# USE OF THE DRY- MIX SHOTCRETE PROCESS FOR THE CONSTRUCTION OF LARGE CURVED WALLS AT THE MUSEUM OF THE HISTORY OF POLISH JEWS IN WARSAW

## *DER EINSATZ VON TROCKENSPRITZBETON-TECHNOLOGIE IN DER UMSETZUNG VON GROSSEN GEKRÜMMTEN BETONWÄNDEN IM MUSEUM DER GESCHICHTE DER POLNISCHEN JUDEN IN WARSCHAU*

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The paper presents the design and construction of a curved wall at the Museum of History of Polish Jews in Warsaw. The curved wall designed by architect Professor Rainer Mahlamäki symbolizes the parting of the Red Sea during the Israelite Exodus from Egypt. The original concept of constructing wall elements with fiber concrete panels was not adopted. The decision was made to use dry-mix shotcrete technology instead. The paper discusses the construction issues, the spatial location of XYZ points of the concrete shell and the order of the execution of individual job stages. Special attention was paid to the architectural aspect of the external wall surface, drawing elements and the planned colour.

*Der Beitrag präsentiert das Konzept und die Durchführung einer gekrümmten Wand am Museum der Geschichte der polnischen Juden in Warschau. Die gekrümmte Wand entworfen vom Architekten Professor Rainer Mahlamäki symbolisiert die Teilung des Roten Meers während des israelitischen Exodus von Ägypten. Das ursprüngliche Konzept der Umsetzung von Wandelementen aus Fasernbetonplatten wurde nicht angenommen. Die Entscheidung wurde gefällt, die Trockenspritzbeton-Technologie zu verwenden. Der Beitrag bespricht die Bauprobleme, die Raumposition von XYZ Punkten der Wandschale und die Reihenfolge der einzelnen Arbeitsschritte. Spezielle Aufmerksamkeit wird auch auf die architektonischen Aspekte (Grafik, Farbe) wie die Ausführung der Außenfläche der Wand gerichtet.*

### 1. Introduction

The ongoing rich, thousand-year history of Polish Jews and its impact on today's Poland resulted in the decision to create a Museum of the History of Polish Jews in Warsaw, Poland. In January 2005, the City of Warsaw, the Polish Ministry of Culture and National Heritage and the Association of the Jewish Historical Institute of Poland signed an agreement establishing a joint cultural institution: the Museum of the History of Polish Jews. This historical event was made possible thanks to the voluntary involvement of many individuals and institutions. Among others, Aleksander Kwasniewski, the former President of Poland, offered his patronage over the Museum and Shimon Peres, the then Prime Minister of Israel and current President, became the chairman of the Museum's International Honorary Committee. On June 30th, 2005, the Association of the Jewish Historical Institute of Poland published the results of the international architectural competition for the building of the Museum of the History of Polish Jews (MHPJ). The prestigious competition attracted famous architects from all over the world, among others Daniel Liebeskind, Peter Eisenman, Zwi

Hecker, Kengo Kuma and David Chipperfield. Finnish architects Rainer Mahlamäki and Ilmar Lahdelma of a Helsinki-based architectural studio won the competition. In June 2009, a contract was signed between the Employer – the Ministry of Culture and the City of Warsaw – and the Main Contractor, Polimex-Mostostal SA. The company TORKRET from Poznan became a subcontractor to the Main Contractor responsible for completion of a curvilinear wall.

In the years 2011-2012 SPB TORKRET Ltd completed a unique shotcrete project in Warsaw, Poland [1]. It was a 26 m high wall of an approximate surface area of 6000 m$^2$. The three-dimensional, curvilinear wall forms the main spatial element of the interior of the Museum of the History of Polish Jews.

## 2. Description of the building construction and original project assumptions

The museum building consists of two parts with an extension joint between them. The first part visible in Fig. 1 is the main building with dimensions of 67.30 x 67.30 m, having four floors above the ground and one underground level, with a total height of 26 m. The building was designed as a reinforced concrete stud wall construction with monolithic external walls. The elevation was to consist of slanted narrow vertical glass panes, fixed to the reinforced concrete structure with a light steel structure made of galvanized steel square tubes. Steel girders make up 2/3 of the roof area. The second part of the building, not visible in Fig. 1, is the technical part (services compound) consisting of only one underground floor with dimensions of 67.30 x 41.70 m. The building situated on a slab foundation.

