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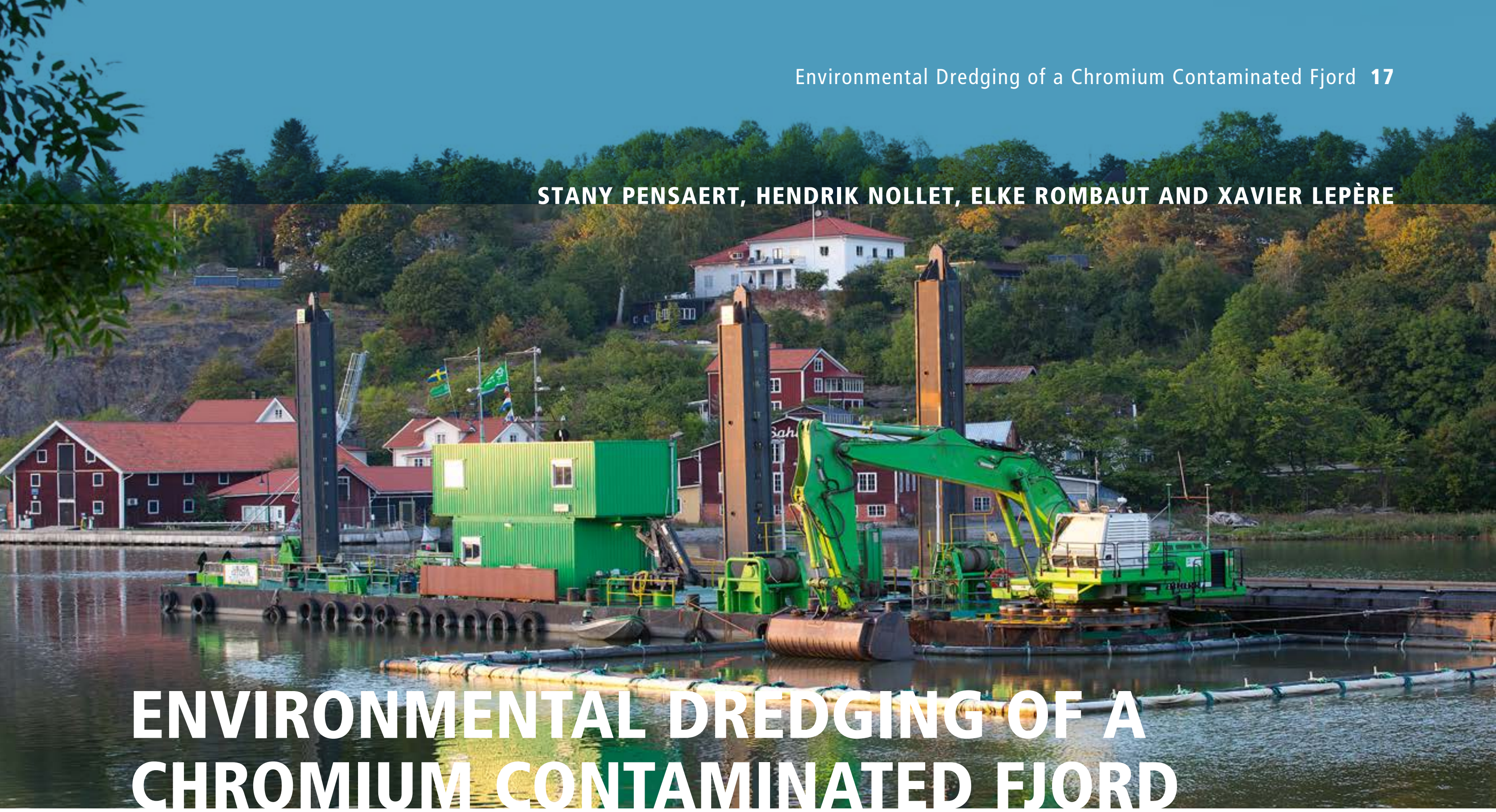

Above: Dredging operations being conducted to remediate chromium contaminated sediments in the Valdemarsviken fjord.

