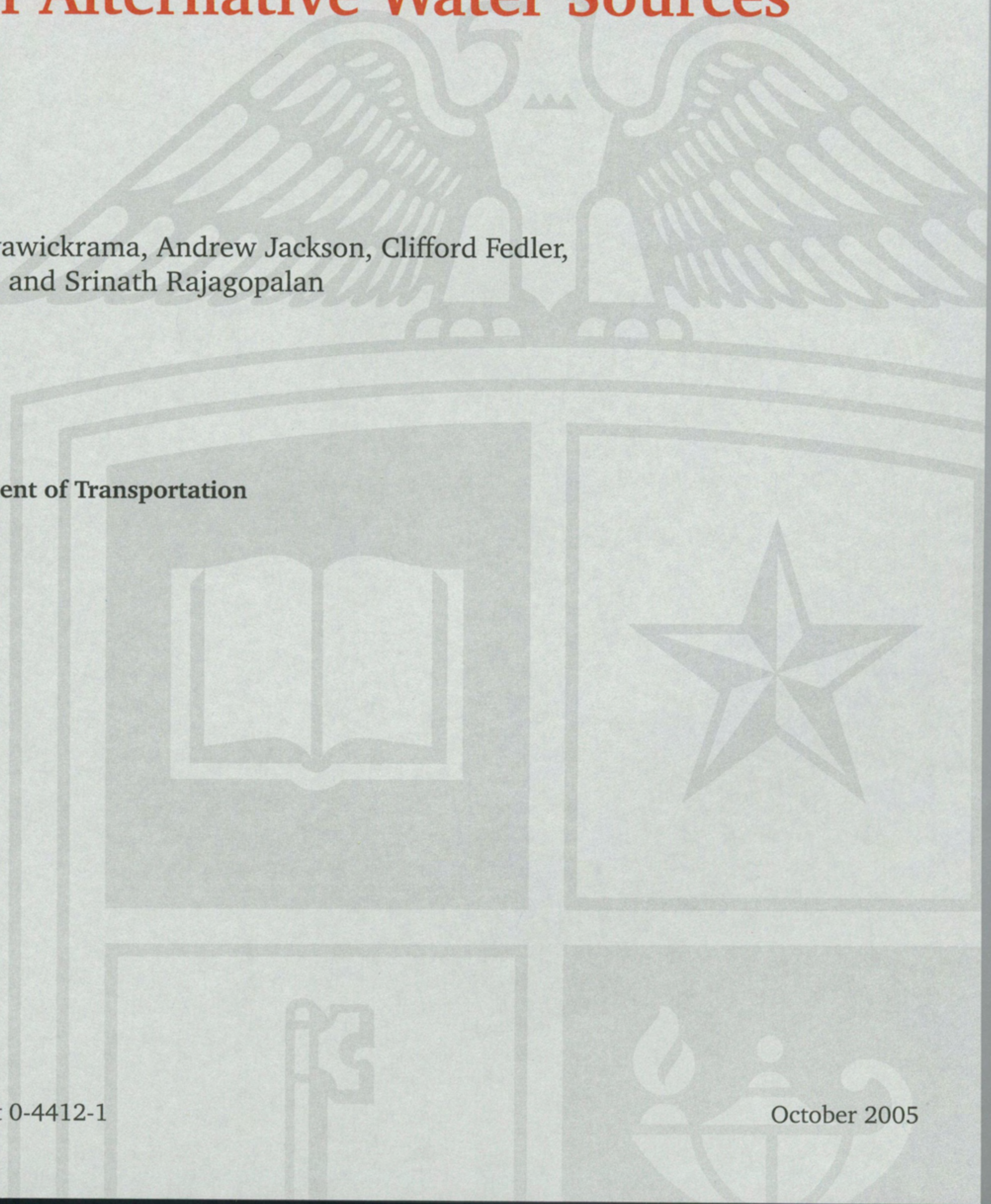
TEXAS TECH UNIVERSITY
Multidisciplinary Research in Transportation

Use Of Alternative Water Sources



Priyantha Jayawickrama, Andrew Jackson, Clifford Fedler,
Audra Morse, and Srinath Rajagopalan

Texas Department of Transportation

Research Report 0-4412-1

October 2005

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.
FHWA/TX-05/0-4412-1

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Use of Alternative Water Sources

5. Report Date
October 2005

6. Performing Organization Code
TechMRT

7. Author(s)
Priyantha Jayawickrama, Andrew Jackson, Cliff Fedler, Audra Morse, Srinath Rajagopalan

8. Performing Organization Report
0-4412-1

9. Performing Organization Name and Address
Texas Tech University
Department of Civil Engineering
Box 41023
Lubbock, Texas 79409-1023

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
Project 0-4412

12. Sponsoring Agency Name and Address
Texas Department of Transportation
Research and Technology Implementation Office
P.O. Box 5080
Austin, TX 78763-5080

13. Type of Report and Period Cover
Technical Report
9/1/01 – 8/31/03

14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract:

Due to rapid growth in population and construction activity, the demand of good quality water continues to increase in many parts of Texas. The use of non-conventional, or “alternate,” sources of water as a substitute for quality drinking water in construction applications could potentially reduce the cost of construction while conserving quality water resources. The primary objective of this research project was to identify alternative water sources that may be used in construction applications such as pavement subgrade, base, embankment fill and structure backfill compaction, vegetative watering, soil stabilization, and dust control. The alternate sources of water considered in this study are: wastewater from municipal wastewater treatment plants, brine water from oil wells, surface and groundwater that do not meet the drinking water quality standards, and ocean water. The various issues addressed by this research project are the effect of alternate water on construction materials, legal issues addressing the use of alternate water in Texas, safety and health concerns of workers and the public, and the impact on the environment by the use of low quality alternate sources of water. A decision matrix is presented to facilitate the evaluation of alternative water construction applications combinations.

17. Key Words
Alternative Water, Construction Applications, Wastewater, Brine Water, Impaired Surface Water, Ocean Water.

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161, www.ntis.gov

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
122

22. Price

USE OF ALTERNATIVE WATER SOURCES

by

Priyantha Jayawickrama, Ph.D.
Andrew Jackson, Ph.D.
Clifford Fedler, Ph.D.
Audra Morse, Ph.D.
Srinath Rajagopalan, Ph.D.

Research Report 0-4412-1
Project Number 0-4412
Project Title: Use of Alternative Water Sources in Construction Operations

Performed in Cooperation with the

Texas Department of Transportation
And the
Federal Highway Administration

by the

CENTER FOR MULTIDISCIIPLINARY RESEARCH IN TRANSPORTATION

TEXAS TECH UNIVERSITY

October 2005

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PATENT DISCLAIMER

ENGINEERING DISCLAIMER

TRADE NAMES AND MANUFACTURERS’ NAMES

Acknowledgements

The authors would like to thank the project director, Keith Dunmire, who has provided needed guidance and assistance. Special thanks go to the program coordinator, Lauren Garduño, and the project advisor, Dennis Wilde, whose recommendations have been very helpful. We also appreciate the assistance that we received from Ciro Baeza, Norberto Brito, and Lewis Gamboa in recovering soil samples for laboratory sampling. Numerous other TxDOT personnel also took time to provide insights and information that assisted the project, and we sincerely appreciate their help. Finally, we wish to express our appreciation to TxDOT for its financial sponsorship of the project.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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* SI is the symbol for the International System of Units. Appropriate

(Revised September 1993)

CHAPTER I

INTRODUCTION

1.1 Overview

Due to rapid growth in population and construction activity, the demand of good quality water continues to increase in many parts of Texas. In those regions that receive little rainfall, there is an even greater emphasis on the need to conserve high quality water sources for drinking and other household uses. Since the need for drinking water is increasing and its supply decreasing, it is prudent that Texas Department of Transportation (TxDOT) investigate the possibility of using water from non-conventional sources for construction projects that do not require high quality water. The use of non-conventional, or "alternate," sources of water as a substitute for quality drinking water in construction applications could potentially reduce the cost of construction while conserving quality water resources. The alternate sources of water considered in this study are: wastewater from municipal wastewater treatment plants, brine water from oil wells, surface and groundwater that do not meet the drinking water quality standards, and ocean water.

The Texas Department of Transportation (TxDOT) requires large quantities of water for road construction projects for such purposes as dust control, erosion control, preparing subbase for highways, and rinsing construction equipment. The use of quality drinking water for these types of construction applications may become cost prohibitive in the future. TxDOT needs alternate sources of water in order to reduce the future cost of construction applications and to reduce the delays in construction works in case of drought or water rationing. However, the environmental and health impacts from the use of alternate water sources and the effects on constructability need more investigation.

Alternate water sources such as municipal wastewater and brine water are two major sources of water whose supply increases with increases in population and development. The benefits of using alternate water sources like wastewater and brine water include: the possible reduction of cost in construction works, decreasing construction delays if water rationing is imposed on drinking water sources, and conservation of high quality drinking water for human consumption. Such alternate water sources represent an untapped resource and when used saves the cost of disposal of these low quality water resources.

The various issues addressed by this research project are the effect of alternate water on construction materials, legal issues addressing the use of alternate water in Texas, safety and health concerns of workers and the public, and the impact on the environment by the use of low quality alternate sources of water. In order to understand the implications of using the alternate water sources, the quality of the proposed water sources must be analyzed to assess their suitability for construction applications by parameter comparison with the baseline values established from experimental laboratory tests.

The quality and/or chemical composition of alternate water may affect the physical, chemical, and aesthetic properties of construction materials and may even lead to the failure of structures. For example, the constituents found in alternate water may cause physical changes in the soil through a variety of processes like cation exchange, precipitation, and dissolution. These changes may have short-term or long-term effects on soil properties. Some of the soil properties that may be affected by water quality are soil corrosivity, shrink/swell potential, and dispersivity. Corrosion of construction materials such as galvanized steel soil reinforcements and buried drainage pipes may cause reduction in useful service life of structures.

Various laws and regulations govern the use of alternate water sources. The Environmental Protection Agency (EPA) or Texas Commission for Environmental Quality (TCEQ) are charged with the enforcement of these laws. Typically, both the provider and the user must obtain permits from government agencies to use wastewater or brine water. The right of use for surface water, groundwater, and ocean water must also be obtained from the agency or organization in charge of that water source. Legal issues discussed in this report include regulations for reuse, discharge, permitting, as well as health & safety considerations.

Discharge of an alternate water source into a natural water body or land application must be monitored. The quality of an alternate water source is often not as high as that of pristine or higher quality water resources, which may affect the environment and the use of that water. The Texas Commission for Environmental Quality (TCEQ) sets the water quality standards of the water discharged in the State of Texas. The quality of water entering the environment has been regulated and monitored since the enactment of the Clean Water Act and the Safe Drinking Water Act (1974). The discharge of the various sources of alternate water into the environment may lead to the pollution of surface water, leaching into ground water, or into topsoil thus reducing the value of the site. If the runoff of alternative water degrades neighboring lands, it may lead to potential lawsuits.

Workers exposed to alternate water sources must be protected from the water and must be educated about the risks involved while working with the various alternate water sources. The EPA, TCEQ, and World Health Organization (WHO) have issued guidelines about the quality of water and appropriate protection equipment for workers. Similarly, the safety regulations concerned with potential exposures of the general public are more stringent.

Both federal and state agencies enforce laws and regulation on reuse of alternate water. The federal law that governs the quality of water entering the environment is Clean Water Act while 40 CFR 122 is the federal regulation concerning the permitting process of discharge and reuse of alternate water. Texas Water Code chapter 26, enforced by TCEQ, governs the discharge of reclaimed wastewater into state waters and chapter 27, enforced by Railroad Commission, governs the discharge of waste brine water used in oil and gas production. The major state regulations that cover the reuse of alternate water are 30 TAC 210, 30 TAC 305, and 30 TAC 307 for reuse of municipal wastewater, and 16 TAC 1, 16 TAC 3, 30 TAC 106 for discharge and use of brine water. The statute, 30 TAC 307, regulates the quality of alternate water that can be discharged into state water bodies.

1.2 Objective and Scope of Research

The primary objective of this research project is to identify alternative water sources that may be used in construction applications such as pavement subgrade, base, embankment fill and structure backfill compaction, vegetative watering, soil stabilization, and dust control. In order to achieve this objective, as a first step, alternative water supplies must be identified and characterized with respect to quality and volume availability. Moreover, each proposed alternative water source must be evaluated to determine if there is any adverse environmental impact from their use in specific construction applications. Any regulations that govern the reuse of wastewater sources must be reviewed and applicable pemitting processes identified. Secondly, water from alternative sources must be evaluated to determine whether their use in construction would have any adverse impact on material behavior and/or compromise performance of the constructed facility. Finally, a protocol was developed to aid TxDOT personnel in identifying and determining the water types and water quality that would be suitable for use in specific construction and maintenance applications.

1.3 Report Organization

This report documents the procedures followed and results obtained in each research task that was completed during the course of the study. Chapter II deals with the identification of alternative water sources that are available in sufficient quantities and therefore, may be considered for use in TxDOT construction projects. Chapter II also examines health and safety concerns related to the use of each type of alternative water source. Any regulatory restrictions on the discharge of alternative water into the natural environment are identified. Chapter III deals with specific TxDOT construction applications in which such alternative water may be used. The concerns related to material behavior and performance are discussed as well. Chapter IV describes the laboratory test program that was undertaken in this research study to address the concerns with regard to impact of water quality on material properties and behavior. Chapter V reviews and analyzes data obtained from the laboratory investigation and draws useful conclusions. Chapter VI provides a detailed description of the development of a decision matrix for TxDOT's use. This decision matrix is a tool that enables TxDOT engineers to determine whether water obtained from a specific alternative water source is suitable for use in a given construction application. The final chapter, Chapter VII presents conclusions and recommendations from the research.

CHAPTER II

ALTERNATIVE WATER SOURCES

2.1 Overview

This chapter provides a detailed description of each type of alternative water and specific issues related to health and safety as well as potential impact on the environment. It also includes a discussion of availability of each type of alternative water and applicable permitting procedures. This chapter also presents the results from an analysis conducted on the important water quality parameters such as TDS, Sulfate, Chloride, and Sodium ion concentrations, and fecal coliforms.

This chapter does not deal with specific construction applications in which alternative water may be used. This aspect as well as potential impacts that impaired quality water may have on material behavior and performance is discussed in subsequent chapters.

2.2 Alternate Water Sources

2.2.1 Wastewater

Wastewater or reclaimed water is the treated effluent from municipal wastewater treatment plants. The quality and quantity of wastewater available can be obtained from wastewater treatment plants. Treated wastewater can be potentially used for irrigation, dust control, erosion control, rinsing of equipments, and preparation of base layers in highway construction and other such applications (30 TAC 210).

The important water quality parameters for municipal wastewater includes: organic matter, disease causing pathogens (e.g. fecal coliforms), nutrients (nitrogen and phosphorous compounds), toxic contaminants (metals and organic compounds), suspended solids, and dissolved minerals (salts). The effect of these parameters on health and performance will depend on the degree of treatment and the quality of the original water source. The general composition of secondary treated wastewater effluent and corresponding drinking water standards are shown in Table 2.1. Total dissolved solids (TDS), sodium (Na^+), potassium (K^+), calcium (Ca^{+2}), and magnesium (Mg^{+2}) affect the physical and chemical properties of construction materials while total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen (N), phosphorous (P), and chlorides (Cl) affect the environment and health of the humans and other organisms exposed.

Table 2.1 Composition of Secondary Treated Municipal Wastewater Effluents

PARAMETERS	RANGE ppm	TYPICAL ppm	DRINKING WATER STANDARDS ppm
Total Solids	Unavailable	425	
Total Dissolved Solids	200-1300	400	<1000
PH	6.8-7.7	7.0	8.0
BOD	2-50	20	
COD	25-100	70	
Sodium	50-400	100	
Potassium	10-30	15	
Calcium	25-100	50	
Magnesium	10-50	20	<40 ($CaCO_3$)
Total Nitrogen	10-30	20	<10
Ammonium nitrogen	0.1-25	10	0
Nitrate Nitrogen	1-20	8	<10
Total Phosphorous	5-40	10	
Chloride	50-500	75	<300

Adapted from Asano et al. (1984), Treweek (1985), TCEQ

Reclaimed water is classified as either type I or type II by Texas Natural Resources Conservation Commission (TCEQ) depending on the extent of treatment and the quality of the effluent water. Type I water can be used in locations where the general public is exposed as it has more stringent regulations for water quality parameters while type II water cannot be used in places where the general public is exposed. The regulated water quality parameters for type I water are difficult to attain and this type of water is less common than type II water. Type II water is more economical as it is cheaper to treat to type II standards and can be used for construction applications where the public is not exposed. Table 2.2 and Table 2.3 list the required water quality criteria for type I and type II water respectively.

Table 2.2 Water Quality Standards for Type I Reclaimed Water

PARAMETERS	THRESHOLD
BOD_5 or $CBOD_5$ (not to exceed)	5 mg/l
Turbidity (not to exceed)	3 NTU
Fecal coliform geometric mean (not to exceed)	20 CFU/100 ml
Fecal coliform single grab (not to exceed)	75 CFU/100 ml
Nematode eggs	<1 egg/ 100 ml

Table 2.3 Water Quality Standards for Type II Reclaimed Water

PARAMETERS	THRESHOLD
BOD_5	30 mg/l
$CBOD_5$	15 mg/l
Fecal coliform geometric mean (not to exceed)	200 CFU/100 ml
Fecal coliform single grab (not to exceed)	800 CFU/100 ml
Nematode eggs	<1 egg/100 ml

One of the major criticisms for reuse of alternate water source is the health and safety concern of the exposed workers and the general public. Workers who are directly exposed to alternate water sources are to be educated and informed of the risks and suitable protection must be made available to them. As far as possible, the public must not be exposed to alternate water sources.

