Ultra Thin Heavy Reinforced High Performance Concrete Overlays.

Peter Buitelaar Contec ApS Denmark

ABSTRACT

Since the developments of the so-called D.S.P materials in 1978 and C.R.C in 1986 by civil engineer Hans Henrik Bache and co-workers at Aalborg Portland Denmark different changes to the original concept have been made. For the use in civil engineering, accentuate emphasize to industrial floors, pavements and concrete renovation, there are 3 main disadvantages from the original concept i.e. the workability, the finishability and the chemical shrinkage, all related, direct or indirect, to the extreme low water/binder ratio and the high amount of micro-silica containing binder. Especially in cases where it is important to get full benefit of the properties of an ultra high strength concrete like in ultra thin overlays in combination with high volumes of traditional steel bars and steel fibres the workability and finishability is of main importance for the final result and the qualities from the hardened matrix.

1 Introduction

The function of an industrial floor or industrial pavement is of crucial importance for a company. Surface damage, cracks, broken joint edges, dust, etc. can result in an uncomfortable use and damage of transportation equipment. In the food industry en with the so-called fluid tight constructions are not only the requirements of the user of importance but as well the requirements from the authorities. In the rehabilitation or renovation from industrial floors or industrial pavements the factor time is the most important key factor. Shutdown time must be minimized since every stagnation in the complex process of production, transport and storage will have immediately great financial consequences for the company. The choice for a resurfing system for the industrial floors will be mainly based on two factors: the necessary shut down time and the expected service life from the new topping or overlay. Esthetical and financial factors are of less importance as long as the new topping meets the standards and specifications from the user and the related industry. Cement based thin toppings or overlays have several important advantages compared to other materials. The advantages come into play particularly in the case of industrial flooring and paving and in the rehabilitation of civil constructions. Thanks to recent developments in cement technology there are now many renovation applications for cement-based toppings and ultra thin overlays using high strength- or ultra high strength high performance concretes. The application of thin toppings and overlays is still difficult. Failure or success is depending on factors as quality of the sub base, bonding, placing

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conditions, and curing and last but not least the properties of the HPC. In rehabilitation projects other factors are also of main importance especially the local circumstances and the parameters from the sub base with regard to strength, quality, cracks, pollution, etc. Many times the contractor is confronted with these problems after demolishing the existing topping and than under pressure from the time schedule a good technical solution must be found. This requires a lot of technical and practical improvisation talent since the interests and financial consequences can be large. Between the contractor and the other parties involved such as the client, the consultant and suppliers must than be a good collaboration to solve these flooring problems under time pressure. Many floors are not sound, they have cracks or are contaminated with oil, chemicals, etc., or have a topping made from polymer or bitumen or are even under dimensioned for the actual loads. The only good way is to clean the sub base, to remove weak area’s, to repair or placing new concrete, etc. This can be a huge problem for companies which are working 24 hours a day, don’t want to have dust, noise etc., which can not accept a thick overlay or when they need a new topping very fast. Because of the unique properties of the UHSC/ HPC it is possible to make a solution for this kind of problems. A flooring system that can be laid without joints in places where the quality of the existing base is not satisfactory.

In the case of the rehabilitation or re-strengthening of infrastructure constructions like bridges shut down time have to be absolutely minimized due the immediately impact on the economical situation and the commercial and environmental consequences. In heavily trafficked area’s like on the highways between the main cities in the western part from Holland a shut down of an important infrastructure construction, like for instance a bridge, for maintenance or rehabilitation must be planned several weeks previously to be able to re-route the traffic streams over alternative highways. When maintenance is necessary this should thus be done as good as possible within the available time schedule and in such a way that the repair will last for the longest possible period.

2 The Ultra Thin Heavy Reinforced High Performance Concrete Overlay System

The UTHRHPc overlay marketed under the name Contec Ferroplan System is especially developed to meet all the technical standards and practical requirements for industrial floors placed with standard equipment and by traditional floor layers. The UTHRHPc overlay system is especially developed to cope with problems as described above: not sound or cracked concrete, sub bases from diverged materials and weak constructions. Particularly in these cases the combination of a HSC or UHSC in combination with reinforcement is very interesting to produce strong and ductile “floating” overlays or to connect an extremely strong and ductile overlay to the sub base. Different scientists in publications describe the effects of high amounts of fibers in combination with high amounts of conventional reinforcement in HPC or UHPC, first introduced by Bache, in detail. Composites like SI FCON, RPC and Ductal which are consisting of a HPC or UHPC with the addition of a high amount of fibers are not
technically attractive since they are not designed to place in large thin overlays which will result in difficulties with casting and finishing. These products are especially technically attractive for prefab- and industrial applications.

