UHPC Giant Tiles for Long-lasting Water Tightening of a Subsurface Waste Storage: from Conceptual Design to Prototyping and Trial Site-Ageing for Qualification

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Abstract

Protecting and ensuring water tightness of a subsurface nuclear waste storage facility for over 300 years, so that underground water around the site can be preserved from radioactive pollution, represents a challenge for which traditional technical solutions may need to be improved / complemented. ANDRA, the French operator of the facility, has identified ultra-high performance fiber-reinforced concrete (UHPC) as a potential solution to cover the site and complement the natural soil, bituminous membrane and gravel layers which already protect the waste barrels. From the attractive conceptual design of a UHPC tight layer, it turned out necessary to check technical and economic feasibility through a detailed design stage, considering service loads but also accidental seismic or storm cases, and constructability issues. This engineering task was carried out by LRIng design office, with the advisory help of various experts in UHPC, seismic and geotechnical engineering. Strength and stiffness optimization as well as durable anchoring of the « tiles » to resist high winds and keep efficiently assembled were demonstrated with realization,

by Innobéton precast concrete firm, of prototype elements installed onsite to demonstrate performance. The paper emphasizes how this detailed engineering project enabled progress in demonstrating the ability to constitute a complete durable continuously watertight jigsaw puzzle of UHPC elements properly anchored in the ground, meeting the durability expectation of the operator and thus possibly implemented in the future. Moreover, this project might derive into further technical alternatives and solutions for similar or further demands of long-lasting "roofing".

Keywords: Tiles, Protection, Water Tightness, Durability, Constructability, Prototype.

1. Introduction: Context of the Design and Qualification Project

ANDRA, the French Agency for Radioactive Waste, operates different storage centers among which CSM (Figure 1), which has been used to host low and intermediate activity level short life waste from 1969 to 1994. From then on, a multilayer overall capping system has been disposed, including a bituminous geomembrane to provide protection against rainwater infiltration. Monitoring during 25 years has confirmed the satisfactory limited ageing and high efficiency of the system. Requirement of a further 300 years-safe storage period with minimum maintenance has however suggested improvements of the protection system to address risks emphasized at long-term (associated to a longer return period): embankment loss of stability in case of an intense seism, and peripheral rainwater infiltration with possible contamination of collected water.

Different civil engineering improvements have been considered (Marchiol, 2023). Among them, the solution consisting in protecting the peripheral slopes of the center by UHPC tiles, connected to the top geomembrane, has appeared as promising. This was however based on very preliminary assumptions (thin large tiles, 150 kg/m² on average). For a possible aware selection and realization in the next ten years, ANDRA has launched a more detailed design study to clarify any feasibility issue and obtain a reasonable technical and economic evaluation.

Figure 1: CSM storage facility: general overview, peripheral embankments, map of infiltration risks

2. Project Requirements and Main Orientations

2.1. Functional Specifications

General requirements mainly consisted in mechanical protection of the granular material constituting the embankments, and prevention of any rainwater infiltration, over the 300 years-period of the facility "monitoring" period (with as few as possible maintenance tasks). Design critical accidental situations included seism, exceptional rainfall and storm. Additional safety principles comprised avoidance of multiple materials with a short-term degradation mechanism, and prevention of human-induced degradations over time, such as tiles removal. The solution should keep robust with respect to climatic evolutions (e.g. temperature range) which is an a priori benefit of a UHPC mineral solution as compared to vegetal cover. As an additional consideration, risk of vertical settlement within the bulk storage should lead to limited degradation of the tiles. Moreover, in case of local degradation or accidental failure, the tiles should be possibly replaced one by one. Besides current elements, special top-tiles ensuring connection with the geomembrane, as well as provisions for complying with slope changes should be designed so that any risk of impossible constructability be avoided.

2.2. Main Orientations of the Conceptual Design

The solution studied by LRIng answering the tender launched by ANDRA has been based on the concept of triangular large tiles including side channels (Figure 2), as a follow-up of the concept implemented for the roofing of Jean Bouin Stadium (Mazzacane et al. 2013). Long-sides of the triangles should be perpendicular to the main slope, to limit the water flow rate. As a genuine feature however, the water should be collected in UHPC channel elements instead of metallic ones, and these elements should be sized to ensure water efficient run-off along the main slope direction. Geometrical adaptation to the possible settlements could be ensured in letting the tiles rest on only three points, and adopting inclined edges of the side channels to allow some rotation between adjacent tiles, and between tiles and channel elements.

