Sustainable Pavement Construction: Use of Non-Potable Water and Smart Techniques for Compaction

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1.0 Introduction

1.1 Background

Climate change is contributing to the observed increases in longer-lasting drought periods and warmer temperatures. The National Climate Change Adaptation Strategy published by the Department of Environmental Affairs in the Government Gazette [1] highlights the projected future changes in climate in South Africa. The impact of longer-lasting drought periods is relevant to the available potable water and use in the construction process in South Africa. The projected future changes in climate in South Africa are [2]:

- Increases in the number of heat-wave days and very hot days.
- 2080–2099 period: Temperature increases greater than 4°C across South Africa. Increases greater than 6°C are possible in the western, central, and northern interiors.
- Under low mitigation: temperatures to increase drastically.
- Under high mitigation: temperature increases in the interior could be constrained between 2.5 and 4°C

The western cape government [2] reported an annual mean near-surface (2m) temperature (°C) change from the median and the 10% and 90% percentiles projected for 2036 – 2065 and 2066 – 2095. Across most of the country, model-simulated rainfall is slightly lower than observed, although the east-west gradient in rainfall is adequately represented. Autumn, which is the transition period between summer and winter, denotes slightly higher rainfall in the observed east and Western Cape region. Winter rainfall is higher in the Cape Town region in the observations, compared to the model simulations.

The temperature and rainfall variations have a direct impact on the restriction of available potable water required. Due to the limited peer-reviewed research and use of non-potable water in road construction, this chapter will investigate preliminary laboratory research into the area as well as smart compaction techniques.

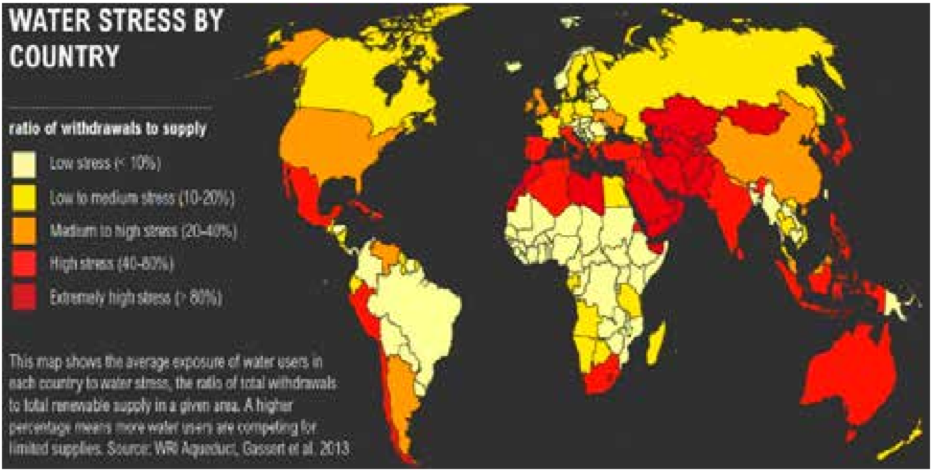
1.2. Relevance

The relevance of addressing and reporting on using non-potable water and smart compaction techniques has long-term effects on the sustainability of the country. It will form a critical component in obtaining alternatives to using potable water for road compaction in water-constrained environments as well as reviewing current practices on water use in road compaction. There are direct impacts on the socio-economic and environmental impacts in addressing the relevant issues such as the diversion of potable water from the construction industry to water-scarce communities.

1.3. Objective

- The objectives of this chapter are as follows:
- To create awareness of the threats of longer-lasting drought periods on the construction industry

Figure 1: Water stress by country [3]



- To understand alternative construction processes, feasibility, and international technologies not reliant on potable water
- To improve the understanding of the use of non-potable water in road construction and its effect on performance
- To investigate smart compaction techniques relevant to the road and pavement industry

2.0 Status of potable water in South Africa

The Department of Water and Sanitation (South Africa) has published a situation report on the status and drought regarding water in the Western Cape [2]. Statistics and highlights are depicted below.

