ANKARA YILDIRIM BEYAZIT UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

ROLLER COMPACTED CONCRETE PAVEMENT AS A SUSTAINABLE SOLUTION FOR SOMALI PORT TERMINALS

M.Sc. Thesis by

Abdirahman Salad HASSAN

Department of Civil Engineering

December, 2024

ANKARA

ROLLER COMPACTED CONCRETE PAVEMENT AS A SUSTAINABLE SOLUTION FOR SOMALI PORT TERMINALS

A Thesis Submitted to

the Graduate School of Natural and Applied Sciences of

Yıldırım Beyazit University

In Partial Fulfillment of the Requirements for the Degree of Master of Science of Civil Engineering, Department of Civil Engineering

by

Abdirahman Salad HASSAN

December, 2024

ANKARA

M. Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"ROLLER COMPACTED CONCRETE PAVEMENT AS A SUSTAINABLE SOLUTION FOR SOMALI PORT TERMINALS"** completed by **ABDIRAHMAN SALAD HASSAN** under supervision of **ASSIST. PROF. DR. EMİN ŞENGÜN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Assist. Prof. Dr. Emin ŞENGÜN

Supervisor

Prof. Dr. İsmail Özgür YAMAN

Jury Member

Prof. Dr. Mehmet BARAN

Jury Member

Prof. Dr. Sadettin ORHAN

Director

Graduate School of Natural and Applied Sciences

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ACKNOWLEDGMENTS

First and foremost, I want to show my utmost thankfulness to my supervisor, Assist. Prof. Dr. Emin ŞENGÜN, for his constant support and priceless advice during my research. His in-depth understanding and thoughtful suggestions have played a crucial role in influencing this study. His guidance has been essential throughout my research and the writing of this thesis.

I would also like to express my deep gratitude to my mother, Fatima Abdikarin, and my father, Salad Hassan, for their constant support and love. Their unwavering assistance has been a fundamental element in my successes. Additionally, I am profoundly thankful to my whole family, including my brother and sisters, for their constant support and comprehension.

2024, 30 December **Abdirahman Salad HASSAN**

ROLLER COMPACTED CONCRETE PAVEMENT AS A SUSTAINABLE SOLUTION FOR SOMALI PORT TERMINALS

ABSTRACT

Somali's port terminals, including Mogadishu, Berbera, and Bossaso, are crucial for boosting the country's economy and global trade. With planned expansions, the total country capacity is expected to grow by 2.5 million TEU in the coming years. Despite recent upgrades to Berbera, other terminals require varying degrees of rehabilitation. Although Somalia's ports have traditionally used flexible-asphalt concrete (AC) pavement, there has been a recent shift toward rigid pavements. Roller Compacted Concrete (RCC) pavement, combining concrete's durability with asphalt's placement methods, has yet to be implemented in Somalia. Its proven resistance to heavy static and dynamic loads makes it a cost-effective option for port terminals, as successfully demonstrated in the USA and Canada. This study evaluates the performance of existing asphalt pavements at Somali ports and compares them with RCC pavement alternatives. Based on field visits to Somali ports and a literature review, the existing typical asphalt pavement layer was modeled using a finite element-based pavement analysis program to evaluate its responses under critical dynamic handling equipment and static container stacking conditions. The analysis predicts that the asphalt pavements in Somali ports will be subjected to significantly high stresses under critical loading conditions, which could lead to substantial deterioration. In contrast, when the RCC pavement alternative is preferred, deformation can decrease by up to 50% compared to asphalt pavements. Additionally, cost analyses reveal that while RCC pavements have a slightly higher initial cost compared to asphalt pavements, their significantly lower maintenance and repair requirements result in a substantial advantage in life cycle cost analysis, offering up to a 33% reduction.

Keywords: Heavy-duty pavement design, Somalia ports, roller compacted concrete pavement, asphalt concrete pavement, FEM based analysis, cost analysis.

SOMALİ LİMAN TERMİNALLERİ İÇİN SÜRDÜRÜLEBİLİR ÇÖZÜM OLARAK SİLİNDİRLE SIKIŞTIRILMIŞ BETON KAPLAMA

ÖZ

Mogadişu, Berbera ve Bossaso gibi Somali liman terminalleri, ülkenin ekonomisi ve küresel ticaret hacmini artırmak için kritik öneme sahiptir. Planlanan genişletme çalışmalarıyla toplam ülke kapasitenin önümüzdeki yıllarda 2,5 milyon TEU kadar çıkacağı tahmin edilmektedir. Somali limanlarında geleneksel olarak esnek asfalt beton (AB) üstyapı türü kullanılmış olsa da son zamanlarda rijit üstyapılara doğru bir eğilim başlamıştır. Ancak Silindirle Sıkıştırılmış Beton (SSB), geleneksel betonla benzer malzeme içeriğine sahip olup asfalt kaplamaya benzer şekilde uygulanmaktadır. Henüz Somali'de kullanılmayan SSB teknolojisi, ağır statik ve dinamik yüklere karşı gösterdiği yüksek dayanıklılık ve maliyet etkinliğiyle liman terminalleri için güçlü bir alternatif sunar. ABD ve Kanada'da bu teknoloji yıllardır başarıyla kullanılmaktadır. Bu çalışma, Somali limanlarındaki mevcut asfalt kaplamaların mekanik performansını değerlendirmekte ve bunları SSB kaplama alternatifi ile karşılaştırmaktadır. Yapılan Somali liman saha ziyaretleri ve literatür incelemesi sonucu mevcut kullanılan tipik asfalt üstyapı katmanı, kritik elleçleme ekipmanı ve konteyner istiflemesi için sonlu elemanlar temelli üstyapı analiz programıyla modellenmiş ve kaplama tepkileri hesaplanmıştır. Analizler sonucunda, Somali limanlarında AB kaplamaların kritik yükleme koşulları altında önemli ölçüde yüksek gerilmelere maruz kalacağı öngörülmektedir. Bu da AB kaplama bozulmalarına yol açabilecek önemli etkenlerden biri olmaktadır. Buna karşılık, SSB kaplama alternatifinin tercih edilmesi durumunda, doğası gereği AB kaplamalara göre deformasyon %50' ye kadar azalabilmektedir. Ayrıca, yapılan maliyet analizlerinde SSB kaplamaların ilk maliyeti AB kaplamalardan biraz daha yüksek olmasına rağmen, daha düşük bakım onarım gereksinimleri nedeniyle SSB kaplamalar, yaşam döngüsü maliyet analizinde %33'e varan oranlarda önemli bir avantaj da sunmaktadır.

Anahtar Kelimeler: Ağır hizmet tipi üstyapı tasarımı, Somali limanları, silindirle sıkıştırılmış beton kaplama, asfalt beton kaplama, FEM tabanlı analiz, maliyet analizi.

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ABBERVIATIONS

AC	Asphalt Concrete
ACI	American Concrete Institute
AGV	Automated Guided Vehicle
ARTG	Automated Rubber-Tyred Gantry
BPA	British Ports Association
CBR	California Bearing Ratio
CRCP	Continuously Reinforced Concrete Pavement
CTB	Cement-Treated Base
ESAL	Equivalent Single-Axle Load
FEL	Front-End Loader
GDOT	Georgia Department of Transportation
GPA	Georgia Ports Authority
HMA	Hot Mix Asphalt
JRCP	Jointed Reinforced Concrete Pavement
MEPDG	Mechanistic-Empirical Pavement Design Guide
MHC	Mobile Harbor Cranes
MPA	Mogadishu Port Authority
PCC	Portland cement Concrete
RCC	Roller Compacted Concrete
RMG	Rail-Mounted Gantry
ROM	Spanish Port Terminal Pavement Design Guidelines
RTG	Rubber-Tyred Gantry
SP	Side Pick
TEU	Twenty-foot Equivalent Unit
TP	Top Pick

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CHAPTER 1

INTRODUCTION

1.1 General

Roller compacted concrete (RCC) is a suitable option for applications where no-slump concrete can be effectively transported, placed, and compacted using earth-moving and rock-fill construction equipment, or in the case of pavements, with asphalt paving equipment. Application of RCC is often considered when it is economically competitive with other constructions [1,2]. The two major applications for RCC are for mass concrete such as dams and heavy-duty pavement applications including intermodal yards, port facilities, warehouse and other industrial parking and storage areas [3].

RCC typically shares key ingredients with ordinary Portland cement concrete (PCC), although unique proportions that include higher fine aggregate, reduced cement content, and a lower water-to-cement ratio. Unlike conventional PCC, RCC is characterized by significantly enhanced flexural, compressive, and shear strengths. Current RCC flexural strength and compressive strength range from 4 MPa to 7 MPa and 30 MPa to 60 MPa, respectively, and RCC clearly eliminates rutting and associated maintenance because of its higher shear strength [4,5]. This robust performance is particularly advantageous under heavy concentrated loads, such as those imposed by industrial equipment or stacked terminal containers. In contrast, traditional asphalt surfaces, owing to their lower modulus of elasticity, often exhibit premature deterioration under such loads, leading to depressions or cracks [6], especially in regions prone to wet freeze-thaw cycles. Thus, RCC pavement emerges as a resilient and sustainable solution for infrastructure subjected to high-concentrated loading conditions [7]. Nevertheless, despite these inherent advantages of RCC, it remains significantly underutilized at port terminals in worldwide, particularly outside the United States and Canada. Somalia serves as a pertinent example, where the reliance on flexible pavement specifically asphalt prevails in port terminal

infrastructure. This preference persists despite Somalia's heavy dependence on port terminals to facilitate a substantial portion of its trade volume. The implementation of RCC technology has yet to be achieved in Somalia, highlighting a substantial opportunity for the integration of more resilient and sustainable pavement solutions in this critical infrastructure sector.

1.2 Objectives

The thesis objectives can be summarized as follows:

- Evaluate the existing flexible asphalt pavements used at Somali port terminals, particularly Mogadishu and Berbera ports, in terms of their structural integrity, durability, and maintenance requirements under current loading conditions.
- Explore the feasibility and potential benefits of adopting RCC pavements as an alternative to traditional asphalt pavements in Somali ports.
- Analyze the structural performance of RCC pavements under similar loading conditions to those experienced by existing asphalt pavements, utilizing finite element modeling (ISLAB 2005) to simulate the performance of both pavement types under critical dynamic (handling equipment) and static (stacked container) loading conditions.
- Conduct a life cycle cost analysis comparing the initial construction costs and long-term maintenance expenses of asphalt pavements versus RCC pavements for Somalian port terminals.
- Identify the most cost-effective and sustainable pavement solution for the long-term operational efficiency of Somali port terminals.

1.3 Thesis Organization

The thesis consists of six chapters:

- Chapter One introduces the thesis and outlines its objectives.
- Chapter Two discusses the overview of Somalia port terminals.
- Chapter Three presents basics of port terminal pavement designs

- Chapter Four discusses the application of RCC as an alternative solution for port terminal pavements.
- Chapter Five presents an analysis of the structural performance of RCC pavements under similar loading conditions to those experienced by existing asphalt pavements at Somali port terminals. It also includes the results of a comparison between the proposed RCC and the existing asphalt pavement, with a focus on life cycle cost analysis.
- Chapter Six presents the conclusion and discussion.

CHAPTER 2

OVERVIEW OF SOMALIA PORT TERMINALS

This chapter will focus on the overflow of Somalia's port terminal, Somalia is strategically located on the eastern coast of the Horn of Africa see Figure 2.1, with a land area of 637,540 square kilometers, and Somalia holds significant strategic importance. It boasts the longest coastline among all African nations, extending approximately 3,300 kilometers in length and 200 nautical miles in width. The country's strategic importance is evidenced by its pivotal role in international trade routes, including the Suez Canal and the Cape route, which facilitate the efficient movement of goods across continents. In Somaliland, the port is a cornerstone of the economy and by 2035 is expected to facilitate trade equivalent to nearly 27 per cent of GDP and 75 per cent of total trade, supporting indirectly 53,000 jobs in Somaliland [8].

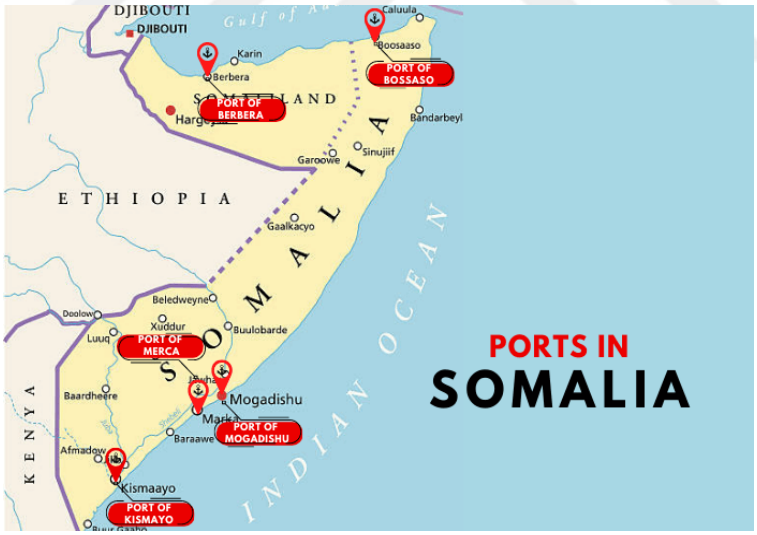


Figure 2.1 Somalia Port Terminals Map (adapted from https://www.marineinsight.com)

Somalia's four main ports, Mogadishu, Berbera, Bossaso, and Kismayo port are vital lifelines that support a diverse array of maritime activities. Mogadishu is notable for its capacity to handle a wide range of cargoes, with a particular focus on banana exports. Berbera is a leading exporter of livestock, while Bossaso serves as a key hub

for both cattle and general cargo. Kismayo and Merca are also significant contributors to the export of bananas, livestock, and seafood. These port terminals not only facilitate the import and export of goods critical to Somalia's economy but also serve as essential nodes for regional and international trade networks. The efficient operation of these ports is of paramount importance in supporting the country's economic growth and ensuring the smooth flow of goods, essential for local consumption and export markets.

2.1 Mogadishu Port Terminals

Mogadishu Port is situated on the southeastern coast of Somalia, in the capital city and a few nautical miles from the strategic port of Mombasa in Kenya. With a substantial artificial breakwater spanning 359 meters and a navigable channel depth of 14 meters, it serves as a pivotal hub for handling significant volumes of maritime traffic. Historically known as Sarafian during Roman times, the port underwent substantial modernization efforts in the late 18th century under Italian stewardship, marking a transformative period in its development as a key maritime infrastructure [9]. Despite facing closures and administrative changes from 1991 to 2006, including governance transitions involving the Union of Islamic Courts and Ethiopian military interventions, concerted efforts led by the African Union and Somali authorities, supported by organizations such as the World Food Program, have been dedicated to revitalizing the port's operations and bolstering its infrastructural resilience.

The Port of Mogadishu plays a pivotal role as Somalia's primary gateway for international trade. Since its management commenced in 2014 from Al-Bayrak Company, the port has concentrated on enhancing operational efficiency and infrastructure development. It facilitates a diverse range of cargo services, including container handling, bulk cargo, and general cargo operations. The Port of Mogadishu covers an area of 303,000 square meters and is equipped with essential facilities to support its operations. These include general cargo berths, container terminal berths, and a grain terminal with a storage capacity of 30,000 tons as shown in Figure 2.2. The port features a container yard with the capacity to handle up to 500,000 TEUs (Twenty-foot Equivalent Units) annually and can manage over 3 million tons of cargo per year.

The port's terminals comprise a general cargo terminal, a container terminal operated by the port management, and two oil terminals capable of accommodating tankers up to 30,000 deadweight tons [10].

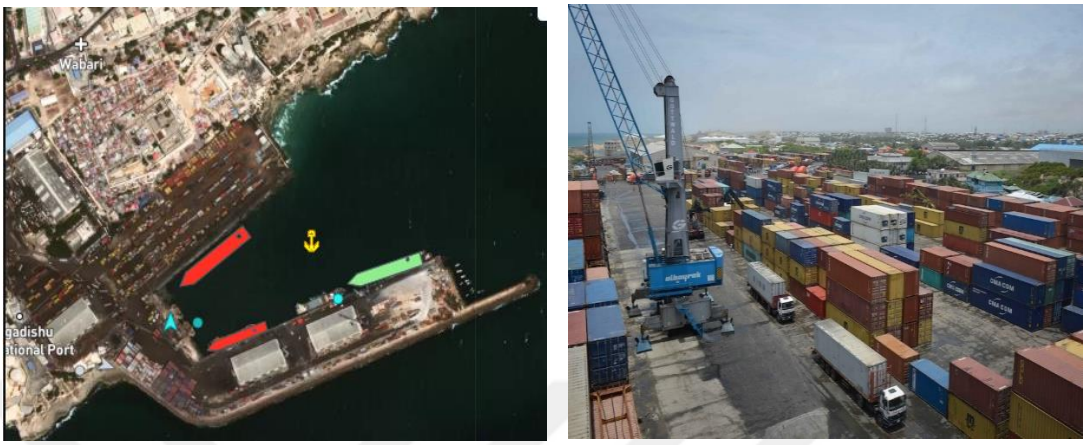


Figure 2.2 Facilities from Mogadishu Port Terminals (adapted from official Mogadishu Port Terminal Website https://mpa.so/wp-content/uploads)

According to the Ministry of Finance of the Federal Republic of Somalia's 2017 document, as in the seen masterplan of New Mogadishu Port in the development of the New Port of Mogadishu is planned in three phases, scheduled for completion by 2045 as shown in Figure 2.3. The first phase, initiated in 2020, focuses on constructing a container terminal and essential port services such as fire stations, port authority buildings, and medical centers, alongside infrastructure improvements like water supply and utilities. By 2025, the multipurpose terminal development will commence, increasing the port's annual handling capacity to 2.3 million tons with three berths for various vessel types. The final phase, starting in 2028 and operational by 2030, will expand capacity to 484,000 TEUs per year, adding facilities for empty containers and an additional container vessel berth. This phased approach, outlined in a public-private partnership, is estimated to cost approximately $380 million USD, as detailed in the ministry's report [11].

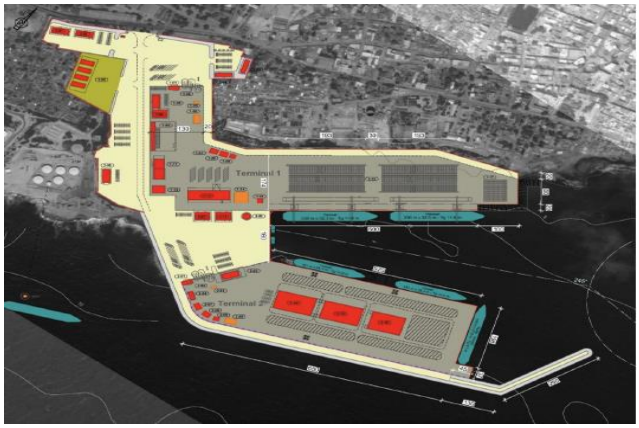


Figure 2.3 Masterplan of Mogadishu Port 2045 (adapted from official Government Document)

2.2 Berbera Port Terminal

Berbera Port is located on Somalia's northern coast, at the southeastern extremity of the Gulf of Aden see in Figure 2.4. It is created by a low-lying sandy spit in the north, which serves as a breakwater for the quays in the south. The entry canal is 800 meters wide and approximately 16.5 meters deep, with two anchorages. It is notable for exporting animal skins, ghee, gum, and animals such as sheep and goats. Cotton goods, sugar, rice, and dates are among the most often imported commodities. Berbera port handles around 250,000 tons of cargo and more than 130 boats each year [12]. It was founded over a century ago and operated as a naval facility for the Somali government throughout the 1990s. Following a 1962 agreement between Somali authorities and the then-Soviet Union, the latter funded the port's expansion. The United States of America erected a 350-meter-long dock in 1984 as the Somali government established trading links with the country. Since then, the port has developed significantly, contributing to the economic development of the Somali land population [13].