ENVIRONMENTAL DREDGING OF A CHROMIUM CONTAMINATED FJORD

ABSTRACT

This article has been adapted from a paper that was presented at the CEDA Dredging Days in November 2015, Rotterdam, the Netherlands (see 'REFERENCES' for citation).

The sediments in Valdemarsviken fjord, Sweden, were contaminated with chromium from the discharge of untreated wastewater from tannery operations some decades ago. Thus, the remediation of the fjord was very important for the water quality in the Baltic Sea. The contaminated sediments in the inner part of the fjord were dredged, dewatered, solidified and placed as engineered fill on a nearshore area. It was observed that the dredging operations on one side, and the backfill operation on the other side, would affect the stability conditions along the shores. As such, stabilisation of quays, shores and the backfill area by means of lime-cement columns was required. The dredging of contaminated sediments covered about 200,000m³ spread over a 350,000m² large area. During the detailed design phase, prior to the start of the works, the site conditions and sediments were monitored and investigated thoroughly. Lab scale tests were performed to verify that the chosen process for the dredging, dewatering and solidification met the set requirements with regards to the strength of the backfilled stabilised sediments specified by the client. The lab work also formed the basis of the process design for the on-site solidification plant. The dredging operations met the stringent environmental demands towards turbidity and the generation of spill. The sediments were dredged by using hydraulic excavators equipped with a level-cut clamshell bucket or a visor bucket. The sediments were then pumped to a continuous mixing unit for solidification with a cementitious binder. Any water released from the activities was collected and treated by a specially designed on-site water treatment plant.

INTRODUCTION

The Valdemarsviken fjord is located in Valdemarsvik municipality in the southeastern part of the Östergötland county on the eastern coast of Sweden. Valdemarsviken represents the only threshold fjord on the East Coast and stretches about 11km from the town of Valdemarsvik out to the mouth at the Gryt archipelago in the Baltic Sea.

The sediments in Valdemarsviken were heavily contaminated with chromium from decades of discharge of untreated wastewater from tannery operations at the Lundberg Läder factory, which operated from 1873 until its closure in 1960. Chromium III salts were used extensively in the tanning process as it enabled faster and cheaper production of highly resistant and durable leathers. Today, more than 80% of finished goods are still tanned using basic chromium salts.

The remediation of the Valdemarsviken fjord is very important for the water quality in the Baltic Sea. The fjord has for a long time produced the biggest single release of chromium to the Baltic Sea, estimated to be about 250kg per year.

Valdemarsviken is primarily used as a recreation area for activities such as boating, fishing and swimming. The existing plans for continued development of the area are linked to the development of marine operations and to some extent housing. There are also plans for new areas for outdoor recreation and sports activities.

In light of this, Valdemarsvik municipality decided to remediate the Valdemarsviken fjord with respect to chromium contaminated sediments. The project was put out to tender in 2009 and the actual execution took two years – between 2012 and 2014. The remediation measures included dredging, treatment of dredged sediments, water treatment, reuse of dredged material, shoreline reinforcements, construction of quay and clearing of obstacles for dredging. The majority of the contaminated bottom in the inner part of the fjord had to be removed. The dredged and dewatered bottom sediments had to be used as engineered fill material for a small valley area about two kilometres south-east of the village. The dredging works covered an area of about 350,000m² and removed as much as 400 tons of chromium, which equalled a reduction in the emission of chromium by 90%.

Ultimately, the project was meant to reduce the load to the Baltic Sea and to achieve the objective of a 'non-toxic environment'.

SITE INVESTIGATION

The sediments in the Valdemarsviken fjord were mainly contaminated with trivalent chromium. The average chromium concentration observed during site investigation varied from about 1000 mg/kg dry matter at the deepest levels up to about 3000 mg/kg dry matter in the near-surface sediments. The maximum measured chromium concentration was approximately 7000 mg/kg dry matter. The primary contaminant was trivalent chromium. During the site investigation by the client the very toxic hexavalent chromium was initially not found, but during the works it was detected several times at considerable levels. In addition to chromium, the sediment samples also contained low levels of copper, lead, zinc, arsenic and mercury. According to the main site investigation report, the total mass of chromium was estimated at 700 to 800 tons.

