Improvement of the long-term trafficability of harbour container terminals with composite geogrid reinforcement

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ABSTRACT: Due to the globalisation of the world economy existing ports are being developed and new ports are being built in order to cope with the increasing volume of goods in transit. New container terminals or port extensions are mostly built on reclaimed land from the sea. As the nourishments with their low or medium compactness of the ground only have an insufficient bearing capacity to take up the final loads of the container terminals, the long-term stability and trafficability of the gained ground must be improved. An economic measure to improve the bearing capacity of different existing and newly developed terminal areas is the use of composite reinforcements as reinforcing and separating layers. As the geogrid can take up greater tensile stresses than the base course itself, the tension in the reinforced base course is being reduced. This leads to a more efficient load distribution within the base course and thus to a less vertical deformation (settlement and rutting) at the terminal traffic surface, which thus clearly increases the serviceability of these intensively used traffic areas. As shown in laboratory and field tests, a geogrid/nonwoven composite material can provide a tremendous increase in long-term trafficability compared to areas without reinforcement or only with the use of normal geogrids. This paper will give an overview on the state-of-the-art using geogrid/nonwoven composite materials to increase the bearing capacity of the base course at various international port projects as e. g. in Turkey, the Sultanate of Oman and the USA.

1 INTRODUCTION

1.1 *General*

Container storage areas carry large traffic volumes and typically have concrete or paved surfacing over a base layer of aggregate. The combined surface and base layers act together to support and distribute traffic loading to the subgrade. Problems are usually encountered when the subgrade consists of soft clays, silts and organic soils. These types of soils are often water sensitive and, when wet, unable to adequately support traffic loads. If unimproved, the subgrade will mix with the road base aggregate, which leads to a reduction of strength, stiffness and drainage characteristics, promoting distress and early failure of the roadway. Contamination with fines makes the base course more susceptible to frost heaving.

1.2 *Separation of Subgrade and base course*

A geotextile which is placed between the subgrade and the base course layer provides physical separation of subgrade and base materials during construction and during operating life of the trafficked area (see Figure 1).

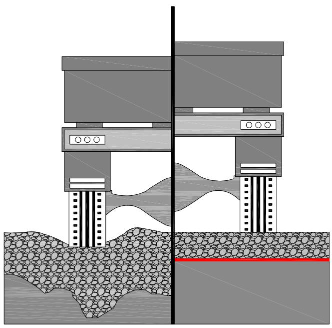

Figure 1. Illustration of geotextile separation function

The separation function of the geotextile is defined by a prevention of mixing, where mixing is caused by mechanical actions. The mechanical actions generally arise from physical forces imposed by construction or operating traffic and may cause the aggregate to be pushed down into the soft subgrade and / or the subgrade to be squeezed up into the base aggregate. A properly designed geotextile separator allows the base aggregate to remain "clean", which preserves its strength and drainage characteristics. The use of geotextile separators ensures that the base course layer in its entirety will contribute and continue to contribute its structural support of vehicular loads; the separator itself is not viewed to contribute structural support to the aggregate layer. Yoder and Witczak (1975) state that as little as 20% by weight of the subgrade mixed in with the base aggregate will reduce the bearing capacity of the aggregate to that of the subgrade. This highlights the importance of a geotextile separator with regard to the performance of base aggregate layers on fine-grained subgrades.

1.3 *Reinforcement of base courses using geogrid reinforcement*

Vehicular loads applied to the surface of trafficked areas create a lateral spreading motion of the unbound aggregate layers. Tensile lateral strains are created at the interface subgrade/geogrid as the aggregate moves down and sideways due to the applied load. Through shear interaction of the base aggregate with the geogrid, a.k.a. inter-locking, (see Figure 2), the aggregate is laterally restrained or confined (see Figure 3) and tensile forces are transmitted from the aggregate to the geogrid.

