GEOPOLYMER CONCRETE - AN ANCIENT MATERIAL TOO?

FRANTIŠEK ŠKVÁRA, PAVEL SVOBODA*, JOSEF DOLEŽAL*, ZDENĚK BITTNAR**,
VÍT ŠMILAUER**, LUBOMÍR KOPECKÝ**, ROSTISLAV ŠULC

Department of Glass and Ceramics, Institute of Chemical Technology Prague,
Technická 5, 166 28 Prague, Czech Republic
** Department of Building Technology, Faculty of Civil Engineering, Czech Technical University in Prague,*
Thákurova 7, 166 29 Prague, Czech Republic
*** Department of Structural Mechanics, Faculty of Civil Engineering, Czech Technical University in Prague,*
Thákurova 7, 166 29 Prague, Czech Republic

E-mail: skvaraf@vscht.cz

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The present paper surveys data pointing to the possibility of the "concrete" technology being used during the erection of Egyptian pyramids (a hypothesis submitted by Davidovits). On the one hand, some published data corroborate this hypothesis but, on the other hand, there are other data that deny it strictly. A shortage of relevant data available from a sufficient number of specimens taken in pyramids and other buildings represents a fundamental drawback when the supposed use of the "concrete-based" forming technology (geopolymers, lime-based binders) is being assessed. Czech Egyptologists who have been excavating in Egypt for decades have not been able to discover any sign that would point to the use of the "concrete" technology during the erection of ancient Egyptian buildings (for instance, formwork marks). Nevertheless, ancient building materials - if they were indeed produced by human beings - would represent a promising body possessing a long-term stability suitable for the immobilization of toxic compounds.

Institute of Glass and Ceramics of Institute of Chemical Technology Prague and Department of Building Technology and department of Structural Mechanics of Czech Technical University in Prague have been involved in the research of alkali-activated materials for many years now and, specifically, since 1973. At present, the attention has been focused on the technological and materials research into geopolymer materials and particularly concretes. Geopolymer materials based on rejected (mostly brown coal) fly ash have been investigated. The results obtained within the framework of the research projects indicate that the geopolymer concrete is an economically advantageous material exhibiting an excellent resistance. Recapitulative data obtained during the investigation into the polymer concretes were divulged in a variety of communications [1-4] and several patents were filed too. The ulterior research activity has not neglected drawbacks exhibited by the geopolymer concrete either, e.g. its tendency to the formation of efflorescences.

The investigation into the durability of geopolymer materials must also deal with their long-term properties (of the order of several centuries). As regards the materials based on Portland cement, fundamental long-term material data related to medieval and ancient constructions are available (covering a period of about 2 000 years). The data refer to materials with hydration products comparable to those of Portland cement. These are materials in which highly hydraulic lime or mixed Roman cement was used as a binder.

Davidovits [5,6] formulated a hypothesis about the use of geopolymer binders during the construction of ancient (and particularly Egyptian) monuments that are more than 4 000 years old. In his opinion, the "concrete" technology was used during the erection of Egyptian pyramids for laying geopolymer mixes (with a limestone aggregate) into formwork; individual blocks were thus produced step by step. The hypothesis is corroborated by analysis of inscriptions on ancient Egyptian steles. The above worker argues that the pictures of hieroglyphs should rather be interpreted in technical terms than in the literary ones (as this has been done so far). These deliberations accompanied by the interpretation of analyses (microscopy, IR and NMR spectroscopy) of sparse specimens from ancient Egyptian constructions were published in papers [5,6]. This interpretation is also corroborated in the Demortier's work [7] who expressed the opinion that the "concrete-based laying" technology was known in the Cairo region in ancient times. Demortier drew his conclusions after studying the appearance of pyramid blocks (the blocks exhibit different porosities in the top and bottom sec-

tions) and performing X-ray and NMR analyses. A few small pieces of pyramid blocks were used for analyses. He interpreted some ancient Egyptian scenes as pictorial descriptions of the "concreting" during the pyramid construction.

Barsoum and Gangula [8] analyzed specimens (5 in total) from various Egyptian pyramids including that of Cheops. For comparison's sake, natural materials (limestones) from mines used as a source of raw materials during the construction of pyramids were also analyzed. Petrographic and point-by-point analyses (ESEM) were carried out. Based on the data obtained the above workers argue that a much larger number of analyses needs to be carried out before the application of the "concrete" technology during the pyramid construction might be taken into consideration.