In order to achieve the remediation objective, which was a 90% reduction of the chromium emission, the client defined a remediation target concentration of 500 mg/kg dry matter for chromium. Based on the intensive site investigation by the client this target was translated into a dredging design level for the whole fjord. This design level was the basis for the contractor to deliver the works.

STABILISATION OF THE SHORELINE

Around Valdemarsvik there are soil layers of clay with low shear strength – known as quickclays – that pose a high risk of landslides. Dredging of the sediments in these areas would affect the stability conditions along parts of the shores. Furthermore, the topographical and geotechnical conditions in the bay, with steep banks and loose soil layers of clay ensure that even relatively small load changes can result in landslides. Therefore, near-shore dredging in some areas had to be combined with soil reinforcement measures.

These soil reinforcement measures were executed in three areas along the coast line. The technique proposed by the client was to perform the ground reinforcement with vertical quicklime-cement columns (KC-columns: Kalk-Cement columns).
A dry mixing method by means of a vertical auger of a diameter of 600mm with pneumatic injection of the binders was used to stabilise the very weak soils along the shore line in Valdemarsvik.
The dosing and ratio of the lime-cement blend was defined by an extensive testing programme. It covered the testing of various combinations of binding agents KC 50%/50% and KC 25%/75%. Based on the results of these tests, eventually the area was treated by using the binding agent KC 25%/75%, 28kg of binder per vertical metre. The vertical mixing rate applied was 25 mm/rotation.

The results of the tests with KC 25%/75% and 28 kg/m showed that the columns reached an unconfined compressive strength (UCS) of at least 50 kilopascal (kPa) after two days and 150kPa after 14 days. The surface had to be subjected to loads about seven days after the installation of the columns.

Purpose-designed drilling rigs were used for the installation of the KC-columns, which were equipped with a special mixing tool at the end of the mixing rod. The drilling rigs installed the columns from a working platform or reinforced clay surface (Figure 1). Columns with a diameter of 600mm were installed up to a depth of 22m. Dosing and mixing of the dry binder blend with the soil took place while the rod was withdrawn. The KC-mixture was delivered by bulk trailers from the supplier and stored into a shuttle on site. The binder was transported from the shuttle to the rig through connecting hoses using compressed air. The binder dosing could be adjusted as desired. The columns were installed in a fixed pattern (Figure 1).

The mixing device moved in a corkscrew motion till it reached the fast bottom or the designed length. After that, the operator opened the valve and lifted the mixing device with a predefined lifting and rotation speed. The operator controlled the whole process while producing the column. When the process neared the surface, adding of the mixture was stopped and the length of the stabilised column was recorded. About

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ELKE ROMBAUT
has been working for 14 years in project engineering, works management and project management within the DEME group. She worked for almost 10 years on projects abroad such as France, Qatar, Angola and Sweden. She was the project manager of the DEC project, the environmental dredging of the chromium contaminated fjord in Valdemarsvik, Sweden. Elke organised, ensured and managed the execution of the project according to the contract and in accordance with client requirements.

HENDRIK NOLLET
has a background in environmental technology and more than 13 years of experience in project engineering, works management and strategic project management. He worked for almost 10 years on projects abroad such in the UK, Sweden, Italy, Canada and Norway. Hendrik always ensured that the works were executed according to the contract, in accordance with the client requirements and within the budget. He supported the Valdemarsviken project during the design phase. He has authored and co-authored about 20 international peer-reviewed publications.

XAVIER LEPÈRE
has been working for eight years as project engineer for the R&D Department of DEC. Xavier gives scientific and technical support to the sites and other departments of the company. Apart from supporting innovative activities within DEME, he is also responsible for defining and/or developing the best technique to use for each environmental project. This includes upscaling lab trials to full scale, modelling and optimising the process of treatment installations. He also ensures process quality control for lots of different activities such as acid tar remediation, environmental dredging, and soil/sediment stabilisation.

400,000m of quick lime-cement columns were installed.

After installation of the KC-columns, validation tests based on in-situ vane tests were executed in the installed columns. Those tests were performed at two moments after the installation – around 14 days and around 28 days. If the strength was not enough or if weak spots were noticed in the columns, the amount of binder was increased (e.g. 32 or 34 kg/m).