*Figure 1: A birdseye view of the ground-level part of the building during construction (photo from www.jewishmuseum.org.pl)*

In the main hall of the building, the most important element shaping the aesthetics of the inside and serving as the structural elements supporting the ceilings are two walls of a wavy shape (Fig. 2). Both walls cover the entire height of the building from the foundation to the roof. They only partly start from the ground floor. The two walls support all floors. The walls were designed as steel stud walls with thin shells mounted on the steel substructure of the base frame. The basic structure of the walls was made as a stud wall of tubular profiles rolled from steel S355J2H. The vertical tube elements with diameter of 273 mm and different wall thicknesses varying from 16 to 20 mm, bent in one plane, were concentrated horizontally and braced with tube profiles with diameter of $\phi$193.7x12 mm wall thickness. On the level of the connection with the reinforced concrete ceilings, tubes with diameter of ϕ244.5x16 mm thickness connected with the ceiling by HEA 200 rigid inserts were designed. To such a prepared frame it was planned to install, using the subconstruction of H-section rolled steel profiles, the system of adjustable fasteners used for suspending precast concrete reinforced with glass fibre according to the prototype design by JORDAHL & PFEIFER company (Stahlton AG technology).

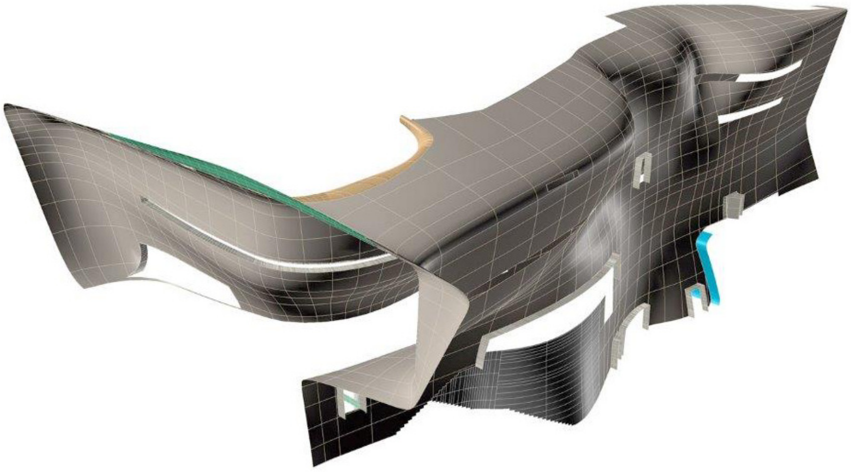


*Figure 2: Visualisation of the shape of a thin-wall shell (MHZP – Project)*

The plan was to prepare precast concrete thin-wall shells using a concrete mix reinforced with glass fibre. The technology was to enable making the elements from 10 to about 35-50 mm thick (depending on the adopted outer structure of the element and its size). The precast panels, which were to form the finishing layer of the curvilinear walls, were designed to be 15 mm thick. The precast elements were designed to be diamond-shaped with the area of several $m^2$, with four fasteners located at the corners for mounting the precast element on the substructure. The panels had to have double curvature surfaces in accordance with a developed digital model (Architectural Project, Fig. 2) and had to meet the following conditions:

– colour - stained concrete throughout the whole volume, the colour similar to pale yellow limestone (the colour was inspired by the colour of the Western Wall in Jerusalem), approved by the Architect on the basis of samples; staining resistant to UV; panels impregnated and with anti-graffiti protection.
– geometric condition – 15 mm thick panels, the edges of about 40 mm width thickened also to 40 mm to strengthen the joints and deepen the gap between panels.
– functional condition and in-use performance - the contractor was obliged to develop the details of the fastening system according to their own technology with the proviso that the system must provide load-bearing capacity, stability of panels and must meet the requirements of fire regulations and enable the installation of the panels on both sides of the curvilinear wall.

Due to a number of difficulties, an alternative technology of coating preparation was adopted – the application of shotcrete directly on the job site.

## 3. Implementation of internal thin-wall curvilinear shotcrete wall

After completing the basic load-bearing structure of the building (foundation slabs, external reinforced concrete walls, internal stud wall structure of reinforced concrete and steel, roof girders, Fig. 3), the implementation of thin-wall multi-curve walls was started using the dry mix shotcrete method. Relevant material as well as structural research and calculations were made, taking into account the need to fulfil the colour, geometric, functional and in-use performance requirements defined in the original project.