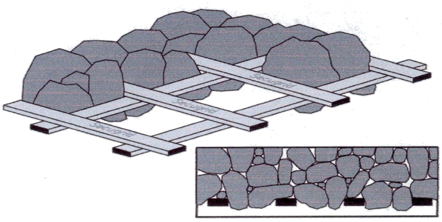

Figure 2. Interaction of aggregate with geogrid

As the geogrid is much stiffer in tension as the aggregate itself, the lateral stress is reduced in the reinforced base aggregate and less vertical deformation at the road surface can be expected. This interaction between geogrid and base course material increases the shear strength and thus the load distribution capacity of the used base course material.

Figure 3. Lateral restraint of aggregate using high modulus laid and welded geogrids

The increased load distribution capacity reduces vertical stresses on the subgrade, which finally reduces the deformation (rutting) on the surface of the aggregate layer. This correlation enables the reduction of reinforced base course thicknesses in comparison to un-reinforced layers (see Figure 4).

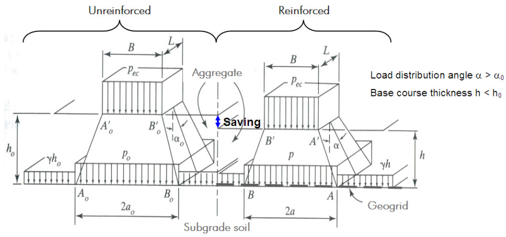

Figure 4. Increase of load distribution capacity with the use of geogrids (Giroud et al 1981)

In many projects, good quality base course aggregate is not available on site or close to the site. As a result, high transport costs of imported, expensive good quality base aggregate have a great influence on the total project costs. Especially under those conditions geosynthetic reinforcement and separation products can help to save money by reducing the amount of imported fill material needed to achieve the specified bearing capacity for the expected loads on the base course.

To combine the function of reinforcement and separation in one product, so called Geocomposites have been developed. Geocomposites as e.g. Combigrid® (see Figure 5) allow faster construction rates compared to separately installed geogrid and geotextile components.

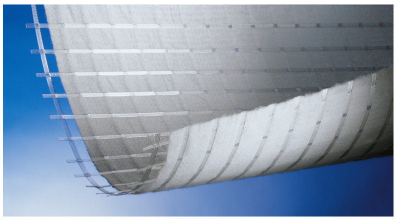

Figure 5. Combigrid® Geocomposite (geogrid reinforcement & needle punched nonwoven geotextile, firmly bonded between the cross laid reinforcement bars)

2 PERFORMANCE OF BASE REINFORCEMENT GEOGRIDS IN ROADWAY STABILIZATION APPLICATIONS

2.1 Large Scale Laboratory Test

The purpose of the study was to evaluate the reinforcement benefit provided by different geogrids. Benefit was defined in terms of the number of load cycles to reach a specific permanent rut depth of 3 inches (75 mm) in the aggregate surface layer for each section and Traffic Benefit Ratio (TBR), which is the number of load cycles for a reinforced section divided by the number of load cycles to reach this same rut depth for a comparable unreinforced test section. The test sections were instrumented to measure geosynthetic deformation and subgrade pore water pressure response.

The pavement test box facility used for the laboratory test was designed and constructed for the purpose of conducting laboratory, full-scale experiments on reinforced and unreinforced pavement sections and it meets the requirements of specifications developed for AASHTO Subcommittee 4E as contained in Berg et al., 2000. The test box facility is designed to mimic pavement layer materials, geometry and loading conditions encountered in the field as realistically as possible with an indoor, laboratory based facility. This type of test box facility allows a high degree of control to be exercised on the construction and control of pavement layer material properties.

Each roadway test section was constructed with a nominal cross-section consisting of 12 in. (300 mm) of base course aggregate and 40 in. (1.1 m) of subgrade soil with a CBR = 1. The geosynthetic was placed between the base course and subgrade layers. A control test section having the same cross section without a geogrid was used for comparison to the geogrid stabilized sections. A cyclic, non-moving load with a peak load value of 9 kips (40kN) was used to mimic dynamic wheel loads. Sensors were used to measure applied pavement load, pavement surface deformation, and stress and strain in the base aggregate and subgrade soils. At a later state, the results of the dynamic plate loading laboratory tests shall be compared to results from test sections in the field, where moving wheel loads (three axle dump truck) are used to generate the pre-defined deformation rates. In both, the laboratory and the field test, the boundary conditions of the prepared subgrade and base course (as e.g. type, moisture content, gradation & angularity of base) are comparable.