Reclaimed water or wastewater is the alternate water source with the most health and safety concerns. Type I reclaimed water does not cause any health concerns. Type II reclaimed water reused for irrigation, dust control, erosion control, preparation of base layers for highways, embankments and other similar applications may expose the workers to the water and can affect the health of the workers (30 TAC 210.32). The presence of toxic chemicals and pathogenic microorganisms in wastewater creates the potential for adverse health effects where there is contact, inhalation, or ingestion of the chemical or microbiological constituents.

Aerosols are particles less than 50 um in diameter suspended in air. Viruses and most pathogenic bacteria are in the respirable size range; hence, one potential means of human infection from exposure to aerosols is by inhalation. Aerosols may be emitted during spray irrigation or dust control. The health risk associated with aerosols from treated reclaimed water is negligible (EPA, 1980). Control measures for health concerns include elimination or reduction in concentration of the toxic constituents in reclaimed water and, where appropriate, practices to prevent or limit direct or indirect contact with the reclaimed water.

The EPA recommends reasonable standards of personal hygiene for the workers at water reuse sites. According to the EPA, use of protective clothing, change of clothing at the end of the work period, avoiding exposure to reclaimed water where possible, and care in hand washing and bathing following exposure and prior to eating, appears to be effective in protecting the health of workers. These recommendations seem effective regardless of the level of treatment provided.

Discharge of alternate water sources into a natural water body or land application must be monitored as the quality of alternate water may not be as high as some of the pristine or higher quality water. For the applications discussed in this project, the alternate water sources are not discharged, but they are reused. The regulations for discharging alternate water sources do not apply to the applications discussed in this project. These regulations are applicable when the alternate water is discharged into natural water bodies of the state. Discharge of alternate water into a natural water body may affect the use of the water body, or reduce the real estate value of adjacent land. The Clean Water Act, Safe Drinking Water Act, Pollution Prevention Act and other such laws and acts govern the quality of the effluents that can be discharged into the water bodies. These criterions would not be a concern for the construction application discussed in this project, as the amount of water used in these applications would not be considered as discharge.

The TCEQ regulates the water quality standards of water discharged into surface water (30 TAC 307). Chemicals causing taste and odor must not be discharged in amounts, which interfere with production of potable water, impart unpalatable flavor to food (fish) and cause offensive odor in the water. Water discharged into surface water must not contain any floating debris or suspended solids that may affect the aquatic ecosystem or produce putresible sludge deposits. Water discharged must not cause any substantial or persistent changes from ambient conditions including foaming and frothing. Toxic or radioactive substances that may affect human beings, terrestrial or aquatic organisms by ingestion or from dermal contact must not be discharged into surface water body. Nutrient from the discharge must not cause excessive plant growth leading to eutrophication of the water body. Discharge into the surface water body must not alter the temperature, salinity or salinity gradient to such an extent that it affects the ecosystem or the intended or proposed use of the water. Discharge to the water body must not affect the dissolved oxygen level permanently.

Discharge of reclaimed water into natural water is governed by TCEQ regulations. The major concerns of reclaimed water discharge are fecal coliforms, BOD and other safety parameters. If reclaimed water is classified as type I by TCEQ or if the water source has a discharge permit from TCEQ then the water can be safely discharged. Type II water can be discharged at places where public will not be exposed. Discharge of reclaimed water would not be a concern for the applications considered in this project. Only type I or type II reclaimed water is considered an alternate water source and type II water is to be used in places where the public is not exposed.

The reclaimed water provider must notify TCEQ and obtain written approval to provide the reclaimed water to another entity for allowable reuse of the water (30 TAC 210). The notification must include quantity, quality, origin, location, and purpose of the intended reuse of the water. The notification must also include documents stating that the user will be apprised of their responsibilities, and the provider's authority to terminate the reclaimed water use that is noncompliant with the permit. The notification must include documents authorizing both the user and the provider to terminate the use of alternate water. Major changes such as change in boundary of approved service area, change in intended use, and changes from either type I use or type II use to other uses must also be reported to TCEQ. Under the Reclaimed Water Act (Federal), RCW 90.46.040, a permit is required for land application of reclaimed water. The permit is issued to the generator of the reclaimed water who may then distribute the water, subject to permitted provisions governing the location, rate, water quality and purposes of use.

The reclaimed water producer must transfer reclaimed water of at least the minimum quality required by the permit at the point of delivery to the user (30 TAC 210.6). The provider must sample and analyze the water at regular intervals in accordance with the permit and report the results to TCEQ. The provider must notify the executive director of TCEQ in writing within a period of five days of obtaining knowledge of misuse of water by the user.

The reclaimed water user must obtain the permit to use the water from the provider (30 TAC 210.5). The user must maintain records and report to TCEQ the quantity of water, use of water, and any significant changes in quality of water after use. The user must obtain a separate permit to utilize reclaimed water if the water use poses potential or actual adverse impacts upon human health, aquatic life, or soil and ground water resources. If the user accepts type II water but the application requires type I water then the user must treat the water to meet type I standards before using it. The additional treatment must be approved by TCEQ and a separate permit must be obtained for such treatments.

Reuse of wastewater is permitted through the Texas Commission of Environmental Quality. Through conversation with TCEQ personnel (Herrin, 2003), wastewater reuse permission is authorized by the city. The city (permittee), must indicate if the wastewater diversion from the typical acceptors is temporary or permanent. The amount of water diverted must be incorporated into their Daily Monitoring Forms, which is a monthly report submitted by the wastewater treatment plant to the TCEQ. The data supplied must include the amount of water diverted and its quality. To streamline the process, a process will need to be developed with the TCEQ, which should reduce the amount of permit processing time and improve the ease with which wastewater may be used in TxDOT construction and maintenance projects.

Due to the high quality of treated wastewater, wastewater quality should not be a limiting factor in pertinent construction and maintenance applications.

2.2.2 Impaired surface water

Impaired surface water includes water bodies that may be impaired according to a list of concerns developed by the state. The concerns focus on the ability of the water to be used for all designated uses, if appropriate as a drinking water source, and to protect human and environmental health. The natural water sources that can may also be used in TxDOT construction and maintenance applications. Many of the impaired water bodies are classified as impaired because constituents present in the water exceed the levels set forth by the end users; however, it is unlikely that the concentrations of organic and inorganic constituents will be great enough to prevent use in TxDOT construction and maintenance operations.

Natural water bodies, which are not fit for drinking standards, can be used as alternate source of water for construction works. The water quality and quantity records of surface waters can be obtained from TCEQ, EPA and other federal, state, and local agencies that regularly monitor and analyze the ability of water body to meet standards for use. This information is published as The State of Texas Water Quality Inventory. The information about these water bodies can be obtained from The State of Texas List of Impaired Water Bodies Clean Water Act section 303 D.

There are no general health effects or regulations in using surface water, groundwater, or ocean water. The water must be checked for total solids, pathogens, benzene and other water quality parameters for which the water is termed impaired. The workers must be informed of the risks and reasonable standards of personal hygiene must be maintained at the work site. Suitable protection must be offered to workers if the water is impaired.

There are no standard criteria for discharging surface and ground waters into the environment. The discharged water must not cause a violation of the Texas Surface Water Quality Standards adopted by the TCEQ (30 TAC 307). Surface and ground water are usually of higher quality than reclaimed water or brine water. Discharging these waters would not cause any significant concern as the pollutants, if any, would be too diluted to cause a problem.

There are no permits required to use surface water. The right to use these waters must be bought from the owners of the water or from state or federal agencies responsible for that water source.

2.2.3 Brine water

Brine water, formation water, or produced water is the waste component of oil production and refinement. Brine water is produced along with oil and natural gas pumped from oil wells. Due to geological formation of oil wells, the water and oil are saline. Part of the brine water produced is pumped back into the ground so that it maintains the underground pressure and brings oil and gas to the surface (Mills, 2001). Seven barrels of brine water are produced for every barrel of oil produced. Approximately 400 million gallons of brine water is produced daily (TWRI, 2000).

Brine water or produced water does not warrant a health issue by microbial constituents. The major health and safety concern caused by brine water is from toxic chemicals present in the water. Brine water may contain a variety of dissolved minerals including sodium chloride and significant quantities of dissolved gases such as carbon dioxide, hydrogen sulfide, and some hydrocarbons in suspension. Hydrogen sulfide represents a significant health hazard. Produced water may contain naturally occurring radioactive materials (NORM) such as uranium, radium, and radon dissolved in water due to prolonged reaction between water and rock/soil (USGS FS-142, 1999). Brine water can contain up to 80,000 mg/L of chlorides (nearly twice as much as ocean water). High chloride concentrations enhance the solubility of other elements like radium.

Brine water is mildly irritating to eyes and non-irritating to skin (Deschner, 1999). Inhalation of brine water mist may cause mild mucous membrane irritation of the nose, throat, and upper respiratory tract. Ingestion of large quantities of brine may cause gastrointestinal upset, and an increase in blood pressure. Workers must avoid contact of brine water with eyes, skin, or clothing; avoid breathing vapors, fume, or mist. Workers are to use safety glasses with side shields for eye protection. Workers should wash thoroughly after handling brine water and launder contaminated clothing before reuse.

Brine water or produced water is rich in dissolved solids and other hydrocarbons. Brine water is highly saline (twice as much as ocean water). Brine water is usually rich in chlorides and sodium. Naturally Occurring Radioactive Materials (NORM) may also be present in brine water. Table 2.4 lists the water quality of brine produced in some of the oil fields.

Table 2.4 Representative Oil-field Water Analysis.

Pool	Reservoir Rock	Cl^- Ppm	$SO_4{}^{-}$ ppm	Na^+ $+K^+$ ppm	Ca Ppm	Mg ppm	TDS ppm
Conroe, TX	Conroe sands	47,100	42	27,620	1865	553	77,468
East Texas	Woodbine sand	40,598	259	24,653	1432	335	68,964
Rodessa La-Tx	Oolitic limestone	140,063	284	61,538	20,917	2874	225,749

Adapted from Levorsen, 1967.

Disposal of the brine water is a major problem encountered during reuse of brine. Salt must be disposed of in a manner that will not pollute sources of surface or ground water. Brine water or other wastewater produced from oil fields must not be discharged by any method without obtaining a permit to dispose of such wastes (16 TAC 3.8). Brine water, discharged into surface waters shall not cause a violation of the Texas Surface Water Quality Standards adopted by the TCEQ (30 TAC 307). The brine water discharged must not pollute the waters of the Texas offshore and adjacent estuarine zones (saltwater bearing bays, inlets, and estuaries) or damage the aquatic life there. The disposal of liquid waste material into the Texas offshore and adjacent estuarine zones shall be limited to saltwater and other materials that have been treated, when necessary, for the removal of constituents that may be harmful to aquatic life or injurious to life and property. Some clay compounds and other filter media reduce the level of pollutants in brine by adsorbing the pollutants and thus making brine safe for disposal (TWRI, 2000.) Subsurface injection of brine water is the most common method of disposal. A permit to discharge brine into tidally influenced water is required from the Railroad Commission, if the discharge rate exceeds 0.1 MGD (16 TAC 3). Discharge of brine water during the applications considered in this project would not be a concern as the brine water would not be discharged into natural waters, and the amount of water used in these applications would not cause a concern.

Permits to use brine water must be obtained from either Railroad Commission (Oil and Gas Division) or from TCEQ (16 TAC 3.8). Permits issued will contain conditions reasonably necessary to prevent the waste of oil, gas, or geothermal resources to pollute the surface and subsurface waters. A permit to transport brine water must be obtained by the carrier from Railroad Commission (Oil and Gas Division). It is the responsibility of the brine generator to make sure the carrier has a permit to transport brine water. Brine water must not be discharged into surface waters in quantities that alter the physical, thermal, chemical, or biological quality of surface and subsurface water that renders the water harmful or detrimental to humans, animals, vegetation, or properties. The brine water user must obtain a permit from Railroad Commission and TCEQ before utilizing the water. There are no specific regulations for reusing brine water. Permits are to be obtained on a case-by-case basis.

2.2.4 Natural Water Sources – Ocean, Surface and Groundwater

Ocean water is the most abundant water resource available. The ocean water is far less saline as compared to brine water (almost fifty percent) and poses less health hazard than wastewater, or brine water as it is both swimable and fishable. The average salinity of the ocean water is around thirty five percent (Florida Oceanographic Society). Six ions that contribute to the majority of the salinity are listed in Table 2.5. Although ocean water is an abundant source of alternate water, it is not readily available to most part of the state. Only in the costal regions of Texas, is the use of ocean water economically feasible. The discharge criterion for ocean water into natural water bodies is similar to recycled water.

Table 2.5 Major Constituents of Ocean Salinity.

Ion	Percentage of total salts	Concentration g/L
Chloride	55.04	19.35
Sodium	30.61	10.76
Sulfate	7.68	2.71
Magnesium	3.69	1.29
Calcium	1.16	0.41
Potassium	1.10	0.40
Total	99.28	34.92

Adapted from Florida oceanographic society

Surface water, groundwater, and ocean water are usually of higher quality than reclaimed water or brine water. While there are no general health regulations in using surface water, groundwater, or ocean water, these waters must be checked for total solids, pathogens, benzene and other water quality parameters. Workers must be informed of the risks and instructed in reasonable standards of personal hygiene to be maintained at work site. Suitable protection must be offered to workers if the water is impaired and a health concern.

Although ocean water is far less saline than brine water, discharge of ocean water creates similar concerns as discharge of brine water. Ocean water can be discharged safely into bays, tidally influenced water bodies, and oceans. Discharge of ocean water into fresh water must not violate the Texas Surface Water Quality Standards adopted by the TCEQ (30 TAC 307). Discharge of ocean water would not be a concern for the applications considered in this project as the amount of water discharged would be too little to cause a problem.

There are no permits required to use surface water, ground water, or ocean water. The right to use surface or ground waters must be bought from the owners of the water or from state or federal agencies responsible for the water source. Ocean water is usually available to everyone.

2.3 Environmental Impacts of Alternate Water Sources

The water quality entering the environment is regulated and monitored by the Clean Water Act (1972). The alternate water discharged into the environment may pollute the surface water or leech into ground water or topsoil thus reducing the quality of more pristine or potable water as well as the real estate value of the site. If the runoff degrades neighboring lands, it may lead to general degradation of the area thereby reducing the real estate value of the neighborhood which could lead to potential lawsuits. These are the major constituents of water which may affect the environment; metals like arsenic, barium, cadmium, chromium, mercury, iron, manganese, selenium, sodium, copper, silver and zinc; anions like fluoride, chloride, nitrate, sulfate; and other substances like dissolved solids, volatile organic carbon (VOC), SOCs and radioactive materials such as gross alpha and gross beta. When nutrients like nitrate and phosphate enter lakes and ponds, they may accelerate the eutrophication of those water bodies, which may render them useless as a source of potable water. Heavy metals like arsenic, chromium, selenium, and mercury are toxic to aquatic life as well as to animals and humans who use the contaminated source of water. This may cause the water body to be classified as impaired which is a great loss of a natural resource. Sodium and sulfate destroys the structure of soil, and alters soil properties, which may increase erosion and make the soil unsuitable for agriculture and other purposes. Iron and manganese cause taste problems in water and may alter the conductivity of soil thereby destroying the soil properties. Additionally, affected soil may lose its strength and become anaerobic causing odor problems.

The environmental impacts caused by the discharge of alternate water from construction applications discussed in this research are negligible. Construction applications like dust control, compaction, and stabilization usually require a one-time application of water. There are no significant impacts and no specific regulations for one-time applications of alternate water. Irrigation and erosion control may require regular applications of water, which may cause some impacts. According to TCEQ regulations, type I and type II reclaimed water can be used without any environmental concerns, if the water meets the permit quality. Surface and ground water sources are usually free from environmental concerns. Environmental impact assessment for other water sources is done on a case-by-case basis during permitting.

One objective of this research is to generate a decision matrix that allows TxDOT engineers to evaluate a water source for various construction applications. The alternate water sources are evaluated for water quality parameters that affect the health of the workers and exposed public, and for detrimental effects to the physical and chemical properties of soils on which the water is applied.

The alternate sources of water considered are wastewater from municipal wastewater treatment plants, brine water from oil fields, ocean water, impaired surface water and groundwater. The water quality parameters considered in the decision matrix that affect the health of the workers and public exposed are Biochemical Oxygen Demand (BOD), turbidity, fecal coliforms, nematode eggs, benzene, and sulfides. The parameters that affect the soil properties are total dissolved solids (TDS), sulfates (SO_4^{2-}), sodium (Na^+), calcium (Ca^{+2}), magnesium (Mg^{+2}), and pH. Soil parameters like electrical conductivity of the soil, SAR, and ESP also affect the soil performance. All the parameters shown in the decision matrix (sulfates, SAR, ESP, and EC) except TDS and pH are soil parameters measured for the soil water mix. Further laboratory testing outside the scope of this thesis will be done to correlate these soil parameters with water quality parameters. Electrical conductivity can be converted to TDS (Approximately 65.1 mg/L of TDS equals1 meq/L of EC).

2.4 Identifying Water Availability

Wastewater, reclaimed water or recycled water is the treated effluent from municipal wastewater treatment plants. Treatment plants must report the quantity and quality of the effluent water to state and federal agencies. The state (TCEQ) and federal (EPA) agencies maintain a database of records reported by the treatment plants. The databases considered for this research work are the Environmental Protection Agency's Permit Compliance System (EPA PCS) database and the Texas Commission on Environmental Quality (TCEQ) database. Both the EPA PCS and TCEQ databases were received from TCEQ office at Austin, TX. The TCEQ database contains detailed location and contact information while the EPA PCS database contains detailed water quality information.