To develop an UTHRHPB overlay which can be placed under different conditions with traditional equipment and skilled labour it is, most of all, important to understand the complicated process and the difficulties from floor laying since this is the most important key to success of any system. From the point of view of the floor layer the following items are important: The laying of the concrete must be fast and easy enough to be able to place a large area without spending to much time on details; Compaction must be easy and without bleeding and/or segregation in the concrete mix; Floating the surface must be as fast as possible after compacting; It must be easy to reach a smooth and pore free surface. For the engineer and the end-user the final quality and properties are important like for instance: the strength, the wear resistance, the chemical resistance and the esthetical aspects.

The UTHRHPB overlay system consists of a special pre-blended micro silica containing high performance concrete, acrilic fibers, steel fibers and one or more layers of welded mesh reinforcement. The HPC or UHPC can be mixed at the building site or in a batching plant and can be transported with dumpers or truck mixers. The flow and workability is, despite the large amount of aggregates and fibres, made so that the material is easy to compact with the use of a laser screed or a double vibration screed. Immediately after compacting it is possible to float the overlay with a finishing machine with a closed disc (power float). The set time of the HPC or UHPC is equal of that from traditional concrete and thus also depending on temperature and humidity. During several hours after casting it is possible to finish the HPC or UHPC with mechanical finishing machines to obtain the desired surface structure. After finishing the UTHRHPB overlay, it must be protected against further evaporation of the mixing water. After curing for approx. 24 hours of the HPC, a very high quality overlay with a very high bending tensile-, compressive- and impact strength is ready for use. Due the mesh reinforcement and steel fibers the hardened HPC is able to absorb a certain amount of movement from the base without transmitted damaging cracking to the surface.

The technical explanation for the success of the UTHRHPB overlay is that the mixture is containing just enough mixing water and a good composition of fine and larger aggregates what makes that the HPC or UHPC is relatively easy to place and to compact through which the reinforcement is completely encapsulate in the matrix. Due to the long process of finishing during several hours the HPC or UHPC is even more compacted and air is pressed out, the longer the finishing process the better thus the result. Also it seems that this finishing process is of positive influence for the chemical shrinkage of the mortar despite the fact that a large part of the mixing water will evaporate during placing and finishing. By compressing the mortar during several hours with mechanical finishing machines the chemical shrinkage is partly compensated. Further research will be focused on these characteristics of the UTHRHPB overlay.
### Table 1: Technical Data of the high performance concrete without steel fibers.

<table>
<thead>
<tr>
<th></th>
<th>Granite 2 - 4 mm</th>
<th>Calcinated Bauxite 2- 4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength in MPa after: 1 day / 7 days / 28 days:</td>
<td>45/80/100</td>
<td>75/115/150</td>
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<tr>
<td>Flexural strength in MPa after: 1 day / 7 days / 28 days:</td>
<td>7/9/11</td>
<td>9/12/15</td>
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<tr>
<td>Wear resistance DIN 52108 Böhme - value in cm³/50 cm²:</td>
<td>&lt;7</td>
<td>&lt;4</td>
</tr>
<tr>
<td>Density in kg / m³:</td>
<td>2.500</td>
<td>2.700</td>
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</table>

### Table 2: Technical Data of the UTHRS overlay including welded mesh reinforcement.

<table>
<thead>
<tr>
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<th>Granite 2 - 4 mm</th>
<th>Calcinated Bauxite 2- 4 mm</th>
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</thead>
<tbody>
<tr>
<td>Compressive strength in MPa:</td>
<td>&gt; 120</td>
<td>&gt; 170</td>
</tr>
<tr>
<td>Flexural strength in MPa:</td>
<td>40 - &gt;100</td>
<td>50 - &gt;120</td>
</tr>
<tr>
<td>Impact resistance:</td>
<td>Very high</td>
<td>Extremely high</td>
</tr>
<tr>
<td>Frost/thaw resistance SS 13 72 44A-IV</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Chemical resistance compared to high quality concrete (45MPa)</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Water penetration DIN/ISO 7031</td>
<td>&lt; 1,5 mm</td>
<td>&lt; 1,5 mm</td>
</tr>
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### 3 Projects