Amongst others, the results shall be used to quantify the influence of circular (plate load) versus biaxial loading (wheel load) on the development of rut deformation.

2.2 Test-Box and Loading Apparatus

Test sections were constructed in a 6.5 ft (2 m) by 6.5 ft (2 m) by 5 ft (1.5 m) deep box shown in Figure 6. The walls of the box consist of 6 inch (150 mm) thick reinforced concrete. The front wall is removable in order to facilitate excavation of the test sections.

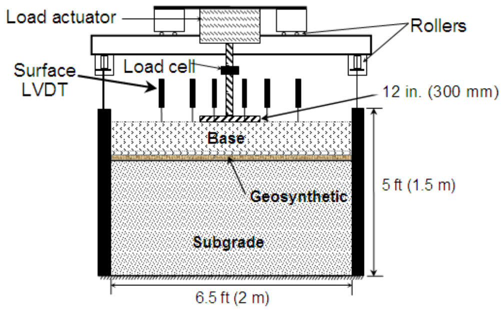

Figure 6. Schematic diagram of the pavement test facility

I-beams set into two of the concrete walls serve as a base for the loading frame. The load frame consists of two additional I-beams that span and react against the I-beams set into the concrete walls of the box. A load actuator, consisting of a pneumatic cylinder with a 12-in. (300-mm) diameter bore and a stroke of 3 in. (75 mm), is placed between the two I-beams of the frame. A 2-in. (50-mm) diameter steel rod extends from the piston of the actuator. The rod is rounded at its tip and fits into a cup welded on top of the load plate that rests on the pavement surface.

The load plate consists of a 12-in. (300-mm) diameter steel plate with a thickness of 1 in. (25 mm). A ¼-inch (6.4 mm) thick, waffled butyl-rubber pad is placed beneath the load plate in order to provide a uniform pressure and avoid stress concentrations along the plate's perimeter. Figure 2 shows an image of the load plate resting on the pavement surface. A binary solenoid regulator attached to a computer controls the load-time history applied to the plate. The software controlling the solenoid is the same software used to collect data from the pavement sensors. The software is set up to provide a linear load increase from zero to 9 kips (40 kN) over a 0.3 second rise time, followed by a 0.2 second period where the load is held constant, followed by a load decrease to zero over a 0.3 second period and finally followed by a 0.5 second period of zero load before the load cycle is repeated, resulting in a load pulse frequency of 0.67 Hz. The maximum applied load of 9 kips (40 kN) resulted in a pavement pressure of 80 psi (550 kPa). This load represents one-half of an axle load from an equivalent single axle load (ESAL).

Instrumentation was included in each test section. The instrumentation is designed to evaluate rutting in the stabilization aggregate, strain distribution in the reinforcement with distance away from the wheel load, and pore water pressure response of the subgrade during placement, compaction and subsequent loading. Instrumentation was included to make the following measurements:

1. Vertical surface deformation in the stabilization aggregate layer.
2. Applied load to the plate using a calibrated load cell.
3. Pore pressure in the subgrade during construction and pavement loading.
4. The geosynthetics were instrumented with wire extensometers, which were connected to LVDTs to measure the transfer of stress away from the wheel loading area.
5. The geosynthetics were extended through the front of the test box and visually monitored to determine if any movement was occurring at the edge of the box during application of the load.

2.3 *Geosynthetic Materials*

The geosynthetic materials used in these tests were a welded polypropylene biaxial geogrid and a composite geogrid using a welded polypropylene biaxial geogrid where a needle punched nonwoven geotextile is firmly bonded between the cross laid reinforcement bars. Tests were also performed with the welded polypropylene geogrid placed directly over a needlepunched nonwoven polypropylene separation geotextile (NP NW GTX). The used geotextile had a mass per unit area of 150 g/m^2. The relevant properties of the used materials are shown in Table 1.