Berbera port has five conventional berths, each measuring 125 meters and with a depth of 7.3 meters. It also features an extra RORO berth that spans 100 meters and has a water depth of 9 meters. These facilities, which can accommodate ships with a length of 200 meters, the container terminal currently has 500,000 TEU capacity are mostly used to accept livestock carriers and large humanitarian relief cargoes. New and modern port equipment was obtained in 2014. Berbera port contains ten mobile cranes with a lifting capability of 70 tones, two forklifts, three reach stackers, and five port

vehicles. Ample storage capacity is offered, including a 5760 m^2 warehouse facility capable of holding 120,000 tons of goods and paved yards extending 64,000 m^2. A second jetty accepts oil from ships and connects directly to the petroleum store via a network of pipes [14].

The DP World Berbera New Port, inaugurated on June 24, 2021, is a major port in Berbera, Somaliland, operated by DP World. It features a new 400-meter berth and three ship-to-shore gantry cranes with a capacity of 500,000 TEUs per year. The port facility, which currently has the capacity to handle 500,000 TUE capacity, is expected to expand into handling 1,000,000 TEU of 20 and 40-foot mixed units. The port is part of a $442 million investment deal between DP World and the Somaliland government, aimed at establishing a regional trade and logistics hub. Additionally, Ethiopia holds a 19% stake in the port, further enhancing its strategic importance in the region.



Figure 2.4 Photos from Berbera Port Terminals (adapted from official DP World Website)

2.3 Bossaso Port Terminals

Bossaso, also known as Bender Qaasim Port, is located in the southern Gulf of Aden. The harbor is protected by a 420-meter mole in the north and a 200-meter-long breakwater in the south. It is an important seaport that serves the Puntland area in northeastern Somalia. Livestock exports include cattle, sheep, and camels. It also receives large cargoes of cement, sugar, rice, and building materials. Bossaso Port was established largely to carry cattle to Middle Eastern countries, notably the UAE and Saudi Arabia. The construction began in the mid-1990s and was completed with the installation of new facilities and equipment in 2012. During these years, civil

conflict and political upheaval stalled the port development project. However, in the early 2000s, the port was cleaned up and the dockyards were cleared of undesired rubbish. The second phase involved dredging and building more docks to handle bigger ships. In 2017, P & O Ports, owned by DP World, was granted a 30-year concession to manage and extend the Bossaso port. As a result, construction began in 2017 on a 455-meter-long wharf and a 5.5-hectare storage facility. It was dredged to a depth of 12 meters, and the corporation invested in the newest IT terminal operating system and port equipment as shown in Figure 2.5 [15].

Livestock has been central to the growth and sustenance of the Bosaso port. Its development into a major livestock hub has helped the local pastoral communities and has boosted the economy of Puntland. A major gateway to Yemen, Bosaso has enormous scope for diversifying its services.



Figure 2.5 Photos from Bossaso Port Terminals (Second photo taking by the author)

2.4 Kismayo Port Terminals

Kismayo Port, situated on Somalia's southern coast, features a protected harbor and a southern concrete breakwater that facilitates berthing for ships. Initially constructed in 1966 primarily for exporting bananas and facilitating shipments of agricultural produce and light machinery during monsoon months when road access to Mogadishu is limited, the port serves the lower Jubba region. Currently, the port faces significant operational challenges, with 80% of its infrastructure in need of urgent restoration. It accommodates approximately 50 small ships and barges annually, handling humanitarian cargo vessels and occasional containers, including imports from the

Mediterranean Shipping Company and sugar shipments by the Hormuud Business Company. However, as it is seen in Figure 2.6, Kismayo Port suffers from inadequate handling equipment, possessing only four warehouses, the largest of which can store up to 1,400 tons [10].

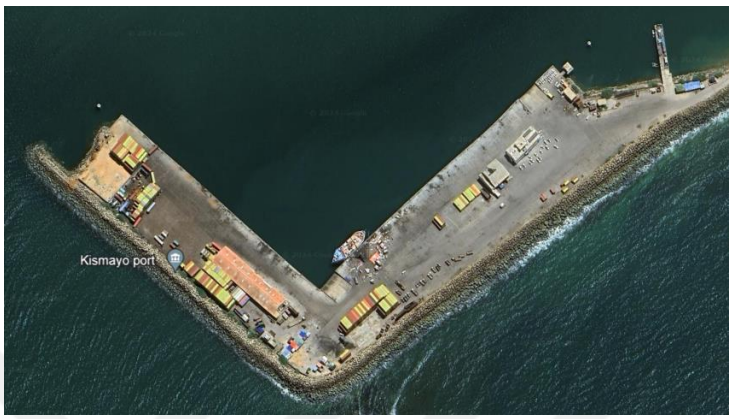


Figure 2.6 Kismayo Port Terminals (adapted from https://earth.google.com/web/search/Kismayo)

CHAPTER 3

BASICS OF PORT TERMINAL PAVEMENTS

3.1 Port Terminal Operation Areas

A Port Terminal is a broader term referring to any designated area within a port where cargo is transferred between different modes of transportation, such as ships, trucks, or trains. In contrast, a container terminal is a specialized type of port terminal dedicated exclusively to handling containerized cargo. While a port terminal may manage various types of cargo, a container terminal is primarily focused on the stacking and movement of containers.

The primary functions of a container terminal include the receipt, storage, and transshipment of standardized shipping containers, leveraging advanced technologies and organizational practices to ensure optimal efficiency [16]. This thesis will concentrate exclusively on container terminal pavements, discussing them in detail throughout all the chapters.

Container terminals are also integral to the global supply chain, playing a vital role in the movement of goods and commodities across various modes of transportation. By providing a streamlined process for transferring cargo, container terminals significantly enhance the overall efficiency and effectiveness of international trade [17].

A container terminal is a crucial component of port infrastructure, facilitating the efficient transfer, storage, and management of cargo containers between ships, trucks, and trains. These terminals serve as pivotal nodes in the global logistics network, enabling the seamless integration of maritime and inland transportation systems. The primary functions of a container terminal include the receipt, storage, and transshipment of standardized shipping containers, leveraging advanced technologies and organizational practices to ensure optimal efficiency Container terminals are integral to the global supply chain, playing a vital role in the movement of goods and

commodities across various modes of transportation. By providing a streamlined process for transferring cargo, container terminals significantly enhance the overall efficiency and effectiveness of international trade. Container terminal systems comprise a complex interplay of operational procedures, state-of-the-art technology, and robust infrastructure. These systems are designed to meet the demands of an increasingly interconnected commercial environment, integrating logistics, automation, and information technology to improve the efficiency of cargo handling operations [18].

The modern container terminal system is characterized by its emphasis on connectivity, digital innovation, and sustainable practices. These systems highlight the crucial role of eco-friendly technology in maritime transportation, advancing international commerce while promoting environmental responsibility [19].

The strategic elements of container terminal systems include significant investments in technology, the development of efficient processes, and cooperative engagements among stakeholders. These components are essential for enhancing the resilience and robustness of global supply chain networks, ensuring that container terminals can adapt to and recover from various disruptions [20]. The design and management of pavement in container terminal operation areas are critical for optimizing operational efficiency and minimizing maintenance costs. These areas include wharves, container stacking (storage) areas, intermodal railroads, truck gate facility, trailer storage areas and container handling equipment parking and maintenance areas, container maintenance areas, as well as buildings, and car park areas [21,22].

3.1.1 Wharf

The wharf area is critical for the transfer of containers between ships and the shore, typically using gantry cranes as shown in Figure 3.1. The layout includes runways for cranes, access lanes for traffic, and laydown areas for containers. Various methods are employed to move containers from the wharf to stacking areas, including straddle carriers, reach stackers, and yard trucks [22].



Figure 3.1 Wharf Area Layout (adapted PIANC. 2015 [7])

3.1.2 Gantries and Gantry Roads

Gantries, such as Rail Mounted Gantries (RMG) and Rubber Tyred Gantries (RTG), are used for high-density storage and frequent re-handling of containers. These cranes span large areas and facilitate container stacking and transfer to and from trucks or rail cars. The layout often includes container stacking rows, runways, access lanes, and rail tracks as shown in Figure 3.2 [22].



(a) To Road **(b)** To Rail

Figure 3.2 Gantry Crane Layout (adapted from Port of Berbera website)

3.1.3 Container Stacking Areas

Container stacking areas are a crucial part of terminal operations, providing temporary storage for containers as they transition between transportation modes like ships, trucks, and trains. Efficient management of these areas ensures smooth logistics, minimizes delays, and optimizes the use of limited space in busy terminals.

Stacking areas function as buffers, accommodating containers of various types—import, export, and transshipment. Each type has specific storage and retrieval requirements. For instance, export containers may arrive days before shipment and need careful organization based on vessel schedules, while import containers require timely retrieval for onward transportation. Transshipment containers often need quick access to maintain shipping schedules in Figure 3.3.

One of the primary challenges in container stacking is space management. As global trade grows, terminals face pressure to handle more containers in limited areas. Stacking containers higher can help, but this approach raises safety concerns, especially in adverse weather. Another common issue is reshuffling, which happens when containers need to be moved to access others stored beneath them. Reshuffling is time-consuming, increases costs, and disrupts operations [22].

Efficient equipment use is also vital in container stacking areas. Yard cranes (YCs) and automated stacking cranes (ASCs) are commonly used to handle containers. Proper coordination of these cranes reduces bottlenecks and ensures smooth operations. Scheduling techniques, such as first-come-first-served (FCFS) and dynamic programming algorithms, help minimize crane travel time and idle periods. Automation further enhances efficiency, reducing reliance on manual handling and improving precision in stacking and retrieval.

Strategic stacking practices are critical to operational success. Containers are often organized by weight, destination, and type to facilitate easy retrieval. Heavier containers, for example, are placed at the bottom to ensure stability and allow for proper loading sequences. Advanced technologies, such as real-time tracking systems and predictive analytics, are increasingly used to optimize stacking and retrieval processes, ensuring terminals can quickly adapt to dynamic demands.

In conclusion, container stacking areas are central to the efficiency of terminal operations. Addressing challenges like space constraints, reshuffling, and equipment coordination through technology and strategic planning enables terminals to manage growing trade volumes effectively. Well-managed stacking areas not only reduce costs

and delays but also strengthen the role of terminals as vital nodes in the global supply chain.



Figure 3.3 Stacking Area Layout (adapted from official PIANC 2015 [7])

3.1.4 Intermodal Rail Roads

Intermodal railroads facilitate the transfer of containers between rail, trucks, and stacks. Larger facilities may use gantry cranes or reach stackers for loading and unloading double-stacked containers as shown in Figure 3.4. The design must consider all operational modes and equipment used in these areas [10].



(a) Intermodal with FEL **(b)** Intermodal with Gantry

Figure 3.4 Truck Grids (adapted from Australian Flexible Pavement Association (AFPA)) [22].

3.2 Port Terminal Equipment

Container terminals employ various types of equipment to facilitate the movement and storage of containers. Each type of equipment has specific operational characteristics and impacts on the pavement structure. This section details the main types of equipment used in container terminals.

3.2.1 Rubber Tired Gantry Cranes (RTGs)

Modern Rubber Tired Gantry Cranes (RTGs) typically span a space that includes up to six container stacks and a truck travel lane, with a gauge of up to 25 meters and a self-weight between 100 to 150 tons as shown in Figure 3.5. The stresses exerted by these machines on the pavement are significantly high due to the concentrated traffic being channeled onto tracks parallel to the container storage areas and the concentrated parking in one location. While older machines might have four wheels, one on each leg, newer RTGs can have up to sixteen wheels, arranged in eight dual-wheels configurations. This distribution helps in reducing the load stress on the pavement.

To mitigate pavement maintenance along the RTG alignment, some operators install reinforced concrete runway beams flush with the paved surface. Additionally, rotating the wheels or bogies on the RTG is sometimes necessary, and temporary or permanent plates are often placed to prevent heavy scuffing of the turning tires. Despite their advantages, operators have increasingly favored Automatic Stacking Cranes (ASCs) over RTGs due to ASCs' superior reliability, speed, and operational efficiency, albeit at a higher initial capital cost [23].



Figure 3.5 Rubber Tired Gantry Cranes (adapted from official Mogadishu Port Terminal website)

3.2.2 Straddle Carriers

Straddle carriers offer the combined capability of stacking and transporting containers over long distances. They position a container between their two rows of wheels and lift it to the required stacking height as shown in Figure 3.6 and Figure 3.7. Most straddle carriers are built for “one-over-two” operations, though some terminals have adopted “one-over-three” straddle carriers. These carriers typically have three to four single-wheel axles, and the steering of the wheels is coordinated to allow for tight turning circles.

Straddle carriers generally exert less stress on pavements than reach stackers due to better load centering. However, the three-wheeled straddle carrier, used for loading/unloading trailers, is particularly damaging to the pavement due to its highly maneuverable configuration. Automated straddle carriers (AutoStrads) operate with minimal lane wander, unless intentionally implemented by terminal management. Proper documentation and design for the degree of lane shuffle implemented are crucial for economical pavement design [23].



(a) 1 over 3 Straddle Carrier **(b)** Straddle Carrier in Truck Grid

Figure 3.6 Straddle Carriers (adapted from AFPA [22]).



(a) One over One Shuttle Carrier **(b)** Shuttle Carrier One over Trailer

Figure 3.7 Shuttle Carrier/Terminal Transfer Vehicles (adapted from AFPA [22]).

3.2.3 Front End Loaders (FELs)

Front End Loaders (FELs) are versatile pieces of equipment used in container terminals. FELs come in three common configurations: Top Pick (TP), Side Pick (SP), and Reach Stacker (RS). Each type has specific applications and impacts on the pavement as shown in Figure 3.8.

- Top Pick (TP): This configuration involves a spreader mounted on a vertical mast, which picks up the container by its four top corner castings. It is used for both loaded and empty container movements.

- Side Pick (SP): Similar to the Top Pick, but it picks up the container by the two top corner castings closest to the FEL. This is used for empty container movements only.

- Reach Stacker (RS): The spreader is mounted on a hydraulically lifted, extensible boom, allowing it to pick up containers by their four top corner castings and handle them at some distance from the machine.

Front End Loaders (FELs) can have an unladen weight of up to 80 tons, and fully loaded front axle weights can exceed 100 tons, placing substantial stress on the pavement. The maneuvering of the FEL on its two single steering rear wheels generates high shear stresses on the pavement surfaces [23].



(a) Reach Stacker **(b)** Empty Container Forklift

Figure 3.8 Front End Loaders (adapted from PIANC 2015 [7])

3.3 Typical Load Analysis for Port Terminals

Two primary methods are commonly used to evaluate loads from industrial equipment: the Equivalent Single-Axle Load (ESAL) and the Equivalent Single Wheel Load (ESWL). The ESAL method, widely applied in highway pavement design, standardizes various load magnitudes and frequencies into an equivalent quantity of a single load type (80 kN or 18,000 lb). This approach is essential in accounting for axle load distributions and the dynamic impact of industrial equipment on heavy-duty pavements, particularly in ports, container terminals, and industrial zones. Various

design guidelines incorporate these dynamic factors, emphasizing the need to accurately assess load impacts and pavement responses. Conversely, the ESWL method calculates the load of a single tire or wheel that produces an equivalent stress, deflection, or distress at a specific location, mirroring the effects of multiple wheel loads. For the effective design of heavy-duty pavements, it is critical to base calculations on the wheel load and repetition values that cause the most significant damage to the pavement structure (Sengun et al. 2023). The ESWL method is particularly well-suited for pavements in conditions such as port terminals, as well as in scenarios with some unique heavy vehicles on highways. In these contexts, load magnitude and dynamic effects—such as cornering, braking, acceleration, and other challenging maneuvers—often have a more significant impact than load repetitions alone. These conditions require pavement designs that can better withstand concentrated, high-magnitude loads and dynamic stresses, which are not as effectively addressed by traditional ESAL load repetition-based approaches. The ESWL approach will be considered within the scope of this thesis, particularly effective in heavy-load handling equipment scenarios such as terminal container areas or airport pavement designs, where the pavement must accommodate the heaviest aircraft.

The ESWL method considers three concepts: i) tire inflation pressure, ii) wheel proximity, iii) dynamic effects. The contact area of a handling plant tire is determined by dividing the weight on a single wheel by the tire inflation pressure. For highway vehicles, the contact geometry between a tire and the driving surface has been determined to be a 1.6 ellipse. The minor axis is equal to 0.894 multiplied by the square root of the contact area. The primary axis is parallel to the regular path of motion, while the minor axis is perpendicular. However, using an ellipse for thickness design is needlessly intricate, and a circular contact shape has been implemented. The tire footprint of heavy container handling equipment closely resembles a rounded rectangle. Not all facilities use conventional pneumatic road tires, and several plants may be equipped with specialized tires that provide better grip on soft terrain. Lug or tread bars decrease the tire's contact area, resulting in increased contact stress. Pneumatic tires typically function at a pressure of about 1.0 N/mm² (145 psi), while certain transfer trailers are equipped with solid rubber tires, exerting stress on the contact area depending on the trailer load, typically around 1.7 N/mm² (247 psi)

If two wheels are close together on specific industrial equipment, the stress under each wheel increases due to the proximity of the other wheel (Figure 3.9). The radial stress closely resembles the tensile stress just under the loaded wheel, with adjacent wheels generating tangential tensile stress that adds to the radial stress applied by the main wheel. The 'Wheel Proximity Factor' represents the proportion of combined radial and tangential tensile stresses produced by the primary wheel [7].