To explain the potential of the UTHRHPHC two case are described hereafter, one case is an existing reference since 1997 and the other case is a large research project for the Dutch Ministry of Transport, Public Works and Water Management. Beside these two projects several 10.000 m² UTHRHPHC overlay are placed during the last 8 years in different kinds of industry, on civil constructions and even in ships. Sub bases vary from polluted and or cracked concrete to asphalt and steel.

#### 3.1 Association Flower auction Aalsmeer (VBA)

The Association Flower auction Aalsmeer in Holland consists of a very large complex of connected buildings with a total floor surface of more than 900.000 m² and is one of the largest industrial buildings in the world. The supply and removal of flowers is done by trucks, which are using many doors to come in and out of the building. Internal transport is done by special tractors with a mass of several hundreds until more than 2.000 kg with 1 up to more than 30 together coupled flower lorries with a mass from minimum 400 kg each. Due the absence of enough cold storage space a formal internal
parking deck with a floor surface from 9,200 m$^2$ was in 1995 build in a cold store for flowers. The construction was dimensioned for cars, which had consequences for the total acceptable weight from the insulated floors. A choice was made for foam glass isolation with a hydraulic bound bitumen emulsion topping. The building-up from the total construction was thus as follows:

- Double T beams with a length of 23 m\textsuperscript{1} and an arch from 20 mm.
- A levelling layer from a hydraulic bound bitumen emulsion topping with a thickness of approx. 20 mm.
- An insulation layer of 80 mm foam glass.
- A topping from 30 mm hydraulic bound bitumen emulsion topping.

Already during the placing of the topping in the last part of the cold store, damage occurred in the insulated floors due the very intense and heavy traffic during loading and unloading of the cold store. The Association Flower auction Aalsmeer asked ABT-Consultants for Building Technics and Netherlands Pavement Consultants (NPC) to research the damage and to workout a repair proposal. During a period of two years different proposals where worked out and different test area’s where placed but without any satisfactory results. The damage of the insulated floors continued and could only be repaired temporary and therefore a good and durable repair was even more necessary for the owners of the building.

In the spring of 1996 Contec ApS was consulted by ABT for a possible solution and the UTHRHPC overlay system was suggested in a thickness of 22 mm in combination with a welded mesh reinforcement of $\varnothing$ 6 mm and squares from 50 mm. Two trial area’s from 25 m$^2$ each where placed, one on top of the existing hydraulic bound bitumen emulsion topping and one on the foam glass directly. In the same time tests were performed in the laboratory from TNO Delft and fatigue test where made in the laboratory from NPC.

<table>
<thead>
<tr>
<th>Age in days</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Fracture load (N)</th>
<th>Flexural strength (MPa)</th>
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<tr>
<td>10</td>
<td>152</td>
<td>20</td>
<td>8576</td>
<td>84,6</td>
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<td>14</td>
<td>147</td>
<td>20</td>
<td>8768</td>
<td>89,5</td>
</tr>
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<td>28</td>
<td>147</td>
<td>20</td>
<td>8560</td>
<td>87,3</td>
</tr>
</tbody>
</table>

*Table 3: Results from flexural strength tests on samples with reinforcement $\varnothing$ 6 mm.*

The fatigue tests in NPC where done in a complete simulation from the actual floor construction in combination with the UTHRHPC overlay. For the tests a special machine was used to simulate the wheel load on the total construction and the effects of these loads on the different layers. The UTHRHPC overlay was tested in two thicknesses, 20 and 30 mm, and with the reinforcement placed in the favourable- and unfavourable position. Even with extreme loads, which resulted in a considerable bending of several cm, and after cracking of the high performance concrete matrix the
bended sample came back in the original zero position after unloading, almost without any visible cracks.

Table 4: $\sigma - \varepsilon$- Diagrams from samples from table 3.

After a successful testing period of 9 months from the two-sample area’s made, the end-user gave the order for the placement of the overlay in the first cold store with a total floor surface from $2.500 \text{ m}^2$. Decided was to place the UTHRHPC overlay on top of the hydraulic bound bitumen emulsion topping, this to meet the requirements to control the amounts of waste material and to shorten the necessary shutdown period.