Absolutely negative opinions regarding the use of geopolymer binders in ancient constructions appear in other papers [9-11]. The workers base their opinions on the analyses of pyramid specimens supplied by British Museum and those making part of the so-called "Lauer collection". Freestone and Middleton7 undertook a detailed analysis of specimens from the pyramid of Cheops (British Museum) by using optical and electron microscopy (with the point-by-point analysis), X-ray diffraction and IR spectroscopy. Campbell[8] paid particular attention to the petrographic investigation of specimens from the pyramid of Cheops and rocks (mostly limestones) from the mines exploited during the construction of pyramids. Jana[9] performed a detailed petrographic and microscopic investigation (optical and electron microscopy, X-ray diffraction) of specimens from the Khufu pyramid as well as from the Lauer collection; furthermore, he also studied natural limestone from an ancient Egyptian mine and samples of a man-made limestone geopolymer prepared by Davidovits. The research workers could not identify any traces left by binding geopolymer phases in the specimens: the specimens corresponded to natural limestone mined in Egypt. They were also able to detect a fundamental difference between the limestone from pyramids and the man-made limestone geopolymer prepared by Davidovits. In their opinion [9-11], the hypothesis assuming an alleged application of the "concrete" technology during the construction of Egyptian pyramids ought to be corroborated by a systematic investigation carried out with a credible and reliable set of specimens and data.

For the sake of objectivity, it should be stressed, however, that the research workers [6-9] did not subject the specimens from the pyramids or samples of natural materials to the investigation with the aid of NMR spectroscopy (Si, Al, Na) in solid state.

Czech Institute of Egyptology [12] (Faculty of Philosophy, Charles University, Prague) has been excavating in Egypt for many decades (since 1960); it has also been exploring ancient Egyptian constructions (pyramids, shaft tombs, tombs of high-rank officials and members of the royal family) in the Abusir locality (Cairo). The exploration of ancient Egyptian constructions did not reveal any signs hinting at the use of the "concrete" technology, e.g. formwork marks on building segments. Nevertheless, the imprints of human fingers were discovered in mortars (lime-based) or on (unfired) clay bricks. A phenomenon suggesting a closer relationship of ancient Egyptian materials with the concrete could only be discovered in lime plasters and lime-based filler layers in sarcophagi which also contained pebbles in addition to lime binder. The excavated shards indicate that lime mortars and filler layers in (evidently) rather liquid conditions were transported into the tombs (to a depth of 21 m in the case of Iufa shaft tomb) in ceramic jugs up to 60 cm high. Shards of such vessels containing residues of a thin mortar or lime filler were even found in tombs in other places too. Therefore, in theory, there may have been a sort of a "concrete-mixing plant" in the desert in the tomb vicinity where such bodies were prepared (just to give an idea, the necessary volume of the filler body in the case of the Iufa sarcophagus is estimated to be of the order of a few tenths of cubic meter and it seems that the filling body was cast more or less in one single step). It may not be excluded that even this procedure or the subsequent transportation of the mortar or any such material would be captured in Egyptian reliefs. Sorts of sledge loaded with a stone block and drawn (obviously) by slaves were used during the construction of pyramids (for the transportation of stone blocks). A slave stood on the sledge and poured clay slurry from a vessel into the sledge trajectory, the slurry formed a slippery path facilitating the sledge motion. Such slurries was also applied as bearing courses of horizontal joints; vertical joints between the blocks were also filled with the slurry. As mentioned by Davidovits, even hairs could be found in the joints.

On concluding this communication we have to admit that

> "it is not quite evident how ancient Egyptians succeeded in transporting the last block weighing a ton to the top of the pyramid …".

Hence, the ulterior research in this field is very much needed.

It should be declared quite openly that - if ancient materials (geopolymers or lime-based materials) prepared by human beings thousands of years ago would be discovered - then such materials would be convenient for immobilization of high-toxicity rejects and, in particular, radioactive wastes. The stability over thousands of years is namely required from solid materials with

immobilized nuclear (radioactive) waste. Therefore, solutions to the problems of modern times (the future of the nuclear power technology) are being sought in the mist of passed millennia.

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GEOPOLYMERNÍ BETON
- TAKÉ STAROVĚKÝ MATERIÁL?

FRANTIŠEK ŠKVÁRA, PAVEL SVOBODA*,
JOSEF DOLEŽAL*, ZDENĚK BITTNAR**,
VÍT ŠMILAUER**, LUBOMÍR KOPECKÝ**,
ROSTISLAV ŠULC

Ústav skla a keramiky,
Vysoká škola chemicko-technologická v Praze,
Technická 5, 166 28 Praha
** Katedra technologie staveb, Fakulta stavební,*
České vysoké učení technické v Praze,
Thákurova 7, 166 29 Praha
*** Katedra mechaniky, Fakulta stavební,*
České vysoké učení technické v Praze,
Thákurova 7, 166 29 Praha

V práci je uveden souhrn poznatků o možnosti použití „betonářské" technologie při stavbách egyptských pyramid (Davidovitsova hypotéza). Publikované poznatky na jedné straně podporují tuto hypotézu, jiné ji striktně odmítají. Základním nedostatkem při posuzování hypotézy o použití „betonářské, vytvářecí" technologie (geopolymery, vápenná pojiva) je nedostatek relevantních dat z dostatečného množství vzorků z pyramid a dalších staveb. Čeští egyptologové nenalezli při svých dlouholetých vykopávkách v Egyptě náznaky použití „betonářské" technologie ve staroegyptských stavbách (např. otisky bednění). Starověké stavební materiály, pokud byly vytvořeny lidskou rukou, představují perspektivu materiálů pro fixaci toxických látek s dlouhodobou stabilitou.