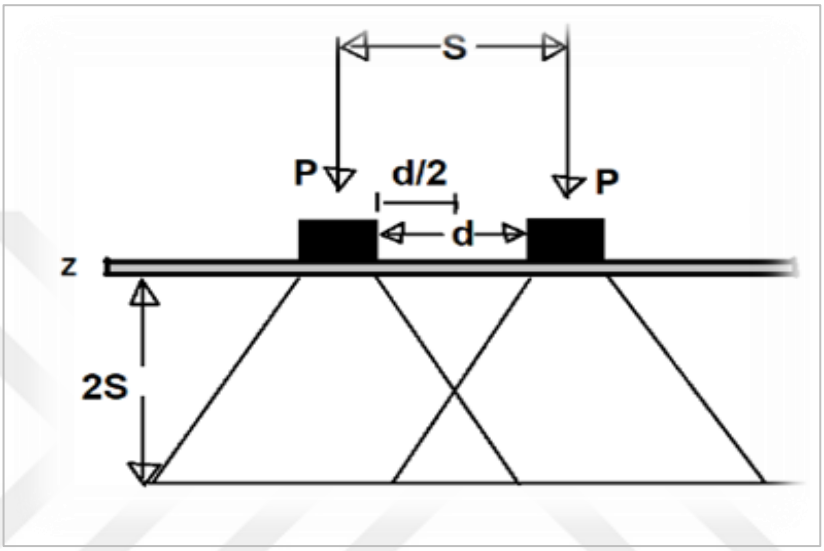


Figure 3.9 Equivalent Single-Axle Load (ESWL) load concept [24].

The proximity factor is the ratio of the sum of radial stress (from the primary wheel) and tangential stress (from the second wheel) to the radial stress [25] (Eq-1).

$$\sigma_{Radial} = \frac{W}{2\pi}\left[\frac{3r^2 z}{\alpha^{5/2}} - \frac{1-2\vartheta}{\alpha + z.\alpha^{1/2}}\right] \quad \textbf{(2.1)}$$

$$\sigma_{Tangential} = \frac{W}{2\pi}[1-2\vartheta].\left[\frac{z}{\alpha^{3/2}} - \frac{1}{\alpha + z.\alpha^{1/2}}\right] \quad \textbf{(2.2)}$$

Where:

- W is wheel load
- R is the horizontal distance between wheels

- Z is the depth to the position of stress calculations
- ϑ is Poisson's ratio

To simplify the calculation of the wheel proximity factor in the British Port Association (BPA) method, a design table based on the wheel spacing and California Bearing Ratio (CBR) of the subgrade can be used. The Equivalent Single Wheel Load (ESWL) approach will be considered within the scope of this thesis, particularly effective in heavy-load handling equipment scenarios such as terminal container areas or airport pavement designs, where the pavement must accommodate the heaviest aircraft.

3.3.1 Critical Load

When the loading exceeds typical highway levels, it is often due to off-road machinery like Straddle Carriers, Front Lift Trucks, or Reach Stackers handling containers. The wheel loads of these plants are directly proportional to their weight and the container or cargo being carried. The design should be based on the Critical Load, defined as the load whose value and number of repetitions lead to the most pavement damage. A small number of high-load repetitions may cause less damage than a greater quantity of lower load values. The entire load regime should be expressed as repetitions of the critical load. Certain pavement design software can examine various cargo weight distributions and their impacts, eliminating the need to identify a critical load. The assessment of the crucial load and its impact includes determining the number of repetitions required for that load to be effective.

The detrimental impact caused by a plant manipulating a container of a certain mass is determined using the cumulative damage factor equation:

$$D = (W/12000)3.75 * (P/0.8)1.25 * N$$

Where:

D = Damaging effect

W = Wheel load corresponding to specific container weight (kg)

P = Tyre pressure (N/mm^2)

The critical weight container is determined by the combination of the container weight (W) and the distribution frequency (N) that yields the maximum value of (D). All future wheel load estimations for that plant should be based on the container's weight. Empirical evidence from the United Kingdom has shown that standard heavy-duty containers typically weigh. These values can be used in preliminary design studies.

- 22000 kg for 40 ft containers (100%)
- 20000 kg for 20 ft containers (100%)
- 21000 kg for a combination of 40 ft and 20 ft containers in equal proportions (50/50)

3.3.2 Dynamic Factors

The complex physics of weight transmission between wheels and tires and its significant impact on pavement design at container ports. It emphasizes the crucial importance of dynamic elements in this design approach, focusing on equipment acceleration, deceleration, cornering, and braking. These dynamic forces significantly impact how the load is transferred to the pavement surface. Designing pavements for container terminals necessitates considering several dynamic elements related to operational mobility. These considerations include unproductive container maneuvers (false moves), such as repositioning for ship loading/unloading or temporary removal for customs inspection. Estimating these extra movements as a fraction of overall trade-related moves is crucial. It is also vital to account for the consequences of using materials handling equipment in areas not specifically designed to support their wheel loads. Pavements must endure repeated use by all machinery operating within the port. Preferences for docking locations may result in imbalanced traffic flow within the terminal, contributing to uneven weight distribution on the pavement. Dynamic elements like braking, cornering, acceleration, and surface unevenness significantly impact weight transmission to the pavement surface and should be considered in pavement design see in Table 3.1.

High-speed automated container handling systems (AGVs and ARTGs) require augmenting dynamic variables by 50% to accommodate heightened pressure on the pavement. The effects of braking and acceleration are most noticeable at container stack entrances and exits and Ro-Ro ramp areas, potentially causing damage at junctions and stack ends. Lateral forces during cornering increase the weight carried by outer wheels, necessitating careful consideration of channelization and wander phenomena. Channelization, involving equipment relocation within designated traffic lanes, and wander, the lateral movement of vehicles, significantly influence pavement design concerns for container ports.

Table 3.1 Dynamic load factors for port terminals pavement design [7].

Condition	Plant Type	f_a
Braking	Reach Stacker/Front Lift Truck	± 30%
	Straddle Carrier	± 50%
	Side Lift Truck	± 20%
	Tractor and Trailer	± 10%
	Rubber Tired Gantry Crane	± 10%
Cornering	Reach Stacker/Front Lift Truck	40%
	Straddle Carrier	60%
	Side Lift Truck	30%
	Tractor and Trailer	30%
	Rubber Tired Gantry Crane	Zero
Acceleration	Reach Stacker/Front Lift Truck	10%
	Straddle Carrier	10%
	Side Lift Truck	10%
	Tractor and Trailer	10%
	Rubber Tired Gantry Crane	± 5%
Uneven Surface	Reach Stacker/Front Lift Truck	20%
	Straddle Carrier	20%
	Side Lift Truck	20%
	Tractor and Trailer	20%
	Rubber Tired Gantry Crane	± 10%

3.3.3 Traffic Patterns

Various traffic patterns need consideration in pavement design for container terminals. The path traveled by Straddle Carriers for imports and exports in narrow container block aisles requires assessing braking and accelerating actions. Additionally, dynamic load factors must be applied to some movements. Container handling equipment typically follows predetermined paths parallel to the quay, with the number of passes

at each site estimated based on parallel specified routes [7]. The region behind the vessel designated for hatch cover storage may exacerbate congestion in other areas. Arterial routes connecting terminal stacks are often spacious, but elevated container storage capacity can temporarily position containers near road edges, causing congestion. Channelization and wander phenomena, particularly in broader terminal roads, must be considered, as they significantly affect pavement performance. False moves, involving unproductive container actions, should be calculated as a proportion of overall trade-related movements.

In conclusion, container terminal pavement design must consider factors such as overweight containers, weight limits, container stacking, handling equipment, and false moves. Overweight containers can lead to improper stowing, equipment damage, and premature pavement degradation. Special care is needed for terminal trailers carrying large containers, with pavement solutions accommodating aisle rotation and stacking heights. Load distribution and the need for greater sub-base and capping materials must also be considered in pavement design.

3.4 Port Terminal Pavement Materials

A pavement is a layered structure built on top of natural soil sub grade, designed to evenly distribute the weight of traffic and prevent the soil from being overloaded. The design and construction of container terminal pavements involve multiple layers, each with specific materials tailored to withstand heavy loads and environmental conditions. These layers typically include the surface layer, the structural layer, and the foundation layer. Various materials are employed in each layer to ensure durability and functionality [7].

The surface layer materials used in container terminals are critical for ensuring durability, load-bearing capacity, and ease of maintenance. These materials can include:

- High stability asphalt surfacing
- Open-graded asphalt filled with hydraulic cement grout
- In situ plain concrete

- Concrete block paving
- Roller compacted concrete (RCC)

The container terminals require strong and long-lasting pavement structures due to the enormous loads and regular traffic of container handling equipment. The pavement structure in container terminals is often made up of numerous levels, each with a unique function. The materials used in these layers must be carefully chosen to ensure long-term function with little maintenance. Geotextiles and geogrids are often used at layer interfaces to enhance separation and strengthen pavements. The base materials can include:

- Asphalt treated base course
- Cementitious treated base course
- Cement-stabilized subgrade materials
- Roller Compacted Concrete (RCC) base course
- Lean concrete base course
- High-quality crushed rock
- Recycled construction materials

Pavements are generally classified into two main types based on design principles: flexible and rigid pavements. Flexible pavements comprise multiple layers of granular materials designed to deform under traffic loads, distributing the stress across layers. In contrast, rigid pavements, constructed using Portland Cement Concrete (PCC), exhibit higher stiffness and carry most of the load through the concrete slab. These pavement types differ significantly in their load distribution mechanisms, as depicted in Figure 3.10, where flexible pavements rely on all layers for load support, whereas rigid pavements primarily utilize the slab to bear the load [26].This chapter explores the characteristics, advantages, and disadvantages of both pavement types in detail.

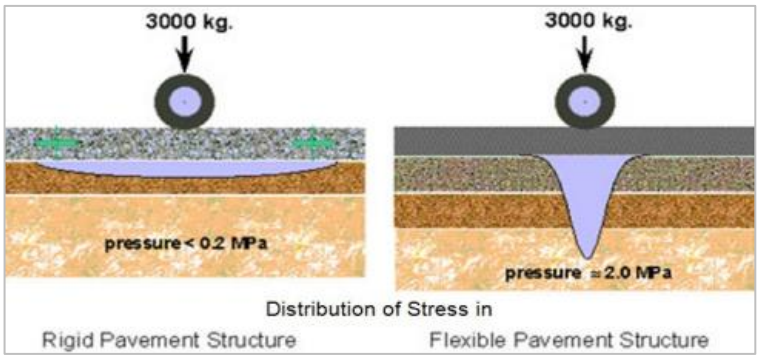


Figure 3.10 Stress distribution of (a) Rigid pavements (b) Flexible pavement (adapted from Dr. András Timár lecture notes)

3.4.1 Flexible Pavements

Flexible pavements are typically constructed with layered structures, where the upper layers are composed of stiffer materials, and the lower layers consist of weaker materials. This structure enables the distribution of wheel loads through the granular layers, reducing stress with increasing depth (Figure 3.11). These pavements are characterized by their low flexural strength, which allows them to adapt to traffic-induced stresses. Despite their lower initial construction costs, flexible pavements generally have higher maintenance expenses over time [27,28].



Figure 3.11 Typical cross-section of a flexible pavement [24]

Typical advantages and disadvantages of flexible pavements can be summarized as follows [26,29–31]:

- Advantages: Cost-effective for construction and repair. Asphalt layers can be melted and reused, supporting sustainability. Does not require expensive

placement equipment. Enables the use of waste bitumen, reducing material waste. Easier to achieve a smooth surface finish during construction. Provides good traction for vehicles, enhancing safety. Offers a smooth and comfortable driving experience.

- Disadvantages: Susceptible to damage from concentrated loads and environmental factors. Aging issues lead to material deterioration over time. Phase changes under temperature fluctuations can affect durability. Requires frequent maintenance, increasing lifecycle costs. Shorter lifespan compared to rigid pavements.

On the other hand, the evaluation of the performance of flexible pavements in port terminals aligns more closely with the objectives of this thesis compared to their typical road applications. In this context, one of the most comprehensive studies on the performance of flexible pavements in port or industrial terminals was conducted in Australia by the Australian Flexible Pavement Association (AFPA) [22]. This study focused on the design procedure and specifications for flexible pavements in container terminals, analyzing the performance of pavements in 15 major container and intermodal terminals across Australia, which had been in service for periods ranging from 1 to over 30 years.

The study revealed that some pavements were specifically designed for container handling equipment and operations, while others utilized designs and materials commonly used for roads and highways. The loading conditions in these terminals included highway trucks, terminal trucks and trailers, front-end loaders, straddle carriers, and shuttle carriers. Identified pavement performance issues included surface shape deformation, rutting, cracking, damage from corner casting, and operational activities at the terminals, some of which impacted performance. Figure 3.12 illustrates a typical distress type observed in asphalt pavements, specifically rutting and surface deformation caused by heavy concentrated stacking of containers, reach stackers, and straddle carriers, highlighting the challenges flexible pavements face under high concentrated loading scenarios in port environments.



a) Rutting due to straddle carries



b) Rutting due to trucks



c) Rutting due to reach stackers



d) Surface deformation due to stacked containers



e) Surface deformation



f) Surface deformation

Figure 3.12 Typical flexible pavement distresses in port terminal environments (adapted from APFA report [22])

3.4.2 Rigid Pavements

Rigid pavements are predominantly utilized in areas with weak soil conditions and high traffic loads. They consist of a concrete slab, which has a high flexural strength, supported by a granular base or subbase (Figure 3.13). These pavements distribute traffic loads efficiently over a wide area, leading to longer service lives and reduced maintenance costs

compared to flexible pavements [24,32,33]. Although the costs of rigid pavements are relatively high, they have less maintenance costs and longerservice lives than flexible pavements [34].

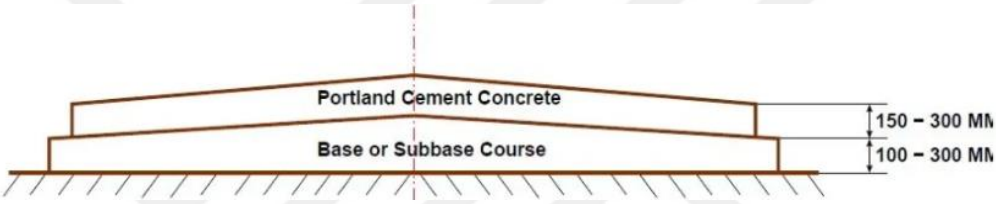


Figure 3.13 Typical cross-section of a rigid pavement [24]

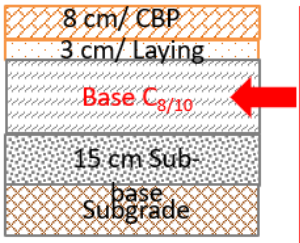
Advantages and disadvantages summarized as follows [24,29,32–34]:

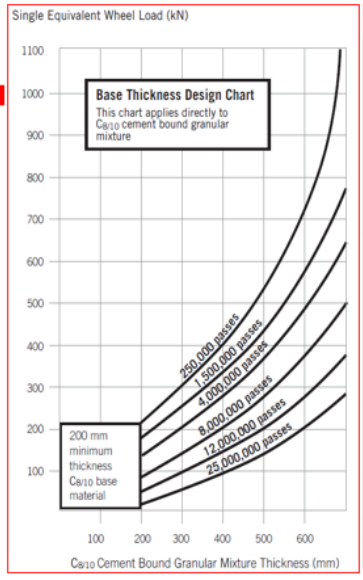
- Advantages: Long service life up to 40 years. Minimal maintenance and repair needs during the service period. Resistant to deformation under concentrated loads and high wheel loads, leading to 10-20% lower vehicle fuel consumption. Unaffected by exposure to oils, fuels, and automotive chemicals. Durable under adverse weather conditions. Produces fewer emissions during production compared to asphalt. Utilizes abundant resources like cement instead of scarce petroleum-based material.
- Disadvantages: Relatively higher initial construction cost compared to flexible pavements. High maintenance costs in certain scenarios. Requires skilled labor for proper construction and maintenance. Relatively higher demand for specialized equipment. Susceptible to curling and warping stresses caused by temperature and moisture fluctuations. Entire concrete slabs must be replaced if significant damage occurs. Slippery surface conditions during rain or snow, raising safety concerns.

When rigid pavements are considered for use in port terminal applications, concrete block pavements (CBPs) have been widely utilized in container terminals as heavy-duty pavements. Some researchers and practitioners claim that their ability to endure severe dynamic and static loads, as well as their resistance to fuel and hydraulic oil damage, settlement, and differential settlement. Moreover, CBPs are often regarded as a more economical solution compared to traditional asphalt or rigid concrete pavements in many cases, making them a preferred choice in heavy-duty applications [35].

One of the main reasons for this preference is the encouragement by the British Ports Association (BPA), which regards CBP as a cost-effective and high-performance solution. The BPA's terminal pavement guidelines, titled Heavy Duty Pavements: The Structural Design of Heavy-Duty Pavements for Ports and Industrials, extensively feature CBP in their recommendations.

The BPA manual proposes a structured approach for designing concrete block pavements, as illustrated in Figure 3.14, which shows the typical layer thicknesses of the pavement structure.





Material Grouping	Preferred Pavement Base Construction Material	Material Equivalence Factor (MEF)
Hydraulically Bound Mixtures	$C_{12/15}$ to BS EN 14227-1	1.74
	C_{16} to BS EN 14227-1	1.38
	C_{20} to BS EN 14227-1	1.16
	$C_{28/35}$ to BS EN 14227-1	1.00
	$C_{32/40}$ to BS EN 14227-1	0.87
	$C_{40/50}$ to BS EN 14227-1	0.79
	$C_{50/60}$ to BS EN 14227-1	0.74
	$C_{12.5/15}$ to BS EN 14227-2&3	1.74
	C_{16} to BS EN 14227-2&3	1.38
	C_{20} to BS EN 14227-2&3	1.10
	$C_{28/35}$ to BS EN 14227-2&3	0.95
	$C_{32/40}$ to BS EN 14227-2&3	0.85
	$C_{40/50}$ to BS EN 14227-2&3	0.79
	$C_{45/55}$ to BS EN 14227-2&3	0.76
	$C_{50/60}$ to BS EN 14227-2&3	0.72
	$C_{60/75}$ to BSEN 14227-2&3	0.68
	$C_{70/85}$ to BS EN 14227-2&3	0.63
Concrete	C8/10 to BS8500-1	1.00
	C12/15 to BS8500-1	0.87
	C16/20 to BS8500-1	0.79
	C20/25 to BS8500-1	0.74
	C25/30 to BS8500-1	0.65
	C25/30 to BS8500-1 including 20 kg/m³ steel fibre	0.60
	C25/30 to BS8500-1 including 30 kg/m³ steel fibre	0.55
	C25/30 to BS8500-1 including 40 kg/m³ steel fibre	0.50
	C28/35 to BS8500-1	0.62
	C32/40 to BS8500-1	0.60
	C32/40 to BS8500-1 including 20 kg/m³ steel fibre	0.55
	C32/40 to BS8500-1 including 30 kg/m³ steel fibre	0.50
	C32/40 to BS8500-1 including 40 kg/m³ steel fibre	0.45
	C35/45 to BS8500-1	0.58
Traditional Cement Bound Materials	CBM1 to SHW (4.5 N/mm² minimum 7-days compressive cube strength)	1.60
	CBM2 to SHW (7.0 N/mm² minimum 7-days compressive cube strength)	1.20
	CBM3 to SHW (10.0 N/mm² minimum 7-days compressive cube strength)	1.00
	CBM4 to SHW (15.0 N/mm² minimum 7-days compressive cube strength)	0.80
	CBM5 to SHW (20.0 N/mm² minimum 7-days compressive cube strength)	0.70
	No-fines Lean Concrete for Permeable Paving	1.00
Bitumen Bound Materials	HDM as defined by SHW	0.82
	DBM as defined by SHW	1.00
	HRA as defined by SHW	1.25
Unbound Materials	Crushed Rock sub-base material of CBR ≥ 80 %	3.00
Concrete Block Paving	Concrete Block Paving as a surfacing (80 mm blocks and 30 mm laying course)	1.00

Figure 3.14 Summary of BPA design procedure for port terminal pavements (adapted from [25,36])

The BPA design method utilizes finite element modeling to simulate the behavior of heavy-duty pavements under extreme wheel loads. These models are calibrated using performance data from real-world pavements. Subsequently, the finite element outcomes are integrated with a fatigue model to produce a simplified design chart, which aids pavement designers in determining appropriate layer thicknesses. In cases where the subgrade's California Bearing Ratio (CBR) value is less than 5%, a capping layer is advised to improve the foundation's support. The base thickness, a critical design parameter, is determined using the BPA design chart. The initial design assumes the use of concrete block pavements; however, if alternative materials are preferred, the designer can employ Material Equivalence Factors (MEFs) to convert the CBP design into options such as jointed concrete pavements with varying compressive strength grades (e.g., C25/30, C35/45) or fiber-reinforced concrete. Additionally, Roller Compacted Concrete (RCC) pavements are not mentioned as an alternative surface layer in the older version of the BPA guideline (1993). However, RCC is prominently highlighted in the Britpave Guide (2022) to RCC Pavements-Guidelines for Design, Materials, and Construction. According to this guide, RCC with a concrete grade of C35/45 is compatible with the achievable in-situ strengths necessary for heavy-duty pavements. Furthermore, the guidelines are flexible enough to accommodate bitumen-based materials as alternatives, providing designers with a range of solutions tailored to the specific requirements of port terminal operations.