### 3.1.1 Placing of the UTHRHPC overlay

After filling out the damages in the insulated floors with hydraulic bound bitumen emulsion reinforcement rebar’s $\varnothing \ 5 \text{ mm}$ and each 500 mm where placed over the whole surface to act as a distance keeper for the welded mesh reinforcement. The fixation of these rebar’s was done with Hilti nails which where shot under an angle from 60 degrees in flat steel strips and in some places with insulation fasteners.

On top of these distance keepers a welded mesh reinforcement from $\varnothing \ 6 \text{ mm}$ and squares from 50 mm was placed and welded together to avoid any movements.
Because of the total thickness from the overlay from only 22 – 25 mm is it very important that the welded mesh reinforcement is properly placed in each other with a dowel length from at least 50 mm. Iron L – profiles where placed along the walls to avoid curling due to shrinkage and loads.

**Drawing 1: Detail UTHRHPC overlay near existing walls.**

At the separation joints to the connected halls a steel profile was welded to the reinforcement. Daily production joints where made by placing flat iron bars on the reinforcement, to avoid pollution from the next production area plastic sheets where taped under the flat iron bars.

**Photo 3: Placing HPC.**  
**Photo 4: Finished UTHRHPC overlay.**

The necessary pre-blended dry materials for the HPC were supplied in big bags in units for $\frac{1}{2}$ m$^3$ en was mixed in a mobile mixer, which was placed outside the cold
store. Transport from the mixer to the building site was done with a small dumper equipped with a transport worm to spread the HPC and with small vibrators. The dumper could simply drive over the stiff reinforcement and place the HPC in front of the double vibration screed. After compacting the HPC the surface could be floated immediately with trowelling machines with a closed disc. After this and during the setting from the HPC, the surface from the overlay can be polished with trowelling machines with steel blades during several hours to get the desired surface structure but in this particular case the end-user wanted to have a skid resistance surface structure. After finishing the surface, a curing compound was sprayed on the surface and the next morning plastic sheets were placed over the surface and made wet. After a testing period from 4 months the rest of the overlay in the cold store was placed including a test area in a thickness from 30 mm with double reinforcement $\Phi$ 5 mm squares 50 mm directly placed on polystyrene isolation panels. The UTHRHP overlay is now in use for more than 5 years and for fills all the expectations from the owner.

### 3.2 Rehabilitation of orthotropic steel bridge decks

Holland is known for its many rivers and channels and to cross these a lot of bridges were and are constructed in both concrete and steel. During the last years fatigue cracks have been found in the orthotropic steel bridge decks of several large bridges in the main highways in Holland. In one case even the bascule from one of the most important bridges near Rotterdam in the west from Holland had to be replaced due the amount of fatigue cracks. In cooperation with the Civil Engineering Division of the Ministry of Transport, Public Works and Water Management research programs were carried out to investigate the reason for these fatigue cracks and to determine the possible solutions. The main reason for these fatigue failures are the high stress concentrations in combination with the local wheel loading and high traffic volume.

![Sectional view orthotropic steel bridge with 6 driving lanes.](http://www.ferroplan.com)

These fatigue problems due the intensive traffic loads, the relatively thin steel deck (10 – 12 mm) and stresses in the steel due welding results in different cracks in mainly three critical places:
1. Welded connections between the stiffener and the deck plate. These cracks are propagated through the deck plate and wearing course.
2. Welded connections between the stiffeners and cross beams and at the cope holes.
3. Welded plate connections between the stiffeners.

The typical wearing course on steel bridges in Holland is two layers of melted asphalt placed on mastic, a membrane and a primer. Since the last years also open graded asphalt concrete is used on top of a membrane to replace one layer of melted asphalt. The composite action between bituminous wearing course and the orthotropic steel deck is not performing well under high and intensive traffic loads and results, especially in the winter periods, in delamination of the wearing course. When damage comes into existence in the bituminous wearing course, the affected driving lane is closed down and the wearing course including the membrane is removed. After inspection of the steel deck plate possible cracks will be welded together and a new membrane and wearing course will than be placed. Typical service life for the wearing course on the problematic orthotropic steel bridge decks is 4 – 6 years, and sometimes even shorter when damage occurred suddenly.