South Africa is an arid country and one of the 30 driest countries in the world.

The country has not recovered from the 2014 drought, with the Western Cape Province experiencing the worst drought in 400 years, at that given time.

Level 6 restrictions were announced but are still not achieving the target of 500 megalitres per day and consumers are overusing by approximately 86 megalitres per day, with a slight decrease of 8 megalitres per day week on week.

Residents were required to use no more than 87.5 litres of municipal drinking water per person per day in total irrespective of whether at home, work, or elsewhere.

Gassert et al [3] investigated the water stress per country by determining the ratio of withdrawals to supply of water. Figure 1 shows that South Africa is at high stress (40 – 80%).

3.0. Pavement compaction and use of potable water in construction

Compaction is the process of mechanically increasing the density of a material. Soil and asphalt are made denser by reducing the voids between the particles, which make them up. In time, loose material would settle and compact itself naturally. By applying various mechanical forces, we shorten the time required to get compaction from years to hours [4].

Compaction is the process of compressing a material from a given volume into a smaller volume. This is done by exerting force and movement over a contact area, causing particles within the material to move closer together. The voids between the particles–air, water, or a combination of force and movement. The four forces that are used in compaction are static pressure, manipulation, impact, and vibration.

To achieve optimum compaction, materials are usually compacted at or about optimum moisture content which for pavement layer materials will usually be between about 7 and 12 % of the mass of the material being compacted. In broad terms, this requires the use of between 150 and 200 thousand litres of water per layer per kilometre. Figure 2 shows a water truck spraying a layer and preparing it to be compacted.

Although much of the water used in construction ultimately evaporates from the road and is returned to the earth's surface as precipitation, this is a long process and local depletion can occur rapidly, particularly in areas becoming drier through progressive climate change [5].

There are many factors to consider when compacting a pavement. Due to the large variability, there may be a need for further investigation into the specifics of each parameter in providing the best option for sustainability. These properties include mix property factors (aggregate grading, size, shape, and binder specifications), construction factors (roller types, passes, timing, production temperatures, foundation support, and suitability for different surfaces) and environmental factors (wind, air, and ground temperatures).

There are no direct specifications for the quality of water used in road construction; however, COLTO [6] specifies the following definition:

"Only clean water, free from undesirable concentrations of deleterious salts and other materials, shall be used. All water sources used shall be subject to the engineer's approval".

This statement does not provide any specifications in terms of the concentrations of deleterious salt, undesirable concentrations, and other materials.

A water consumption study was conducted by the Blackwood Solar Energy Facility [7] for the development of the area in the Free State. Water consumption during the construction process is associated primarily with the compaction of roads to meet minimum quality requirements. The requirement is estimated to be 50 l/m^3 for 35 000 m^3 of granular material. Given the cost of water, the cost of water per cubic metre of construction material was R2.23.

4.0 Literature review

4.1. Use of seawater in pavement construction

Research has been conducted by academics and investigators in the pavement construction field on the use of seawater in road compaction. Although the focus area is limited and project-specific, progress has been made in the advancement of knowledge. Research advancements include:

- Experimental sections were constructed in 1976 at Lüderitz on the arid coast of Namibia to develop methods of successfully using seawater for the

Figure 2: (Left and middle): Use of potable water in compaction (picture taken by G Mvelase at Transnet track formation layers construction), (Right): Video of use of water tanker sprayer on base layer to ensure optimum moisture content near King Shaka International Airport

compaction of all layers of a new road with a G3 base course under a Cape seal surfacing. These experiments have shown that, provided certain precautions are taken in the design and construction, seawater can be used in all layers including a G3 base course without experiencing any significant degree or extent of salt damage, either during construction or in the long term – at least up to 36 years [8].