Although the French LCPC guideline does not directly consider RCC as a primary design option, similar to the Britpave approach, it equates RCC to a concrete grade of approximately C35/45. Additionally, RCC was notably employed in November 2021 for the construction of a new storage platform for vehicles in transit at the Port of Brégaillon. This platform, built on a former industrial site used for aggregate crushing, demonstrates RCC's suitability and efficiency in port infrastructure applications.

The Spanish method (ROM-94: Guidelines for the design and construction of port pavements) [37] stands out by explicitly recognizing RCC as a viable surface paving material for port terminal rigid pavement designs. It provides detailed specifications for RCC, offering it as an alternative to traditional materials. Notably, the

recommended RCC thickness aligns closely with that of vibratory cement concrete pavements, highlighting its comparability in structural capacity.

Another alternative for port terminal pavements is the use of in-situ concrete runway beams. This approach differs significantly from others by incorporating concrete beams to reinforce roadways subjected to dynamic, such as those from straddle carriers. These beams are designed to bear and distribute concentrated loads effectively. Figure 3.15 illustrates an application at the Sydney Port Botany Container Terminal. Additionally, for container storage areas with fixed locations, the regions beneath corner castings are also reinforced using these beams, ensuring enhanced structural integrity in critical zones.

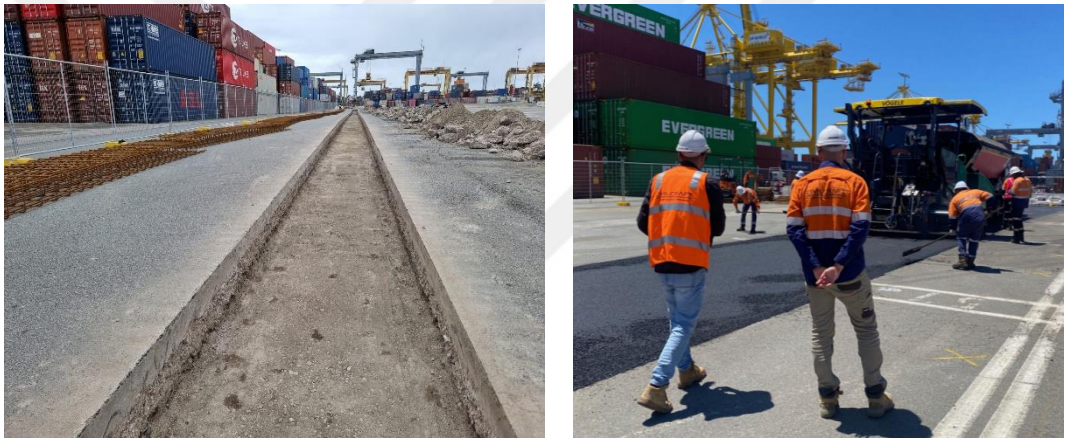
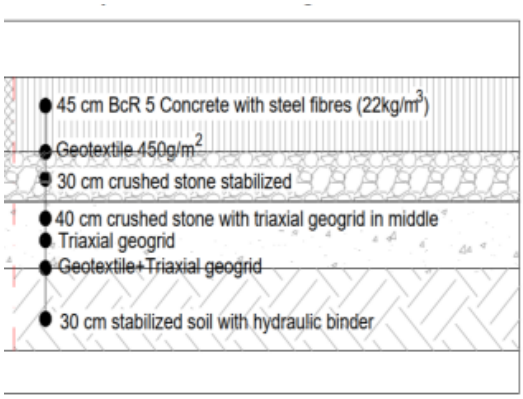


Figure 3.15 Concrete beam construction on Port Botany Terminal in Sydney, Australia (adapted from civilcraft website)

Another notable application of concrete pavement in port terminals involves the use of steel fiber-reinforced concrete (SFRC), where steel fibers are added to the concrete mix to enhance its performance. A large-scale implementation of SFRC was carried out during the expansion of the Constanta South Container Terminal SRL (Romania) between 2020 and 2023. In this project, SFRC was prepared by incorporating 22 kg/m³ of steel fibers into concrete with a minimum flexural strength of 5 MPa (BcR 5)[38].

The terminal, expected to handle an annual capacity of 2 million TEU, utilized a pavement section consisting of 45 cm SFRC placed over 70 cm (40 cm + 30 cm) of crushed stone, separated by a geotextile layer. This construction method, as shown in

Figure 3.16, highlights the suitability of SFRC for accommodating the heavy and repetitive loads typical of high-capacity port terminals.



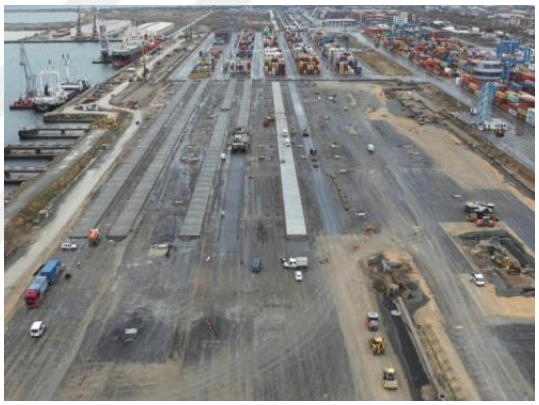
a) SFRC section for port terminals



b) Steel dispersions in concrete



c) SFRC application in Constanta South Container



d) Site overview during the SFRC application

Figure 3.16 SFRC application in Constanta South Container Terminal SRL in Romania [38]

Typical problems observed in concrete pavements used at port terminals include fatigue cracking caused by dynamic loads, surface deflections due to static concentrated loads and dynamic factors, curling and warping cracks resulting from thermal and moisture variations, and cracks and surface roughness arising from subgrade settlement. Additionally, raveling, which is the progressive loss of fine particles in the surfacing material, is common across all terminal pavement surfaces. Scaling, a surface deterioration phenomenon, can also occur. A study by AFPA on flexible pavement performance at port terminals highlights those similar issues, though less frequent, are also present in concrete pavements. These include raveling, fatigue

cracking, and surface deflections. Despite their relatively limited occurrence in concrete pavements, these issues are noted in the associated documentation. An example of such distresses is illustrated in Figure 3.17, showing typical surface deflection, raveling and fatigue cracking in terminal pavements.

Another significant study in this field was conducted by the Spanish State Ports Authority (SSPA) in collaboration with Madrid Technical University. The study aimed to observe the performance of existing container terminals, develop a new pavement condition index for container terminals, and calibrate the Spanish design guide (ROM-94). As part of this study, 20 ports with high traffic and container volumes were selected, of which 79% comprised concrete pavements, while 19% consisted of asphalt pavements.



a) Rutting and shoving in CBP

b) Rutting in CBP

c) Cracking due to fatigue

d) Raveling and scaling on CBP

Figure 3.17 Concrete pavement distresses in port terminal environments (adapted from APFA [22])

The methodology included digital visual surveys, deflection measurements, core sampling, laboratory testing, and data processing. Concrete pavements were analyzed for a wide range of distresses, such as: Parallel to traffic cracking, double parallel to traffic cracking, perpendicular to traffic cracking, double perpendicular to traffic cracking, multiple cracking, map cracking spalling, corner breaks, diagonal cracks, curve cracks, potholes, patches, scaling, faulting, settlement, reinforcement uncovering, ponding, wear and tear, water bleeding and erosion.

Table 3.2 presents the distribution of encountered distresses based on an analysis of 2,140 concrete pavement slabs. The results indicate that the most prevalent distress types were cracks caused by handling equipment and container corner castings, emphasizing the significant structural demands placed on these pavements.

Table 3.2 Results of distress visual survey in concrete pavements in Spanish Port Terminals conducted by Spanish State Ports Authority [39]

Concrete pavement distress type	Percentage of occurrence
Multiple cracks	33%
Longitudinal cracks and double longitudinal cracks	17%
Large and small joint spalling	15%
Transverse cracks and double transverse cracks	14%
Corner breaks	10%
Map cracking	6%
Scaling	4.5%
Diagonal cracks	1%
Faulting	1%
Pop outs	0.5%

Additionally, the study concluded that concrete pavements dominate as the primary pavement type for port terminals in Spain. This finding underscores the preference for concrete pavements in handling the demanding structural and durability requirements of high-traffic and high-load port environments.

3.4.3 Comparison of Flexible and Rigid Pavements

Flexible and rigid pavements demonstrate significant differences in both their structural behavior and performance characteristics, which are influenced by their design, materials, and load distribution mechanisms. Flexible pavements are typically constructed using multiple layers of granular materials, where each layer contributes

to distributing the applied load across the surface. These pavements are designed to deform under traffic loads, transferring the stresses to the lower layers through granular material. In contrast, rigid pavements are primarily constructed using PCC, with a strong, inflexible slab designed to resist deformation under concentrated heavy loads. The concrete slab carries most of the applied load, distributing it across a wide area, which minimizes stress on the underlying layers. The rigidity of these pavements provides longer service life, but their construction costs tend to be higher, and they require careful attention to joint design due to potential thermal stresses. In summary, flexible and rigid pavements exhibit fundamental differences in their structural behavior and performance characteristics [29,40,41]:

- Load Transfer Mechanism: Flexible pavements, the load is transferred through grain-to-grain contact, whereas rigid pavements utilize flexural action within the concrete slab.
- Design Principles: Flexible pavements rely on load-distributing characteristics across multiple layers, while rigid pavements are designed based on flexural strength and slab action.
- Flexural Strength: Flexible pavements possess low flexural strength, contrasting with the high flexural strength of rigid pavements.
- Subgrade: Flexible pavements, deformation occurring in the subgrade is transferred to the upper layers, whereas rigid pavements do not transfer such deformations due to their stiff slab structure. Flexible pavements rely on the strength of the subgrade, whereas the strength of rigid pavements is less dependent on the subgrade.
- Subbase/ Base: Flexible pavements require both a base and a subbase for proper support, whereas rigid pavements can often be laid directly on the subgrade, depending on the project requirements, and may only necessitate a thinner base section.
- Lifespan: Flexible pavements have a shorter lifespan compared to the longer service life of rigid pavements.
- Cost Considerations: The construction costs of both pavement types are influenced by factors such as material prices, availability of local materials,

previous experience, subgrade conditions, and traffic loading. However, flexible pavements typically have lower initial construction costs compared to rigid pavements but can show higher life cycle costs due to maintenance frequency and shorter service life.

- Thermal and Moisture Stresses: Both asphalt and concrete pavements are susceptible to thermal stresses. However, flexible pavements, due to their thermal properties, are more resilient to temperature fluctuations. Concrete retains heat for longer periods, leading to more pronounced thermal gradients between the top and bottom of the slab. These gradients can cause curling and warping, which increases thermal stresses. In contrast, asphalt cools down more quickly and has a lower thermal gradient, reducing the potential for stress. Additionally, asphalt's flexibility allows it to absorb thermal stresses and accommodate temperature changes without significant cracking or damage. On the other hand, rigid pavements are more susceptible to thermal and moisture stresses due to their brittle nature and limited capacity for expansion and contraction, which requires the installation of expansion joints to manage these stresses effectively.
- Surface Texture: Flexible pavements typically achieve sufficient skid resistance due to the roller finishing applied after construction, aided by the porous aggregate gradation. However, conventional concrete pavements require special surface treatments after installation to improve skid resistance and facilitate proper drainage, as they are prone to slippery surfaces, especially in wet conditions.
- Service Opening Time: Flexible pavements can be opened to traffic within 24 hours of construction, whereas conventional concrete pavements require a curing period to achieve sufficient strength for traffic loading. However, this limitation can be mitigated by using special chemical admixtures, alternative cement types, or employing special type of concrete like roller-compacted concrete pavements.

CHAPTER 4

ROLLER-COMPACTED CONCRETE AS PORT TERMINAL PAVEMENT ALTERNATIVE

4.1 Overview of Roller-Compacted Concrete Pavement

Roller-compacted concrete (RCC) is a specialized form of concrete that can be compacted immediately after placement using dead-weight or vibrating rollers. Its composition is similar to conventional concrete but with distinct mix proportions to support immediate load-bearing capacity. Proper mixture proportioning is essential to achieve uniform compaction and the desired material density. Guidelines for RCC proportioning are provided in ACI documents, including. Which detail factors like free water content, cement and pozzolan amount, sand and aggregate size, air-entraining admixtures, and other additives. RCC offers sustainability benefits, with potentially lower embodied carbon dioxide and more sustainable resource use compared to other equivalent pavement options. RCC can incorporate recycled concrete aggregates, which is particularly advantageous when sourced from the pavements being replaced, enhancing environmental sustainability [3,5,42,43]

RCC has gained widespread use in construction, particularly in applications where no-slump concrete can be efficiently transported, placed, and compacted using earth and rock-fill construction equipment. This is especially advantageous for large placement areas with minimal interferences or discontinuities, making it economically competitive with other construction methods. The primary applications for RCC include mass concrete projects like dams and heavy-duty pavement applications, such as intermodal yards, port facilities, warehouses, and industrial parking and storage areas. Although this method has historical roots dating back to before the First World War, it gained prominence in North America in 1942 with the construction of the Yakima-Washington Road by the Seattle Division of the U.S. Army Corps of Engineers. The use of RCC for pavement applications has seen substantial growth in North America, particularly in the construction of low-volume roads and parking lots

and industrial areas over the past decades. These advancements highlight RCC's versatility and effectiveness in modern construction practices.

Conventional concrete pavements are designed as rigid pavements whilst asphalt pavements are designed as flexible pavements and therefore RCC has the structural design approach of conventional concrete pavements and the construction approach of asphalt. It is a zero-slump material that must be compacted by roller to achieve the required density. It differs from conventional hydraulically bound materials in that it can provide the wearing surface to traffic, and it is a material that does not fall within the current scope of the European Standard for Hydraulically bound mixtures, EN 14227-1:2004, or into the European Standard for Concrete, EN 206-1 without utilizing the specification of 'Other technical requirements'. RCC is a rapid form of construction, which is an advantage over the slower pavement-quality concrete construction. Trafficking at much earlier ages than with conventional pavement concrete is possible due to its rapid gain of strength. RCC's durability comes from its low water/cement ratio, although this is not a specification requirement, and its high density. Some of its earliest uses were for heavy-duty industrial pavements where strength and durability were the prime consideration. RCC typically does not include air entrainment and evidence suggests that air entrainment is usually unnecessary, even in situations where freeze-thaw damage may occur [42]. There are a few cases where this generalization does not apply. The first requirement in the model specification is that the aggregates must be able to resist freeze-thaw cycles. There must be enough fine material for a cohesive structure and proper compaction of the RCC according to specifications to ensure actual resistance is met. RCC, like concrete block paving, derives much of its freeze-thaw resistance from the presence of air voids, which are similar in size and distribution to entrained air voids. This characteristic has been particularly evident in North America, where significant experience with RCC's freeze-thaw durability has been documented. In 2006, a large-scale comprehensive study (Service d'Expertise en Matériaux, 2006 [44]) evaluated the frost durability of RCC pavements. The study involved selecting 25 test sections from existing RCC projects, transporting samples to the laboratory, and conducting a wide range of tests, including: compressive strength test, flexural strength test, characteristics of the air-void system, microscopic observations by SEM, frost durability, deicer salt-scaling

resistance, freezing and thawing durability, pulse velocity measurement, chloride penetration test and surface and internal microcrack measurement. These RCC samples had been exposed to more than 10 harsh winters, and the results provided valuable insights into RCC's performance in cold climates like Canada [44]. The findings indicated that after over a decade of service, the experimental pavements remained in good condition, demonstrating RCC's robust frost resistance and long-term durability in severe climatic conditions. Nevertheless, when there is doubt about the RCC's ability to resist freeze-thaw, freeze-thaw testing should be included in the initial testing of the RCC mix. Interestingly, the standards used for numerous freeze-thaw assessments are strict and might not accurately reflect the performance of RCC (and other types of concrete) that have proven to be successful in real-world applications [45].

The real-world application of RCC is underway at Fort Cavazos, where the material's durability and resilience are tested under the weight of heavy military equipment see in Figure 4.1.



Figure 4.1 40-Year-Old 10-inch RCC Pavement at Fort Cavazos Supporting Military Tanks (adapted from cementx.org web site)

Notably, this installation celebrates 40 years of exceptional performance of RCC, supporting the heaviest military machinery since 1983 without requiring maintenance. This longevity, paired with RCC's low-maintenance nature, translates into significant cost savings and minimized operational interruptions—key factors for military and industrial applications alike. Incredibly, the entire RCC pavement installation at Fort

Cavazos is projected to be completed in just seven days, a timeline significantly shorter than the four months typically needed for conventional pavement methods using a night-schedule approach. Additionally, RCC's rapid-set properties enable traffic flow within 24 hours of placement, supporting loads up to 72 tons within 20 hours. This efficiency not only minimizes disruptions but reinforces RCC's superior durability, rapid serviceability, and economic viability for high-demand infrastructure [45].

As mentioned, RCC, due to its dense and smooth finish after compaction, is ideal for applications such as parking lots, storage areas, and low-speed roadways. However, for high-speed road applications, additional treatments can be necessary to ensure skid resistance and surface regularity. One common solution in European countries is to overlay the RCC with an asphalt surface course, which enhances skid resistance and provides the needed surface smoothness. In the United States, diamond grinding is another approach used to improve surface tolerance and skid resistance by grinding and grooving the RCC surface. The mix proportioning significantly affects the surface finish, as extremely dry RCC mixes cannot achieve the same finish quality as conventional pavement-quality concrete. Consequently, without additional treatment, RCC is generally limited to areas with low-speed traffic, such as industrial zones, port terminals, and parking facilities [46]. In Figure 4.2 illustrates a typical RCC surface finish, highlighting the limitations of achieving high-speed skid resistance with untreated RCC surfaces.