A special task force working party within the Civil Engineering Division was formed to investigate the performance of possible surfacing materials to re-strengthening the orthotropic steel decks of the problematic bridges. Different concepts where investigated and trial area’s where executed like for example: special types of asphalt concrete, welding or glueing of thin steel plates, glueing hard wood beams, injecting
foam in the stiffeners, etc. Due different publications about an HPC overlay on an orthotropic steel deck from a bridge in Canada and Dutch publications about the UTHRHPC overlay in the Association Flower auction Aalsmeer the Civil Engineering Division became interested in 1999 in the use of HSC/HPC as a possible solution.

3.2.1 Material tests

The first research and tests in 1999 with the UTHRHPC overlay was done at the Adhesion Institute at the Delft University of Technology on prefab samples placed on 12 mm thick steel plates. To get a composite action between the UTHRHPC overlay and the orthotropic steel deck an two component epoxy paste adhesive was used as a bonding agent because welding will result in new concentrated stresses in the steel deck. The first research was thus focused on three possibilities:

1. Placing prefab UTHRHPC panels in a wet two-component epoxy paste adhesive.
2. Placing an UTHRHPC overlay in a wet two-component epoxy paste adhesive.
3. Placing an UTHRHPC overlay in a dry two-component epoxy paste adhesive with shaked in aggregates.

The first two methods, especially the second, were promising but were not accepted as practical possible on large orthotropic steel bridge decks. Further tests will only be focused on method 3. The samples where made with the standard pre-blended materials with granite as aggregates, with 100 kg of 0,4 x 12,5 mm steel fibers m$^3$ and with additional reinforcement.

The reinforcement principle consisted of a special welded mesh reinforcement 50 x 50 mm with three layers of Ø 8 mm rebar’s placed on a 8 mm rebar as a distance keeper. Thus the total amount of reinforcement was approx. 24 kg/m$^2$ conventional reinforcement and approx. 5 kg/m$^2$ steel fibers. The reinforcement is placed in such a way that the rebar’s at the bottom and the rebar’s at the top are placed in the width from the bridge to re-strengthening the area above the stiffeners. The total thickness of the UTHRHPC overlay was 50 mm. Tests where made as three point loads with a variation in the location for the force and tests where done in both the compressive – and tensile load direction.

Conclusions of the tests and calculations made by the Adhesion Institute TU Delft:

1. As well static as after fatigue the UTHRHPC overlay is decisive and not the two-component epoxy paste adhesive.
2. When loaded static until failure at the load direction: the tensile stress in the UTHRHPC overlay at the end of the curve is 10 MPa, thus a factor 4,5 higher than the actual stress by a 35 kN wheel.
3. When compressed static until failure at the tensile direction: the tensile stress in the UTHRHPC overlay at the end of the curve is 32 MPa, thus a factor 16 higher than the actual stress by a 35 kN wheel.
4. In the load direction: no fatigue or reduction in strength after 1 million load cycles at 2 MPa shearing in the UTHRHPC overlay and 1 million load cycles at 4 MPa shearing in the UTHRHPC overlay.

5. In the tensile direction: no fatigue or reduction in strength after 1 million load cycles at 4 MPa tensile force in the UTHRHPC overlay and 1 million load cycles at 8 MPa tensile force in the UTHRHPC overlay.

6. The reinforcement gives an extra additional strength and coherence of the high performance concrete matrix. By this there is no clear transition to failure perceptible.

3.2.2 Test area on an orthotropic bridge deck

To get more understanding of the logistic process and the possibilities for placing the UTHRHPC overlay under different conditions the working party of the Civil Engineering Division decided to start with a test area on the removed bascule from the Van Brienenoord bridge which where stored and kept for further testing in an outdoor storage area.

A 60 m² test area was placed in October 2000, half of it was placed on a dry two-component epoxy paste adhesive with shaken in aggregates and the other half was placed directly on the steel deck where some of the distance keepers where welded on. Placing went very well but after some weeks two small cracks occurred and drill cores showed that the high performance concrete was not compacted well in some areas.