### 3.1 Preparatory work

Dry mix shotcrete mix was prepared at TORKRET's mixing plant as a production unit exclusively dedicated to the construction of the curvilinear walls. The first coating was applied using a traditional shotcrete mix based on rounded quartz aggregates 2 – 4 mm, Ordinary Portland Cement CEM I 42,5 R, silica fume and not alkaline accelerator chemical admixture. The second phase was also made based on a selection of quartz aggregates up to 2 mm, but the binding material was white cement CEM I 42,5R with adequately matched dyes like oxide iron yellow and titanium white. According to the designers' wish the wall colour was to reflect the colour of rocks in Israel. Sample examples are presented in Fig. 4. Maintaining the uniform colour was one of the biggest challenges.


*Figure 3: Entrance - the structure before starting the internal multi-curve walls (photo from www.jewishmuseum.org.pl)*

*Figure 4: Shotcrete samples: double-coating concrete with an external pale yellow architectural coat made according to „cut" technique (photo auth.)*

Knowing the possibilities of curvilinear surface forming in shotcrete technology, TORKRET prepared 3 reference models of a curvilinear wall. At a meeting with the architect and representatives of the investor and main contractor, which was held at TORKRET's office in September 2010, a presentation of the wall construction method and the prepared reference models was made (Fig. 5). After the visit, a positive opinion was given with regards to the shotcrete application to form the curvilinear wall. Static and fire resistance tests of the received model were required.

Laboratory studies carried out at Poznan University of Technology (Fig. 6) concerning the two elements of 2.10 x 0.8 x 0.05 m cut out from a thin wall structure made of reinforced shotcrete demonstrated that the built structure and its mounting on the steel support construction is the right solution enabling the development of large-scale projects. It was found that the large-scale structure worked as a multiple-point-of-anchorage concrete shield (spacing of anchors 0.8×0.8 m) loaded only with its own weight. The steel mesh was made of ϕ4.5 mm bars with 100×100 mm mesh width, mounted in the centre plane of the wall. It is an element securing the structure against complete destruction in the case of exceptional loads (impact, rupture of anchors, etc.).

*Figure 5: Reference sample of curvilinear wall with the division into diamond-shaped elements at the contractor's polygon. Prof. Mahlamäki first from the right (photo auth.)*

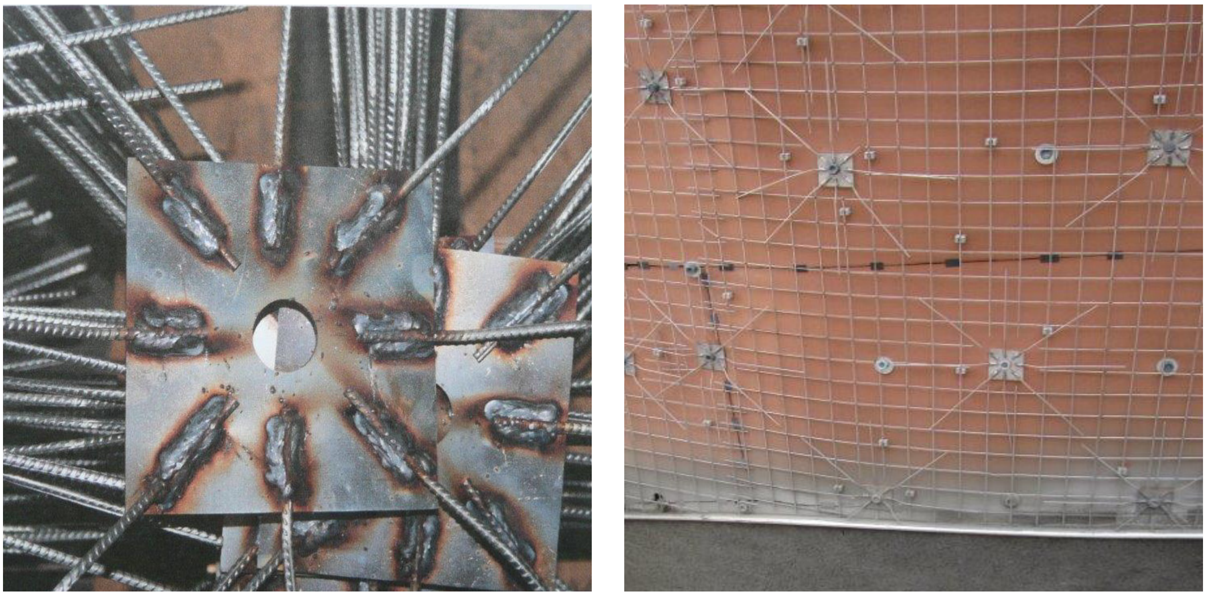

*Figure 6: Testing of the 2.1 x 0.8 x 0.05 m panel cut out from the reference wall. Spacing of anchors 0.8 m, the load distributed by the C-channel in the centre (photo auth.)*