Figure 4.2 Typical surface finish with 20mm (left) and 10 mm (right) maximum aggregate size (adapted from by CEMEX UK website)

Although the American Concrete Institute (ACI) guidelines provide foundational knowledge on traditional RCC pavement mix proportioning and field applications, significant advancements in RCC pavement practices have emerged, particularly in the US, in recent years. As noted by RCC Pavement Council Research Board Director:

- Harsh, difficult-to-work RCC mixes have evolved into more workable, stable mixtures, resulting in tighter, smoother surfaces with improved abrasion resistance and appearance.
- High-density pavers with compaction rates up to 95% have been employed as a more effective alternative to traditional asphalt finishers. These pavers can compact RCC layers to near-final density in a single pass, minimizing the need for subsequent compaction with rollers,
- Conservative thickness design methods are being updated with newer techniques to better align pavement structural design with real-world performance.
- Joint spacing practices have shifted, moving from wide, unsawn joints on older projects to narrower, precisely spaced joints for better crack control in recent applications.
- Joint seals or fillers, rarely used in earlier RCC pavements, are now often included for added durability and performance.
- Modern RCC projects frequently incorporate hydration-retarding admixtures and other additives, enhancing mix compaction and allowing extended working times between mixing and placement.
- Advances in surface finishing have introduced sprayed-on finishing aids and trowel machines, which improve surface quality beyond what pavers and rollers could achieve alone.
- Many experienced RCC contractors have adapted their equipment to avoid the need to cut and waste the paving edge after rolling.

RCC mix proportions have evolved significantly in recent years. Early applications often relied on either a single aggregate stockpile or two stockpiles one for course and one for fine aggregates—with a typical maximum aggregate size of 37.5 mm. Over time, however, the industry recognized the benefits of smaller aggregate sizes and

more graded fractions. Mixes with larger aggregates not only created rougher surface textures but also showed higher tendencies for segregation and were harder to compact to high density compared to mixes with smaller, well-graded combined aggregates with a maximum size of 25 mm or smaller. To address these challenges, modern RCC mixes incorporate three or four aggregate fractions (e.g., 0-4, 5-12, 12-19 mm) to produce a more uniform blend and improve compaction. Cement dosages have been increased to at least 275-300 kg/m³, and more chemical admixtures are now used, such as hydration inhibitors and surface-enhancing additives. Optimized paste concrete and aggregate gradation continues to be a focus, aiming for smoother textures, economic and increased durability with minimal compaction effort [47].

4.2 Application of Roller-Compacted Concrete in Terminal Pavements

Terminal areas typically require extensive pavements to handle the demanding conditions of container and freight storage. These pavements must endure high static loads from containers and heavy equipment while maintaining cost-effectiveness, with low initial construction expenses and minimal upfront investment. Durability is also critical, as these pavements are expected to have a long service life and require limited long-term maintenance. Traditionally, two options are common for port terminal pavements: asphalt (flexible) and concrete (rigid), as outlined in Section 3.4. Asphalt is widely used in Somali ports due to its affordability and ease of construction. This material provides a smoother surface for container-handling equipment but is prone to rutting under high static loads and has limited capacity for the heaviest containers. Moreover, it may not withstand dynamic forces from equipment like reach stackers effectively. Alternatively, RCC pavement offers enhanced load-carrying capacity, exceptional shear strength, and longevity with minimal maintenance. In the United States, as shown in Figure 4.3, RCC pavement is increasingly used in intermodal and port facilities.

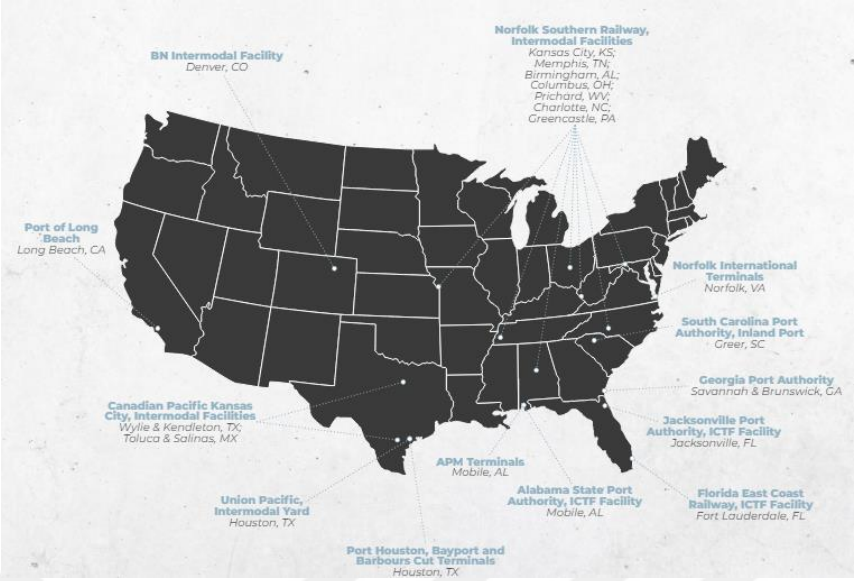


Figure 4.3 Used RCC Pavement for Intermodal and Port Facilities in US (adapted from US RCC Pavement Council Report)

As an example of RCC pavement application in port terminals, the APM Terminals in Alabama, as shown in Figure 4.4. Key advantages of RCC include its high load-bearing capacity, resistance to heavy handling equipment and container stacking, and the ability to open for use quickly. Since RCC is primarily used in low-speed areas, it does not require special surface texturing, further reducing maintenance needs. For port operations, RCC minimizes downtime during maintenance and construction, providing a robust and time-efficient solution. The choice between asphalt and RCC is determined by criteria such as usual container weights, traffic volume, and budget limits. While asphalt may provide initial cost savings and faster operational readiness, concrete's ability to bear large loads may be preferable for high-traffic terminals.

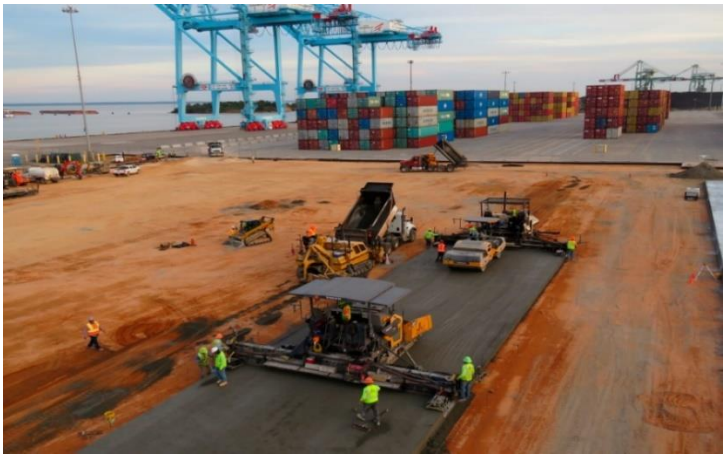


Figure 4.4 Port of Mobile in Alabama (adapted from https://www.linkedin.com/pulse/paving-10m-widths-without-joints-using-duo-tamp-screed-woodhead/)

The Port of Houston currently hosts one of the largest RCC pavement projects in the United States, reflecting a significant commitment to this robust material for high-traffic, load-bearing areas. Since 2007, the port has utilized RCC extensively, primarily in the Bayport and Barbours Cut terminals, to support its high-demand infrastructure needs. Over 520,000 cubic yards (around 385,000 m^3) of dual-lift RCC pavement are projected for use, enhancing both durability and load-bearing capacity for container storage. By late 2024, the port anticipates having over 400 acres (1.6 km^2) of RCC pavement in place and production rates routinely exceed 1,500 cubic yards (1,200 m^3) per day, making it one of the nation's largest RCC paving sites in the United States [48]. RCC's adoption at the Port of Houston has significantly reduced both construction timelines and ongoing maintenance costs, marking it as a cost-effective choice for large-scale container operations (Figure 4.5).

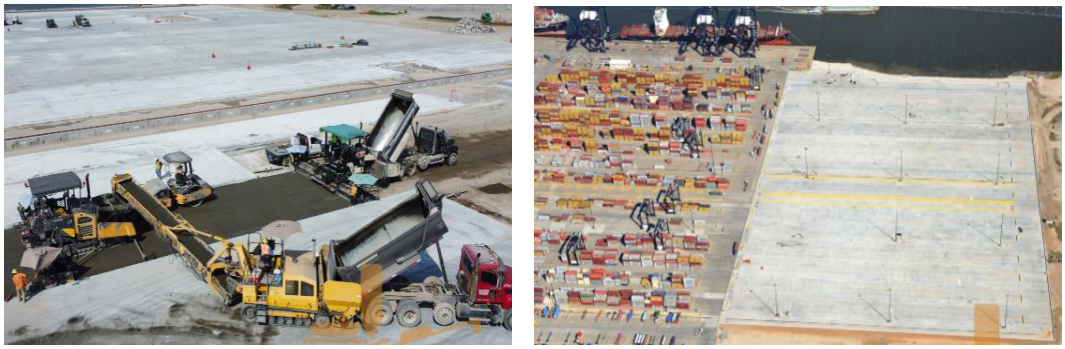


Figure 4.5 Photos from RCC application in Houston Bayport Port Terminals (Completed October 2023) (adapted from US RCC Pavement Council)

In the Port of Houston, three distinct loading environments were analyzed during the port expansion projects: grounded container storage, wheeled container storage, and circulation roads. The design team proposed several pavement options aimed at achieving a 30-year service life. The RCC pavement design included the following layers: (1) cement/lime-stabilized subgrade due to poor present subgrade condition, (2) a geotextile fabric, (3) an open-graded drainage layer, (4) a cement-treated recycled concrete aggregate subbase, and (5) an RCC surface layer, as depicted in Figure 4.6. To better understand the cross-section of RCC pavement, the following approximate conversions are applied: 4 inches as 10 cm, 8 inches as 20 cm, 12 inches as 30 cm, 14 inches as 35 cm and 18 inches as 45 cm.

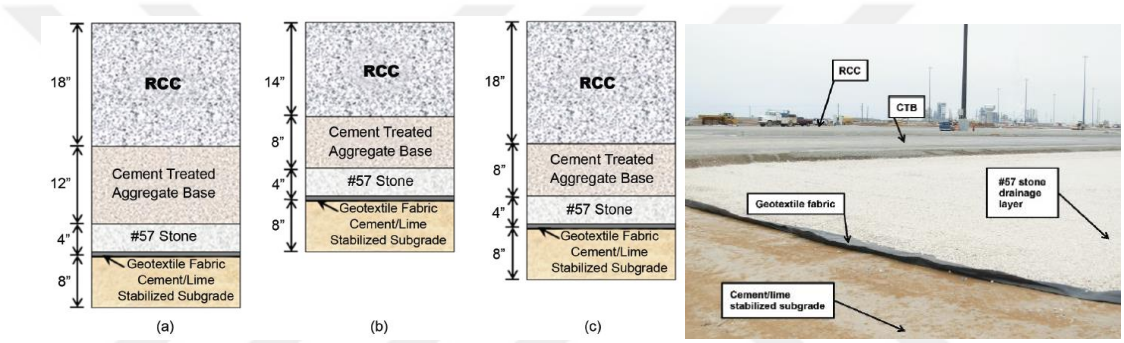


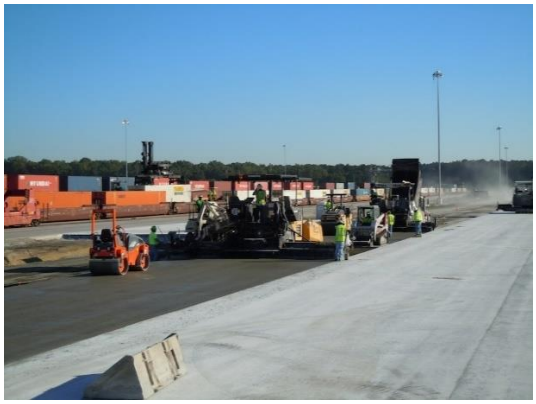
Figure 4.6 Pavement sections of the Port of Houston extension project: (a) Grounded container storage; (b) Wheeled container storage; and (c) Circulation roads [48]

In those projects, the RCC mix was a carefully optimized combination of Type I/II Portland cement, washed concrete sand, manufactured sand/crusher screenings, and coarse aggregate. The RCC was specified to achieve a flexural strength of 550 psi (3.8 MPa) at seven days and a compressive strength of 5000 psi (35 MPa). Quality control measures included testing for density and compressive strength, requiring a minimum average density of 98% based on the modified Proctor method. Furthermore, given Houston's limited aggregate resources, the CTB supplier recommended the use of recycled crushed concrete as the CTB aggregate. Additionally, the adoption of RCC for the Bayport and Barbours Cut terminal expansions resulted in a significant cost reduction of approximately 15%.

For additional examples of RCC's advantages in port terminal projects, such as those depicted in Figure 4.7(a), the CSX Intermodal Facility in Fairburn, Georgia, stands

out. In 2010, this facility transitioned from traditional asphalt to RCC to boost port capacity, primarily due to asphalt's poor performance and the high load requirements of the new pavement. The facility opted for RCC in the Rubber Tire Gantry lanes and truck/trailer lanes, achieving enhanced durability and load-bearing capabilities, essential for accommodating the heavy, repetitive loads typical in high-demand environments.

In 2012, the Georgia Ports Authority (GPA) expanded its Ocean Terminal's capabilities by incorporating RCC alternative. GPA engineers, comparing the typical HMA design with an RCC design over a cement-treated base (CTB), found that a 7 inches (17.5 cm) RCC layer over 9 inches (22.5 cm) of CTB delivered 33% higher strength at an initial cost savings of 19%. As of April 2023, this RCC installation has shown impressive performance over 11 years, as shown in Figure 4.7(b), handling a range of heavy cargo, including items weighing over 120,000 lbs. (54 tons), without any need for maintenance a testament to RCC's durability and load-bearing capabilities in a high-traffic port environment.



a) CSX Intermodal facility in Fairburn



b) Ocean Terminal in George



(c) The Mobile Container Terminal at Choctaw Point



(d) Hoyer Chemical Container Storage Terminal

Figure 4.7 Some photos from RCC container storage areas (adapted from RCC Pavement Council of USA website)

The Mobile Container Terminal at Choctaw Point, constructed in 2012 as part of a $300 million project, exemplifies RCC's suitability for modern container areas, as shown in Figure 4.7(c). With 120,000 yd^3 (97,750 m^3) of RCC, including 101,000 yd^2 (83,600 m^2) of 16 inches (40 cm) pavement and 299,000 yd^2 (230,000 m^2) of 8 inches (20 cm) pavement, RCC was selected over asphalt to expedite the project and achieve substantial cost savings. This choice not only reduced the construction timeline but saved the client over $1 million in initial costs, highlighting RCC's economic and operational advantages in extensive container storage applications.

In 2014, the West Virginia Department of Transportation achieved national recognition by winning the Gold Award (Prichard Intermodal, Prichard, WV; a gold

award winning project) in the Roller Compacted Concrete (Industrial) category from the American Concrete Pavement Association. The project involved constructing 18 inches (45 cm) thick RCC pavement placed in two 9 inches (22.5 cm) lifts, with the top lift spread within 30 minutes of the bottom to ensure optimal bonding. This successful execution of RCC pavements has set a precedent for future industrial applications requiring highly durable surfaces for intensive use.

The 2018 construction of a 9 inches (22.5 cm) RCC pavement at the Norfolk Southern Intermodal Facility in Kansas City underscores RCC's efficiency and adaptability in large-scale projects. Despite some weather delays, RCC placement proceeded smoothly, with production often exceeding 1,000 yd^3 (765 cm^3) per shift. The facility's well-graded mix created a dense, "tight" surface texture, and the 15 feet (4.5 m) saw cuts have proven durable over time, exemplifying RCC's longevity and low-maintenance characteristics under intermodal transport conditions.

In 2023, the Georgia Department of Transportation (GDOT) implemented an RCC design-build solution for the Hoyer Chemical Container Storage Terminal, as shown in Figure 4.7(d). With RCC pavement varying between 10 to 16 inches (25 cm to 40 cm) thick, this project covers 358,000 ft^2 (33,000 m^2), providing a robust and safer environment for container storage. This initiative aligns with GDOT's goals to enhance durability and safety for high-traffic, heavy-load areas, further establishing RCC's role as an effective solution for long-term infrastructure resilience and operational efficiency.

CHAPTER 5

NUMERICAL ANALYSIS

5.1 Data Inventory for Somalian Ports

In this chapter, a rigorous data collection process was conducted to model the pavement systems of Somali port terminals and evaluate their performance. The process involved identifying existing pavement configurations at all Somali port terminals, compiling an inventory of the handling equipment used, and obtaining data on maximum container weights and stacking heights. Data sources included online reports, official port terminal websites, and open-source databases, supplemented by face-to-face interviews with Somali port officials. However, challenges such as limited online resources, security concerns during face-to-face visits, and difficulties in reaching authorities prolonged the data collection process and resulted in fewer data points than anticipated. The collected data for the Somalian port terminals is presented in Table 5.1 and Table 5..

Table 5.1 Inventory of pavement and equipment data for major Somalian port terminals

Data	The Port of Mogadishu	The Port of Barbera	The Port of Bossaso
Opening date	1974	1969	1980
Location	Mogadishu City	Barbera City	Bossaso City
Current capacity as TUE	~200,000	~500,000	< 5,000
Area size	300,000 m^2	500,000 m^2	20,000 m^2
Container Types	20 ft & 40 ft	20 ft & 40 ft	20 ft & 40 ft
Average Container Weight	25,000 kg	20,000 kg	10,000 kg
Critical stacked container heights	5	5	3
Stacked container dimensions	20ft in length, 8ft in width, and 8.6ft height	20ft in length, 8ft in width, and 8.6ft height	20ft in length, 8ft in width, and 8.6ft height
Handling equipment types	Mobile Harbor Cranes (Gottwald), Reach Stackers, Forklifts, Tug-master, Terminal Tractors	Mobile Harbor Cranes , Reach Stackers, Forklifts, Terminal Tractors	Mobile Harbor Cranes , Forklifts, Terminal Tractors

Table 5.1 (continued) Inventory of pavement and equipment data for major Somalian port terminals

Data	The Port of Mogadishu	The Port of Barbera	The Port of Bossaso
Critical handling equipment	MHC-100 tones Reach Stacker-45 tones	N/A	N/A
Pavement types	Old sections-Flexible Pavement New Sections-Mixed	Old sections-Flexible Pavement New sections- CBPs	Old sections-Flexible Pavement New sections- CBPs
Pavement thickness	300 mm asphalt layer	300 mm asphalt layer	N/A
Base material and thickness	400 mm aggregate base	400 mm aggregate base	N/A
Sub grade soil type condition (CBR value)	CBR 10%	CBR 10%	N/A
Average Max Temp	34 ºC	34 ºC	43 ºC
Average Min Temp	19 ºC	22 ºC	21 ºC
Daily Temp Variations	5 ºC	8 ºC	9 ºC

Based on the complied data, the average critical stacked container weights at the country's largest ports, The Port of Berbera and The Port of Mogadishu, are 25 tons and 20 tons, respectively, with stacking heights not exceeding five containers. It was also determined from officials that similar handling equipment is used at these ports, with the most critical loads originating from mobile harbor cranes and reach stackers. Consistent with road pavements in Somalia, flexible (asphalt) pavements are typically preferred for port terminal infrastructure especially in old sections, utilizing dense-graded granular aggregate layers as the base. Discussions with officials revealed that a catalog thickness design method is employed to determine the pavement thickness for port terminals pavements. A standard pavement thickness of 300 mm is typically applied, consisting of a 170 mm bitumen-bound base, an 80 mm asphalt binder with modified bitumen, and a 50 mm surface course (HMA) with modified bitumen. Additionally, in certain cases, a 200 mm sub-base layer with 100% CBR is utilized depending on the subgrade conditions. This comprehensive data forms the foundation for the numerical modeling and performance estimation of the port's pavement infrastructure.