Investigation showed that some of the vibrators on the double vibration screed didn’t function well. To prove that these kind of problems could be avoided, a second test area was made in July 2001. Here the HPC was compacted very well and despite the high temperature of more than 25°C and a hard warm wind no cracks occurred. The finishers where also able to float the mortar during several hours to get an almost shiny smooth finish what resulted in a very hard and dense toplayer. The drill cores, which were taken out, showed a very good compaction of the HPC around the dense reinforcement and also around the overlaps between the reinforcement.
Bonding test which where taken in the two area’s showed a bonding strength above 1,5 MPa up to more than 3 MPa but reliable figures couldn’t be made due the deviation in the drill cores mainly due to the high amount of reinforcement and the difficulties to drill a straight drill core. A part of the surface is shot blasted to test the skid resistance according the Dutch Standard for roads. Also a part from the first test area is removed to test the possibilities to remove the UTHRHPH overlay from the deck plate without any damage. By cutting the UTHRHPH overlay with a cutting machine equipped with a diamond sawing blade until 95% of the full depth the total area was divided in small area’s which where broken out with a hydraulic demolition machine. No damage of the steel deck was visible after removing the UTHRHPH overlay.

3.2.3 Overview first conclusions

After the first tests at the Delft University of Technology and after placing the two test area’s a report is made by the working party of the Civil Engineering Division with the first conclusions and recommendations.

Conclusions of the tests and calculations made by the working party of the Civil Engineering Division:

- Stress reduction compared to a standard orthotropic bridge deck without wearing course and an UTHRHPH overlay of 50 mm is reduced from 124 MPa to 28 MPa (a stress reduction from a factor 4) at the backside, the problematic area, from the deck plate.
- Calculations with two “bridge cases” with the relatively rigid UTHRHPH overlay are not showing that this will result in extreme stresses in the orthotropic bridge as a whole.
- Conclusions of the tests and calculations made by the Adhesion Institute TU Delft.
- The investment for placing of the UTHRHPH overlay is equal to the costs of a traditional bituminous wearing course of melted asphalt.
• Placing under strict quality control and under different conditions is possible. Mixing, casting, compaction and finishing of the UTHRHP is no problem and can be done with traditional equipment and with skilled floor layers.
• It is possible to remove parts of the UTHRHP overlay without damaging the orthotropic bridge deck.
• The skid resistance is very good after shot blasting the surface: according the Dutch Standard 71 SRT unities, this compared to 55 SRT unities for an open graded asphalt concrete wearing coarse surface and 65 SRT unities for a dense asphalt concrete wearing coarse surface.

3.2.4 Further test program
At this moment, March 2002, the next test program is started at the Delft University of Technology to investigate further properties of the UTHRHP overlay. Research will be focused on material properties; strength; strength development; shrinkage and the influence on the shrinkage from compacting, finishing and curing; bonding and the influence from the shaked in aggregates; frost/ thaw resistance and chloride penetration. Also a large part of the UTHRHP overlay including the orthotropic steel bridge deck, stiffeners and a crossbeam will be taken out for different fatigue tests. Final results will be known in approx. July/ August 2002.

4 Other applications
The UTHRHP overlay and its exceptional mechanical characteristics combined with the durability and the possibilities for placing is a technically and economical attractive solution for several problems with existing constructions in industries, port- and harbour pavements and airports. Not for only orthotropic steel bridge decks but also for concrete bridge decks with for instance damage due frost/ thaw cycles in combination with chloride penetration or concrete bridges in a more aggressive environment can be rehabilitated with the UTHRHP overlay. In these cases the UTHRHP overlay can be structural anchored to the construction beneath by use of anchors. Also structures like offshore platforms and supply boats can be protected and even re-strengthen with this kind of UTHRHP overlays. There also must be possibilities for the UTHRHP overlay in the re-strengthening of constructions in earthquake sensitive areas.

5 Further development program
Further research and investigation will be focussed on the behaviour of the UTHRHPC overlay in combination with different kind of bonding, anchoring and reinforcement principles and than in combination with different kinds of sub bases ranging from concrete to steel with different strength and qualities. Also research will be done on new concepts for composite materials like for instance on hybrid bridge decks.
Acknowledgements.
The pioneering work and the research and developments made by Hans Henrik Bache are a continuously inspiration, his enthusiastic support and his recommendations are always taken in serious account. Special thanks to the Civil Engineering Division of the Dutch Ministry of Transport, Public Works and Water Management for the good co-operation and support during the test programs for the rehabilitation of orthotropic steel bridge decks.

References