Table 1. Geogrid characteristics

Properties	Laid and welded PP geogrid (30 kN/m) (LW GG30)	Laid and welded PP geogrid (60 kN/m) (LW GG60)	Geocomposite material of laid and welded PP geogrid (30 kN/m) + PP nonwoven GTX (GC GG30)
T_{ult} MD (kN/m)	30	60	30
T_{ult} XD (kN/m)	30	60	30
$T_{2\%}$ XD (kN/m)	10	36	10
$T_{2\%}$ XD (kN/m)	10	36	10

2.4 *Subgrade Soil*

Piedmont silt (ML-MH) from Georgia was used for the subgrade. The residual soil was selected based on its problematic construction characteristics that include pumping and weaving at near optimum moisture contents, which usually requires chemical or mechanical stabilization, especially when wet of optimum (as is most often the case). Residual soils tend to retain the parent rock structure (e.g., joints and fractures) with additional fractures occurring due to stress relief during excavation. Excess water collected in this structure results in high sensitivity when disturbed. These soils are also often characterized by a relatively fast dissipation of pore water pressure as opposed to more cohesive soils.

The gradation tests (ASTM 422 and ASTM 1140) indicate that the soil is micaeous sandy silt (ML-MH) with 95% passing a 1mm sieve and 65% passing a 0.075 mm sieve. The soil has a maximum dry unit weight of about 109 lb/ft^3 (15.2 kN/m^3) at an optimum moisture content of 17%.

2.5 *Base Course Aggregate*

The base course material used in all test section was a graded aggregate base meeting the Georgia Department of Transportation specifications. Standard Proctor compaction test (ASTM D 698) and gradation tests were performed on the aggregate base course. The gradation test results on the aggregate base indicate that it meets the Georgia Department of Transportation specifications for base course materials. The aggregate has a maximum dry density of about 145 lb/ft^3 (22.8 kN/m^3) at an optimum moisture content of 5.4%. The graded aggregate base was estimated to have a friction angle of 43° based on large direct shear tests that have been previously performed on similar materials at GTX.

2.6 *Test Results*

The primary results of the stabilization test are in terms of the deformation response of the aggregate layer. Figure 7 provides a summary of the permanent deformation response for all test sections constructed with 12 inches (305 mm) of aggregate and a CBR = 1%. Table 2 provides a comparison of the performance characteristics from each test section, including the number of cycles and the corresponding Traffic Benefit Ratio (TBR) for each of the test result at 1 inch (25 mm) and 3 inch (75 mm) of rutting. Rut depths between 1 and 3 inch are acceptable deformation rates for unpaved roads but not for paved roads.

The results clearly show a difference in the performance of the geosynthetics evaluated in the study. The Geocomposite material (laid and welded geogrid (30 kN/m) + nonwoven needlepunched geotextile firmly bonded between the cross laid reinforcement bars) performed the best of all materials tested and reached over 850 cycles of loading before reaching 3 in. (76 mm) of rutting and had a TBR value of over 170. Over 10,000 cycles were required to reach a rut depth of 4 in. (100 mm). Open geogrids may be at a disadvantage with the type of soil used, as no filter stability between the coarse aggregate and the fine grained subgrade is given, so that the soft subgrade can easily be penetrated by gravel particles from the base course layer until interlock is developed. Regardless, both laid and welded geogrids provided significant improvements in deformation response over the control section with TBR values between 11 and 19.

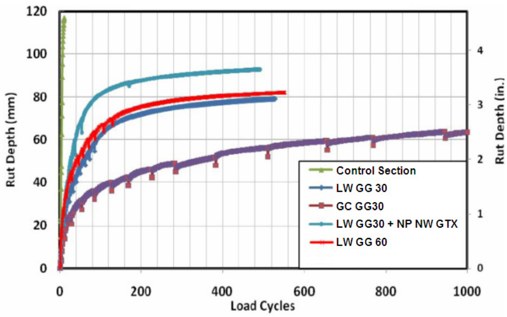

Figure 7. Permanent Deformation Response versus Load Cycles for CBR = 1 Subgrade

Table 2. Performance Characteristics (TBR) of each Test Section

Section	Number of Cycles		Traffic Benefit Ratio (TBR)	
	1-in. (25mm) rut	3-in. (75mm) rut	1-in. (25mm) rut	3-in. (75mm) rut
Control	1.5	5	1	1
LW GG30	4.5	97	3	19.4
LW GG 60	1.5	55	1	11
GC GG30	6.5	855	4.3	171
LW GG30 + NP NW GTX	1.2	31	0.8	6.2