Figure 2: Principle of fitting triangular tiles with side channels for the roofing of Jean Bouin Stadium

The tiles should be made of type S-UHPC according to NF P18-470 (steel fibers, characteristics compressive strength of 150 MPa at least), so that the design rules of NF P18-710 can be applied. In a preliminary design step, consistent assumptions were taken for the material: 50 GPa for the Young's modulus, 10 MPa for the characteristic limit of elasticity in direct tension, 1,25 for the global orientation factor. Use of stainless-steel fibers is recommended. Execution of the elements in a precast concrete plant should promote quality control and possible tiles local replacement. Overall tiles dimensions correspond to about 2 m wide by 5 m long triangles. UHPC cracking has not been permitted at serviceability limit states, which is stricter than the current standard provision: this should ensure water-tightness. The design temperature range has been taken as 40°C. Together with geometrical tolerances, this has led to cope with minimum 5 mm-allowance for tiles relative position. Besides XC4 / XS1 / XF1 exposure conditions (to which UHPC is utmost durable), an abrasion risk XM1 has been considered with a 5 mm-sacrificial thickness (not included in design verifications).

3. From Conceptual Tiles to Effective Solution of Giant Tiles, Channels and Boxes

3.1. Detailed Project Hypotheses

Protection of the ground and resistance to relatively low thermal, snow and live loads (two 150-daN point loads for maintenance operations), were ensured even with a relatively small 30 mm-slab thickness. Consideration of the tornado risk over the design service life (EF2 category according to Fujita scale), however, needed a detailed study with numerical fluid mechanics simulations in consideration of dominant winds orientation. This has led to lifting or crushing pressure values of about 60 daN/m² at SLS (about 90 daN/m² at ULS) for the normal wind, but cumulated tornado effects reach about 275 daN/m². Together with anticipation of effective implementation of the elements on the embankments, this imposed to resist lifting effects with ballasted boxes, to which the channel elements and tiles are connected. While such connecting details would have generally been made of stainless-steel inserts for current façade or roofing building components, for the sake of long-term durability it was decided to design assembly provisions entirely made of UHPC. These provisions have been made compatible with both direct force transmission in case of instantaneous loadings, relative movement elements for assembling, and mechanical clearance / orientation flexibility for thermal variations or long-term settlements. Verification of the installation kinetics was achieved using digital printing of small-scale mock-ups. The matching embossed parts should resist local shock forces in case of tornado or seismic action, typically amounting about 1600 daN.

3.2. Effective Sizing and Possible Optimization Routes

Final size of current tiles corresponds to 810 kg elements (surface weight of about 170 kg/m²), with a safety factor of 1,85 against ULS uplift. The 40 mm thickness has been kept for channel elements (about 970 kg). The total necessary weight of ballasted boxes amounts about 3250 kg. Verification of the elements with respect to the different design load cases included checking the seismic stability of embankments with the additional dead weight of the tiles and channel elements, and pessimistic assumptions regarding the water table, following the methodology recommended by the French Nuclear Safety Authority.

Based on the validated dimensions of the elements (ribbed tiles, channels and boxes) and quantities that would correspond to the CSM peripheral embankments protection (about 60,000 m²), an economic evaluation was carried out from the point of view of the precast concrete factory who would be in charge of producing the over 11,000 tiles, 2,800 channels and 2,800 box elements. A 3 year-duration would seem probable for realistic mold rotation. In a first approach, raw constituents would correspond to 25 to 30 % of the price (assuming a 50 % margin), and a similar proportion would be the workmanship. Molds, handling devices and tools represent less than 10 %. It should be noted that the UHPC volume of this operation represents more than 5 times the largest previous ones, like the Jean Bouin Stadium roofing (Mazzacane et al., 2013). This could lead to cost optimizations, related to the UHPC premix, molds, limitation of UHPC wastes, workers' skills. Altogether, the economic evaluation ranges from 1 to 2, yet the overall cost per square meter may compare favorably to a large number of current watertight roofing solutions, given the high safety and durability expectations.