However, some terminals like Mogadishu Port Terminal adopt a hybrid approach by incorporating jointed plain concrete as a surface texture in certain sections alongside asphalt pavements (see Figure 5.1).

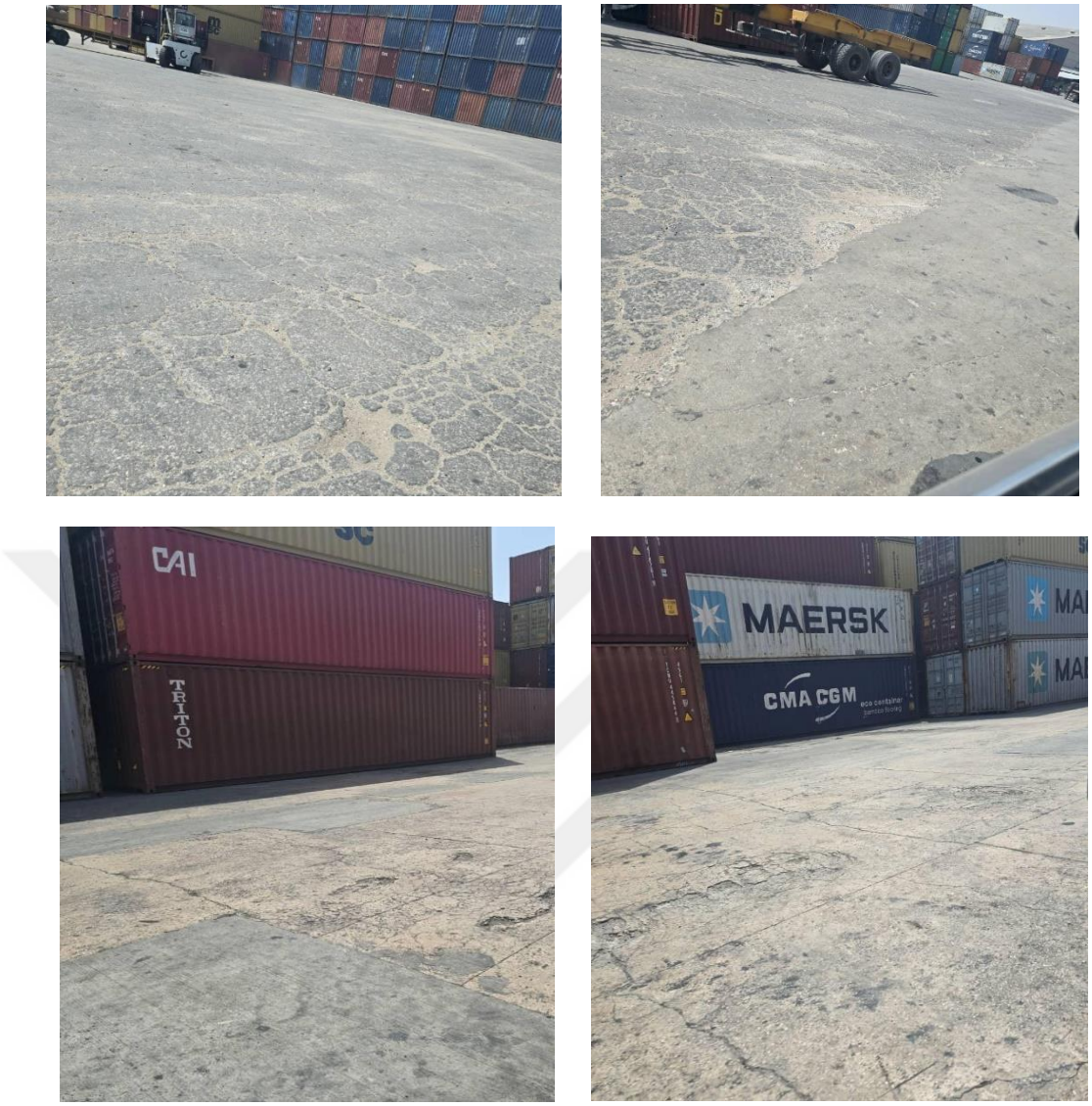
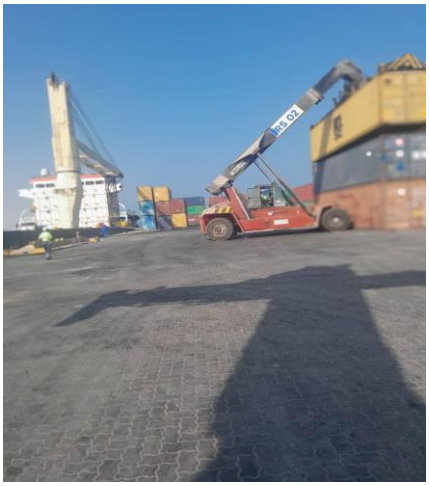


Figure 5.1 Photos from Mogadishu Port Terminals showing jointed plain concrete and asphalt pavements used together (taken by author)

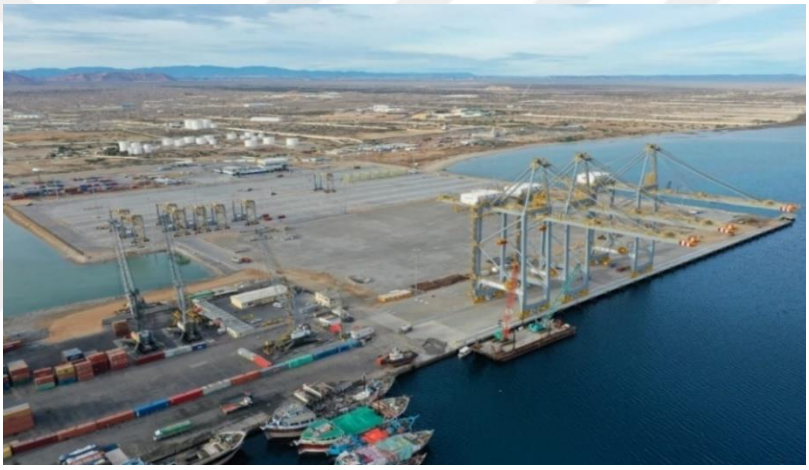
On the other hand, there has been an observed increase in the application of rigid pavements in the renewal of Somali Port Terminals. For instance, in the renovated sections of the Bossaso Port Terminals, concrete block pavements (CBPs) have been adopted as the surface layer, as shown in Figure 5.2 (b).



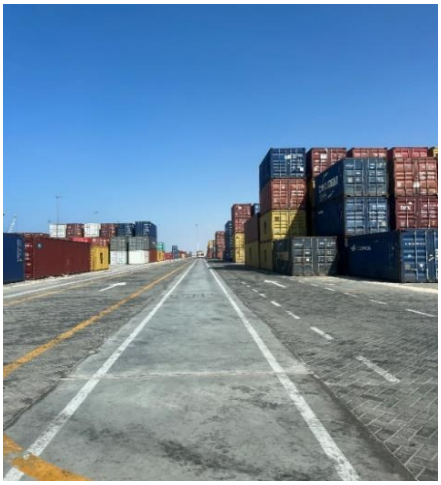
a) Port of Bossaso showing older sections

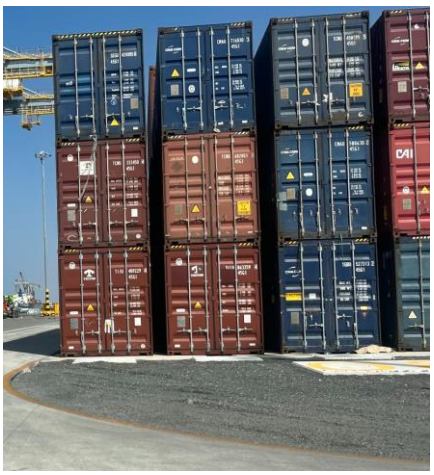


b) Port of Bossaso showing new sections



c) Port of Berbera- news section concrete pavement old sections asphalt pavement





d) Expanded New Sections of Berbera Port (taken by Dr. Nasir M. Ali)

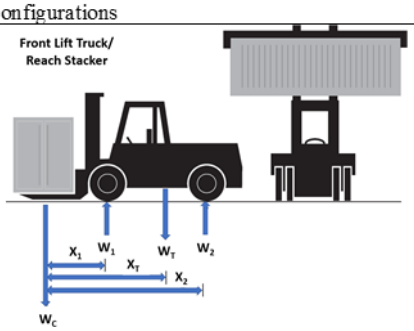
Figure 5.2 Photos from the Port of Bossaso and Berbera (taken by author)

Additionally, Berbera Port Terminal, a key port in Somaliland, now includes a 400-meter berth and three ship-to-shore gantry cranes with a 500,000 TEU annual capacity. Expanded areas feature jointed plain concrete pavements and CBPs, as shown in Figure 5-2 (c). Additionally, it is observed that containers at Berbera Port are directly placed on a crushed aggregate base with very thin concrete blocks, as shown in Figure 5-2 (d).

5.2 Critical Loads in Somalian Port Pavement Design

Heavy-duty, industrial, or port pavements, while structurally similar to highway pavements, have distinct requirements due to their higher wheel loads, slow-moving equipment, and specific operational demands. These pavements must support heavy equipment with higher tire pressures, resist deformation from container storage, and accommodate increased loads from braking and uneven surfaces. Traditional highway pavement design methods based on equivalent single axle load (ESAL) where normalize vehicle loads to a standard axle, usually 18,000 lb or 8,000 kg are insufficient for these applications. Instead, the Single Equivalent Wheel Load (SEWL) approach is more suitable than ESAL method for terminal application since container terminals experience axle loads significantly greater than highway vehicles, necessitating an investigation of individual wheel loads and their rationalization to SEWL. The SEWL method considers tire inflation pressure, wheel proximity, and dynamic effects. For industrial equipment, the tire contact area is calculated by dividing the single wheel load by the tire inflation pressure, with a circular contact shape adopted in design manuals despite heavier equipment footprints resembling rectangles with rounded corners. Additionally, if two wheels are sufficiently close together, the stress under each wheel is increased by a proximity factor due to the presence of the other wheel. Port, container terminal, and industrial area operations typically utilize various intermodal equipment, including forklifts, reach stackers, straddle carriers, and gantry cranes. As detailed in Table 5., Mobile Harbor Cranes (MHC), reach stackers, and forklifts are prominent in Somalia port terminals. Despite MHCs having higher tonnage, reach stackers exert more significant stress at subgrade depths due to their heavy front axles and high dynamic impacts, as illustrated in Table 5.2.

Table 5.2 Critical reach stacker load calculation and dynamic loads (adapted from [36])

Heavy Industrial Equipment Types and Configurations	Wheel Load Calculation	Dynamic factors (f_d)
	$W_1 = f_d \times \frac{A_1 W_1 + B_1}{M}$ $W_2 = f_d \times \frac{A_2 W_c + B_1}{2}$ $A_1 = \frac{-X_2}{X_1 - X_2}$ $A_2 = \frac{-X_1}{X_2 - X_1}$ $B_1 = \frac{W_T(X_T - X_2)}{X_1 - X_2}$ $B_1 = \frac{W_T(X_T - X_2)}{X_1 - X_2}$ Where: W_1: Load on front of wheel W_T: Self weight of truck M: Number of wheels on front axle W_C: Weight of container W_2: Load on rear of wheel	Braking: ± 30% Cornering:40% Accelerating:10% Uneven Surf:20%

Reach stackers are essential in intermodal container handling, featuring telescopic arms that facilitate the efficient management and stacking of cargo containers at ports, train yards, and intermodal hubs. They optimize terminal area use by enabling multi-tiered container arrangements and can be equipped with various attachments, enhancing their versatility in handling different cargo types [7]. In smaller terminals and medium-sized ports like Somalia Port Terminals, reach stackers have become the preferred choice over traditional forklifts due to their telescopic masts, which offer efficient short-distance transport and superior stacking capabilities. Unlike forklifts, reach stackers can access containers within existing rows, facilitating denser container blocks up to four containers high. In addition to the dynamic loading effects, another crucial factor in port terminal pavement design is the high-concentrated static container stacking loads. Containers transfer loads to the pavement via slightly elevated corner castings measuring 178 mm x 162 mm, which are elevated by 118 m. The pavement designer must consider the pressure exerted by these container corner castings when designing the pavement for a container-storage area. According to the International Standard Organization [49], the weights of standard 20-foot and 40-foot containers are approximately 24,000 kg and 30,480 kg, respectively, and containers are sometimes stacked up to eight-high [7]. However, as shown in Table 5.1, the maximum stacking height in Somalia port terminals reaches only five containers. The maximum average container weight in these terminals is about 25,000 kg. Consequently, this study identifies the reach stacker as the critical dynamic handling equipment for pavement design and a maximum five-height container stack as the critical static load for Somalian port terminals, as illustrated in Figure 5.3.



Figure 5.3 Critical static (container) and dynamic (reach stacker) pavement loading for Mogadishu Port Terminals (adapted from Official Mogadishu port website)

5.3 Modelling of Somalia Port Pavement

After reviewing the data on Somalia's port terminals through site visits and available documents, and analyzing the critical loading conditions, it was found that the two largest ports in the country share similar loading conditions and pavement sections, particularly in their older areas. Consequently, the existing asphalt pavement at Mogadishu Port Terminal was modeled for critical dynamic and static loading conditions based on the collected data. In this study, pavement modeling was conducted using ISLAB 2005 [50], a finite element program developed by the ERES Division of Applied Research Associates (ARA) with support from the Michigan and Minnesota Departments of Transportation and the University of Illinois at Urbana-Champaign. This program serves as the primary structural model for generating pavement responses in the new generation Mechanistic-Empirical Pavement Design Guide (MEPDG) software used in the US and Canada [51]. Table 5.3, presents the inputs and values required during modeling for the ISLAB 2005 software. For the critical reach stacker loading, the maximum rear and front tire weights and geometries obtained from the manufacturer were used.

Table 5.3 Existing pavement properties and model inputs of Mogadishu Port for ISLAB 2005

Input Variables	Range *
Asphalt Concrete Wearing Course (AC-WC) Asphalt Concrete Binder Course (AC-BC) Asphalt Concrete Base (AC-Base)	Thickness-2 in. (5 cm), Elastic Modulus- 400,000 psi (2750 MPa) Thickness-3 in. (8 cm), Elastic Modulus- 375,000 psi (2500 MPa) Thickness-7 in. (17 cm), Elastic Modulus- 300,000 psi (200 MPa) Poisson Ratio- 0.35 CTE- $2x10^{-6}$ in./in./ ^{0}F ($3.6x10^{-6}$ in./in./ ^{0}C) Unit weight- 0.061 lb/in^3 (1680 kg/m^3)
Granular Base	Thickness-16 in (40 cm) Elastic Modulus- 30,000 psi (200 MPa) Poisson Ratio- 0.35 CTE- $1.8x10^{-6}$ in./in./F^0 ($3.2x10^{-6}$ in./in./ ^{0}C) Unit weight- 0.061 lb/in^3 (1680 kg/m^3)
Coefficient of Subgrade Reaction (k value)	100 pci (27,000 kN/m^3)
Temperature Differential	Linear 10 ^{o}F (10 ^{o}C)
Critical Dynamic Loads	Reacher Stacker (100 tons)
Dynamic Factors	Breaking and Cornering
Critical Static Loads	Stacked Container with 5-deep

*The software supports only Imperial units.

Additionally, the effect of dynamic loading induced by cornering and braking was taken into consideration by applying a dynamic factor. According to the PIANC report [7], when a section of a pavement is subjected to dynamic effects, the plant's wheel loads should be increased by the factors provided with the equipment's descriptions. In this study, for braking and cornering, a dynamic factor of 70% (30% for braking and 40% for cornering) was applied, thereby increasing the static wheel load by 70%.The existing data and modeling of Mogadishu Port pavement involved an analysis based on ISLAB 2005 results, which revealed key stress and deflection measurements as shown in Figure 5.4.