Much of the difference between the two laid and welded geogrids with 30 kN/m and 60 kN/m (LW GG30 & LW GG60) tensile strength can be attributed to the differences in the first few load cycles which are applied at the beginning of the test. As it is not possible to maintain a consistent loading during the application of the first few load cycles movement occurs due to shoving and displacement of aggregate during interlock. In stabilization research performed by the US Army Corps of Engineers, these cycles are referred to as "initial seating" (Tingle and Jersey, 2005) and they are removed from the data. If this procedure is followed and the first 3 cycles are removed, the hierarchy of the data remains the same, however then the deformation response of the 60 kN/m laid and welded geogrid is slightly better (less rutting) compared to the 30 kN/m laid and welded geogrid. The laid and welded geogrid placed over the nonwoven needlepunched geotextile (LW GG30 + NP NW GTX) did not perform as well as the 30 kN/m geocomposite (GC GG30). The higher deformation response of the separately installed components is attributed to sliding of the geogrid over the nonwoven geotextile.

A summary of the pore pressure response of each test section is shown in Figure 8. The pore pressure directly corresponds to the results in Figure 7 with the high initial pore pressure developing for test sections where the largest amount of deformation per cycle was measured. The pore water pressure results indicate the disturbance due to aggregate penetration into the subgrade in the control section and the open geogrid section, which leads to high pore water pressure. The increase in pore water pressure reduces the effective strength of the soil, resulting in an undrained subgrade strength that is actually less than CBR = 1% and correspondingly increased rutting occurs. This rapid pore pressure build up does not occur in the Geocomposite (GC GG30) due to the separation provided by the geotextile.

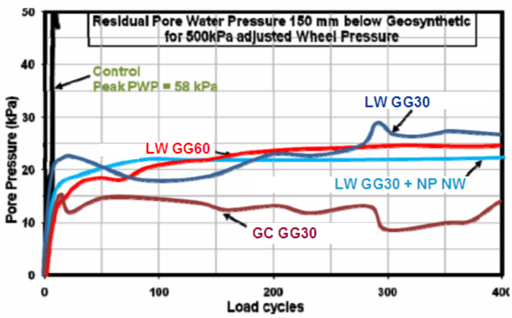

Figure 8. Pore pressure in Subgrade versus Load Cycles for CBR = 1 Subgrade

3 CASE HISTORIES

3.1 *Mersin Port, Turkey*

Mersin is situated on Mersin Bay, a broad body of water that is open southward to the Mediterranean Sea. Mersin Harbour is close to the extreme north end of the bay and is constructed on a southeast-facing shore line. It is the main port for the Eastern Mediterranean Region's industry and agriculture. The port's rail link and its easy access to the international highway make it an ideal transit port for trade to the Middle East. With its modern infrastructure and equipment, efficient cargo handling, vast storage areas and its proximity to the free trade zone, Mersin is one of the important ports in the East Mediterranean. The facilities at the port handle general cargo, containers, dry and liquid bulk and Ro-Ro Port.

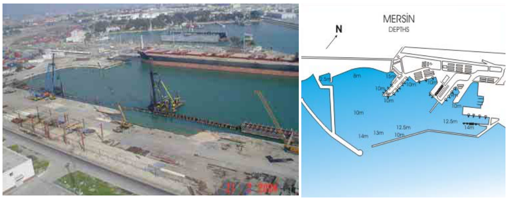

Figure 9. Mersin Port, Turkey

In 2004 it was planned to rehabilitate certain lots of the container terminal because of large rut depths at the pavement surface which had been caused by mobile cranes, trucks and containers. The differential deformations at the pavement surface had a major influence on the traffic safety and even on the safety of the stacked containers. Containers, which were stacked up to 5 high, even fell off, which finally lead to a shortage in the terminals' storage capacities.