- Long-term experimental sections of slurry seal made with seawater were used to complete a 19 mm Cape seal near Saldanha Bay, South Africa. Sections included seawater in both layers of slurry, in the top only, and in the bottom only, as well as control sections using freshwater. It is concluded that saltwater at least as saline and of similar composition to the seawater (3.2 % total salts, dominantly sodium chloride with some sulfate) can safely be used to make cationic slurries [9].
- The effect of salt on bituminous pavements has been quantified by Shahin et. al [10]. In the study, 80/100 pen-grade bitumen was used with aggregate and varying amounts of salt. Material properties of the salt, aggregate, and filler were characterized. The salt content was varied and its effect on solubility, softening point, penetration, flash point and ductility was captured.
- Emarah and Saleem [11] investigated a case study on lime-treated soil mixed with seawater to determine engineering properties for road construction. In clays, the introduction of swelling can result in stress. The material properties, chemical characteristics, and samples are defined. The presence of seawater as mixing water in the lime-treated soil has formed a new fabric structure of high rigidity as well as high shear strength. Accordingly, the new fabric structure became capable of resisting the compression process.
- Otoko [12] investigated the effect of saltwater on the physical properties, compaction characteristics, and unconfined compressive strength of clay, clayey sand, and base course. Results of laboratory investigation show that the plasticity index decreased when using saltwater as opposed to tap water.
- The effect of salty water of the Persian Gulf was investigated on the proctor compaction and CBR tests on the SP-SM (poorly graded sand with silt and gravel) soil samples which were taken from five trial sections in Abu Dhabi (UAE). The maximum dry unit weight increased by adding Persian Gulf water compared to the samples tested using tap water in the lab [13].
- The occurrences of salt-damaged pavements have been described covering Botswana as well as international situations. A detailed examination of soluble salt damage to bituminous sealed roads was investigated in several regions of South Africa following the widespread occurrence of blistered surfacings. Early occurrence of salt damage, sodium and magnesium sulfates present in mine waste material used for pavement construction were identified to be responsible for the salt damage problem. The pavement material was a quartzite waste from industrial mine processes [22].

4.2. Use of treated wastewater in pavement construction

Similar to the advancements made on research using seawater as a non-potable source in pavement construction, there has been limited work done on the use of treated wastewater in the same context. Research advancements include:

- Attom et al [14] investigated the effect of treated wastewater on compaction and compression of fine soil. The main objective of this paper was to study the effect of treated wastewater (TWW) on the compaction and compressibility properties of fine soil. Two types of fine soils (clayey soils) were selected for this study. The maximum dry unit weight increased for both soils and the optimum water content decreased as much as 13.6% for highly plastic soil.
- Al-Jabri et al [15] investigated the effect of using wastewater on the properties of high-strength concrete. Chemical analysis results showed that although more chemicals were found in wastewater than in tap water, the water composition was within the ASTM standard limits for all substances indicating that the wastewater produced can be used satisfactorily in concrete mixtures. It is noted that excess organic material can delay the setting of concrete and the development of strength.

Local experience has confirmed that although it is possible to achieve acceptable compactions at low moisture contents, the strength obtained is usually less than that obtained during dry compaction

Usable return flows of runoff (i.e. treated wastewater), which comprise about 14% of the overall yield and approximately double the groundwater yield, are indirectly reused for potable supply i.e. extracted by drinking water treatment works from surface waters after discharge from wastewater treatment works (WWTWs) a distance upstream. With the aridity of the region and the substantial quantities of usable return flows generated daily, there is an argument for the direct reuse of these return flows for some non-drinking applications [16].

4.3 Dry compaction techniques

Normally all types of soil are compacted most efficiently at optimum water content. However, in some areas such as arid or semi-arid areas, it may be impractical or too costly to water the soil. In such cases, gravel and sand can be compacted in a dry state (water content < 1.5 %).

Steyn and Paige-Green [5] reviewed the use of the dry compaction technique. It has been shown that many materials have a second maximum dry density peak over and above the traditional peak at optimum moisture content, at very low moisture levels (usually below 3%).

Limited work on dry compaction has been carried out concluding that the majority of materials can be compacted at moisture levels at or below about 3% [17] although the findings were that the air voids are very high, and the strength development is not as good as when wet compacted.

