make today—they didn't have kilns capable of super heating limestone to 2,000+ degrees Fahrenheit. Rather, the Romans pioneered a form of geopolymer concrete. They combined volcanic ash mined from sources like the island of Pozzollo with lime made from kilning limestone at relatively low temperature to make a strong concrete, much of which is still around.

Imagine how we could revolutionize today's concrete masonry industry by rediscovering the Egyptians' formula. Low-cost, sustainable, resilient, and highly durable masonry could be produced nearly everywhere on the planet from materials sourced locally, all without ultra-high embodied energy binders.

Watershed Materials, with the help of the National Science Foundation, has been exploring just that. Two phases of SBIR grants have been applied toward creating durable concrete masonry from the geopolymerization of alumina silicates found naturally in common earthen materials. If we're successful, we may be able to revive part of the science that allowed the Egyptians to make man-made stones so durable that they've not only lasted for over 4,000 years but have also fooled modern historians by appearing identical to geologically formed, quarried rock.



Left: The ceiling of the Pantheon in Rome—the largest unreinforced concrete dome in the world—still standing 2,000 years later.

Watershed Materials has developed the first prototype of a new masonry block machine that applies intense compressive force to allow the interparticle contact necessary for geopolymerization of common earthen materials of relatively low reactivity. Along with the design of a new machine for producing sustainable masonry, Watershed Materials is developing mix designs to create strong durable geopolymer masonry from common clays and earthen aggregates found nearly everywhere across the planet.

While we may have been wrong about how the ancient Egyptians built the pyramids, learning the right answer has implications for modern materials science and provides a new way forward toward developing far more durable and sustainable alternatives.