PCS is a national system that contains National Pollutant Discharge Elimination System (NPDES) data and tracks permit issuance, permit limits, monitoring data, and other data pertaining to facilities regulated under the NPDES. PCS records water-discharge permit data on more than 75000 facilities nationwide and more than 3000 facilities in the state of Texas. PCS contains general descriptive information on each permitted facility such as facility name, mailing address, and standard classification of the facility. PCS contains detailed information describing each outfall within a permitted facility and the discharge monitoring requirements associated with each. The information also includes monitoring locations, parameters to be monitored, the quantity and concentration limits for each pollutant, and the units in which pollutant concentrations are reported. PCS also tracks reported measurement values for effluent parameters including those that are violations of established limits of the permit. The database also tracks information related to violations of compliance schedules. Values for critical water quality parameters (parameters that affect health and constructability: TDS, sulfates, sodium, calcium, magnesium, BOD, CBOD, fecal coliforms, and pH) for the facilities in a particular county or district can be queried. Measured concentrations (MCAV (average), MCMX (maximum), and MCMN (minimum)) for all the critical parameters in the queried facilities would be displayed too. Table 2.6 lists the important fields in the EPA PCS database and their descriptions.

Table 2.6 Field Description of EPA PCS Database.

Acronyms For Fields	Definitions
STNO	State ID Number (TCEQ WQ Permit Number)
NPID	NPDES ID (EPA TX Number)
FNMS	Facility Name - Short (permittee)
RDF9	TCEQ Segment Number (example 1211)
CNTN	County Name
PRAM	Parameter Code (storet code for permitted limit)
LCAV	Limit: Concentration Average (permitted quality)
LCMN	Limit: Concentration Minimum (permitted quality)
LCMX	Limit: Concentration Maximum (permitted quality)
LCUC	Limit: Concentration Unit Code (permitted quality)
MCAV	Measurement: Concentration Average (reported quality)
MCMN	Measurement: Concentration Minimum (reported quality)
MCMX	Measurement: Concentration Maximum (reported quality)
VPRM	Violation/Measurement Parameter Code (storet code for reported data)

The Texas Commission on Environmental Quality (TCEQ) database is a state agency database consisting data for over 3800 facilities all over Texas. This database contains detailed information on locations and contact information of permitted wastewater treatment facilities. The TCEQ database was connected to EPA PCS database using TCEQ permit number. TCEQ database was used only to obtain location information (latitude, longitude, street address).

Brine water, formation water, or produced water is the waste produced from oil and gas wells while oil and gas are pumped from oil wells. The United States Geological Survey (USGS) maintains a provisional database on produced water quality, locations, geological formations and sampling methods. The database is called Produced Water Compositional Database and it can be downloaded from the USGS website. The database was last modified on May 2002. The database contains location and water quality information. The fields, which identify the location of the produced water source, include state, county, latitude and longitude, and oil and gas field name. The latitude and longitude data can be used to create a GIS map and database. The geologic setting of the sample is described by the geologic basin (province), the name of the geologic unit from which the fluid was produced and the age of that geologic unit. The major water quality parameters typically considered are sodium, potassium, calcium, magnesium, chloride, bicarbonate, sulfate, and TDS.

This version of the Produced Water Database used in this project is a subset of the original database. The database compiled for this project represents only the state of Texas. The database records consist of more than 14500 entries that can be queried based on Texas Counties or TxDOT districts. Table 2.7 lists the field description of the Produced Water Database.

Table 2.7 Field Description of Brine Water Database.

Field Name	Description
UNIQUEID	Unique Identifier for each record used as a primary key
COUNTY	County name in which the water source is located
GEOBASIN	Geological Basin
USGSPROV	USGS geological province
USGSREG	USGS geological region
FIELD	Oil and gas field name
FLDCODE	Oil and gas field code
SECTION	Section number as assigned by the public lands survey grid
LATITUDE	Latitude of the well.
LONGITUDE	Longitude of the well
API	American Petroleum Institute well number
WELLNAME	Name of the source well
PH	pH of the water sample
UNITS	Concentration units mg/L or ppm
BICARB	Concentration of Bicarbonate ions
CALCIUM	Concentration of Calcium ions
MAGNESIUM	Concentration of Magnesium ions
CHLORIDE	Concentration of Chloride ions
POTASSIUM	Concentration of Potassium ions
SODIUM	Concentration of Sodium ions
SULFATE	Concentration of Sulfate ions
TDS	Total Dissolved Solids concentration
SOURCE	Identifies the source of the record. Typically, this lists the name of the petroleum company or the analytical laboratory responsible for the analytical data.

Surface waters considered as alternate water source are impaired water bodies, which are not fit for municipal purposes. A list of these water bodies are given in TCEQ Impaired water bodies list (303 D) which can be downloaded from the TCEQ website on TWQILIQ. A Microsoft Access database was created from this list. The database consists of river basin name, segment name and segment id number for location purpose and critical water quality parameters like chloride, sulfate, TDS, and fecal coliforms. The database can be queried based on river basin, river, or segment. Table 2.8 lists the field description of the Surface Water Database.

Table 2.8 Field Description of Surface Water Database.

Field	Description
River	River Basin Name
Segment	Segment ID
Water body	Water Body Name
Fecal coliforms	Fecal Coliform Geometric Mean #/100 mL
Sulfate	Concentration of Sulfate ppm
Chloride	Concentration of Chloride ppm
TDS	Concentration of Total Dissolved Solids ppm

The maximum, minimum and mean value of the concentration of critical parameters in the database was found to get an idea of water quality available for each alternate water sources. Distributions of the concentration of critical parameters were also found to get the general idea of water quality available. The range and distribution of critical parameters for each water type is discussed in the following section. Figures 2.11 to 2.5 show the percentage of data points falling in each range for sulfate, TDS, Chloride, sodium, and fecal coliforms respectively.

The data range of critical parameters found in wastewater is listed in Table 2.9. It is found that sulfate, sodium, TDS, and pH are not a concern with wastewater. From Figure 2.2 (concentration distribution of TDS), it is found that more than 90 percent of the wastewater has a TDS value of less than 2000 ppm. Sodium and chlorides are not a concern for most of the wastewater sources. If a water source is suspected to contain sodium in amounts greater than threshold value of sodium, then the water must be tested for sodium concentration. From Figure 2.4, it can be seen that almost 85 percent of the wastewater can be used for type II applications. Most of the wastewater sources can be used for any of the construction operations if it qualifies on safety concerns. The major concerns of wastewater are BOD, fecal coliforms, and other health concerns.

Table 2.9 Critical Parameters Range in Wastewater Database.

Parameter Name	Maximum value	Mean Value	Minimum Value	Units
Sulfate	1790	440	14	mg/L
Sodium	2745	1042.3	70.5	mg/L
Calcium	1940	753.37	113	mg/L
Magnesium	256	172	61	mg/L
TDS	32900	2252	0	mg/L
BOD	1900	14.18	0	mg/L
PH	9	7.03	4	
Fecal Coliforms	20000	246	0	#/100 ml

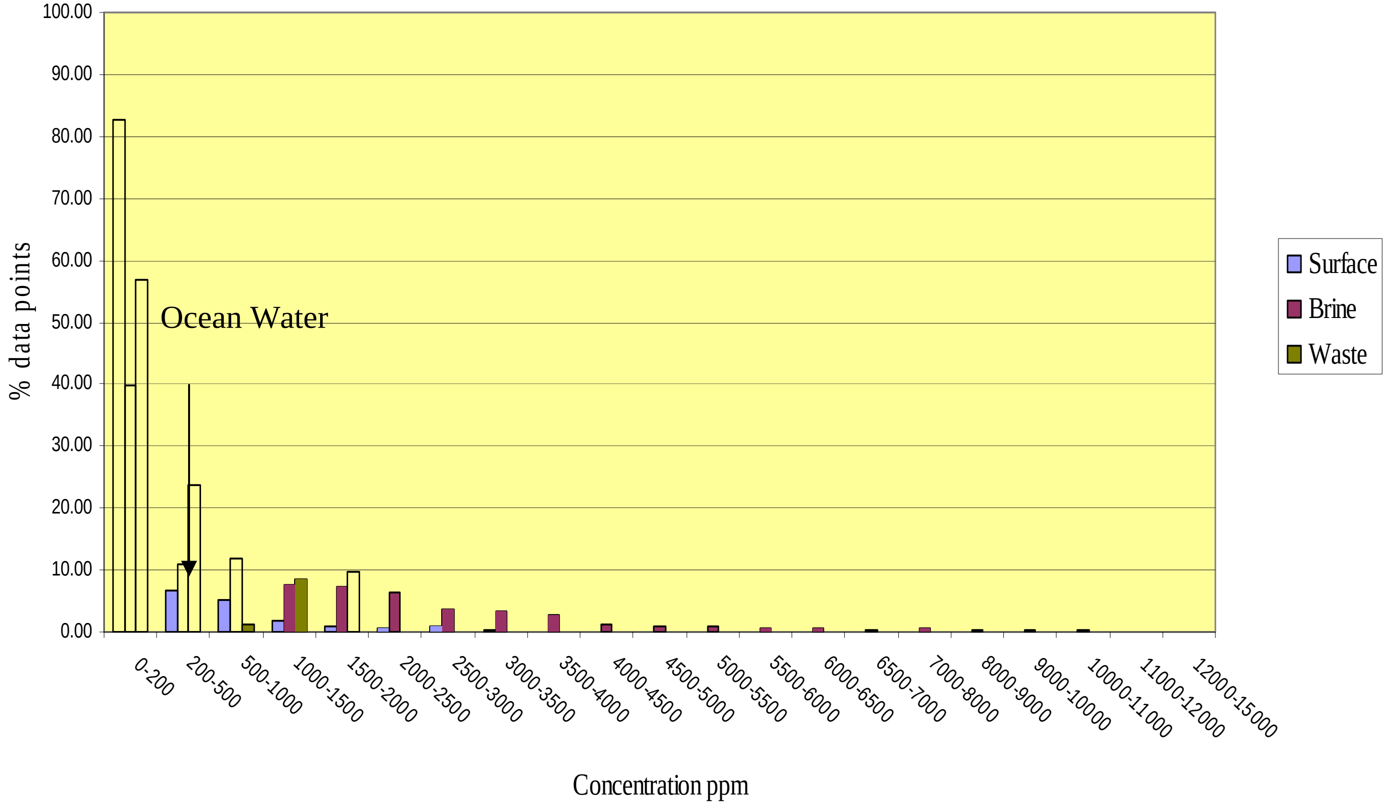

Figure 2.1 Chart for Sulfates Concentration Distribution in Alternate Water Sources.

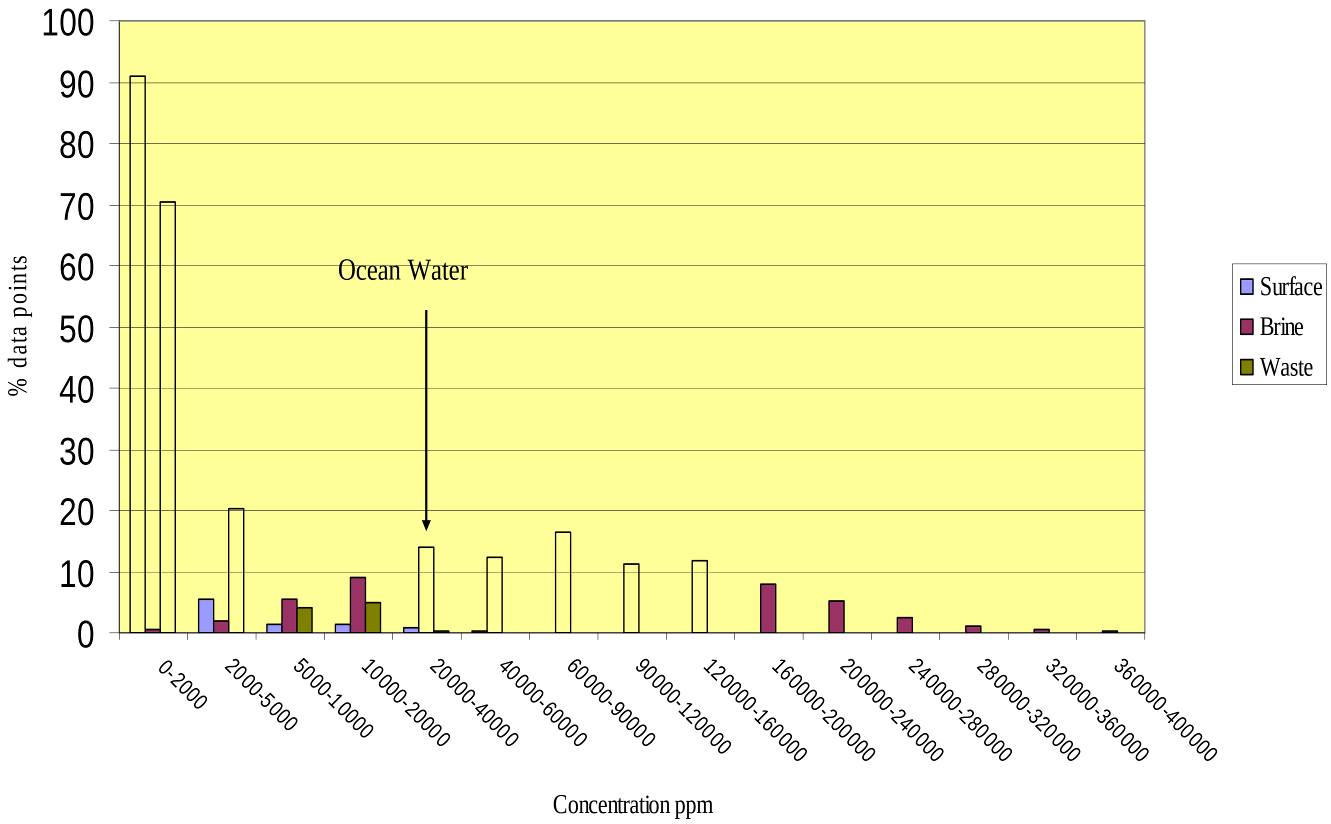

Figure 2.2 Chart for TDS Concentration Distribution in Alternate Water Sources.

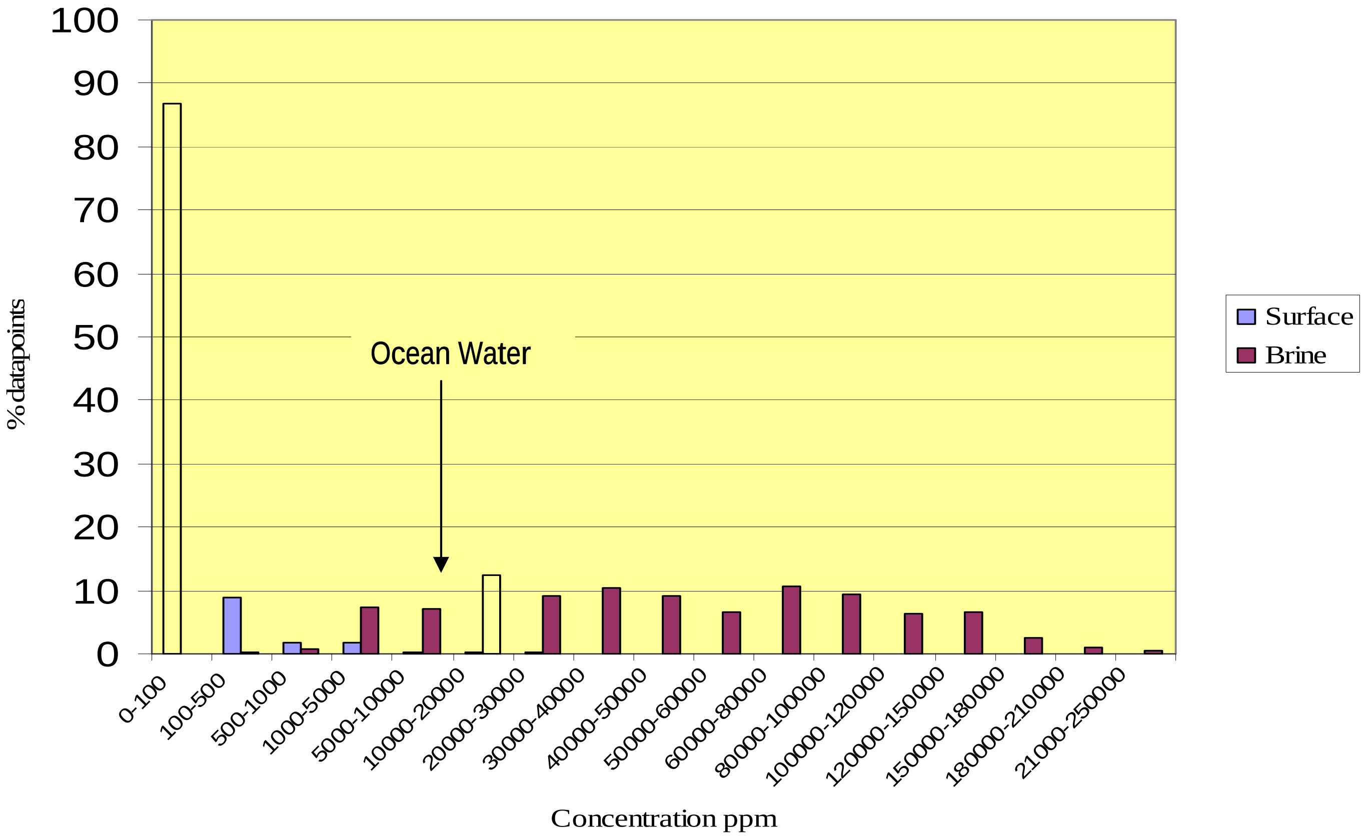

Figure 2.3 Chart for Chloride Concentration Distribution in Alternate Water Sources.