As a consequence, the Railway Authority, who was the responsible body for the operation of Mersin Port, decided to take action for rehabilitating the affected lots in the harbor's container storage area.

Figure 10. Installation of composite base course reinforcement

The chosen rehabilitation measure was the use of composite geosynthetic base course reinforcement, because of the easy installation and handling and mainly because of economical advantages. A sample lot of 5,200 m² was realized at first in December 2004. Then an additional lot of 34,000 m² was realized using the same solution till 2006.

The former slab, which was constructed 20 years ago, together with the fill material underneath were removed up to level of the former in-situ subgrade. The thickness of the removed layer was approximately 1.4 m. On the soft in-situ subgrade, a Combigrid® Geocomposite made of a nonwoven needle-punched geotextile and a high modulus laid and welded geogrid, as shown in Figure 5, was installed. On the same day, a well graded aggregate base course with a thickness of 1.0 m was installed on top of the Geocomposite. Finally the new 0.4 m thick concrete slab was installed.

The lack of separation between the original base aggregate and the in-situ subgrade combined with insufficient compaction of the in-situ subgrade had caused the described ruts at the pavement surface over time. With the use of the composite reinforcement, mixing of the fine grained subgrade and the coarse base aggregate is prevented by the geotextile and secondly confinement of the base aggregate is achieved resulting from the installed geogrid component.

3.2 *Oman Polypropylene LLC plant at Sohar Port, Sultanate of Oman*

Oman Polypropylene LLC started to build its Polypropylene plant at the end of 2004. For the development of the port at Sohar, which is located at the Gulf of Oman, an area of approx. 24 hectares was artificially created by dredging operations.

The total 2,000-hectare Sohar port and industrial zone will house mega industrial facilities ranging from an oil refinery and aluminium smelter to steel mills. The zone will be one of the world’s biggest greenfield petrochemical and metal-based industrial hubs. Oman Polypropylene LLC is integrated with the refinery. The project will add value to Sohar Refinery’s propylene stream to produce polypropylene that can be used in an array of downstream industries.

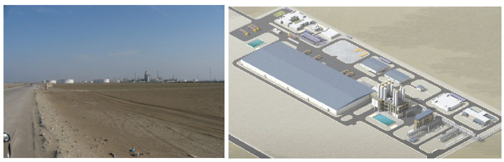

Figure 11 Oman Polypropylene LLC Plant, Sultanate of Oman

Soil investigations have encountered loose to very loose sand and organic silt layers in a depth of approx. 6m. For the development of access roads and storage areas it was therefore required to increase the bearing capacity of the weak subgrade.

As the most economical approach, it was decided to use geogrid reinforcement to provide the required subgrade support for the expected traffic and storage loads. The aggregate base course was installed in two layers of well graded crushed granular material, each 300 mm thick. A base layer of a composite reinforcement layer together with an intermediate laid and welded geogrid reinforcement layer, both having 40 kN/m tensile strength, ensured an increased modulus of the reinforced granular layers and finally a stable platform for the planned roads and storage areas on the originally soft subgrade.

Figure 12 Installation of composite base course reinforcement

The separation geotextile component of the used composite base course reinforcement ensured the integrity of the base course by preventing fines from migrating into the aggregate layer or aggregate from being pushed into the soft subgrade. Altogether approximately 150,000 m^2 of the described composite reinforcement were installed in this project.