ENVIRONMENTAL DREDGING

The volume of contaminated sediments that required dredging was estimated to be about 200,000m³ to be dredged over a surface of about 350,000m². This implied the dredging of rather thin layers of sediment (Figure 2). The depth of dredging, however, went up to 14m.

The entire project was taken into consideration in order to use the right dredging technique. The technique had to meet the following requirements:

- the dredging method had to be compatible and fully integrated with the materials' handling, transport, treatment, and ultimate disposal.
- the dredging execution had to meet the stringent environmental demands towards turbidity and the generation of residual spill.

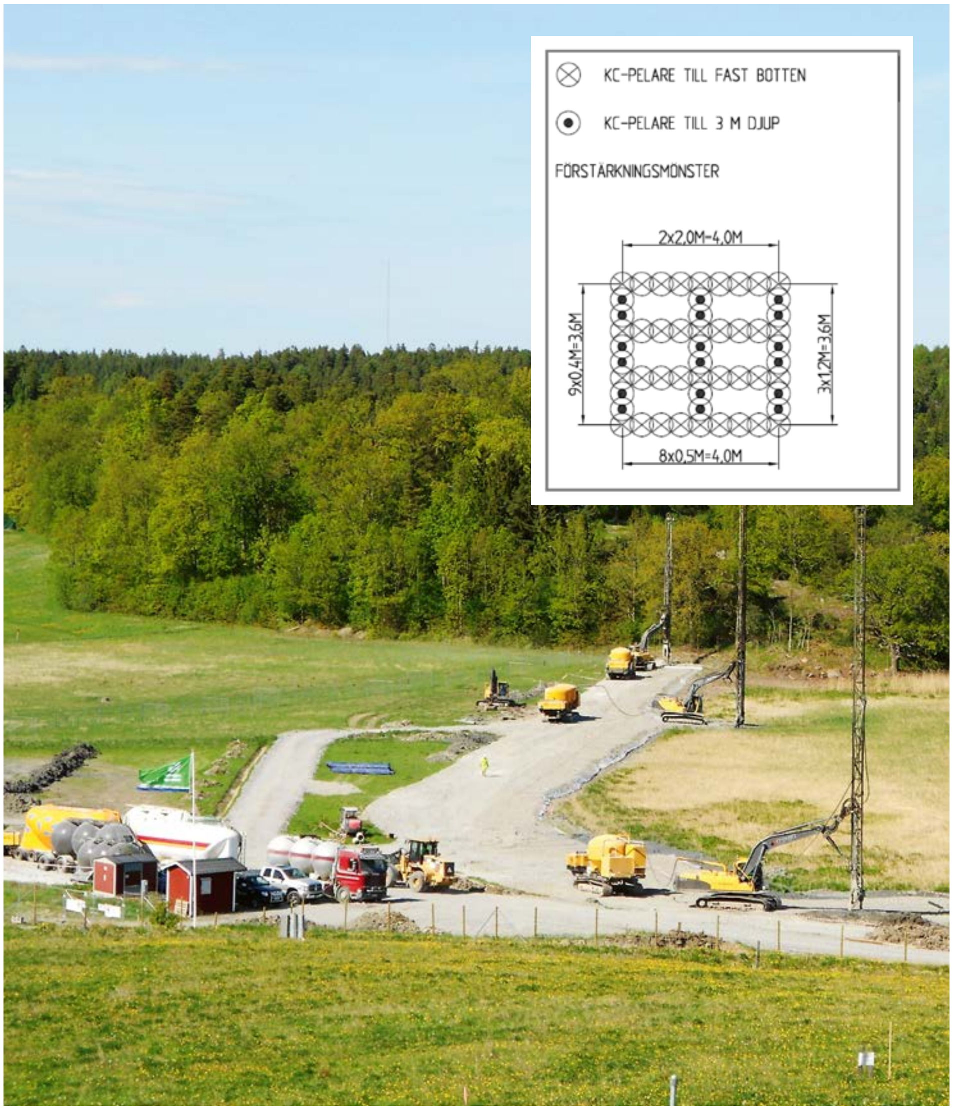

Figure 1. Left: The columns were installed from a working platform or reinforced clay. Right: Installation of the KC-columns in Valdemarsvik. Upper right: The KC-columns were installed in a fixed pattern.