Local experience has confirmed that although it is possible to achieve acceptable compactions at low moisture contents, the strength obtained is usually less than that obtained during dry compaction as no strength due to soil suction (developed during drying back) develops. This is critical for unsealed roads. The strength of lower layers will influence the engineering properties of the layer and the bearing capacity of the structure.

For the dry-bound Macadam pavement, the voids in a layer of almost single-sized stones (usually 53 mm nominal size) are filled with dry, cohesionless fine aggregate filler. The voids are filled with filler with equipment only, and no water is used [18]. PIARC [19] defines the layer as dry crushed rock or crushed slag prepared by laying the larger sizes of aggregates (50 mm) first and then vibrating into the layer the finer aggregates (less than 5 mm).

4.4. Use of smart compaction techniques

Intelligent compaction (IC) techniques have been researched in recent years and provide several benefits for roadway construction over the conventional compaction processes. IC rollers are vibratory rollers equipped with instrumentation fed to a documentation and feedback control system that processes compaction data in real-time for the roller operator.

In addition to reducing the compaction variability of road-building materials, these include:

South Africa is an arid country and one of the 30 driest countries in the world

- *Optimized labor deployment and construction time* – Contractors can roll the material with the right amount of compactive effort on each pass to help ensure that the proper stiffness is achieved. Both under rolling and over- rolling can lead to poor performance.
- *Reduced material variability* – Intelligent compaction equipment allows contractors to more closely monitor the stiffness of the material so that there is less variability in the result. Over the long run, lower variability will result in better pavement performance and reduced maintenance and repair costs.
- *Reduced compaction and maintenance requirements* – The flexibility to make fewer passes to achieve the correct compaction level minimizes fuel use and equipment wear and tear.
- *Identification of non-compactable areas* – Areas that fail to reach the target compaction level can be identified as potential areas for reworking the defective material or removing and replacing it.
- *Ability to make midcourse corrections* – The ability to correct compaction problems in a subsurface layer (before additional layers are placed) ensures that subsurface problems do not affect the entire road surface.
- *Ability to maintain construction records* – Data from intelligent compaction operation, along with GPS coordinates of compaction activity, can be downloaded into construction quality databases and stored electronically by the contractor for future reference.
- *Ability to generate an intelligent compaction base map* – Contractors can identify weak spots (typically used in pavement rehabilitation projects such as mill and fill).
- *Ability to retrofit existing equipment* – Most existing rollers can be easily converted to an intelligent compaction roller using a retrofit kit.

Intelligent Compaction Measurement Value (ICMV) is a generic term for a calculated value based on accelerometer measurements on vibratory roller drums. ICMVs are in different forms of metrics with various levels of correlation to compacted material's mechanical and physical properties. The following describes the "Levels of ICMV" for the systematic classification of ICMV. The classification is based on four criteria [24]:

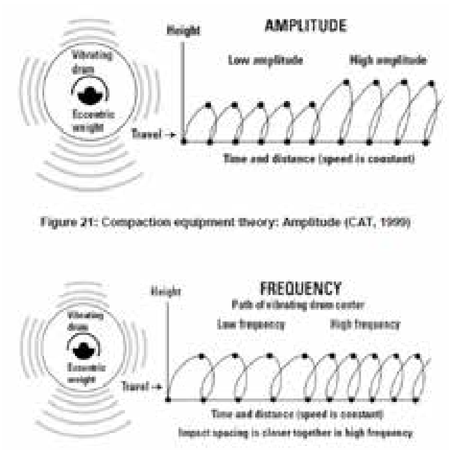
- Correlation with material's mechanical (modulus) and physical properties (density),
- Validity during decoupling when a drum loses contact with the compacted body,
- Capability to allow performance analysis of the compacted body,
- Applicability to obtain layer-specific mechanical and physical properties of the compacted body,
- Capability to be enhanced by advanced technology such as Artificial Intelligence.