This role of the mesh was confirmed by laboratory tests. The point load of the cut two panel suspended between steel beam allows obtaining bending of 41 mm and 35 mm, given the applied force of respectively 4.5 kN and 5 kN. Then the full cracking of the concrete cross section takes place. The fire resistance test T30 was conducted on test elements in the Fire Testing Laboratory of the Building Research Institute, Warsaw.

### 3.2. Implementation at the construction site

The envelope of the curvilinear wall was a 50 mm thin-walled, reinforced concrete structure with mesh reinforcement of 4.5 mm diameter stainless steel, ribbed bars. The wall was suspended using a system of anchors embedded in a substructure resting on steel columns. The steel columns forming the structure's framework are located in both walls of the hall and run along the entire building's height. Vertical elements were made of $\phi$273 mm tubes, composed of sections, bent in one plane, horizontally braced, and formed into a grid by means of tube profiles. Horizontal elements were made of $\phi$100 mm tubes. The thin-walled, curvilinear dry shotcrete walls were mounted via a system of rigid anchors to the tubes serving as the substructure – as described in the foundation project.

The way stresses are distributed from the point of anchorage and dispersed into the wall surface section was an innovative approach. This was obtained by mounting a strap with radial bars on to the anchor (Fig. 7). The mesh of $\phi$ 4.5 mm bars, applied to the profiled substrate made of waterproof plywood is presented in Fig. 8.



*Figures 7, 8: Strap with radial bars mounted on the anchor and the entire mesh before shotcrete process (photo auth.)*

The solution allowed avoiding possible scratching and cracking of the wall at the points of contact with the substructure. For static calculation model purpose the wall envelope was considered as multiple-point-of-anchorage plates loaded with deadweight. By introducing expansion joints, dimensions of a single plate were limited to approximately 16 – 20 m$^2$. A sample of each of the wall elements underwent a destructive testing including a cut out of the finished wall with anchorage. The test of the wall's fire resistance was also crucial. It must be emphasized that the wall is not merely a decorative element and work of art, but also serves as a partition between walking routes for visitors, technical, and office premises.

Another innovative element was specially designed plastic strips embedded both in expansion joints and in control joints (Fig. 9). The structure of strips enabled maintaining of constant shotcrete application layer thickness and delineated the outer surface. This also enabled installation of a membrane preventing moisture loss and protection against dust when applying onto the adjacent element. The expansion joint strips were removed and replaced by fireproof silicone material. The control joint strips were left in the structure reflecting the so-called wall pattern assumed by the architect.

The most important issue from the wall profile shaping perspective was transferring of the 3D design coordinates to the wall modeling space. This was achieved by continuous marking of the points of crossing of joints or other typical points. Strips were mounted on a special wooden plate serving as a stay-in-place formwork. The curvature plate had to meet the elasticity (from the reason of multidirectional overbending) and non-flammability conditions.

Once the plates with joint defining strips are formed and fastened, two layers of concrete were applied. Aliva 246 spraying machines and booster pumps providing water to the nozzle were used.

Curing of fresh shotcrete provided plastic foils hanging on the top of the executed walls (Fig. 10). Completion of the curvilinear wall took 13 months – basic works and several months of finishing work. All the emerging problems, performance-related, technical, and others, were solved right on site by TORKRET's laboratory and R&D unit, during hours of meetings and practical tests. Finally, all wall works were completed in August 2012. The finally results are presented in Fig.11.