Figure 2. Overview of the dredged area with the various sediment depths.

An appraisal was done on several environmental dredging techniques with special attention to the site conditions, sediment characteristics, environmental dredging performance standards, equipment capabilities, operating methods and strategies. As a result, dredging by using a hydraulic excavator equipped with a level-cut clamshell bucket or a visor bucket was selected as it could provide the most optimal dredging production, debris management, and dredging accuracy for site-specific conditions. The equipment is shown in Figures 3 and 4. In order to obtain extreme accuracy in dredging, the dredger was equipped with the latest positioning system. High accuracy dredging is essential for the successful execution of clean-up projects. It leads to less volume to be transported, stored and treated. Furthermore, it leads to less turbidity and spillage.
The level-cut clamshell bucket was designed for the dredging works in Valdemarsviken. The bucket size was adjusted to the depth of the cut to maintain a higher fill factor and limit the amount of water captured in the bucket. This was done to prevent overfilled buckets which can have a significant negative impact on the water quality and residuals.

When thick banks of sediment needed to be removed, multiple dredging lifts of ± 30cm each helped in limiting bank instability and sloughing that can contribute to residuals.

The level-cut clamshell bucket was used to reduce spillage and leakage from the clamshell while being raised through the water column. The total content of chromium in the re-sedimented materials within the whole dredging area of Valdemarsviken after dredging was not to exceed six tons of chromium. This is equal to an average of less than 20g of chromium per metre square (g Cr/m²).

In addition to the operational controls, a mobile silt screen was installed at the dredger around the reach area of the excavator (Figure 3). In addition, fixed silt screens were installed further downstream of the fjord. The maximum allowed increase in turbidity in the Valdemarsviken fjord immediately outside the area where turbidity causing works were in progress (50m from the dredge) was 9 Nephelometric Turbidity Units (NTU) in relation to a reference point upstream.

Finally, the dredged sediments were loaded into sealed barges (400m³ - 600m³) for transport to the stabilisation plant onshore.

SOLIDIFICATION OF THE SEDIMENTS

While the shoreline stabilisation works were ongoing in 2012, the design of the dredging and solidification works were carried out.

The area to be dredged was extensively sampled from a small pontoon by using a manual core sampler, allowing undisturbed sampling at the desired depths. Disturbed and undisturbed samples were collected and the disturbed samples were used to perform the labscale stabilisation tests. The in-situ parameters of the sediments were determined on the undisturbed samples. Special attention was paid to pump off the water layer as shown in Figure 5 to ensure an "in-situ" quality of the sediments of the samples taken at the top of the sediments.

Furthermore, the frequency of the sampling was adjusted in correlation to the volumes to dredge in each part of the area. Each sampling location was individually

Figure 3. The dredger, *Ijburg,* in combination with a level-cut clamshell bucket was utilised to perform the dredging works in the Valdemarsviken fjord.

characterised to have a good overview of the variations of the physical and chemical properties of the sediments. Finally, the individual samples were composited into three composite groups based on various elements such as the location, density, granulometry, and visual observation. Feasibility trials on lab scale were performed on these three composite samples.

The client's requirements were that the sediments would be used to backfill the Grännäs area and this backfill should have a shear strength of at least 25 kPa, one month after placement. In order to achieve this geotechnical objective, all technically possible options were evaluated starting from the dredged sediments. Although dewatering of the sediments by means of a membrane filter press was the most interesting technical solution as it produced filter cakes with the necessary shear strength, the capital costs, space requirements, and execution schedule would become too high.

As such, solidification of the sediments, as originally suggested by the client, turned out to be the most cost-efficient method with the cost, time and space constraints. Therefore, mechanical dredging was obviously preferred to hydraulic dredging as a minimal dilution with water could be achieved, which is better for the binder consumption.
The different binders available in the Valdemarsvik area were tested with different concentrations and curing times. Through the tests, cement-based binders were found to give the best results in creating sufficient strength with a reasonable dosage. An overview of these results is given in Figure 6. It is important to note that the shear strength was tested indirectly by means of determining the Unconfined Compressive Strength (UCS) divided by a factor of two.