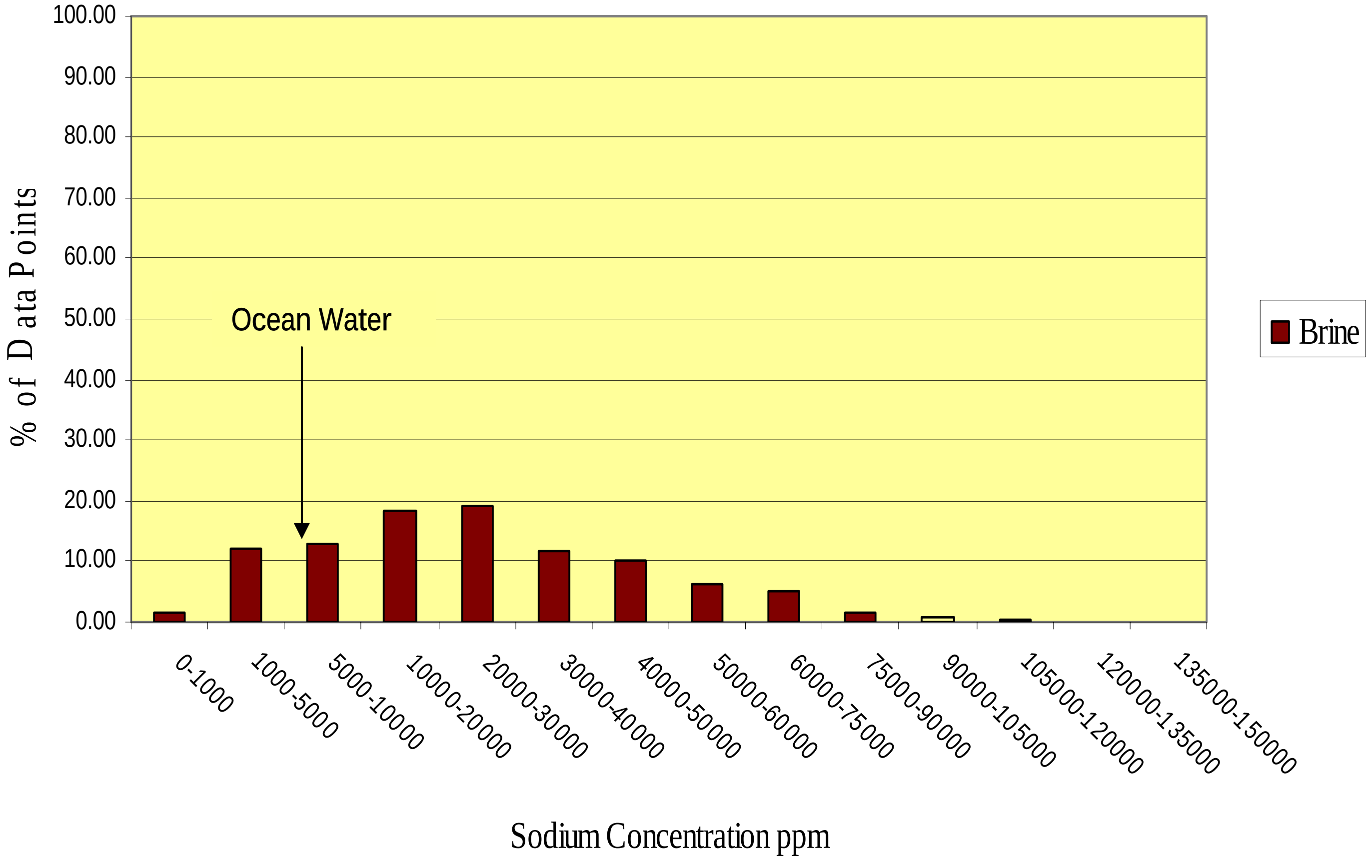

Figure 2.4 Chart for Sodium Concentration Distribution in Alternate Water Sources.

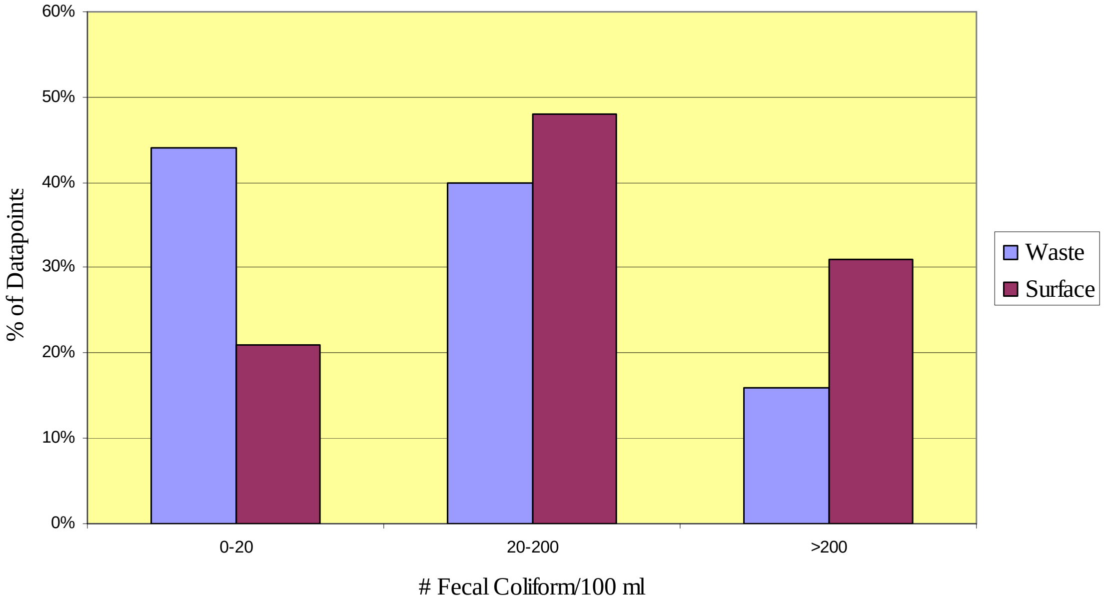

Figure 2.5 Chart for Fecal Coliform Distribution in Alternate Water Sources.

The data range of critical parameters found in produced water is listed in Table 2.10. It is found that sulfate, BOD, fecal coliforms, and pH are not a concern with brine water. From Figure 2.5 (concentration distribution of sulfate), it is found that more than 90 percent of the brine water has a sulfate value of less than 5000 ppm. The major concerns for brine water are sodium, chloride and TDS. Brine water can be used for compaction and stabilization operations. Further lab testing and more research is required to find the maximum threshold values for sodium and TDS.

Table 2.10 Critical Parameters Range in Brine Water Database.

Parameter	MAX	MIN	MEAN	UNITS
Sulfate	14657	0	1167.06	mg/L
Sodium	146770	33	22899.3	mg/L
Calcium	66381	0	4659	mg/L
Magnesium	37620	0	1171.139	mg/L
Chloride	245376	53	54200	mg/L
TDS	398904	1012	90154.54	mg/L
PH	9	5	7.01	

The data range of critical parameters found in surface water is listed in Table 2.11. It is found that sulfate, sodium, TDS, and pH are not a concern for surface water. From Figure 2.2 (concentration distribution of TDS) it is found that more than 90 percent of the surface water has a TDS value of less than 2000 ppm. Sodium is usually not a concern for surface water sources as it would be well within the threshold limit. If the water source is suspected to have a sodium concentration greater then threshold limit then the water must tested before it can be used. The major concerns for surface water are BOD, fecal coliforms, other health concerns, and the parameter for which the water is declared as impaired water. From Figure 5 it can be seen that almost 70 percent of the surface water can be used for type II applications. Most of the surface water sources can be used for almost all of the construction applications.

Table 2.11. Critical Parameters Range in Surface Water Database.

Parameter	Max	MIN	MEAN
Sulfate (ppm)	3123.5	0	71.53
Fecal Coliforms (#/100 ml)	37832	0	444.64
Chloride (ppm)	26637	0	159
TDS (ppm)	40399.2	0	419

Reclaimed water, brine water, and surface water databases can be accessed from the same front-end form. The values pulled out by the databases can be compared with the values of critical parameter concentrations given in the decision matrix. If the database does not give a value for any of the critical parameter then that parameter is not of a concern as the concentration of that parameter is well within threshold limit. The water source can be approved for the construction application if the parameters meet the criteria given by the decision matrix.

CHAPTER III

CONSTRUCTION APPLICATIONS

3.1 Overview

The next important task in this research project involved the identification of specific construction applications in which alternative water could be used beneficially. This task was accomplished as a joint effort between the researchers and the members of the TxDOT project monitoring committee.

One of the criteria used in the selection of candidate construction applications was that the construction process should utilize large amounts of water. This requirement was necessary because, otherwise the benefits to be gained from the use of alternative water would be minimal. A second requirement was that the composition of the water should not have a major adverse effect on the product quality, especially in the long term. An example of a construction application that was excluded for the above reason was water used in the mixing and curing of concrete.

The remaining sections of this chapter describe the construction applications that were included in this research study. Section 3.2 identifies specific construction applications and provides a brief description of each. Section 3.3 examines the issues and concerns arising from the use of alternative water in each construction application. These issues include: sulfate heave potential, increased corrosivity, soil dispersion, increase in swell potential and changes in soil index properties. Section 3.4 deals with the appropriate threshold limits that should not be exceeded to avoid any adverse effects from the use of alternative water sources.

3.2 Construction Applications

The following construction applications were identified by the researchers and the TxDOT project monitoring committee as potential candidates for utilization of alternative water. These construction applications require large quantities of water. If alternative water can be used in these applications during times of water shortage, the potential benefits will be significant.

3.2.1 Sprinkling

This is the application of water for dust control, earthwork or base construction. TxDOT specification Item 204 requires that water shall be clean and free from industrial wastes. It should be applied in a uniform and controllable rate.

3.2.2 Vegetative Watering

Vegetative watering involves the application of water through an aboveground system to promote and sustain the growth of vegetation. Water should be clean and free of any industrial wastes and other substances that can be harmful to the growth of vegetation. The water should be distributed in a uniform and controlled rate.

Table 3.1 Construction Applications and TxDOT Specification Number

Construction Application	TxDOT specification Number
Sprinkling	Item 204
Vegetative Watering	Item 168
Flexible Base	Item 247
Embankment	Item 132
Retaining Wall	Item 423
Lime Treatment for Materials Used as Subgrade (Road Mixed)	Item 260
Lime Treatment for Base Courses (Road Mixed)	Item 262
Lime Treated Base (Plant Mixed)	Item 263
Lime-Fly Ash (LFA) Treatment of Materials Used as Subgrade	Item 265
Lime-Fly Ash (LFA) Treatment for Base Courses (Road Mixed)	Item 266
Portland Cement Treated Materials (Road Mixed)	Item 275
Portland Cement Treated Base (Plant Mixed)	Item 276

3.2.3 Flexible Base Construction

The construction of flexible base layers for roadways involve the placement of crushed or uncrushed aggregate and binding materials and their compaction to achieve a specified density. Prior to compaction, the flexible base material should be sprinkled with construction water to bring its water content to an optimum value. The water used for compaction should be clean and free from industrial wastes.

3.2.4 Embankment Construction

In embankment construction, select fill material is compacted by sprinkling and rolling. Sprinkling should be done in such a manner that the embankment material is wetted uniformly. The sprinkling water should be clean and free from industrial wastes. The embankments under consideration are: earth embankments, rock embankments, and embankments adjacent to culverts and bridges. Rock embankments are those that are primarily composed of rock.

3.2.5 Retaining Wall Backfill

TxDOT Specification Item 423 governs the construction of both reinforced concrete and Mechanically Stabilized Earth (MSE) retaining walls. Construction water is used in the placement and compaction of backfill behind these retaining walls. In the construction of MSE walls, backfill placement must closely follow the erection of each lift of panels. At each reinforcement level, backfill should be leveled and compacted before placing the reinforcement. The normal lift thickness is 8 inches. Each backfill layer should be sprinkled and compacted to no less than 95% density for the top three feet and no less than 90% density for all the other areas.

3.2.6 Lime Treatment

Lime treatment is used for roadway subgrades and base layers to improve workability as well as to enhance strength and durability characteristics of the material. Lime treatment of subgrade soils is achieved by road mixing Item 260). The application and mixing of lime with the soil can be accomplished by two methods; *dry placing* or *slurry placing*. In the dry placing method, dry hydrated lime is distributed over soil uniformly by using a spreader. The material is then sprinkled with water, thoroughly mixed and allowed to cure. In the slurry placing method, hydrated lime is mixed with water to form a slurry and then the slurry is distributed over the soil using a spray truck. The soil and lime is then thoroughly mixed and left to cure several days to give a homogeneous, friable mixture. At the end of the curing period, the material is sprinkled again to bring the moisture content to an optimum value and then compacted to achieve 95% maximum density as determined by Test Method Tex-121-E. Lime treatment of base material will be similar except that treatment may be achieved by road mixing (Item 262) or by plant mixing (Item 263). The water used in lime treatment should be clean and free from industrial wastes.

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3.2.7 Lime-Fly Ash Treatment

Lime-fly ash treatment is carried out for materials used as subgrade and for base courses. The water should be clean and free from industrial wastes. In addition to water the material used for subgrade are lime, fly ash and asphalt. For base courses the additional materials used are lime, asphalt, flexible base and asphalt. Prior to compaction, the material should be aerated or sprinkled to provide the optimum moisture content. Compaction should begin immediately after mixing of the last stabilizing agent.

3.2.8 Portland Cement Treatment

This involves treating subgrade, new and/or existing base, and base courses. The water should be free from oils, acids, organic matter or other deleterious substances and should not contain more than 1000 ppm of chlorides as Cl nor more than 1000 ppm of sulfates as SO_4. Water from municipal supplies approved by the State Health Department does not require testing, but water from other sources needs to be sampled and tested before usage in accordance with AASHTO T26. Water used in white portland cement concrete should be free from iron and other impurities which could cause staining or discoloration. The materials used for portland cement treatment excluding water are flexible base, Portland cement and asphalt.

For road mixed portland cement treated materials, after any required mixing of the materials, the cement should be dry mixed with the materials prior to addition of water. As soon as dry mixing is complete, water should be applied uniformly. The mixture should be mixed and compacted in one lift. Sprinkling should take place at the time of compaction.

For portland cement treated bases the cement, base material, and water should be thoroughly mixed in a stationary plant. Once mixing is complete, additional water should not be added. Cement treated material should be placed on areas where compaction and finishing operations could be completed during the same working day.

3.3 Issues Related To Performance

As discussed in Chapter 2, the soluble mineral content in water obtained from alternative sources can be much higher than in water obtained from conventional sources. In addition, the pH of alternative water can also be significantly different from that for conventional water. Therefore, it is important to examine whether these differences in water composition and pH may have adverse impact on the performance. This section provides an overview of performance related concerns that arise when water from alternative sources is used in construction. The issues discussed include: Sulfate Content, Corrosivity, Dispersivity, Swell Potential and Soil Index Properties.

3.3.1 Sulfate Content

Sulfate induced heave occurs when natural sulfate soils are stabilized with calcium based chemicals such as lime and ordinary Portland cement (Hunter, 1988; Mitchell and Dermatas, 1990; Petry and Little, 1992). It is caused when calcium, alumina, and sulfate combine to form ettringite ($3CaO.Al_2O_3.CaSO_4.12H_2O$), which is highly expansive and may double in volume when exposed to moisture (Hunter, 1988). When water from non-traditional sources is used in soil stabilization projects, the sulfate contained in the construction water will combine with the sulfate contained in the natural soil. If the construction water used has high soluble sulfate content, then the likelihood of having problems due to sulfate induced heave can increase significantly.

Among the different types of alternative water that are being considered in this research, brine water requires the most rigorous scrutiny because it has the highest sulfate concentrations.

3.3.2 Corrosivity

Corrosion is a primary concern in the design of buried metallic structures. MSE wall soil reinforcements and corrugated metal drainage pipe are examples of buried metallic structures that are commonly encountered in transportation construction. The rate of corrosion of these buried structures is controlled by specifying backfill material with low corrosion potential. The most commonly used parameters for determining the corrosivity of soil are *resistivity* and *pH*. The resistivity of a soil depends mainly on its moisture content, the amount of dissolved minerals, level of compaction and temperature. The higher the resistivity of the soil, the lower is the rate of corrosion. High acidity and high alkalinity also increase rate of corrosion. Therefore, mid-range soil pH values are specified for backfill so that corrosion rates can be controlled within acceptable limits. Increasing concentrations of Chloride and Sulfate irons in the soil also increase corrosion potential. When sulfides are present in the soil, it indicates the presence of sulfate reducing bacteria (SRB). SRB shifts the pH in the acidic direction which in turn accelerates corrosion. The most favorable level for SRB is when pH is neutral. The higher the hardness as $CaCO_3$ of soil moisture the lower is the corrosion rate.

Since the concentrations of dissolved minerals, as well as concentrations of chlorides and sulfates in alternative water can be significantly higher than in conventional water, its impact on the corrosivity of backfill soil require careful review.

3.3.3 Shrink/Swell Potential

Presence of clay soil deposits with high plasticity and high shrink/swell potential is a major concern for transportation engineers who work in certain parts of Texas. The composition of the soil pore solution is among the factors that influence the propensity of these clays to shrink and swell. A soil pore solution rich in the monovalent Na^+ cation increases the swell potential of these clays. Conversely, the plasticity and swell potential of these soils can be dramatically reduced by treating them with hydrated lime. When hydrated lime is added to the soil, the overall cation concentration in the soil pore solution increases. At the same time, the divalent Ca^{++} cations replace any monovalent cations that may be occupying exchange sites in clay particles. Both of these mechanisms cause the clay particles to flocculate. Flocculation in turn creates favorable changes in soil properties. The reverse phenomena may occur if the soil is treated with water that is rich in monovalent cations such as sodium, Na^{+}. Since sodium, Na^{+} is abundant in some of the alternative water sources, it will be necessary investigate whether use of such water in construction may cause degradation of soil properties in terms of shrink/swell potential.