Other smart compaction techniques include the control of compaction water on site:

- Compactive efforts: It is critical to establish the amount of roller passes to achieve a required density. To achieve the best results, laboratory and field compaction must be carefully correlated. Figure 3 highlights compaction equipment theory and potential for further research.
- Dynamics of vibratory compactors: In a vibratory compactor, centrifugal force is created by an eccentric weight or weights rotating inside a drum. Centrifugal force is frequently used to rate machines.
- Efficiency: Directly related to the conservation of energy, is the efficiency of compaction equipment. The Army Field Manual [20] describes the efficiency of the equipment.
- The amount of required water: Normally, it is a good practice to adjust the desired moisture content to Optimum Moisture Content plus two percent, but this depends on the environmental conditions

(temperature and wind) and the soil type. Careful control of the moisture content and the application of the water distributor is critical to sustainability.

Figure 3: Compaction equipment theory: Frequency [5]



4.5. Limitations and drawbacks: Use of non-potable water

Netterberg [22] highlighted the impact and effect of salt damage in Namibia road construction in the Saline Materials Guideline. Typical distresses include:

- Disintegration
- Prime damage
- Loose shoulders and layers
- Salt crystallization
- Accelerated weathering
- Blistering
- Curling and cracking

5.0 Preliminary laboratory investigation of non-potable water

5.1 Use of seawater and treated wastewater in pavement construction

Preliminary laboratory testing was conducted at the CSIR Advanced Material Testing Laboratory and included the use of seawater and treated wastewater on granular sub-base material.

- Dolerite, tillite, and sandstone aggregate were used. The material was sampled from local quarries of G5 and G6 standards (subbase). The parent rock type and location of the quarry is given below:
  - G5 Tillite (Ridgeview – Durban)
  - G6 Sandstone (Qala – Durban)
  - G6 Dolerite (Rooikraal – Johannesburg)
- The seawater was obtained from Blythedale Beach in KwaZulu Natal. And followed the South African Water Quality Guidelines for sampling. The treated wastewater was collected from the Rooiwal Wastewater Treatment works in Pretoria.
  - The seawater samples were collected where the depth of the water was less than 0.5 metres. The water was collected from 15 – 30 cm below the surface. Water was collected on the seaward side of a recently broken wave.
  - The treated wastewater sample was collected before being released into the Apies River. It was noted that 150 ML of treated wastewater is released daily from the surrounding treatment works in Pretoria.
- The material was washed, dried, and sampled before testing could continue. Quarries positioned in Kwa-Zulu Natal (KZN) were primarily sampled due to their end-use and proximity to the sea. Approximately 300 kg of material from each quarry was collected.
- A material testing program was developed to test the impact of seawater on material properties. Normal tap water (Pretoria) was used as a control (baseline) for the testing program. The testing includes material grading, Electrical Conductivity, Atterberg Limits (plasticity), Maximum Dry Density (MDD), Optimum Moisture Content (OMC), and CBR (strength of materials) (Table 1 and Figure 4).

Table 1: Material Testing Programme
Figure 4: Mixing and compaction of sandstone samples with non-potable water

Description	Test	Test Method
Control Tests	Grading of aggregate	SANS 3001 GR1
	Bulk Density	TMH1 B9
	Atterberg Limits	SANS 3001 GR10
	Maximum Dry Density	SANS 3001 GR30
	California Bearing Ratio	SANS 3001 GR40
	Electrical Conductivity	TMH1 A21T
	pH of Water Samples	-
Impact of seawater and treated wastewater	Variations in MDD and CBR	SANS 3001 GR30 / 40

5.2 Results and Discussion

The Advanced Material Testing Laboratory at the CSIR completed the testing of samples. The results and discussion of the testing are depicted.

Figure 5 highlights the aggregate testing. The materials were described as well-graded coarse gravel.

The Grading Modulus (GM) indicated that the materials are of relatively good quality and meet the Colto specifications [6] for G5 and G6 gravel. A maximum Electrical Conductivity of 0.15 S/m (or 0.10 depending on drainage) at 25^{0}C is usually specified for untreated road and other pavement base courses [22]. The Electrical Conductivity was between 0.01 and 0.09 S/m. Netterberg [22] specifies a pH between 6.0 and 8.5 for use on untreated materials. The results for all samples were between 7.1 and 8.2. The tap water, seawater, and treated wastewater all met the specifications (Table 2).