The binder dosage depends on the water content of the dredged sediments. This dosage differs during the whole dredging activity as a lot of parameters are involved in these variations such as dredged zone, differences in sediment granulometry, depth of the layer to dredge and slope of the bottom. With the lab trials, it was possible to establish a relationship between the water content of the sediments and the amount of binder needed to meet the criteria. This relationship is shown in Figure 7.

Special attention was paid to the chemistry of the solidified sediments. Investigations by the client showed no leaching of chromium from the solidified samples. However, during the contractors' design programme in 2012 it was shown that chromium leaching did occur. It turned out to be hexavalent chromium. It was demonstrated that the differences in leaching results were due to different analytical protocols used by different analytical laboratories. Although the leaching of hexavalent chromium was limited, the client decided to collect all drainage water arising from the Grännäs backfill area and to treat it in the water treatment plant on site.

Figure 4. A visor bucket in being utilised for dredging at Vademarsviken fjord.

Figure 5. (a). Sediment sampling performed in the Valdemarsviken fjord (b). A manual core sampler collecting sediment sample. (c). A view of the collected sample.

EXECUTION OF THE WORKS

The actual dredging and sediment solidification works were executed between spring and fall of 2013.

As the consumption of the binder during stabilisation of the sediments increased exponentially with increasing water content of the sediment, as illustrated in Figure 7, it was obviously important to select an appropriate dredging technique that avoids excessive addition of water. Mechanical dredging by means of a clamshell or a visor bucket was utilised. After, the sediments were transported by barges to the unloading quay. The decanted water on top of the sediments was carefully removed and treated in a tailor-made water treatment plant on site. This plant consisted of a large decantation buffer, a flocculation unit, lamella separator, sand and activated carbon filters. In the flocculation unit, a ferrous sulphate solution was added in order to chemically reduce hexavalent chromium and precipitate it as trivalent chromiumhydroxide in the lamella separator. The discharge level for chromium was very low, i.e. 1 µg/l.

After the top water was removed the sediments were unloaded by a clamshell excavator from the barges, screened on an in-house designed star screen, and then pumped into the continuous mixing facility. This mixing facility had a throughput between 200 and 300 m³/h. Between the pump and the mixing plant the water content of the sediments was continuously measured by means of an in-line density meter. In combination with the inline flow measurement, this density value was used to calculate the required dosing of the binder. This continuous measurement and process control ensured the right dosage of binder at any given time. During the start-up of the plant the binder dosage was frequently verified by means of portable X-ray fluorescence (XRF) measurements. The net addition of water, after dredging and barge dewatering, was limited to maximum 25% volume.

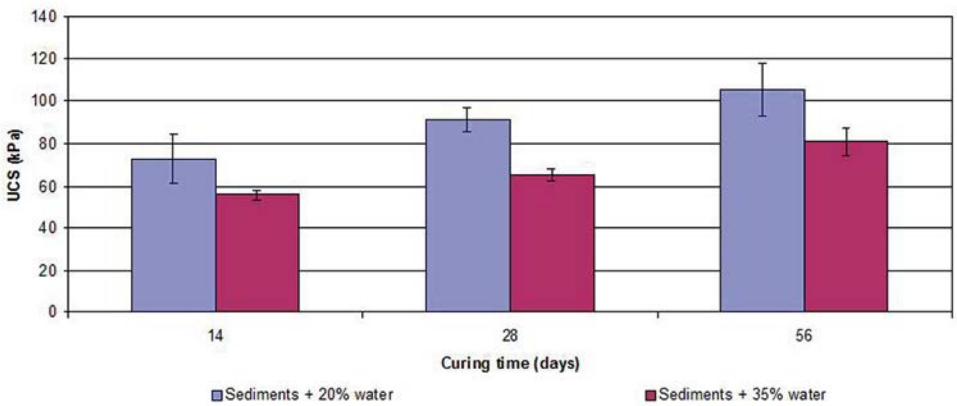

Figure 6. Results of sediment solidification

Immediately after mixing, the sediments were collected in dump trucks and transported onto the Grännäs area where they were spread open by long reach excavators (Figure 8).