3.3.4 Dispersivity

Dispersivity refers to the tendency of clay particles to go into suspension spontaneously upon contact with water. Dispersivity affects the erodibility of soils. Highly dispersive soils will erode even in relatively calm water that has little or no velocity of flow. This could lead to serious erosion damage in slopes and embankments. According to Bell and Maud (1995), dispersive erosion has lead to failures in earth dams and embankments. Dispersivity of a soil, once again, varies with the composition of the soil pore solution. The parameters that have been used to determine the dispersive potential of a soil are: Exchangeable Sodium Percentage (ESP), Sodium Adsorption Ratio (SAR) and the total dissolved minerals.

Exchangeable sodium percentage (ESP) is the amount of exchangeable sodium on the soil's cation exchange complex expressed as a percentage of the total cation exchange capacity (CEC) (van de Graaff and Patterson, 2001). The soil's cation exchange capacity (CEC) is the total negative electric charge per mass of soil, expressed in milliequivalents per 100 g (meq/100 g). CEC is measured in the laboratory by determining the exchangeable calcium, magnesium, sodium, and potassium, plus hydrogen and aluminum ions. ESP is then determined as below.

$$ESP = \frac{exchangeable\ sodium}{cation\ exchange\ capacity} \times 100 \text{ meq/100 g of dry clay.}$$

Sodium absorption ratio (SAR) is a relative measure of dissolved sodium in water compared to the amounts of dissolved calcium and magnesium (van de Graaff and Patterson, 2001). It is defined in the following manner.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \text{ meq/litre.}$$

ESP is a property of the soil while SAR is a property of the soil water. There is a consistent relationship between the SAR of the soil water and the ESP of the soil (van de Graaff and Patterson, 2001).

3.3.5 Soil Index Properties

Index properties of soils are influenced by the chemical composition of the pore solution. Therefore, dissolved ions in the construction water can be expected to have some effect on these soil properties. Similarly, shrink and swell characteristics of base and subbase materials may be affected by the chemical composition of the water that is added during construction. Since index properties of soils, specifically Liquid Limit and Plasticity Index and Bar Linear Shrinkage are used in the selection of base and subbase material, it is necessary to investigate the potential impact that construction water from alternative sources may have on these soil parameters.

3.4 Applicable Threshold Limits

This section discusses the applicable threshold limits for soil sulfate content, SAR and the corrosivity based on literature review and the available guidelines.

3.4.1 Sulfate Content

Many research studies have attempted to establish the critical soil sulfate threshold levels at which sulfate heave in stabilized soil becomes a serious concern. The results from these studies vary. Petry (1994) examined this issue for the Army Corps of Engineers and developed a test procedure. He found sulfate levels of 2,000 ppm (0.2%) have a potential to cause swelling in lime-stabilized materials and 10,000 ppm (1.0%) have the potential to cause serious damage to lime-stabilized materials. This was consistent with Hunter’s (1998) findings. McCallister and Tidwell (1997) suggested the following limits for various levels of sulfate attack on lime-stabilized soils: 100-5,000 ppm (0.01-0.50%) posed a low to moderate risk of heave; 5,000-12,000 ppm (0.50-1.20%) posed a moderate to serious risk of heave and greater then 12,000 ppm (1.20%) posed a very serious risk of heave. Sherwood (1962) found strength loss for lime-stabilized London clay was about 24% at sulfate content as low as 0.25% and approx. 67% at 2.0% of sulfate content.

According to Guidelines for Stabilization of Soils Containing Sulfates (August 2000) recommendations are: less than 3,000 ppm (0.3%), the sulfate levels are too low to be a concern; between 3,000 ppm (0.3%) and 5,000 ppm (0.5%) are of moderate concern; levels between 5,000 ppm (0.5%) and 8,000 ppm (0.8%) represent moderate to high risk and sulfate levels of greater than 8,000 ppm (0.8%) are generally of high risk to stabilize with lime. These sulfate limits were established using TxDOT test procedure. Puppala et.al suggested 1,000-2,000ppm as low risk; 2,000-5,000ppm as moderate risk; 5,000-10,000 as high risk and above 10,000ppm as very high risk.

Based on the above literature review, the following threshold values were chosen for use in this research study. They are: 0-2,000ppm can pose a low risk; 2,000-5,000ppm poses a moderate risk; 5,000-10,000ppm poses a high risk and above 10,000ppm poses a very high risk for sulfate heave.

3.4.2 Corrosivity

For corrosivity, specific guidelines were available in TxDOT Standard Specifications.

The pH range should be from 5.5 to 10.0 and is determined by Test method Tex-128-E.

The resistivity should not be less than 3000 ohms-cm and is determined by Test method Tex-129-E. Material with a resistivity between 1500 and 3000 ohms-cm may be used if the chloride content does not exceed 100 ppm and the sulfate content does not exceed 200 ppm which are determined by method Tex-620-J.

3.4.3 Shrink/Swell Potential

Soil Expansion Index, as determined according to ASTM D 4829, may be used as a measure of the shrink/swell potential of soils.

Table 3.2 below provides the relationship between indication of expansion for results obtained upon testing.

Table 3.2 Expansion index and potential

Expansion Index	Potential Expansion
0-20	Very Low
21-50	Low
51-90	Medium
91-130	High
>130	Very High

3.4.4 Dispersivity

The exchangeable sodium percentage (ESP) has the most dominant influence in the dispersibility of soils. When the soil is treated with water with a relatively high sodium adsorption ratio (SAR), the ESP of the soil will increase. An ESP value of greater than 2 indicates possible dispersion, and an ESP value greater than 10 to 15 indicates probable dispersion of clays in soils of relatively low total salt concentration in the pore water (Mitchell, 1993). Dispersion occurs only at low ESP values and low electrolyte concentration, and increases with increase in soil pH (> 7.0) (Regea et al. 1997).

3.4.5 Soil Index Properties

Threshold limits were obtained from literature and specific guidelines in ASTM standards. For embankments, the Texas Department of Transportation gives specific threshold limits for soils is provided in Table 3.3.

Table 3.3 Dispersivity Thresholds

Liquid Limit	≤ 45
Plasticity Index	≤ 15
Bar Linear Shrinkage	≥ 2

CHAPTER IV

LABORATORY TEST PROGRAM

4.1 Overview

A comprehensive laboratory test program was undertaken to investigate the most critical concerns that arise when water from alternative sources is used in construction projects. These critical concerns include: (a) the effect of soluble salts on soil corrosivity, (b) the potential increase for sulfate heave in base layers stabilized with calcium-based stabilizers, (c) the increase in soil dispersivity and shrink/swell potential as a result of mixing with Na^+-rich alternative water, and (d) the potential impact that soluble salts in alternative water may have on soil parameters that are used in material selection (i.e. Atterberg Limits and Bar Linear Shrinkage).

A second objective of the lab test program was to use the data collected from testing to develop appropriate predictive models that would allow preliminary evaluation of candidate alternative water sources to determine their suitability. In the event that a particular candidate source was found to be unsuitable, then the possibility of blending that alternative water with fresh water may be considered. Predictive models can also be used to determine the appropriate blending ratio for the alternative water with fresh water.

This chapter presents detailed descriptions of the lab test procedures completed. The results obtained from testing and predictive models developed are discussed in the next chapter.

4.2 Selection of Soil Samples for Test Program

Five different soils were selected from actual TxDOT construction projects to cover the broad range of soils that are commonly encountered in construction. The first two soils were subgrade materials that were obtained from highway construction projects in Dallas; one from the Interstate Highway 30 (IH-30) project and the other from the State Highway 121 (SH-121) project. There were two flexible base materials collected from Odessa and Lubbock. The fifth material was concrete sand that was used in bridge deck construction in Lubbock.

4.3 Soil Characterization Tests

Several required characterization tests were performed on each of the five soils to determine their basic properties. These tests included determination of particle size distribution, percentage of fines, Atterberg limits, and optimum moisture content. Using the results of these tests the soils were classified according to USCS classification procedures. TxDOT test standards were followed whenever such standards were available. When TxDOT standards were not available, test procedures were conducted in accordance with ASTM standards. An overview of the test procedures is presented below.

4.3.1 Particle Size Distribution

Tex-110-E was used to determine the particle size distribution of all the soils. Size distribution and the fraction of particles collected on a No. 200 sieve were determined by sieving the soil samples using different screen sizes. Eight sieve sizes were used: 3/8”, No. 4, No. 10, No. 20, No. 40, No. 60, No. 140, and No. 200. First a representative portion of an air dried soil sample was selected by the method of quartering. Then, the sample was washed with tap water over No. 10 and No. 200 sieves until the wash water ran clear. The soil fractions retained on these two sieves were oven dried at 110^{o}C, and the oven dried soils were sieved using a mechanical sieve shaker. The weight of soil retained on each of the eight sieves was recorded, and these data were used to calculate the percentage of soil passing each sieve.

4.3.2 Amount of Material Finer than No. 200 Sieve

To determine the amount of soil fines passing a No. 200 sieve, Tex-111-E was used. An adequate and representative portion of each soil was chosen by the method of quartering and oven dried at 110^{o}C. Then, the sample mass was measured and washed on a No. 200 sieve screen until the water passing through the sieve ran clear. The sieve and the material retained on the sieve were oven dried at 110 ^{o}C. The mass of the oven dried soil retained on the 200 mesh screen was determined by weight difference, and the percentage of material finer than the openings of a No. 200 sieve was calculated.

4.3.3 Atterberg Limits of Soil

The Atterberg limits of interest were the liquid limit (LL) and plastic limit (PL). The procedures for LL, PL, and Plasticity Index of Soils that are described in Tex-104-E and Tex-105-E respectively were used to determine these Atterberg limits for the five soil samples. The Plasticity Index is determined by the difference between LL and PL. For both tests, approximately 400 grams of soil that passed the No. 40 screen was used. Distilled water was added to each sample, and after thorough mixing, the wet sample was covered and set aside for 16 hours before testing. Whenever it was necessary to adjust the water content of a soil sample, the following procedures were used: (1) to reduce the water content, the soil was exposed to warm air from an electric hair dryer, and (2) to increase the water content, water was sprayed from a wash bottle and the sample allowed to reach equilibrium.

The multi-point liquid limit procedure was used to determine the LL of the soil. The soil was placed in a standard cup, and a cut was made to create a 2 mm wide V-shaped groove. Then, the cup was allowed to drop 10mm using a standard, motor driven liquid limit apparatus which was set to produce two impacts per second. The impacts were repeated until the 2 mm groove in the soil closed over a distance of ~13 mm. Two trials consisting of 15 drop impacts, two trials of approximately 25 drops, and an additional two trials of about 25 drops were performed. For each trial, the number of impacts required to close the groove was recorded. Then the moisture content was determined for approximately 25 g of soil scooped from the cup. A line of best fit was drawn through the points obtained by plotting the moisture content against the logarithm of the number of impacts resulting in groove closure.

From this line, the liquid limit, LL, was established by the moisture content that corresponded to 25 blows.

For the plastic limit test, the water content of the soil sample was reduced to a consistency where the soil did not stick to the hand. Using approximately two grams of soil for the plastic limit apparatus, threads of the soil were formed by rolling on a white sheet of paper. The process in which the soil was rolled, kneaded, and re-rolled was repeated until cracks formed when the soil was rolled into 3.2 mm (1/8 in.) diameter threads. Successive threads were collected in three containers, each containing from six to ten grams of threads. The water content of the samples in all three containers was determined, and the average water content was reported as the plastic limit of the soil. As noted earlier, the plasticity index of the soil was determined by subtracting the plastic limit from the liquid limit.

4.3.4 Soil Classification

The TxDOT procedure for "Classification of Soils for Engineering Purposes", (Tex-142-E), was used to classify the soil samples. Using the Unified Soil Classification System (USCS), three major divisions of soil are defined: (1) coarse grained soils, (2) fine grained soils, and (3) highly organic soils. If more than 50% of the soil sample is retained on the No. 200 sieve, the soil is classified as coarse grained. If more than 50% of the sample passes a No. 200 sieve, the soil is classified as fine grained. The three major soil categories are further subdivided into a total of 15 soil sub-groups. Using USCS Classification charts for coarse and fine grained soils, the appropriate group symbol and specific name are determined. Use of the charts first requires the determination of Atterberg limits, a plasticity chart, and a cumulative particle size distribution curve for each soil sample.

4.3.5 Optimum Moisture Content

TxDOT procedure for Moisture-Density Relations of Subgrade and Embankment Soils using 5.5 lb (2.49 kg) rammer and 12 in. (305 mm) drop (see Tex-114-E) was used to find the optimum moisture content of each of the five soil samples. Initially, a soil sample is oven dried at 60 ^{o}C. After drying, aggregations were broken, and the fraction of soil passing a No. 4 sieve was selected. For each soil sample, a total of five specimens were prepared by the addition of water; one for the optimum moisture content and two each on either side of the optimum. A 4 in. compaction mold was used for compaction. The mold extension collar was attached and each specimen was compacted in three equal layers. Compaction was accomplished manually by dropping a 5.5 lb rammer from a 12 inch height. Each layer received 25 blows. After compaction, the specimen was extruded, and the moisture content was determined from a representative portion of the sample. The dry density values were plotted against the experimentally determined moisture content of the specimens. A smooth curve was drawn to connect the points, and the optimum moisture content (OMC) for the sample coincided with the point of maximum dry density on the curve.

The results of the soil characterization tests for the five tested soil samples are summarized in the following Table 4.1. The West Texas soil samples generally exhibited a reduced level of fines as well as lower LL, PL, PI, and OMC characterization values.

Table 4.1 Results from Soil Characterization Tests

Soil Name	% Fines (Passing #200 Sieve)	Atterberg Limits			Optimum Moisture Content (OMC)
		Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	
Dallas SH-121	93	64	33	31	26
Dallas IH-30	73	42	21	21	19
Odessa Flexbase	23	23	13	10	11
Lubbock Flexbase	21	26	18	8	16
Lubbock Embankment	11	27	15	12	11

4.4 Soil Corrosivity

The two primary criteria used by TxDOT to determine the corrosive potential of a soil are (1) electrical resistivity and (2) pH. By convention, for soil to qualify as a mildly corrosive backfill, it should exhibit a resistivity greater than 3000 ohm-cm and register a pH within the range of 5.5 to 10.0. Whenever the resistivity of a particular soil resides between 1500 and 3000 ohm-cm, then the soil can still be used as backfill provided that the chloride content does not exceed 100 ppm, and the sulfate content does not exceed 200 ppm. Initially, each soil sample used in this study was tested only for resistivity and pH. However, since the resistivity of the majority of the soils being investigated fell below 3000 ohm-cm, additional tests to determine the chloride and sulfate concentration levels present in each sample were necessary.

4.4.1 Test Matrix for Resistivity

Literature sources indicate that when water containing soluble salts is added to soil, the resistivity of the soil will decrease. Moreover, any decrease in resistivity is considered to be a direct indication of increased corrosivity of the soil. For these reasons, changes in soil corrosivity might be expected during construction operations whenever water from any source is added to the soil. To quantify the change in soil corrosivity derived from adding water to the soil during construction, different combinations of soils and potential alternative water sources for use in construction were tested in the laboratory. The text matrix used in this investigation is shown in Table 4.2.

As a baseline, each of the five selected soil samples were first tested using only deionized water. This test procedure involves measurement of soil resistivity at progressively increasing water contents. The water content in the soil is increased up to its saturated conditions. The value reported is the minimum value of all soil resistivity measurements. The soil samples were tested following the addition of each of the following five potential construction water sources: ocean water, a single concentration of brine water, and three different concentrations of municipal wastewater. Alternative water with compositions similar to real wastewater were prepared in the lab and using in testing.

Table 4.2 also indicates that four different amounts of each construction water source were added to soil samples SH-121 and IH-30 with the optimum moisture content being the largest amount of water added. Also, three different concentrations from each water source were added to the Odessa and Lubbock flexbase samples. Once again, the experimentally determined optimum moisture content for each soil represented the largest amount of water being added. Similarly, three concentrations of each of the five alternative water types were added to concrete sand. For this latter soil sample, the highest water content was slightly less (25%) than the maximum, optimum water content (26%) of the four other soils.

Table 4.2 Test Matrix for Soil Resistivity

Soil Name	Without Construction Water	Simulated Treated Waste Water			Ocean Water	Brine Water
		7,000 ppm TDS	15,000ppm TDS	25,000 ppm TDS	35,000 ppm TDS	100,000 ppm TDS
SH-121 (Dallas)	Δw = 0%	Δw = 26%	Δw = 26%	Δw = 26%	Δw = 26%	Δw = 26%
		Δw = 20%	Δw = 20%	Δw = 20%	Δw = 20%	Δw = 20%
		Δw = 15%	Δw = 15%	Δw = 15%	Δw = 15%	Δw = 15%
		Δw = 8%	Δw = 8%	Δw = 8%	Δw = 8%	Δw = 8%
IH-30 (Dallas)	Δw = 0%	Δw = 19%	Δw = 19%	Δw = 19%	Δw = 19%	Δw = 19%
		Δw = 15%	Δw = 15%	Δw = 15%	Δw = 15%	Δw = 15%
		Δw = 10%	Δw = 10%	Δw = 10%	Δw = 10%	Δw = 10%
		Δw = 5%	Δw = 5%	Δw = 5%	Δw = 5%	Δw = 5%
Flexbase (Odessa)	Δw = 0%	Δw = 11%	Δw = 11%	Δw = 11%	Δw = 11%	Δw = 11%
		Δw = 8%	Δw = 8%	Δw = 8%	Δw = 8%	Δw = 8%
		Δw = 4%	Δw = 4%	Δw = 4%	Δw = 4%	Δw = 4%
Flexbase (Lubbock)	Δw = 0%	Δw = 16%	Δw = 16%	Δw = 16%	Δw = 16%	Δw = 16%
		Δw = 10%	Δw = 10%	Δw = 10%	Δw = 10%	Δw = 10%
		Δw = 5%	Δw = 5%	Δw = 5%	Δw = 5%	Δw = 5%
Cocrete Sand	Δw = 0%	Δw = 25%	Δw = 25%	Δw = 25%	Δw = 25%	Δw = 25%
		Δw = 15%	Δw = 15%	Δw = 15%	Δw = 15%	Δw = 15%
		Δw = 5%	Δw = 5%	Δw = 5%	Δw = 5%	Δw = 5%

Δw = the amount of construction water added to the soil samples

4.4.2 Test Matrix for pH

When the pH of the soil samples were initially tested using distilled water, four out of five of the soil samples were found to lie between pH values of 5.5 – 10, which is the range recommended by TxDOT for reduced soil corrosivity. Only the measured pH value for concrete sand and distilled water exceeded 10, but this deviation was not considered significant. Therefore, subsequent soil samples were tested only when the addition of alternative construction water resulted in pH values falling within the pH 5.5 - 10 range.