Table 2: pH of water samples

Water used in sample	Tap water (control)	Seawater	Treated wastewater
Dolerite	8.2	8.1	7.1
Sandstone	7.6	7.9	7.6
Tillite	7.6	7.9	7.6
Target [22]		6.0 – 8.5	

Atterberg Limits are empirical tests that are used to indicate the plasticity of fine-grained soil by the differentiation of highly plastic, moderately plastic, and non-plastic soils. The material specifications for G5 and G6 material follow [6]:

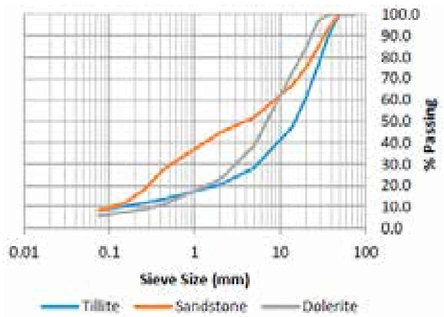
G5 material: The Liquid Limit shall not exceed 30, Plasticity Index shall not exceed 10, and Linear Shrinkage shall not exceed 5%.

G6 material: The Plasticity Index shall not exceed 12 or a value equal to 2 times the Grading Modulus plus 10, whichever is the higher value, and the Linear Shrinkage shall not exceed 5%.

All samples met the Colto [6] specification for Atterberg Limits of the material. The G6 Sandstone Material was described as non-plastic. The Liquid Limit and Plastic Limit depicted a small deviation (at most 3.7% deviation) whilst the greatest deviations can be seen in the Linear Shrinkage.

The California Bearing Ratio (CBR) test is a strength test that compares the bearing capacity of a material with that of a well-graded crushed stone (thus, a

Figure 5: Aggregate material grading (left) and properties of subbase material (right)



Properties of Subbase Material			
Parameter	Tillite	Sandstone	Dolerite
Relative Density	1.380	1.356	1.801
Relative Density (Compacted)	1.558	1.508	2.017
Electrical Conductivity (S/m)	0.03	0.01	0.09

high-quality crushed stone material should have a CBR @ 100%). TRH 14 [23] specifies the criteria for G5 and G6 material.

G5 Material: The material should have a CBR after soaking of not less than 45 percent at 95% Mod AASHTO density and a maximum swell of 0.5 percent at 100% Mod AASHTO density.

G6 Material: The minimum CBR at 93% Mod AASHTO density should be 25.

G6 Dolerite was the only material, which met the target criteria for its specific material classification (seawater and treated wastewater).

Compaction testing was completed according to SANS 3001 Method GR30. Colto [6] specifies that the maximum swell at 100% modified AASHTO shall not exceed 1.0% for G6 and 0.5% for G5. Table 5 depicts the results of the compaction testing.

- All samples met the maximum swell criteria
- A lower OMC is required for Sandstone and Dolerite (seawater and treated wastewater).
- A higher MDD is achieved for Tillite, Sandstone, and Dolerite using treated wastewater.
- The MDD deviated at most 2.0% from the control and OMC deviated at most 10.5%.

Table 3: Atterberg Limits

	Tillite			Dolerite		
Parameter	Tap Water (control)	Seawater	Treated Wastewater	Tap Water (control)	Seawater	Treated Wastewater
Liquid Limit	15.94	16.13	16.08	19.51	19.21	19.74
Plastic Limit	12.85	13.23	13.32	17.43	17.31	16.88
Plasticity Index	3.08	2.90	2.76	2.08	1.90	2.88
Linear Shrinkage (%)	1.67	1.33	1.33	1.62	0.65	1.94