An additional part of the feasibility verification consisted in prototype slabs, channel and box elements effective realization, to confirm validity of this technical and economic assessment.

3.3. Prototype Realization

The corresponding operations were realized at Innobéton precast concrete factory, specialized in UHPC elements production. Based on this knowledge of UHPC technology, although using wood and hard polyester for prototype molds, which may not allow perfect air elimination, representative casting upside-down of a fluid UHPC mix with vents (Figure 3) helped ensuring proper filling, geometrical control (Figure 4) and fine finishing of surfaces in contact for the different types of elements (Figure 5). Size variations turned out less than 2 mm over 5 m.

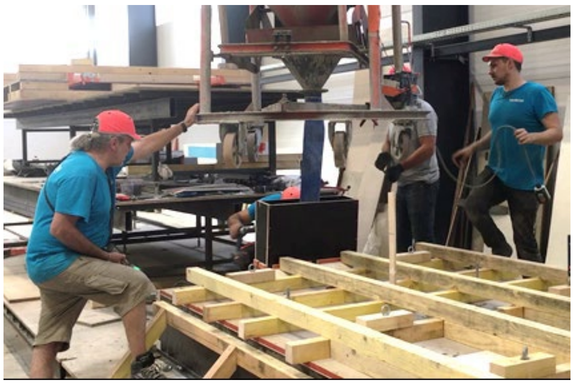

Figure 3: Channel element molding (upside down) and formed on both sides

Figure 4: Tile just demolded – geometric control

Figure 5: Details of molded elements: channels, boxes with retaining hooks, tiles with side channel

3.4. Prototype Functional Testing

A preliminary verification of proper elements assembling was realized directly at the precast concrete plant, leading to immediate verification of the positioning process. This was done with four tiles (both left and right-types), three channel elements and three pairs of upwards/downwards boxes (Figure 6). Although the protruding connections correctly matched (Figure 7), tolerances for inserting the retaining hooks in the holes of the channel elements were found to be increased, and other simplifications were suggested. Once the elements were assembled, a first water-tightness test was performed and demonstrated efficiency of the side ribs/channels of the tiles (Figure 8). A satisfactory simulation of tiles shock on the channel embossments, as would be caused by a seismic action, was carried out and resulted in undamaged connecting parts after tiles being dropped from about 10 cm vertically. Finally, support settlements of ± 5 cm were simulated. Although the planes of successive tiles exhibited significant rotation, interlock kept effective and no damage appeared on the matching surfaces (Figure 9).

Figure 6: First prototype handling and assembling test at Innobéton factory

Figure 7: Assembling details: tiles fitted to channel elements, channel elements retained by hooks of the boxes

Figure 8: Tests at Innobéton factory: water runoff, shaking of the tiles dropped along the channels

3.5. Demonstrator Installation and Testing

A further step of validation consisted in demonstrating the feasibility of assembling a representative set of tiles, including the top ones connected to the geomembrane, with realistic handling and earth-moving equipment. A dedicated site had been prepared with appropriate slope.

Figure 9: Tests at Innobéton factory: tolerance in case of settled support

Realization of this demonstrator, to be kept on the CSM site for natural ageing, confirmed the constructability and preferred channels handling with adjusted lanyards (Figure 10). The possibility to install a single tile without removing a whole range, as in case of repair, was also successfully verified (Figure 11). Intense rainfalls together with blowing winds were simulated on the final demonstrator (Figure 12) and absence of water infiltration was stated.

Figure 10: Demonstrator installation: ballasted boxes, handling of the channel element, retaining hooks

Figure 11: Demonstrator installation: handling, orienting and fitting the single missing tile

4. Concluding remarks

The complex engineering task consisting in designing UHPC protective and watertight interconnected elements resisting to various intense loads for a 300 years-long service life was successfully conducted in a cooperative process until full-scale prototype validation of this ground-anchored jigsaw puzzle, to be monitored for possible implementation and also possibly adapted for further demands of long-lasting high-performance “roofings”.

Figure 12: The demonstrator as finally installed

Figure 13: Full-scale test of water runoff and channeling

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