During the project, daily samples were taken for validation of the stabilisation process. The samples were moulded, stored in a 'library', and used to determine the shear strength after the following days – the first, third, seventh, fourteenth, twenty-eighth and fifty-sixth day. The strength after 28 days was seen as the contractual target. As it was possible to establish a good correlation between the early strength development (which could be seen between the first and third day) and 28 days later, it was possible to extrapolate the strength after three days to 28 days.

A daily high production of about 2000m³ in-situ sediments was achieved. It allowed the contractor to finish the dredging and sediment treatment in less than six months. The backfilled Grännäs area had a surface of about 75,000m². The final profiling and covering with a synthetic geomembrane, bentonite mats and moraine materials, was carried out in spring 2014 (Figure 9).

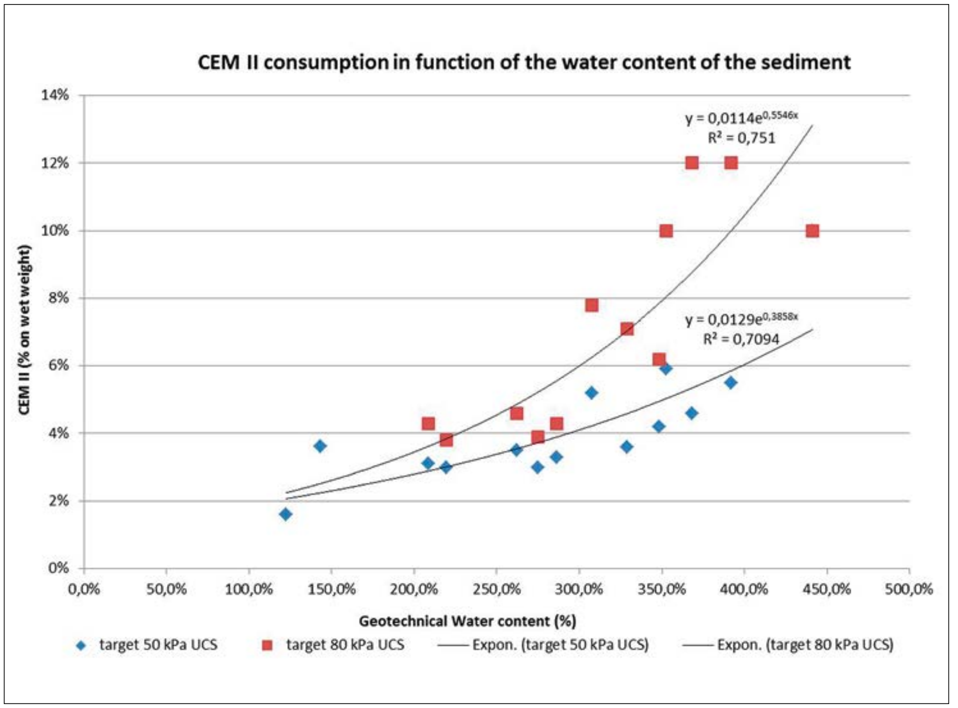

Figure 7. Relationship between water content and cement consumption to achieve 50 or 80 kPa UCS (= 25 or 40 kPa shear strength)

Figure 8. From right to left: Barges are unloaded; the mixing plant; and the stabilised sediments are spread into the backfilling area. At the front of the image, the water buffers from supernatant and run-off water can be seen.

Figure 9. An aerial view of the Grännäs backfill area near completion.

CONCLUSIONS

The remediation of the Valdemarsviken fjord proved to be successful. Through mechanical dredging, it was possible to dredge relative thin layers, up to depths of 15m, at fairly high productions of 2000m³ in-situ per day. In addition, mechanical dredging with environmental grabs or visor buckets, combined with top dewatering of the transport barges, ensured a limited addition of water to the sediments. This was required to limited volume increase and high costs for extra cement addition.

From the project, it was proven that in-line solidification is a cost-efficient, robust, and high capacity technique for the treatment of a large amount of contaminated sediments. This technique allowed for the reuse of the treated material as engineered fill and avoid expensive external landfilling.

Finally, from the project it can be concluded that special attention has to be paid to the leaching of hexavalent chromium from (solidified) sediments. It is important to find the right analytical lab that can accurately analyse hexavalent chromium since it was proven that different analytical protocols between labs can result in false negative figures.

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