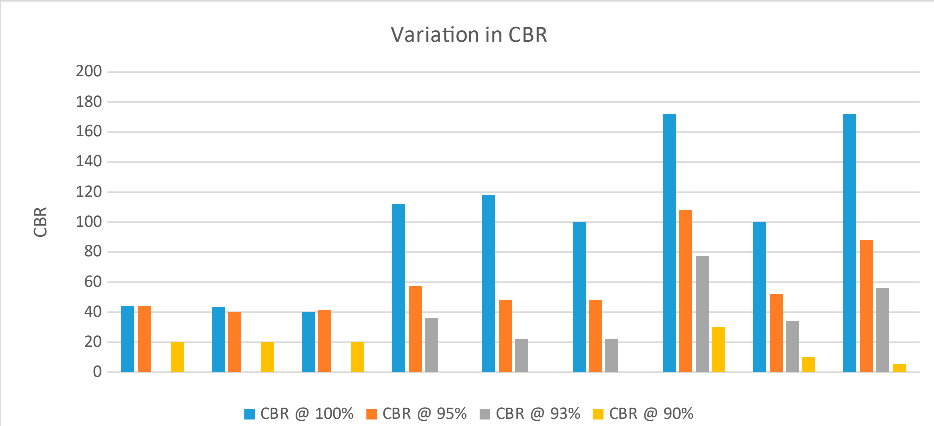


Figure 6: Variations in CBR

6.0. Conclusions

Promising results are shown in the laboratory testing and further research should be required going forward. Areas of expansion of the research include variations in non-potable water, use of different sub-base or base material, and establishment of experimental test sections for long-term pavement performance monitoring.

There is great potential for using seawater and treated wastewater as a non-potable source for pavement construction based on the preliminary laboratory results. Due to the state of available water in Southern Africa and the impact of climate change on road construction, there is a need for further investigation. Laboratory, as well as in-field studies, have been reviewed in this chapter with quantifiable outputs.

Alternate methods to using non-potable water and conventional compaction techniques in pavement construction were investigated in this chapter such as dry compaction and smart compaction techniques (energy-efficient

Table 4: CBR Test Results

	G5 Tillite			G6 Sandstone			G6 Dolerite		
CBR	Tap	Sea	TWW	Tap	Sea	TWW	Tap	Sea	TWW
CBR @ 100%	44	43	40	112	118	100	172	100	172
CBR @ 95%	44	40	41	57	48	48	108	52	88
CBR @ 93%	-	-	-	36	22	22	77	34	56
CBR @ 90%	20	20	20	-	-	-	30	10	5
Target	Not Met			Not Met			Target Met		

Tap: Tap Water, Sea: Seawater, TWW: Treated Wastewater

Table 5: Compaction results of tap, sea, and treated wastewater

	G5 Tillite			G6 Sandstone			G6 Dolerite		
Compaction	Tap	Sea	TWW	Tap	Sea	TWW	Tap	Sea	TWW
MDD (kg/m^3)	2232	2243	2238	2108	2119	2151	2421	2379	2437
OMC (%)	2.7	6.3	5.6	6.8	6.6	6.6	4.2	3.3	3.9
Swell (%)	0.0	0.0-	0.0	0.0	0.1	0.1	0.1	0.0	0.0

compaction equipment). Limitations and drawbacks of each technique were also investigated in this chapter.The use of non-potable water and smart compaction techniques both contribute to the "zero waste" theme.

7.0 Way forward

The study showed promising results in the field of non-potable water in pavement construction. Further research is, however, required with the following recommendations:

- Use of smart compaction and construction techniques to increase sustainability in the industry
- Analysis of a wider range of aggregate materials as well as base layers in a laboratory setting using seawater and treated wastewater.
- Chemical and variability analysis of different sources of seawater and treated wastewater.
- Economic variability of using non-potable water due to transportation.
- Long-term pavement performance monitoring of constructed as well as trial (experimental) sections, which use non-potable water.
- Analysis of other non-potable water sources for pavement construction such as greywater.
- Dry compaction of pavement sections.

• Photo by Raphael Brasileiro from Pexels

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