3.3 *Port Canaveral Fuel Tank Farm, Florida, USA*

Built in the 1950s, Port Canaveral, located just a few miles from the Kennedy Space Center and about an hour from Orlando, has grown into the second busiest Florida port behind Miami. Due to its strategic location, Port Canaveral is one of the world's busiest cargo and cruise terminals; e.g. more than 4.5 million revenue passengers go through the port each year. The port authority has made substantial investments over the past four years to upgrade its facilities and terminals for cruise ships and the infrastructure to support revenue growth from commercial shipping. In 2008 a private company, Netherlands-based Vitol SA, Inc. started construction works for a $115 million petroleum tank farm at the port. The facility is expected to be fully operational in October 2009. With the construction of this new fuel tank farm and underground pipeline, Port Canaveral, Florida has quickly become a major cog in the state's fuel security. Florida is the United States' fourth most-populous state and one of the primary destinations for domestic tourism and seasonal residents. The transportation demands on the state are significant. This fact was underscored in 2004 when hurricanes in the Gulf of Mexico injured fuel supply lines that had been centered in Tampa.

An eastern fuel post was needed, particularly near Orlando, an ever-growing center for tourism, conferences and businesses in central Florida. Port Canaveral was the answer.

Florida is a big state for construction, but it is by no means ideal for engineering. The water table is high and the fine, sandy and clay soils present significant challenges to constructing sites that must support high loads. The establishment of such a large tank farm in Port Canaveral was not going to be easy. The site's soils were mainly organic and with a high plasticity; yet, they needed to support tanks for 3 million barrels (approx. 475 million liters) of fuel and heavy, daily truck traffic. The expected stresses would exceed the soils' existing bearing capacity. Taking the project specific boundary conditions into consideration it was planned to build the tanks on piled foundations, but even for the piling rigs, which would finally install the concrete piles, the in-situ soil did not provide sufficient strength. For this reason it was decided to improve the bearing capacity by a laid and welded PP geocomposite reinforced piling platform.

Figure 13 Installation of geocomposite reinforced piling platform

Figure 14 Piling works in the area of planned fuel tanks

For the complete fuel tank area approx. 130,000 m^2 of geocomposite reinforcement was installed to enable safe installation of up to 160 km of concrete piles. In total approx. 130,000 m^2 of geocomposite reinforcement was installed.

4 SUMMARY AND CONCLUSION

The increase of global trade and transport of goods creates growing demands to handle cargo. To accommodate growing cargo volumes, existing ports are extended and new ports are being built. Soft subgrades are often the basis for the foundation works of new container terminal's pavement systems. As economic construction method geogrids are often used in this case to improve the insufficient bearing capacity for the expected traffic and storage loads. Geogrids first of all allow and secondly improve the compaction of foundation layers on soft soils. The technology of geosynthetic reinforced aggregate layers provides an economic construction method for the development of new container terminals. With the improved structural load-bearing capacity of geogrid reinforced aggregate layers, stress concentrations on soft subgrades can be reduced, which minimizes differential settlements at the pavement surface and automatically improves the transport safety of container-handling equipment.

Increasingly so called "Geocomposite" materials are used which consist of a nonwoven geotextile component and a geogrid reinforcement layer. The geotextile with its separation and filtration function ensures that the base course layer in its entirety will contribute and continue to contribute its structural support of vehicular loads as it prevents the aggregate to be pushed down into the soft subgrade and / or the subgrade to be squeezed up into the base aggregate.

The geogrid increases the shear strength and thus the load distribution capacity of the used base course material. Latest test results from large-scale laboratory testing, which has been presented in this paper, shows the outstanding performance of a specially developed geosynthetic composite material (a welded polypropylene biaxial geogrid with a needle punched nonwoven geotextile firmly bonded between the cross laid reinforcement bars) against individually installed geogrid reinforcement layers or separately installed combinations of geogrid reinforcement and geotextile separators.

The use of the described composite geosynthetic reinforcement in subgrade stabilization projects enables savings with regard to:

- Required installation time when compared to separately installed geotextile separator and geogrid components.
- Reduction of base course thickness compared to unreinforced sections, because of the improved load distribution capacity which is achieved with the use of composite geosynthetic reinforcement.

Besides the economical aspect, also the ecological aspect needs to be highlighted. As "good quality" aggregate is often not available close to the construction site or not in the required quantity, the possible reduction of base course thickness with the use of composite geosynthetic reinforcement reduces transport costs and the consequential environmental impact.

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