Based on a database for brine water, its reported average pH value is 6.96 with a range of 5.00 - 8.91. The TCEQ guidelines state that the pH value of WWTP must be between 6.0 and 9.0 prior to discharge. Finally, reference literature suggest that ocean water is slightly alkaline and typically exhibits pH levels within the range of 8.0 - 8.4. Therefore, the extremes of pH values for the five experimental construction water tests are the WWTP, with a pH equal to 9, and Brine, with a pH equal to 5.0. The test matrix for testing the pH of soil samples was prepared using these parameters as limits as shown in Table 4.3. In this table, the amount of construction water added to the soil samples is denoted by the letter Δw. In each instance the value of Δw is numerically equal to the optimum moisture content determined for each soil sample.

Table 4.3 Test Matrix for Soil pH

Soil Name	Without Construction Water	Brine pH = 5.0	WWTP pH = 9.0
SH-121	Δw = 0%	Δw = 26%	Δw = 26%
IH-30	Δw = 0%	Δw = 19%	Δw = 19%
Flexbase (Odessa)	Δw = 0%	Δw = 11%	Δw = 11%
Flexbase (Lubbock)	Δw = 0%	Δw = 16%	Δw = 16%
Concrete Sand	Δw = 0%	Δw = 25%	Δw = 25%

4.4.3 Preparation of Construction Water for Testing

For this study, the different alternative water sources used for construction and the soil testing experiments were reconstituted in the laboratory. As noted above, the five types of construction water included the following: three simulated WWTP water types having different levels of TDS, brine water, and ocean water. Each of these five represent a possible replacement source for traditional surface or municipal water used in road construction. Since the respective chemical compositions and concentrations of these alternative waters vary, each type of construction water had to be prepared separately according to specific recipes. In most cases the concentration of soluble salts in a construction water sample will vary directly with the measured TDS levels. Furthermore, variations in TDS levels can exist even within a specific type of construction water.

The TDS levels of the wastewater samples prepared in the lab were selected so that they cover the range of concentration levels found in wastewater databases developed as a part of this study. The recipes used specified the chemical constituents of the water. All concentrations were given in units of ppm. Since the unit ppm is essentially equivalent to mg/l, the recipes actually specify the mass in milligrams of each soluble salt that is to be added to one liter of distilled water in order to produce one liter of the construction water of interest. By following the recipe, the correct amount of each constituent salt was added to a specified amount of distilled water. The bulk water solutions were then stirred thoroughly to assure complete dissolution of the added salts.

4.4.4 Wastewater from Treatment Plant

Data on TDS for WWTPs was obtained from both a TCEQ database as well as the EPA's Permit Compliance System database. For WWTPs, the minimum and maximum TDS values for the state of Texas are 155 ppm and 167,982 ppm, respectively. The percent distribution of the data for TDS in WWTP sources is shown in Table 4.4.

Table 4.4 Distribution of Data Points for WWTP

Total Dissolved Solids / ppm	Percent of Data Points
< 1,000	46
< 2,500	76
< 7,000	88
< 25,000	94
< 100,000	98

For the soil testing experiments, three TDS concentrations for the water samples made to simulate actual WWTP effluent were selected. The TDS levels were; 7,000 ppm, 15,000 ppm and 25,000 ppm. The recipes for these desired concentrations were developed using the baseline recipe for 1000 ppm and are given in Table 4.5. This recipe generally follows the relative ratio of the significant dissolved species for wastewate reported in the databases.

When testing the pH of the soil samples, the pH value of WWTP prepared with 25,000 ppm TDS concentration was adjusted to the upper maximum of 9.0 by the addition NaOH or adjusted downward to 9.0 by adding HCl.

Table 4.5 Recipe for TDS in WWTP

Compound	Concentration			
	1000 ppm	7000 ppm	15000 ppm	25000 ppm
NaCl	455	3190	6830	11400
$NaHCO_3$	47.1	330	708	1180
Na_2SO_4	98.2	687	1470	2450
K_2SO_4	40.9	286	613	1020
$CaSO_4$	195	1360	2930	4880
$Mg(NO_3)_2$	6.78	47.5	102	170
$MgSO_4$	140	982	2100	3500
NH_4CL	16.5	115	247	411
TDS	1000	7000	15000	25000

4.4.5 Brine Water

Data on TDS for brine water was also obtained from a USGS provisional database. The maximum TDS value of brine water is 398,904 ppm. The percent distribution of TDS data points for brine water is shown in Table 4.6.

Table 4.6 Distribution of Data Points for Brine Water

Total Dissolved Solids / ppm	Percent of Data Points
< 50,000	36.6
< 100,000	63.5
< 200,000	90.5
< 300,000	98.8

To test a soil sample with brine water, the concentration of brine water was selected as 100,000 ppm. This TDS concentration covers 63.5% of the data points. The recipe used to prepare experimental brine water having a TDS equivalent to100,000 ppm is given in Table 4.7

For testing the pH of soil samples, the pH value of brine water prepared with 100,000 ppm TDS was adjusted upward to 5.0 by the addition of NaOH or adjusted downward by the addition of HCl acid to lower the pH to 5.0.

Table 4.7 Recipe for TDS in Brine Water

Compound	Concentration/ppm
NaCl	80600
KCl	80
$CaCl_2$	13100
$MgCl_2$	3800
$MgSO_4$	1870
$NaHCO_3$	550
TDS	100000

4.4.6 Ocean Water

The TDS of ocean water is represented by a fixed value of 35,200 ppm. Therefore, sea water with only this TDS value was used for all the soil sample tests. The recipe used to prepare ocean water is shown in Table 4.8.

Table 4.8 Recipe for TDS in Ocean Water

Compound	Concentration/ppm
NaCl	27100
$NaHCO_3$	380
KCl	760
$CaCl_2$	1140
$MgCl_2$	2420
$MgSO_4$	3400
TDS	35200

4.4.7 Preparation of Soil Samples for Testing

The laboratory prepared construction waters were individually added to the different soil samples to study their impact on soil corrosivity. The purpose of adding construction water to soils was to incorporate soluble salts into the soil. Accordingly, after allowing adequate time for the absorption of salts, any residual water was allowed to evaporate. The treated soil samples were then tested for both electrical resistivity and pH by the appropriate method.

4.4.8 Adding Construction Water Prior to Testing for Resistivity

Initially, the soil was oven dried at 60 ^{o}C to simulate air dry conditions. After a constant mass reading was reached, the soil was allowed to cool to room temperature. A representative portion of the sample was selected by the method of quartering to yield approximately 1500 g of soil passing through a No. 8 sieve. The soil sample was first passed through the top of the No. 8 screen. Then, whatever soil remained on the sieve was crushed with a grinder and passed again over the same screen until a sufficient amount of soil passing the No. 8 screen was obtained

From the soil that passed No. 8 sieve, 1,500 g of material was selected. Next a quantity of water that would bring the water content of the 1500 g of soil to the desired water content was measured into a beaker. By adding small amounts of this water at a time, the soil was thoroughly mixed to distribute the water uniformly throughout the soil. Care was taken to break any lumps or clods that formed.

Once the required amount of water had been added and the soil was thoroughly mixed, the soil was placed in a storage dish, and covered to prevent loss of moisture and to allow time for absorption of the soluble salts. During the first couple of hours, the soil was remixed from time to time. After allowing the sample to stand covered for approximately 16 hrs (overnight), the cover was removed, the soil sample remixed and placed in the oven at 60 ^{o}C to simulate air dry conditions.

4.4.9 Adding Construction Water Prior to Testing for pH

When testing the soil samples for pH, the soil was first dried in the oven at 60 ^{o}C to simulate air dry conditions. Once a constant mass reading was reached, the soil was allowed to cool to room temperature. A representative portion of the sample was selected by the method of quartering to yield approximately 200 g of soil that had passed a No. 4 sieve. Whatever fraction of the soil that remained on top the No. 4 screen was crushed using a grinder and re-screened.

From the soil sample that passed through the No. 4 sieve, 200 g of material was selected. The required amount of construction water for 200 g of soil was calculated and measured into a beaker. By adding small amounts of this water at a time, the soil was thoroughly mixed and the water uniformly dispersed throughout the soil. Care was taken to break any lumps or clods formed during mixing.

Once all the required water was added and the soil was thoroughly mixed, the moistened soil was placed in a storage dish, covered to prevent any loss of moisture and set aside to allow time for absorption of the soluble salts. During the first couple of hours the soil was remixed from time to time. After allowing the sample to stand for approximately 16 hrs (overnight), the cover was removed, the soil was remixed, and the sample placed in the oven at 60^{o}C to simulate air dry conditions.

4.4.10 Testing Soil Samples for Resistivity and pH

Initially soil samples were tested for resistivity and pH prior to adding any simulated alternative water. That measurement served as a baseline. Then, the same soils were tested following the addition of specific amounts of construction water as described above. The same procedures were followed in the determination of resistivity or pH, prior to and after adding the construction water. The procedures that were followed in the testing of soil resistivity and soil pH are described in Sections 4.4.11 and 4.4.12 respectively

4.4.11 Measuring Resistivity of Soil

The Tex-129-E method was used to determine the resistivity of soil samples. This procedure requires a resistivity meter and a soil box. The resistivity meter was a Nilson Model 400 with 97 Hz, four (4) terminals, and a null balancing ohmmeter. The indicated range of the meter is from 0.01 ohm to 1.1 mega ohm. The dimensions of the soil box were such that the soil box factor was unity so that the measured resistance was equal to the resistivity of the soil.

The following procedure was used to measure soil resistivity prior to adding any construction water. A representative sample of about 1,300 g of soil that passed a No. 8 sieve was selected and oven dried at 60 ^{o}C until constant mass readings were obtained. To test soil samples after the addition of construction water, a sample prepared according to the procedure described in section 4.4.8 was used. In either case, a soil sample dried at 60 ^{o}C, using the appropriate method, was allowed to cool to room temperature. This material was then passed over a No. 8 sieve. The fraction of soil retained on the sieve was reduced in size using a grinder and rescreened with the No. 8 sieve. Of the soil passing the sieve, ~ 1,300 g was selected and set aside for testing. Using a wash bottle, 100 ml of deionized water was added to the screened and dried soil with continuous mixing. The mixing action was continued until the water appeared to be uniformly distributed throughout the soil. The moist soil was then covered and stored at room temperature for at least six hours to allow time for the soil to absorb the moisture. After six hours, the equilibrated sample could be tested for electrical resistivity using the meter and soil box.

In preparation for each test, the soil box was washed and dried. A sample of the damp soil was then placed inside the soil box while compacting the soil lightly. Excess soil placed in the box was then removed with a straightedge so that the soil surface would be level with the top of the box. The "C" electrical binding posts were connected to the end terminals, and the "P" binding posts were connected to the adjacent center terminals of the soil box. Using the range switch and dial indicator on the test meter, the output reading was adjusted until balance conditions was achieved in the sensitivity key. Then, the corresponding resistivity reading was read and recorded.

Following each test, the sample of soil in the box was removed and remixed with the remaining unused soil sample. The procedure just described in the prior paragraph was repeated following each measurement of resistivity of the soil samples and after each addition of moisture. For convenience, the deionized or construction water was added in increments of 100 ml for clay soils and 50 ml for sandy soils, and the soil box was washed and dried each time following a test. The resistivity of soil was measured repeatedly after each change in moisture level until either the measured resistivity decreased several times, there was an increase in the resistivity, or until the soil was saturated. Experience indicated that when the moisture level was close to the point of saturation, the deionized or construction water should be added in increments of 20 ml for greater sensitivity of the measurements. The minimum resistivity, or the resistivity at which saturation occurred, was noted and reported as the resistivity of the soil.

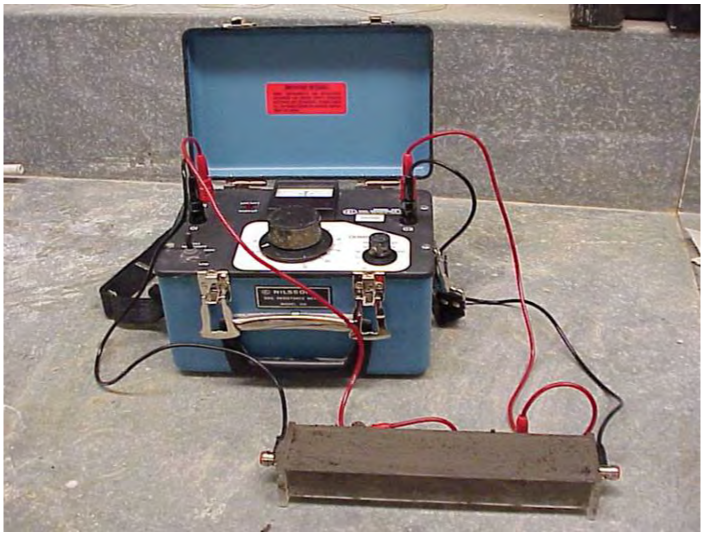


Figure 4.1 Nilson Resistivity Meter and Soil Box for Determination of Soil Resistivity

4.4.12 Measuring pH of Soil

The Tex-128-E test procedure was used to determine the pH of soil. A model 550A bench top pH meter with a Ross ultra electrode was used for these measurements.

To measure soil pH prior to adding construction water, a representative sample of approximately 200 g of soil passing a No. 4 sieve was selected and oven dried at 60 ^{o}C until constant mass readings were achieved. To test the soil after adding construction water, a sample prepared according to the procedure described in Section 4.4.9 was used.

In general, a soil sample prepared according to the appropriate method was first screened through a No. 4 sieve. Soil that was retained on top of the sieve following the initial screening was crushed using a grinder and rescreened to pass through the No. 8 sieve. The screened sample and approximately 200 ml of distilled water were heated to about 50

^{o}C in separate containers. Next, 30 g of the heated soil was added to 150 ml of the distilled or construction water. The slurry was stirred vigorously every 15 minutes for one hour to assure that the soil became thoroughly dispersed in the solution.

The pH meter was standardized using a known pH 7.0 buffer solution and either a pH 4.0 or pH 10.0 buffer standard; whichever was closest to the expected pH of the soil. Then the pH of the solution was measured using the glass electrode while the solution was being stirred with a magnetic stirrer. Once the reading was stabilized, the pH value of the solution was recorded and reported as the pH of the soil.

Figure 4.2 Soil pH Measurement by Tex-128-E Test Procedure

4.5 Sulfate Content in Soil

Tests were performed on all five of the soil samples to establish their sulfate content before and after the samples were treated with the simulated water. The major independent variable in the sulfate test was the amount of simulated water with which the soil was treated.

4.5.1 Preparation of Simulated Construction Water for Soil Sulfate Testing

Information from all databases examined (Chapter 2) for the alternative water sources was considered prior to the preparation of the simulated water samples to be used for sulfate content testing,. The sulfate contents in water samples were selected so that they cover the entire range of sulfate concentrations found in each type of alternative water. Figure 2.1 is a graphical representation of the distribution of sulfate contents in different types of alternate water. Based on this information, five water samples were prepared. Three WWTP samples were prepared with sulfate concentrations of 1,000 ppm, 1,500 ppm, and 3,000 ppm. A sulfate level of 2,700 ppm represented ocean water while a sulfate level of 5000 ppm was selected to represent brine water. Table 4.9 and Table 4.10 show the composition of simulated WWTP, ocean, and brine waters used in sulfate testing.

Table 4.9 Composition of WWTP Water Used in Sulfate Content Tests

Compound	Concentration in ppm		
	1000	1500	3000
NaCl	791	791	791
$NaHCO_3$	110	110	110
Na_2SO_4	420	500	1600
K_2SO_4	515	1330	2690
$CaSO_4$	340	340	340
$MgSO_4$	240	240	240
$Mg(NO_3)_2$	12.0	11.9	11.9
NH_4Cl	29.7	29.7	29.7
TDS	2460	3350	5820

Table 4.10 Ocean and Brine Water Composition for Sulfate Content Tests

Compound	Concentration in ppm	
	2700 (Ocean Water)	5000 (Brine Water)
NaCl	27,100	103,960
$NaHCO_3$	380	900
KCl	760	76
$CaCl_2$	1,140	5,900
$MgCl_2$	2,420	2,200
$MgSO_4$	3,400	6,250
TDS	35,200	119,286

4.5.2 Sulfate Content Test Matrix

Table 4.11 below shows the test matrix used in soil sulfate testing. It included 5 simulated wastewater samples and 5 soil types. For each type of soil and each wastewater source, tests were conducted at initial conditions (i.e. no alternative water added) plus 3 other increments of alternative water. The maximum water content was selected based on the experimentally determined optimum water content of each soil. Two intermediate water content increments were also selected for each soil.