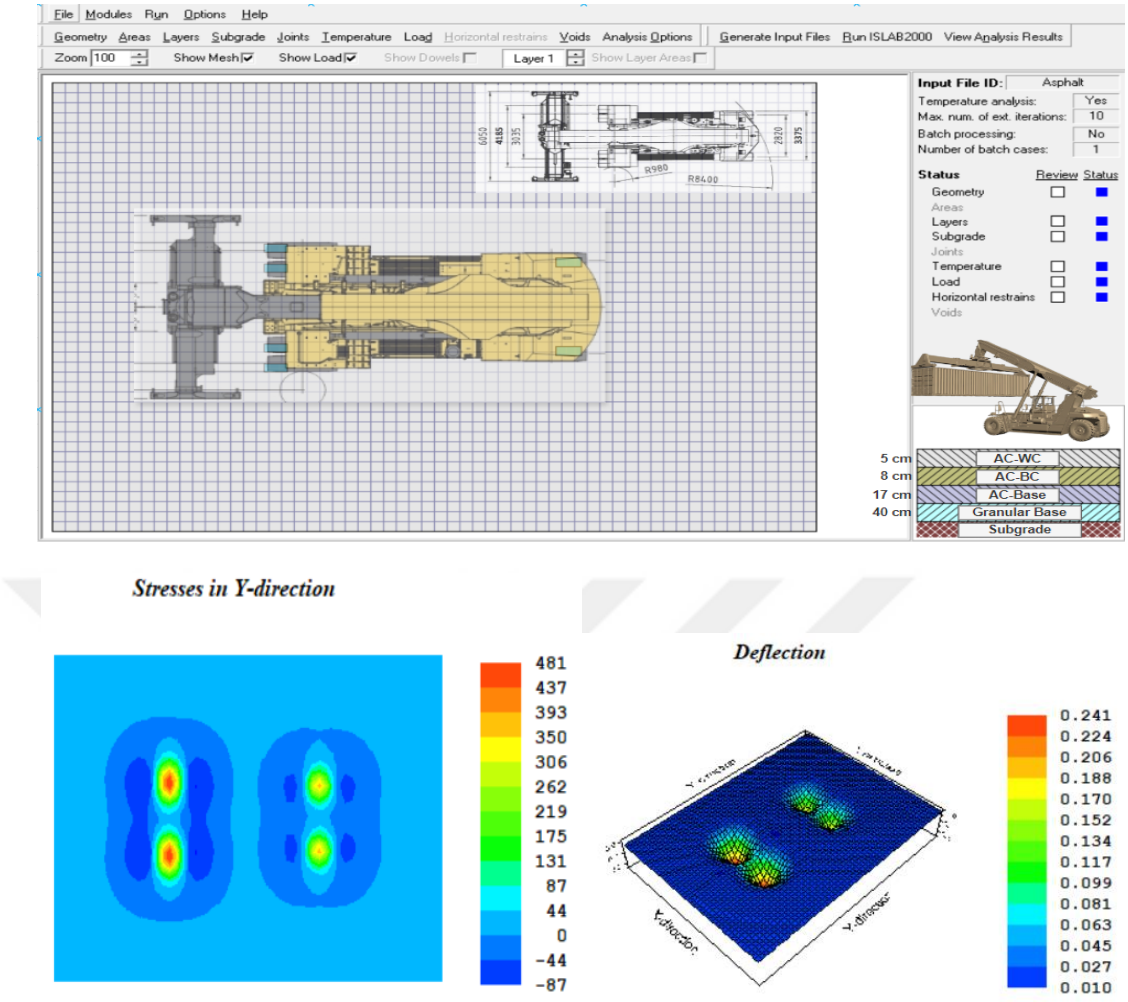


Figure 5.4 Existing asphalt modeling under critical reach stacker loading in Mogadishu Port (stress in psi and deflection in inches)

For the critical dynamic reach stacker loading case, the maximum transverse stress at the bottom of the AC pavement slab was recorded at 2.86 MPa (415 psi), while the maximum longitudinal stress reached 3.31 MPa (481 psi). Additionally, the maximum deflection observed was 6.1 mm (0.241 inches). This analysis provides essential insights into the structural behavior of the current pavement at Mogadishu Port, aiding in understanding its performance under various loading conditions and guiding potential improvements.

The calculated maximum deflection value is below the limit values specified by the MEPDG design guide for AC pavement [51]. Although the maximum tensile stresses in AC pavement (flexible pavement) are not directly utilized in design or long-term

performance prediction, unlike Portland cement concrete (PCC) pavement (or rigid pavement) where they are directly applied to predict cracks induced by critical traffic loads, these stresses still provide significant insights for performance prediction. Because, unlike Portland cement concrete (PCC), asphalt concrete is highly influenced by temperature, loading rate, binder properties, and mix volumetric composition. Therefore, it is difficult to determine a threshold for AC pavement allowable tensile strength. However, studies in the literature show that ultimate tensile strength values for AC pavement range from 4.5 MPa (at -40°C or -40°F) to 0.5 MPa (at 20°C or 68°F) [47,48]. While there is a large variation due to the temperature sensitivity of AC pavement, considering that the average minimum temperature at Somali Port Terminals does not fall below 20°C (see Table 5.2), it is evident that the ultimate tensile strength values for AC pavement will be lower than 0.5 MPa. The calculated values are much higher than these ultimate strength values. Therefore, there is a high probability of observing bottom-up fatigue cracking in the AC pavement at Mogadishu and Berbera Port Terminals, resulting from traffic load independent of thermal stress effects. Indeed, information received from field officials indicates that pavement maintenance or overlays are frequently carried out.

Another critical loading scenario affecting the performance of the pavement at Somalia Port Terminals is the concentrated static loading in the container storage areas. Due to the small size of the container corner casting area (178 mm x 162 mm), very large stresses occur, significantly impacting the AC pavement's performance.

In this part, keeping the pavement layer properties constant from the reach stacker modeling, a new pavement modeling was conducted for an average 25-ton container with a stacking load of five, representing the maximum static container load that Mogadishu and Berbera Port Terminal may encounter. Although 20-ft and 40-ft container dimensions are used as standards worldwide, Somali Port Terminals predominantly utilize 20-ft containers. To accurately simulate the site conditions, the container layout was modeled in single, row, and block configurations. As illustrated in Figure 5.5, the weight of the stacked containers is transferred to the pavement through container corner castings with a small rectangular area, resulting in the highest stresses in block layouts where four container corner castings are combined. The

modeling results revealed that the maximum transverse stress in the pavement was 7.19 MPa (1043 psi), while the maximum longitudinal stress reached 7.14 MPa (1036 psi), almost 8 times that of traditional road trucks [39]. Additionally, the maximum deflection observed was 11.8 mm (0.467). These results indicate that the tensile stresses and vertical deformations under the AC pavement, due to stacked containers, are significantly higher than those caused by reach stacker equipment. Consequently, the container storage areas at Mogadishu and Berbera Port Terminals are likely to experience rapid distress, including depression and cracking, due to the high stresses. Given the inherently low modulus of elasticity of AC pavements, they are insufficient to accommodate the high stresses resulting from stacking five 25-ton containers. Therefore, a thicker pavement section with enhanced engineering properties is necessary to mitigate these issues. Without such improvements, frequent maintenance, repair, or resurfacing will be required, leading to operational delays and substantial economic costs.

However, in practical applications, it is important to note that despite the stress exceeding 7 MPa due to stacked containers, asphalt pavements are still used for port terminals in many countries. One reason for this preference is that asphalt pavements allow controlled deformation. This enables container castings to partially embed into the asphalt, allowing the container bottom rails to rest on the surface. As a result, the loads are distributed over a broader area rather than being concentrated on the small contact footprint (178 mm x 162 mm) of the bottom rails [6].

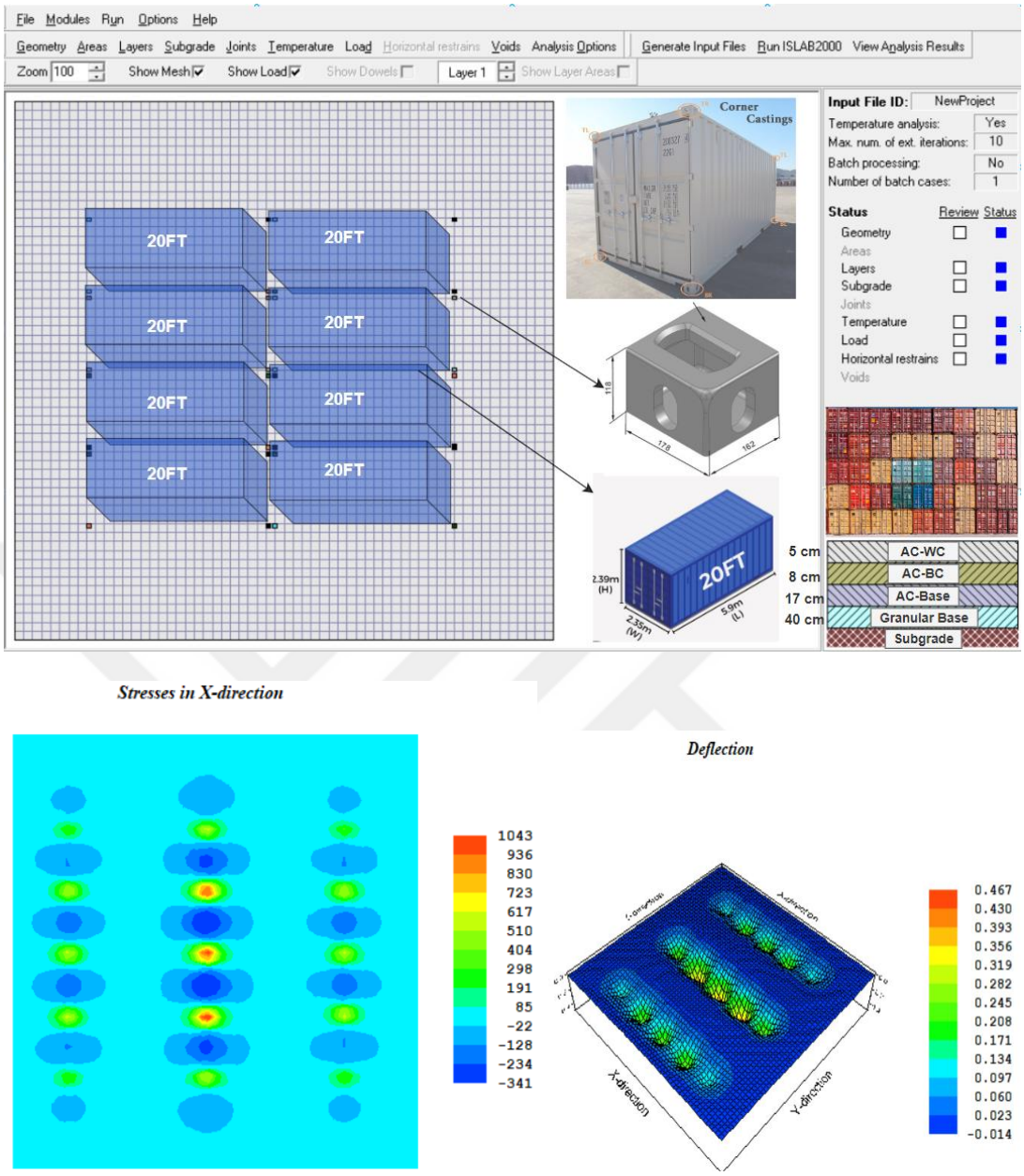


Figure 5.5 Existing asphalt modeling under critical stacked container loading in Mogadishu Port (stress in psi and deflection in inches)

Considering the substantial dynamic loads imposed by handling equipment like reach stackers and the concentrated static loads from stacked containers, it is increasingly common to consider rigid pavement options for port terminals. In regions such as the UK [25], Spain [39], Italy [52], Japan [53], South Korea [54] and the United States [36], rigid pavements are frequently utilized and sometimes preferred over flexible alternatives for high-load applications. As mentioned in Section 5.1, in Somalia, CBPs,

a type of rigid pavement, is increasingly being preferred for the newly rehabilitated sections of port terminals. However, other rigid pavement technologies have not yet been widely adopted in Somalia, and their use is only beginning to emerge. In this new phase, RCC pavement, produced using traditional concrete ingredients and using asphalt compaction techniques, presents itself as a significant alternative. RCC is particularly advantageous due to its high modulus of elasticity, which enhances performance under high static loads, and its cost-effectiveness and rapid deployment capabilities compared to traditional rigid pavements.

5.4 RCC Pavement Modelling as an Alternative Choice for Somalia Ports

RCC pavement modelling as alternative in the second phase of the study, to assess the feasibility of RCC pavement subject to the existing loading conditions at Somalia Port Terminals, RCC pavement modeling was conducted for two critical scenarios: dynamic reach stacker loads and static stacked container loads. Unlike the previous AC pavement modeling, the RCC pavement model consisted of only two layers: an RCC surface layer and an aggregate base, both applied on the subgrade. To ensure comparability with the AC pavement model, the properties and thicknesses of the aggregate base and subgrade layers were kept consistent. Additionally, the RCC pavement model incorporated contraction joints, with load transfer between joints defined through aggregate interlock, a feature does not present in the AC pavement model. This approach allowed for a comprehensive analysis of RCC pavement performance under the specified loading conditions. Since the concrete grade corresponding to Eurocode C30/37 (30 MPa for a 15x30 cm cylinder and 37 MPa for a 15 cm^3 cube characteristic compressive strength) is traditionally used for RCC pavement, the layer modeling was performed using the mechanical properties associated with this strength class, as detailed in Table 5.4.

The maximum deflection values resulting from critical loads modeled for a 30 cm RCC pavement, maintaining the same thickness as the current AC pavement, are shown in Figure 5.6. When the RCC pavement is modeled with the existing AC pavement thickness, it exhibits 60% lower deflection under critical dynamic reach stacker

loading and 40% lower deflection under static stacked container loads. Unlike the AC pavement, where stresses exceed allowable limits for both loading cases, the RCC pavement shows stresses below the allowable stress of the RCC material (<4.75 MPa or 700 psi) for the reach stacker loading case. However, for the stacked container case, the stresses in the RCC pavement also exceed the limit values.

Table 5.4 Alternative RCC pavement model inputs for Somalia Port Terminals

Input Variables	Range
RCC Layer	Thickness-12 in. (30 cm) MoR-700 psi (4.75 MPa) Elastic Modulus- 4,750,000 psi (32 GPa) Poisson Ratio- 0.15 CTE- $5x10^{-6}$ in./in./ ^{0}F ($9x10^{-6}$ in./in./ ^{0}C) Unit weight- 0.087 lb/in^3(2410 kg/m^3)
Joint Design	15 ft x 15 ft (4.5 m x 4.5 m)
Joint Load Transfer	Aggregate Interlock -AGG factor $1x10^6$
Granular Base	Thickness-16 in. (40 cm) Elastic Modulus- 30,000 psi (200 MPa) Poisson Ratio- 0.35 CTE- $1.8x10^{-6}$ in./in./F^0 ($3.2x10^{-6}$ in./in./ ^{0}C) Unit weight- 0.061 lb/in^3 (1680 kg/m^3)
Coefficient of Subgrade Reaction (k value)	100 pci (27,000 kN/m3)
Temperature differential	Linear 10 ^{o}F (10 ^{o}C)
Critical Dynamic Loads	Reacher Stacker (100 tons)
Dynamic factors	Breaking and Cornering
Critical Static Loads	Stacked Container with 5-deep

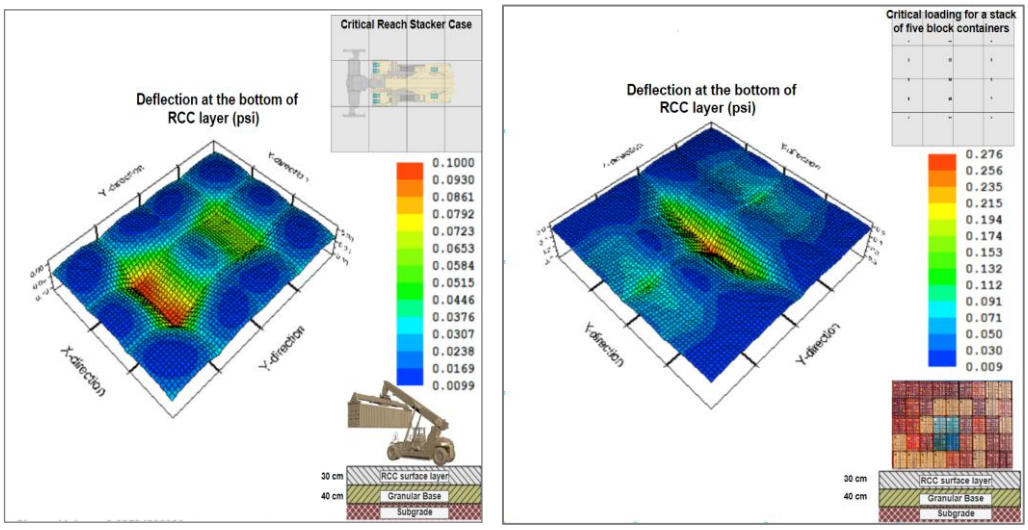


Figure 5.6 Alternative RCC pavement modeling for the similar loading conditions

It is crucial to note that while stress values resulting from loads and temperature variations are key parameters in thickness design, the relationship between thickness,

stress, and deformation often requires complex transfer functions. These functions frequently include calibration coefficients to reflect the correlation with field performance. Therefore, directly comparing stress and deformation values obtained from numerical analyses or closed-form formulations with the allowable stress of the material can be considered a rough approach. For instance, the French method utilizes the finite element program of ALIZE FEM for port terminal pavement design. However, initial thickness designs were found to be significantly overdesigned when comparing the program's stress values with field performance. To address this, calibration coefficients were introduced, reducing the stress values by approximately one-third before comparing them to the allowable strength of the material. Therefore, this thesis focuses not on thickness design but on examining the differences in stress and deformation performance between two pavement types—AC pavement and RCC pavement—when subjected to identical design thicknesses. The analysis also accounts for the impact of environmental temperature variations and the specific loading conditions encountered in port terminals.

In conclusion, due to the inherently low modulus of elasticity and high deformation of the existing AC pavement under concentrated loads, RCC rigid pavement emerges as a significant alternative for Somalia Port Terminals, offering nearly 50% lower deformation characteristics and higher flexural strength for port terminal applications.

5.5 Cost Analysis

This study employs a systematic approach to evaluate and compare the cost implications of the existing AC Pavement and the proposed RCC Pavement at Somalia Port Terminals. The methodology provides a comprehensive cost analysis for a 100m × 100m area, essential for making informed decisions regarding pavement selection by considering both initial and long-term costs. The pavement layers and thicknesses used in Section 5.1 were referenced for the cost analysis. Table 5.5 presents a detailed cost analysis for both pavement options.

The study's data were obtained from the following sources: Primary data: Collected through site visits, interviews with construction experts, and direct observations at Somalia Port Terminals. Secondary data: Sourced from existing literature, technical

reports, and case studies related to pavement materials and construction methodologies.

The existing AC pavement, with an initial cost of $750,000, involves a range of activities including excavation, debris removal, base construction, and asphalt paving. Comparatively, the RCC pavement option, priced at $775,000, includes equivalent preliminary tasks along with the installation of an RCC slab and vibratory roller compaction. It is important to note that the cost analysis was conducted by maintaining a uniform thickness of 30 cm for both AC and RCC pavements. However, as demonstrated in the numerical analysis section, RCC exhibits nearly half the deformation of AC pavement at the same thickness due to its higher modulus of elasticity, as well as higher flexural and shear strengths. If a thinner RCC pavement is considered as an alternative, it becomes evident that RCC will be more cost-effective in terms of initial cost construction.