*Figure 9: Fire protected wall substructure, profiled special wooden plate as a stay-in-place formwork, anchors and reinforcement mesh, spacing strips, the first layer of shotcrete (photo auth.)*

*Figure 10: Shotcreting process. In downing part ready shotcrete wall under the plastic foil which protected it against contamination by mortar blisters. The humid air upon foil cultivated young shotcrete and restricted shrinkage (photo auth.)*

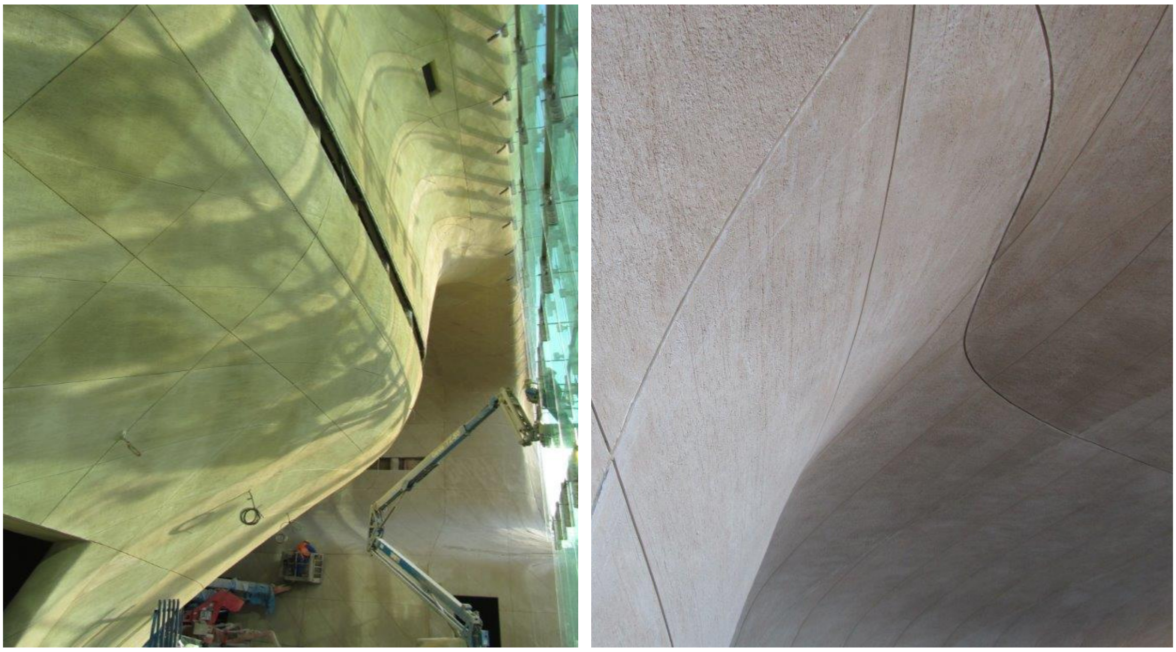


*Figure 11: Finished curvilinear walls; at the left wall with glazing (western exposure) (photo auth.)*

## 4. Conclusions

### 4.1. Construction related issues during implementing this project

A major part of the wall's surface area was made in the open space of the building. Performance of roof covering and execution of a glazed window (approx. 600 $m^2$ – Fig.11 – left), and the entrance structure were ready only at the end of project. This forced to organize works so that preliminary works could be prepared during periods of low temperatures; while the shotcrete was applied during advantageous weather conditions. A major execution-related problem was access to individual wall elements. Placing of a frame scaffolding offering constant access would have been the best solution; we had to rule it out because of the requirement of permanent geodetic survey of the spatial location of the wall to be built. Light and heavy airlifters, scissor lifts were used instead. To access even the highest wall elements, a temporary platform was installed to which a crane track was mounted with a suspended scaffold. This wall access solution made setting-out, control and verification by the client of shotcrete surface upon spraying much easier.

### 4.2. Evaluation of shotcrete technology for possible application in responsible structures

Shotcrete is concrete which offers many advantages over other methods of placing, without a need for extensive structural formwork and complex application by hand.

Rich technical literature describes many traditional applications related to the rehabilitation of concrete [3, 5], but also points to new trends such as sprayable fire-protective layers in traffic tunnels [4]. Shotcrete may also be used for shaping architectural space, for example the North Burlington Skatepark Project [6], as well as large surface architectural concrete elements [1, 7]. New challenges [2] are accompanied by the development of fine aggregate concrete technology with silica fume, chemical admixtures and other mineral additives, with short steel and polypropylene fibres, with very high mechanical performance characteristics. This new generation of fine-grained aggregate concrete, described exactly in [2], is suitable for the application by shotcrete technology.

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