Table 4.11 Test Matrix for Soil Sulfate Content Tests

Soil Name	Without Constr. Water	WWTP Water			Ocean Water	Brine Water
		1000ppm	1500ppm	3000ppm	2700ppm	5000ppm
SH-121 (Dallas)	$\Delta w = 0\%$	$\Delta w = 26\%$	$\Delta w = 26\%$	$\Delta w = 26\%$	$\Delta w = 26\%$	$\Delta w = 26\%$
		$\Delta w = 20\%$	$\Delta w = 20\%$	$\Delta w = 20\%$	$\Delta w = 20\%$	$\Delta w = 20\%$
		$\Delta w = 15\%$	$\Delta w = 15\%$	$\Delta w = 15\%$	$\Delta w = 15\%$	$\Delta w = 15\%$
IH-30 (Dallas)	$\Delta w = 0\%$	$\Delta w = 19\%$	$\Delta w = 19\%$	$\Delta w = 19\%$	$\Delta w = 19\%$	$\Delta w = 19\%$
		$\Delta w = 15\%$	$\Delta w = 15\%$	$\Delta w = 15\%$	$\Delta w = 15\%$	$\Delta w = 15\%$
		$\Delta w = 10\%$	$\Delta w = 10\%$	$\Delta w = 10\%$	$\Delta w = 10\%$	$\Delta w = 10\%$
Flexbase (Odessa)	$\Delta w = 0\%$	$\Delta w = 11\%$	$\Delta w = 11\%$	$\Delta w = 11\%$	$\Delta w = 11\%$	$\Delta w = 11\%$
		$\Delta w = 8\%$	$\Delta w = 8\%$	$\Delta w = 8\%$	$\Delta w = 8\%$	$\Delta w = 8\%$
		$\Delta w = 4\%$	$\Delta w = 4\%$	$\Delta w = 4\%$	$\Delta w = 4\%$	$\Delta w = 4\%$
Flexbase (Lubbock)	$\Delta w = 0\%$	$\Delta w = 16\%$	$\Delta w = 16\%$	$\Delta w = 16\%$	$\Delta w = 16\%$	$\Delta w = 16\%$
		$\Delta w = 10\%$	$\Delta w = 10\%$	$\Delta w = 10\%$	$\Delta w = 10\%$	$\Delta w = 10\%$
		$\Delta w = 5\%$	$\Delta w = 5\%$	$\Delta w = 5\%$	$\Delta w = 5\%$	$\Delta w = 5\%$
Embank. (Lubbock)	$\Delta w = 0\%$	$\Delta w = 11\%$	$\Delta w = 11\%$	$\Delta w = 11\%$	$\Delta w = 11\%$	$\Delta w = 11\%$
		$\Delta w = 8\%$	$\Delta w = 8\%$	$\Delta w = 8\%$	$\Delta w = 8\%$	$\Delta w = 8\%$
		$\Delta w = 4\%$	$\Delta w = 4\%$	$\Delta w = 4\%$	$\Delta w = 4\%$	$\Delta w = 4\%$

4.5.3 Sulfate Content Test Procedure

The sulfate content tests were performed according to Tex-620-J: Determination of Soil Sulfate Content and Chloride Content. According the procedure specified in the test standard, 30 grams of soil screened through a No.40 sieve was heated with 300 grams of deionized water for 24 hours. The resulting slurry was then filtered through Watman No.42 filter paper and the volume of the filtrate that passed the filter recorded.

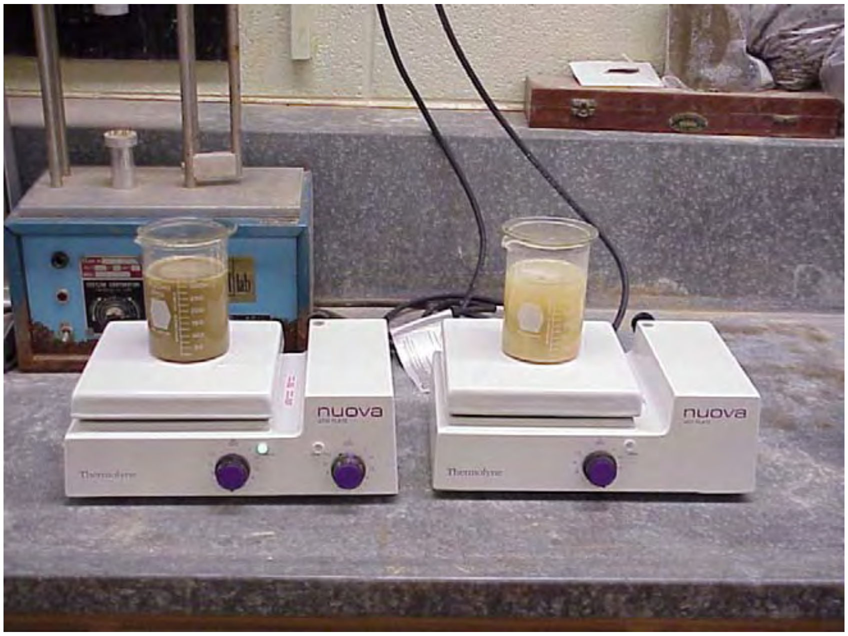


Figure 4.3 Heating Process in Soil Sulfate Content Testing

Samples from each filtrate collected were then analyzed for sulfate content using ion chromatography. The sulfate concentration level determined from the chromatogram and the volumes of filtrate collected were then used to calculate the average soil sulfate content. For soil samples treated with the simulated construction water, the procedure used for the determination of sulfate level remained the same except that the tests were carried out after the treated soil samples had been dried.

Figure 4.4 Filtering Process in Soil Sulfate Content Testing

Figure 4.5 Ion Chromatograph

4.6 Soil Dispersivity

As noted earlier, the dispersion potential of clay soils is sensitive to the composition of soil pore water. Of particular importance is the amount of sodium ions present in the exchange complex compared to divalent cations. The common parameters used in the determination of dispersion potential of soils are: exchangeable sodium percentage (ESP), and the sodium adsorption ratio (SAR).

4.6.1 Preparation of Construction Water for Soil Dispersion Testing

When selecting wastewater compositions for soil dispersivity testing, special emphasis should be given to the relative amount of sodium ions present in wastewater as opposed to divalent cations such calcium and magnesium. For this reason, the procedure used in the selection of wastewater compositions in this test series was different from that used for corrosivity and sulfate content tests. For this test series, the available wastewater composition data was plotted as shown in Figures 4.6 and Table 4.7 so that the most critical water composition parameter combinations could be identified. Figure 4.6 is a plot of sodium ion concentration versus total dissolved solids content in water. Figure 4.7 is a plot of the sodium to calcium and magnesium ratio versus total dissolved solids content in water. Based on the review of the above data four different alternative water compositions were selected. These are identified as: Brine Water #1 (TDS = 10,000 ppm), Brine Water #2 (TDS = 160,740 ppm), Ocean Water (TDS = 35,200), and Wastewater from Treatment Plant (TDS = 8,135 ppm). Each of the simulated, alternative water contained different levels of total dissolved solids (TDS) and different total sodium concentrations representing the most critical conditions found in each wastewater source. The compositions of these water samples and the sodium to calcium plus magnesium ion ratios are presented in Tables 4.12 through 4.14.

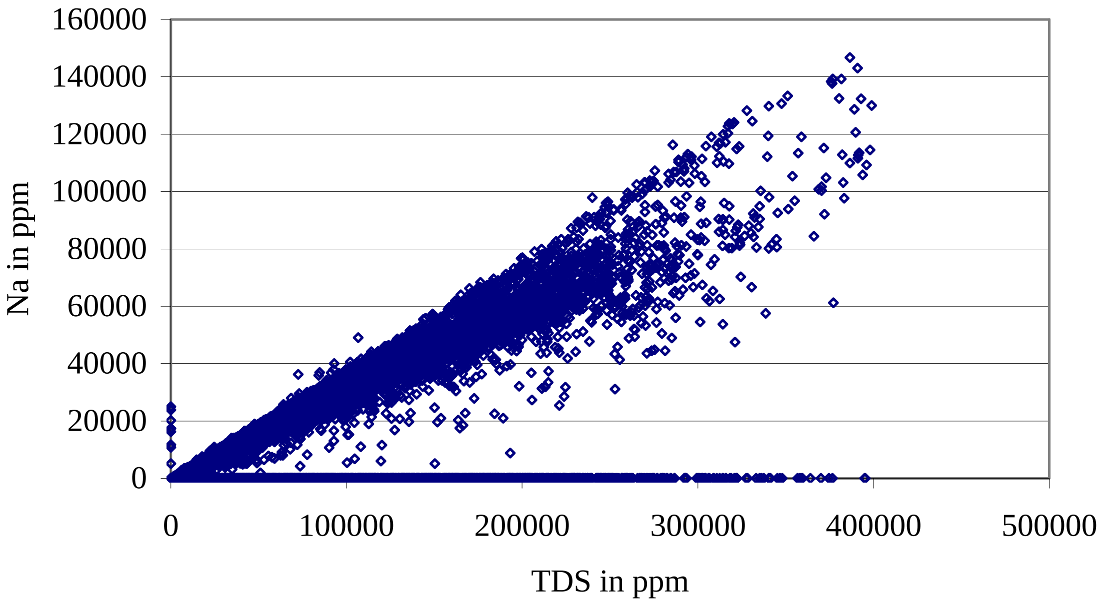


Figure 4.6 Plot of Sodium Concentration versus TDS in ppm.

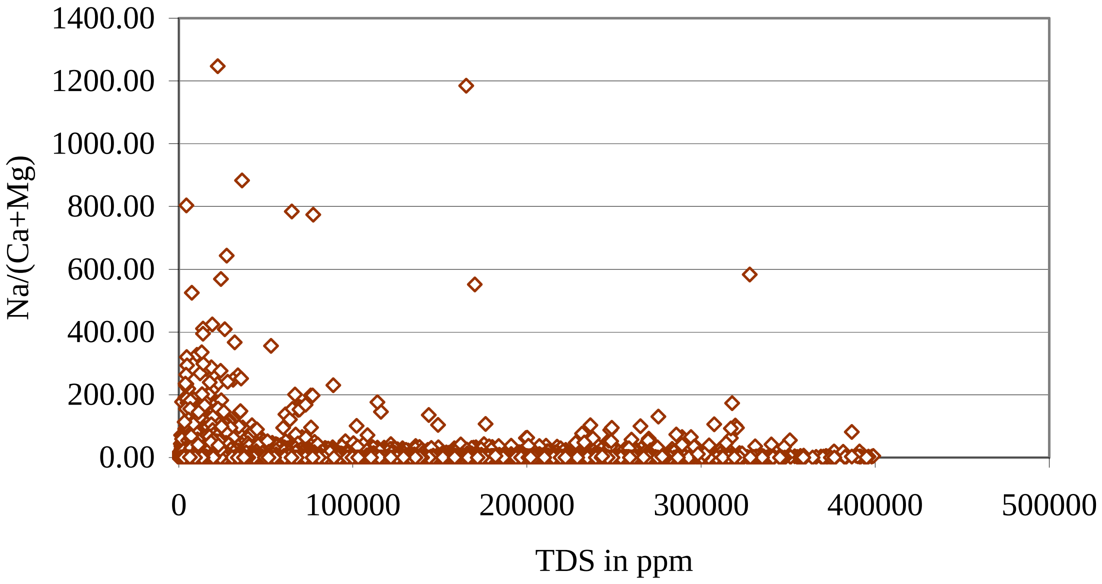


Figure 4.7 Plot of Sodium to (Calcium + Magnesium) ratio versus TDS.

Table 4.12 Recipe for Synthetic Brine Water#1

Compound	ppm
$\frac{Na^{+}}{Ca^{2+}+Mg^{2+}}$	149.99
NaCl	9851.50
NaHCO3	14.18
Na2SO4	5.12
CaSO4	45.20
MgSO4	62.80
K2SO4	21.20
TDS	10000.00

Table 4.13 Recipe for Synthetic Brine Water# 2

Compound	Concentration (ppm)
$\frac{Na^{+}}{Ca^{2+}+Mg^{2+}}$	4.01
NaCl	124000
KCl	160
CaCl2	28300
MgCl2	7050
MgSO4	960
NaHCO3	270
TDS	160740

Table 4.14 Recipe for Synthetic Ocean Water

Compound	Concentration (ppm)
$\frac{Na^{+}}{Ca^{2+}+Mg^{2+}}$	6.32
NaCl	27100
NaHCO3	380
KCl	760
CaCl2	1140
MgCl2	2420
MgSO4	3400
TDS	35200

Table 4.15 Recipe for synthetic alternative water WWTP

Compound	3000 ppm
$\frac{Na^{+}}{Ca^{2+}+Mg^{2+}}$	30.44
NaCl	7475
NaHCO3	107
Na2SO4	99
K2SO4	40
CaSO4	197
Mg(NO3)2	8
MgSO4	194
NH4Cl	15
TDS	8135

4.6.2 Sodium Adsorption Test

The sodium adsorption ratio (SAR) was established for control samples and for the samples pretreated with simulated alternative water. The SAR level is a measure of the potential dispersibility of soil and is established based on a chemical analysis of the pore water of the soil sample. As previously stated, calculation of the SAR is given by the following equation.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}}$$

The calculated SAR level has units of milli equivalents per liter (meq/liter).

4.6.3 Double Hydrometer Test

The potential dispersion characteristics of a specific soil must be determined if the soil is to be used for engineering purposes. In this study, the “Standard Test Method for Dispersive Characteristics of Clay Soil by Double Hydrometer,” ASTM D 4221, was used to test each of the potential soil samples before and after treatment with the synthetic alternative water samples. The percent finer than 5 µm was determined using ASTM D 422 and also using ASTM D 4221. The standard ASTM D 4221 differs from ASTM D 422 in that no chemical dispersant or mechanical agitation is incorporated. The percent finer than 5 µm using D 4221 is divided by the percent finer than 5 µm using D 422, and the result is multiplied by 100 to give the percent dispersion. The Double Hydrometer approach was used to help assess the dispersibility characteristics of the soil, since no single test has been developed that can reliably identify all dispersive soils (Engineering Properties of Soils and Rocks, Bell, F. G., 2000).

4.7 Soil Index Tests

Index properties of soil can be influenced by the chemical composition of the aqueous solution within the soil's pore volumes. Therefore, ionic species dissolved in construction water can be expected to impart some aspect of the soil performance when it is being used in construction. Similarly, shrink and swell characteristics of base and sub base soil materials may be affected by the chemical composition of components in the water that is mixed with the soil during construction. Since index properties of soils, specifically Liquid Limit and Plasticity Index and Bar Linear Shrinkage, are used in the selection of base and sub base materials, it was deemed important in this investigation to determine the potential impact that construction water from alternative sources might have on soil index parameters. The following paragraphs describe the three typical tests used in this study. In each case the construction water used was the same as that prepared and used for the soil dispersive tests just described in Section 4.6.

4.7.1 Atterberg Limit Tests

Atterberg Limit Tests (Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI)) were performed on soil samples both before and after treating it with the simulated construction water. These tests were done on only four of the soil samples. The Odessa Flexbase was not tested because of the amount of material available was limited and also because soil properties such as plasticity index were very similar to the Lubbock Flexbase and Lubbock Embankment soils being tested.

Atterberg Limits Tests were conducted according to Tex-104-E and Tex-105-E test procedures to establish the soil index properties LL, PL, and PI. For soil samples treated with synthetic construction water, the soil was first oven dried at 60 °C for approximately 12 hours before the addition of the construction water. The treated sample was mixed thoroughly and then covered tightly with an aluminum foil to prevent moisture loss. The test samples were kept sealed for 16 hours to allow adequate time for moisture distribution within the soil sample. The sample was then unsealed, dried in the oven for 12 hours, and the Atterberg Limits tests performed according to the standard specifications.

The determination of Atterberg Limits Test characteristics was completed for varying types of construction water with the soil samples. The test matrix is shown below in the Table 4.16. The table shows the initial water content for the untreated soil and the amount of alternative water used in each treatment. The water content chosen for treatment using simulated water was the optimum moisture content for a given soil.

Table 4.16 Test Matrix for Atterberg Limits Tests

Soil Name	Without Construction. Water	WWTP (3000ppm)	Ocean Water	Brine Water	
				Brine 1 (TDS = 10000 ppm)	Brine 2 (TDS = 160740 ppm)
SH-121 (Dallas)	Δw = 0%	Δw = 26%	Δw = 26%	Δw = 26%	Δw = 26%
IH-30 (Dallas)	Δw = 0%	Δw = 19%	Δw = 19%	Δw = 19%	Δw = 19%
Flexbase (Lubbock)	Δw = 0%	Δw = 16%	Δw = 16%	Δw = 16%	Δw = 16%
Embank. (Lubbock)	Δw = 0%	Δw = 11%	Δw = 11%	Δw = 11%	Δw = 11%

4.7.2 Bar Linear Shrinkage Test

Bar Linear Shrinkage investigations were done on the soil samples before and after treating them with the simulated water. Tests were performed on four soil samples, as in the prior Atterberg Limits Tests, with the Odessa Flexbase soil excluded.

The Bar Linear Shrinkage Tests followed Tex-107-E, TxDOT test protocol – Determination of Bar Linear Shrinkage of Soils. Using this procedure, the moist sample remaining after Liquid Limit Test is used to form a soil bar. Water is added until the soil sample under test flows of its own accord and closes the grove created in the liquid limit apparatus. The sample at this point is placed in the shrinkage mold and the initial length of the bars determined. The sample is air dried at 110 °C until it reaches a constant mass. Then the final length is measured and the result is reported in Percent Linear Shrinkage.