Table 5.5 Comparative Initial Cost Analysis of Asphalt and RCC Pavements for Somalia Port Terminals

Asphalt Concrete Pavement			Roller Compacted Concrete Pavement	
Cost Item	Quantity	Total Cost	Quantity	Total Cost
Excavation Unit Cost: $5/m³	Depth: 0.3 meters, Volume: 3,000 m³	$15,000	Depth: 0.3 meters, Volume: 3,000 m³	$15,000
Disposal of Excavated Material Unit Cost: $10/ m³	Depth: 0.3 meters, Volume: 3,000 m³	$30,000	Depth: 0.3 meters, Volume: 3,000 m³	$30,000
Crushed Stone Base Unit Cost: $20/ton	Thickness: 0.4 meters, Volume: 4,000 m³	$80,000	Thickness: 0.4 meters, Volume: 4,000 m³	$80,000
Compacting Opr. Unit Cost: $5/m²	Area: 10,000 m² (both subgrade and base)	$100,000	Area: 10,000 m² (both subgrade and base)	$100,000
AC-Base Unit Cost: $70/ton	Thickness: 0.17 meters, Volume: 1,700 m³	$273,000	RCC layer Unit Cost: $135/m³ Thickness: 0.30 meters, Volume: 3,000 m³	$405,000
AC-Binder Course Unit Cost: $80/ton	Thickness: 0.08 meters, Volume: 800 m³	$147,000	RCC Delivery Unit Cost: $15/m³ Thickness: 0.30 meters, Volume: 3,000 m³	$45,000
AC-Wearing Course Unit Cost: $90/ton	Thickness: 0.05 meters, Volume: 500 m³	$104,000	Vibratory Roller Compaction Unit Cost: $10/m² Area: 10,000 m²	$100,000
Initial Construction Cost		~$750,000		~$775,000

This analysis extends beyond initial construction costs to evaluate the total life cycle costs (LCCA) over a 30-year period. The LCCA analysis incorporates initial construction costs, interest rates, maintenance costs per 100x100 m² area, and reconstruction costs for the AC pavement. Due to the lack of reliable information on maintenance and reconstruction costs during the service life in Somalia, annual maintenance costs for concrete pavement were assumed to be 5% of the initial cost, while for asphalt pavement, a 15% rate was adopted based on a reference study conducted in a neighboring region, Ghana [55]. Additionally, it is assumed that AC pavement will require reconstruction after 20 years, whereas the RCC pavement is expected to have a service life of 30 years. The reconstruction cost for AC pavement is estimated to be approximately 35% of the initial construction cost, based on a case study conducted in another neighboring region, Ethiopia [56]. The analysis did not consider the salvage value due to the uncertainties associated with assessing residual value in the context of Somalia's conditions. The results of the LCCA for the existing AC pavement and the alternative RCC pavement at Somalia Port Terminals are detailed in Table 5.6.

Table 5.6 Life cycle cost analysis of AC and RCC pavement in Somalia Port Terminals

Pavement type	Parameters	Initial Construction Cost (ICC)	Expected Maintenance and reconstruction cost (30 years)	Total Life Cycle Cost (NPV)
AC Pavement	Interest rate: 30% Reconstruction period: 20 years (35% of initial construction cost) Maintenance cost: 10% of ICC per year	$750,000	~$250,000 (maintenance cost) ~$262,500 (reconstruction cost)	$1,262,500
RCC Pavement	Interest rate: 30% Reconstruction period: 30 years Maintenance/Rehabilitation costs: 3% of ICC per year	$775,000	~$77,450 (maintenance cost)	$852,450

As shown in Table 5.6 the extensive maintenance requirements of AC pavements significantly increase their total cost over time. Annual maintenance costs are almost three times higher than for RCC pavements, in addition to the need for major rehabilitation after 20 years. On the other hand, RCC pavement, while requiring a slightly higher initial construction cost, proves to be more economical in the long term. Due to the lower maintenance requirements and the absence of major repairs within

the 30-year period, the total life cycle cost of RCCP is approximately 33% lower than that of AC pavement. This analysis shows that despite the slightly higher initial construction cost, RCC pavement offers significant savings over time, making it the more cost-effective choice for long-term infrastructure projects at Somalia Port Terminals.

CHAPTER 6

CONCLUSION AND DISCUSSION

Port terminals, essential to Somalia's trade volume, represent a significant portion of the country's infrastructure investments. Notably, Berbera Port Terminals, alongside Mogadishu Port, has recently undergone substantial enhancements with over $400 million in investment. Among the critical infrastructure components of container terminals, pavement stands out as a major factor influencing both initial construction expenses and ongoing maintenance costs throughout its service life. Pavement design for port terminals significantly differs from traditional road or aircraft pavements due to the unique traffic loads, patterns, handling equipment, and concentrated static loads from container storage areas. A poorly designed pavement can lead to premature deterioration and suboptimal performance, adversely impacting port operations and market competitiveness. Moreover, the pavement's condition can affect the functionality and longevity of the expensive handling equipment used in these terminals. While AC pavement is commonly used for roadways worldwide, rigid pavement technology is predominantly adopted in countries with advanced port terminals such as the USA, Canada UK, Italy, Spain, and China. However, field visits and literature reviews reveal that Somalia’s port terminals traditionally relied on asphalt pavement, particularly before rehabilitation efforts. Recently, there has been a noticeable shift toward the use of rigid pavement types, especially CBPs, in new sections or improvement projects. This trend indicates a growing consideration of rigid pavement alternatives for port terminals. Among these, RCC pavement, though not yet widely implemented in Somalia, emerges as a strong candidate. Its proven performance and cost-effectiveness in countries like the USA position it as a promising alternative for Somalia’s port terminals.

RCC pavement, a sustainable hybrid alternative, is considered a specialized type of rigid pavement in terms of material composition yet shares production similarities with AC pavement. RCC may offer significant advantages over AC pavements, particularly for port terminals. Due to the inherent properties of rigid pavements, RCC is more

durable and robust, capable of withstanding heavy loads from containers and handling equipment. This results in a longer lifespan and reduced maintenance needs. Additionally, RCC requires less water and cement compared to traditional concrete, lowering its environmental impact and providing cost-effectiveness. The potential incorporation of recycled materials into RCC mixtures further enhances sustainability. This study aims to evaluate RCC pavement technology as a viable alternative to AC pavements for Somalia's port terminals.

In this study, a comprehensive data inventory of Somalia's port terminals was first compiled through field visits and literature review. Critical container weights and heights, handling equipment types and weights, and terminal capacity were recorded, and existing pavement sections were documented. Subsequently, modeling was conducted for both the existing AC pavement and the proposed RCC pavement under critical dynamic loading from handling equipment, specifically reach stackers, and critical stacked container loading in container storage areas. These analyses illustrate the structural behavior and performance of the existing AC pavement and the RCC alternative under critical loading conditions, offering valuable insights into their suitability for Somalia's port terminals and similar infrastructure projects. The final phase of the study involves a cost analysis comparing the existing AC pavement with the sustainable RCC pavement, highlighting the economic aspects for Somalia's port terminals.

Based on the comprehensive inventory of Somalia's port terminals and the analysis results, several notable conclusions can be derived, as outlined below:

- Somalia's port infrastructure is vital to its economic growth and international trade, with pavements accounting for nearly a quarter of the total investment cost.
- Somalia Port terminals are subjected to both static and dynamic loads. For Somali port terminals, critical dynamic loads are associated with reach stacker handling equipment, while critical static loads involve the typical stacking of 5-high containers.

- Traditionally, Somalia’s port terminals have favored AC pavement; however, recent developments indicate a shift. Expanded sections of Berbera Port Terminal and rehabilitated areas of Mogadishu and Bossaso Port Terminals have increasingly adopted CBPs and plain jointed concrete pavement.
- Historically, Somalia's port terminals have transitioned from AC pavements to CBPs and jointed plain concrete pavements, highlighting the inadequacy of AC pavements under critical loading conditions. Major seaports like Mogadishu and Berbera Port Terminals experience significantly high stress levels, particularly under critical container loading scenarios, resulting in premature deterioration.
- In Somalia's port terminals, RCC pavements, widely adopted in the USA due to their long service life, minimal maintenance requirements, cost-effectiveness, rapid deployment, and enhanced resistance to static and dynamic loads, remain untested. The material's inherent advantages, such as high compressive strength, flexural performance, and shear resistance, make RCC a promising alternative for port terminals. Additionally, its placement and compaction process, which resemble traditional AC pavement methods, offer significant advantages in terms of labor and equipment suitability for the Somalian region.
- When modeled and analyzed under the static high concentrated container loads and reach stacker handling equipment typically observed at Somalia Port Terminals, RCC pavements designed with the same thickness as AC pavements are projected to exhibit approximately 50% less deflection under critical loads. This notable reduction in deflection is expected to improve operational performance and reduce the risk of equipment breakdowns and container damage. In addition to its superior structural performance, RCC pavement requires significantly less maintenance compared to AC pavement, offering a substantial advantage for port terminal infrastructure and emphasizing its long-term suitability.
- The cost analyses indicate that RCC pavement presents a significant alternative for Somalia Port Terminals. While the initial cost analysis shows

that RCC pavement is slightly more expensive than AC pavement, its reduced maintenance requirements and extended service life provide a substantial advantage in terms of life-cycle cost efficiency.

In conclusion, the implementation of RCC pavement technology offers significant potential for enhancing the sustainability and cost-effectiveness of Somalia's port infrastructure. However, several challenges need to be addressed, such as lack of experience in RCC mix design, unskilled labor, problems with concrete delivery due to low workability of RCC, insufficient saw cutting experience, and local material availability. Addressing these challenges necessitates further research to make a well-informed decision. Additionally, international collaboration and knowledge transfer are crucial to ensure the successful implementation of RCC technology in Somalia.

REFERENCES

[1] Hejazi, S. J., & Khayri, S. (2022). Technical and economic feasibility study of roller-compacted concrete (RCC) and stone mastic asphalt (SMA) with hot-mix asphalt (HMA) pavement. Arabian Journal of Geosciences, 15(18), 1512.

[2] Selvam, M., Kumar, M. N., & Singh, S. (2024). Comparative analysis of jointed plain concrete pavement and roller-compacted concrete pavement. Transportation Research Record, 2678 (5), 196-210.

[3] Harrington, D., Abdo, F., Adaska, W., Hazaree, C. V., Ceylan, H., & Bektas, F. (2010). Guide for roller-compacted concrete pavements. Institute for Transportation, Iowa State University.

[4] Britpave. (2022) Roller Compacted Concrete Pavements-Guidelines for Design, Materials and Construction, Wokingham, UK. www.Britpave.org.uk.

[5] American Concrete Institute (ACI). (2015). ACI 327R-14: Guide to Roller-Compacted Concrete Pavements. ACI International.

[6] Sullivan, B., Lau, B., Prasad, A. (2019). Performance of Flexible Pavements in Container Terminals, in: Proc 18th AAPA Int. Flex. Pavements Conf. Sydney.

[7] PIANC Working Group 165. (2015). Design and Maintenance of Container Terminal Pavements, Brussels , Belgium.

[8] Foreign & Development Office, UK–Somalia development partnership summary, July 2023, UK Goverment. (2023). https://www.gov.uk/government/publications/uk-somalia-development-partnership-summary/uk-somalia-development-partnership-summary-july-2023#:~:text=In Somaliland%2C the Berbera Corridor,significant opportunities for UK businesses. (accessed August 13, 2024).

[9] Pouwels, R.L. (2002). Eastern Africa and the Indian Ocean to 1800: reviewing relations in historical perspective, International Journal qf African Historical Studies. v35 pp385–425.

[10] Mmari, E. (2018). Somalia Port of Mogadishu, Somalia Port Authority Report. https://lca.logcluster.org/211-somalia-port-mogadishu (accessed August 13, 2024).

[11] Ali, F. (2020). African port planning: Seaport redevelopment in Somalia and Kenya. Master Thesis. York University, Canada.

[12] Economic Commission for Africa (2016). County Profile: Somalia Report. https://archive.uneca.org/sites/default/files/uploaded-documents/CountryProfiles/2017/somalia_cp_eng.pdf (accessed August 20, 2024).

[13] Ahmed, Y. A. (2020). Berbera Port: Prospects and potentials on the regional economy. Horn Diplomat Magazine Journal. https://www.horndiplomat.com/2020/07/25/berbera-port-prospects-and-potentials-on-the-regional-economy/(accessed August 13, 2024).

[14] Adal, M., & Kherallah, H. (2023). DP World and Somaliland Government open Berbera Economic Zone. DP World Magazine. https://www.dpworld.com/news/releases/dp-world-somaliland-open-berbera-economic-zone/(accessed August 13, 2024).

[15] Adal, M., & Hakam, K. (2022). DP World and Puntland Government sign construction agreement to upgrade Port of Bosaso. DP World Magazine. https://www.dpworld.com/news/releases/dp-world-and-puntland-government-sign-construction-agreement-to-upgrade-port-of-bosaso/

[16] He,J. & Tan,C. (2019). Modelling a resilient yard template under storage demand fluctuations in a container terminal, Engineering Optimization. 51 1547–1566.

[17] Günther, H.-O. & Kim, K.-H. (2006). Container terminals and terminal operations, OR Spectrum. 28 437–445.

[18] Liu,Q. (2010). Efficiency analysis of container ports and terminals, PhD Thesis, Centre for Transport Studies Department of Civil, Environmental and Geomatic Engineering University College London.

[19] Johnson, C.M. (2020). Strategic alliances in container shipping and their impacts on non-alliance carriers: a Liberian perspective, Master of Science Thesis, World Maritime University.

[20] Gupta, S., Altay, N., & Luo, Z. (2019). Big data in humanitarian supply chain management: A review and further research directions. Annals of Operations Research, 283(1), 1153-1173.

[21] Bichou, K. (2014). Port operations, planning and logistics. CRC Press.

[22] Australian flexible Pavement Association. (2021). AfPA Guide to the Structural Design of Flexible Pavements for Ports and Container Terminals, Melbourne.

[23] Ligteringen, H., & Velsink, H. (2012). Ports and Terminals (pp. 199-220). Delft, Netherlands: VSSD.

[24] Huang,Y.H. (2004). Pavement analysis and design, Second Edi, Pearson Prentice Hall, Upper Saddle River, NJ.

[25] Knapton, J. (2007). The Structural Design of Heavy Duty Pavements for Ports and Other Industries, Interpave-British Port Association, Leicester, UK.

[26] Delatte, N. (2018). Concrete Pavement Design, Construction, and Performance.CRC Press.

[27] Kumar, P., & Shukla, S. (2022). Flexible pavement construction using different waste materials: A review. Materials Today: Proceedings, 65, 1697-1702.

[28] Mallick, R. B., & El-Korchi, T. (2008). Pavement Engineering: Principles and Practice. CRC Press.

[29] Menekşe, F. (2020). A comparative study on the different rigid pavement design methodologies used for plain and fiber reinforced cement-based materials, Master of Science Thesis, Graduate Program in Civil Engineering, Bogazici University.

[30] Adlinge, S. S., & Gupta, A. K. (2013). Pavement deterioration and its causes. International Journal of Innovative Research and Development, 2(4), 437-450.

[31] Mannering, F. L., & Washburn, S. S. (2012). Principles of Highway Engineering and Traffic Analysis (5th ed.).

[32] Gill, S., & Maharaj, D. K. (2015). Comparative study of design charts for flexible pavement. International Research in Engineering Technology, v2, 339-348.

[33] Ioannides, A. M., & Salsilli-Murua, R. A. (1989). Temperature curling in rigid pavements: An application of dimensional analysis. Transportation Research Record, 1227, 1-11.

[34] Kumar, R., & Sharma, S. (2022). Perpetual Flexible Pavement vs. Rigid Pavement: An Economic and Environmental Cost Comparison. In IOP Conference Series: Earth and Environmental Science, 184 (1). IOP Publishing.

[35] Howe, J., & Macleod, A. (2011). A study of the performance of concrete block pavements in container terminals. In Coasts and Ports 2011: Diverse and Developing: Proceedings of the 20th Australasian Coastal and Ocean Engineering Conference and the 13th Australasian Port and Harbour Conference (pp. 434-439). Barton, ACT: Engineers Australia.

[36] Sengun, E., Kim, S., & Ceylan, H. (2024). A comparative study on structural design of plain and roller-compacted concrete for heavy-duty pavements. Road Materials and Pavement Design, 25 (2), 392–422.

[37] ROM 4.1-94 Standard. (1994). Guidelines for the Design and Construction of Port Pavements;; Puertos del Estado (Government of Spain): Madrid, Spain.

[38] Ionițoaiei, P., & Rotaru, A. (2023). Studies on heavy duty pavements reinforced with steel fibers for port infrastructures. In IOP Conference Series: Materials Science and Engineering.1283(1). IOP Publishing.

[39] Marcobal-Barranco, J. R., Lara-Galera, A. L., & Camarero-Orive, A. (2021). Functional Assessment of Port Pavements: The Case of Container Terminals. Journal of Testing and Evaluation, 49(3), 1824–1836.

[40] Jain, S., Joshi, Y. P., & Goliya, S. S. (2013). Design of rigid and flexible pavements by various methods & their cost analysis of each method. International Journal of Engineering Research and Applications, 3(5), 119-123.

[41] Mohod, M. V., & Kadam, K. N. (2016). A comparative study on rigid and flexible pavement: A review. IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 13(3), 84-88.

[42] Khayat, K. H., & Libre, N. A. (2014). Roller compacted concrete: field evaluation and mixture optimization. Technical Report. Missouri University of Science and Technology. Center for Transportation Infrastructure and Safety. https://rosap.ntl.bts.gov/view/dot/27986

[43] Şengün, E. (2019). Effects of mixture design parameters and compaction methods on the properties of roller compacted concrete pavements, PhD Thesis, Middle East Technical University.

[44] Luhr, D.R. (2006). Frost Durability of Roller-Compacted Concrete Pavements: Research Synopsis, Portland Cement Association. Canada.

[45] Williams, S. G. (2014). Construction of roller-compacted concrete pavement in the Fayetteville shale play area, Arkansas. Transportation Research Record, 2408(1), 47-54.

[46] Aghaeipour, A., & Madhkhan, M. (2020). Mechanical properties and durability of roller-compacted concrete pavement (RCCP)–A review. Road Materials and Pavement Design, 21(7), 1775-1798.

[47] Aosaka, Y., Tsutsui, S., & Miki, T. (2023). Study on mix proportion design procedure for super-high cementitious RCC with stone powder replacement. Journal of Advanced Concrete Technology, 21(3), 123-135.

[48] Matthew, P. & Singel, W. (2010). Building it Right the First Time: Integrated Paving Solutions at the Port of Houston.Cement Council of Texas. Portland Cement Association.

[49] ISO 668. (2020). Series 1 freight containers — Classification, dimensions and ratings, Vernier, Geneva.

[50] ERES Consultants. (1999). ISLAB2000 Finite Element Code for Rigid Pavement Analysis.Version 3.6, Champaign, IL, USA.

[51] AASHTO. (2015). Mechanistic-Empirical Pavement Design Guide (MEPDG)-A Manual of Practice 2nd Edition, The Association American Association of State Highway and Transportation Officials Publications.

[52] Di Mascio, P., Loprencipe, G., & Moretti, L. (2019). Technical and economic 450 criteria to select pavement surfaces of port handling plants. Coatings, 9(2), 126.

[53] Jamshidi, A., Kurumisawa, K., White, G., Nishizawa, T., Igarashi, T., Nawa, T., & Mao, J. (2019). State-of-the art of interlocking concrete block pavement technology in Japan as a post-modern pavement.

[54] Ha, Y. S., Kim, Y. T., Pham, M. V., Park, H., & Oh, M. (2024). Fabrication and assessment of port block pavement based on the deflection and settlement characteristic. Case Studies in Construction Materials, 20, e03284.

[55] Adow, M. A. O., Allotey, S. E., & Sasraku-Neequaye, B. K. (2015). Comparative cost analysis between asphalt pavement and concrete pavement in road construction: A case study using concrete grade 35. Civil and Environmental Research, 7(10), 94–104.

[56] Ketema, Y., Quezon, E. T., & Kebede, G. (2016). Cost and benefit analysis of rigid and flexible pavement: case study at Chancho–Derba-Becho road project. International Journal of Scientific & Engineering Research, 7(10), 181–188.