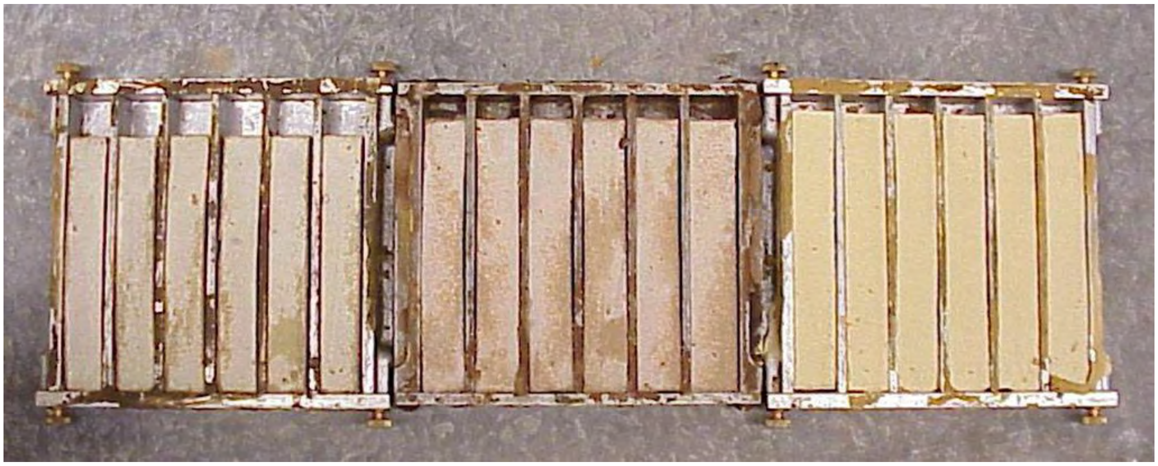


Figure 4.8 Bar Linear Shrinkage Molds.

The Bar Linear Shrinkage Tests were done varying the type of construction water with the soil samples. The test matrix of which is shown below in Table 4.17. The table shows the water content for the treatment level with alternative water and the initial water content for untreated soils. The water content chosen for treatment of the soils with simulated water was the optimum moisture content for each soil.

Table 4.17 Test Matrix for Bar Linear Shrinkage Tests

Soil Name	Without Constr. Water	WWTP (3000ppm)	Ocean Water	Brine Water	
				Brine 1	Brine 2
SH-121 (Dallas)	Δw = 0%	Δw = 26%	Δw = 26%	Δw = 26%	Δw = 26%
IH-30 (Dallas)	Δw = 0%	Δw = 19%	Δw = 19%	Δw = 19%	Δw = 19%
Flexbase (Lubbock)	Δw = 0%	Δw = 16%	Δw = 16%	Δw = 16%	Δw = 16%
Embankment (Lubbock)	Δw = 0%	Δw = 11%	Δw = 11%	Δw = 11%	Δw = 11%

4.7.3 Expansion Index Test

ASTM D 4829, “Standard Test Method for Expansion Index of Soils,” was used to determine the expansion potential of each of the soils. All soils were tested before and after pretreatment with alternative water. Pretreatment was done at optimum moisture content. The specimen is compacted into a metal ring so that the degree of saturation is between 40 and 60 percent. A vertical confining pressure of 6.9 kPa (1 lbf/in^2) was applied to the specimen placed in a consolidometer, and then the setup is inundated with distilled water. The deformation of the specimen was recorded for 24 hours, or until the rate of deformation became less than 0.0005 mm/h (0.0002 in/h), whichever occurred first.

CHAPTER V

REVIEW AND ANALYSIS OF DATA

5.1 Overview

The laboratory test program described in Chapter IV investigated physical/chemical interactions of five different soil samples used in highway construction with five different types of alternative sources. This chapter provides a summary review of the findings from the above lab test program. It includes results from: 1) basic soil characterization, 2) soil resistivity and pH tests, 3) soil sulfate and chloride tests, 4) tests for soil dispersivity, 5) shrink/swell characterization, and 5) soil index properties.

5.2 Soil Characterization Test Data

5.2.1 Particle Size distribution

The weight based, particle size distribution curves for each of the five soil samples are shown in Figure 5.1. The particle size distribution curve for the concrete sand indicates that this material is a poorly graded sandy soil with particle sizes that fit into a narrow band of sieve sizes. The two flexbase soil samples obtained from Odessa and Lubbock were well graded soils with significant fines content. The soils were quite similar in terms of particle size distribution with Odessa flexbase material being slightly coarser than the Lubbock soil. SH-121 and IH-30 soils from Dallas were quite different from the other 3 soils in that they contained much higher percentages of fines.

Each of the five soil samples were also classified according to the bulk fractions of gravel, sand, and fines that they contained. The weight percentages of gravel, sand, and fines for each soil are given in Table 5.1. The soil sample designated SH-121 was composed predominantly of fines, (~ 93%) and contained no gravel. The predominant component of sample IH-30 was also fines, but this soil contained a substantial amount of sand as well (~25%). The two flexbase materials were predominantly gravel, but they also contained significant amounts of sand and fines. As expected, the concrete sand sample consisted of almost solely of sand, ~ 99%, with the remaining 1% consisting of gravel and fines.

Table 5.1 Weight Percent of Gravel, Sand and Fines in Soil Samples

Soil	Percent of Gravel	Percent of Sand	Percent of Fines
SH 121	0	7	93
IH 30	3	24	73
Flexbase (Odessa)	45	32	23
Flexbase (Lubbock)	40	36	24
Concrete Sand	1	99	0

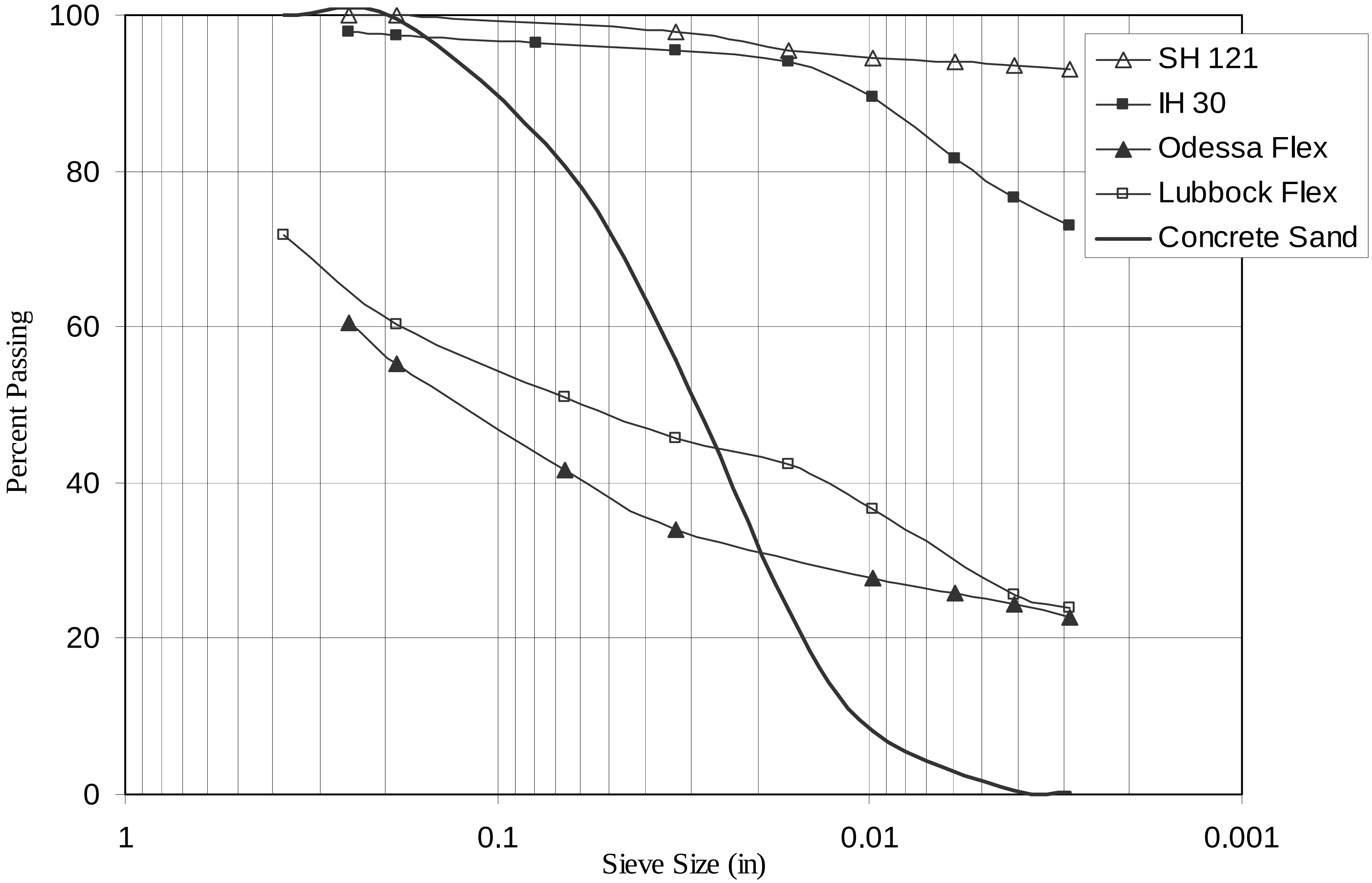


Figure 5.1 Weight Percentage and Particle Size Distribution Curves for the Experimental Soil Samples

5.2.2 Percent Fines

The percentages of fines for the five soil samples used in this study are listed in Table 5.2. Since the percentages of fines for soil samples SH121 and IH30 are both greater than 50%, they are classified as fine grained soils. The two flexbase soil samples from Odessa and Lubbock and the concrete sand sample reflect fines percentages less than 50% and, therefore are classified as coarse grained soils. Based on sieve analysis, the percent fines in concrete sand sample was determined to be 0.19 % fines. This percent fines was considered negligible and, therefore, is reported as zero in Table 5.2. .

Table 5.2 Weight Percentage Finer than No. 200 Sieve for the Five Soil Samples

Soil	Percent Finer than No. 200
SH 121	93%
IH 30	73%
Flexbase (Odessa)	23%
Flexbase (Lubbock)	24%
Concrete Sand	0%

5.2.3 Atterberg Limits

The Atterberg limits determined for the five soil samples are shown in Table 5.3. The table shows the liquid limit (LL), the plastic limit (PL) and the plasticity index (PI) for each soil. Among the five soils, the soil that had the highest percent fines, i.e. SH 121 soil also had the highest PI. IH-30 soil had the second highest PI value. The Atterberg limits of the two flexbase materials were similar, with Odessa flexbase showing slightly higher plasticity. The concrete sand is representative of a non-plastic soil, and therefore its Atterberg limits could not be determined.

Table 5.3 Atterberg Limits Determined for the Five Soil Samples

Soil	Atterberg Limits		
	Liquid Limit	Plastic Limit	Plasticity Index
SH 121	64	33	31
IH 30	42	21	21
Flexbase (Odessa)	23	13	10
Flexbase (Lubbock)	26	18	8
Concrete Sand	NP	NP	NP

NP = Non-Plastic

5.2.4 Soil Classification

The five soil samples were classified according to USCS, and their classifications are given in Table 5.4. As shown, the soils are classified first by a group symbol, which is then followed by the group name. The first letter of the group symbol indicates the predominant component present in the soil.

Table 5.4 USCS Soil Classification for the Five Soil Samples

Soil	USCS Classification
SH 121	MH - Elastic Silt
IH 30	CL – Lean clay with sand
Flexbase (Odessa)	GC – Clayey Gravel with Sand
Flexbase (Lubbock)	GC – Clayey Gravel with Sand
Concrete Sand	SP- Poorly Graded Sand

5.2.5 Optimum Moisture Content

The experimentally determined optimum moisture content for each of the five soil samples is listed in Table 5.5. The maximum dry density of the soil is obtained when the moisture content is equivalent to the optimum moisture content. Because soil sample SH121 exhibited the highest plasticity, it has the capacity to absorb more water and, therefore, registered the highest optimum moisture content. The concrete sand drains well, absorbs very little water and exhibited the lowest optimum moisture content.

Table 5.5 Optimum Moisture Content Measured for the Five Soil Samples

Soil	Optimum Moisture Content
SH 121	26%
IH 30	19%
Flexbase (Odessa)	11%
Flexbase (Lubbock)	16%
Concrete Sand	9%

5.3 Influence of Construction Water Quality on Soil Corrosivity

TxDOT specifications for MSE retaining wall backfill rely on *soil resistivity* and *soil pH* as the primary measures of corrosion potential of a given soil. As mentioned previously, a soil with a resistivity of 3000 ohm-cm or higher is considered acceptable. If the electrical resistivity of a soil falls to between 1,500 ohm-cm and 3,000 ohm-cm, the soil is considered to be marginally corrosive. When this occurs, TxDOT engineers must also consider the total sulfate and chloride concentration level of the soils that might be encountered in the construction project. Accordingly, this study investigated the effect that the alternative construction water quality might have on soil characteristics of resistivity, pH as well as sulfate and chloride concentrations in soil. These findings are discussed in the sections 5.3.1 through 5.3.4.

5.3.1 Soil Resistivity Data

5.3.1.1 Baseline Soil Resistivity

Prior to treating the five soil samples with any of the construction water, the electrical resistivity of the samples was tested using deionized water. This was done to establish the baseline. The treatment procedure was described in an earlier section, and the resistivity results can be found in Table 5.6. The measured resistivity values indicate that the initial resistivity values of the three coarse grained soils, i.e. the two flexbase soils from Odessa and Lubbock and the Concrete Sand, were higher than the two fine grained soils identified as SH121 and IH30. This finding is in agreement with results reported in the *National Soil Survey Handbook (2002)*, which found that coarse textured soils are less corrosive than fine textured soils.

Only two of the soil samples, Lubbock flexbase and concrete sand, exhibited a resistivity greater than 3000 ohm-cm. Therefore, these two soils were categorized as non-corrosive. The Odessa flexbase soil sample exhibited an initial resistivity of 2100 ohm-cm. Since this value lies between 1500 and 3000 ohm-cm, the Odessa flexbase soil was categorized as marginal with respect to corrosivity. A marginal soil can be considered non-corrosive only if its chloride and sulfate content is, respectively, less than 100 ppm and 200 ppm. The initial resistivity values of soil samples SH121 and IH30 were both ~ 1100 ohm-cm, which is below the base 1500 ohm-cm limit for corrosivity. Therefore, irrespective of their pH values, these two soils were considered to be corrosive even before construction water was added.

Table 5.6 Soil Resistivity Values before the Addition of Construction Water

Soil	Resistivity /ohm-cm
SH 121	1100
IH 30	1100
Flexbase (Odessa)	2100
Flexbase (Lubbock)	3000
Concrete Sand	4700

5.3.1.2 Impact of Construction Water on Soil Resistivity

The results from resistivity testing of the five soil samples after the addition of construction water are presented in Table 5.7. These values can be compared with the values of resistivity listed in Table 5.6. The difference in the resistivity values in the two tables reflect the effects of alternative construction water that was added to soil. Each soil sample was tested at several different water content levels. The water content was increased in small increments until the optimum water content of the soil was reached. Since SH-121 and IH-30 soils had higher optimum moisture contents than the other soils, they were subjected to four water contents. The remaining three soil samples were tested with only three water contents for each TDS concentration.

A comparison between Table 5.6 and 5.7 resistivity values show that adding construction water results in a significant drop in the electrical resistivity of all five soil samples. Among the alternative water sources used in testing, the one with the lowest TDS level was a municipal wastewater with a TDS concentration of 7000 ppm. Even this TDS concentration resulted in a significant drop in soil resistivity. After adding only 5% of the above wastewater, the resistivity measured for the flexbase sample from Lubbock dropped from 3000 to 1900 ohm-cm while the resistivity of the concrete sand sample dropped from 4700 ohm-cm to 1600 ohm-cm. Thus, the Lubbock flexbase and the concrete sand soil samples, which were initially classified as non-corrosive, will no longer be in that category. Electrical resistivity tests performed on the same soils and wastewater water with TDS = 15,000 ppm resulted in resistivity levels dropping to 1200 and 1300 ohm-cm. Since both values are now below the established lower threshold of 1500 ohm-cm, these soils will be now classified as corrosive irrespective of their pH levels or sulfate and chloride concentration levels.

Table 5.7 Experimental Soil Resistivity Values after Adding Construction Water

Soil Name	Alternative Water Content	Wastewater from Treatment Plant			Ocean	Brine
		7,000 ppm	15,000 ppm	25,000 ppm	35,000 ppm	100,000 ppm
SH 121	8 %	540	450	330	245	160
	15 %	440	340	265	170	79
	20 %	400	300	225	140	64
	26 %	375	260	180	120	54
IH 30	5 %	740	595	480	325	220
	10 %	620	450	360	225	120
	15 %	525	375	290	165	81
	19 %	450	325	250	150	80.5
Flexbase (Odessa)	4 %	1400	900	820	505	225
	8 %	860	560	510	280	135
	11 %	710	470	420	220	98
Flexbase (Lubbock)	5 %	1600	1200	840	445	210
	10 %	1100	690	460	250	115
	16 %	740	480	330	170	71
Concrete Sand	5 %	1900	1300	860	440	200
	15 %	950	545	345	180	72.5
	25 %	650	360	245	125	51.5

The TDS concentrations for the ocean water and brine water are both higher than the wastewater treatment plant (WWTP) water samples. The data in Table 5.7 indicates with all the soils, the electrical resistivity values recorded with ocean and brine water were lower than the values recorded for the WWTP samples. These observations confirm the fact that the drop in soil resistivity increases with increase in TDS concentration from the alternative water source and, therefore, the soil will become progressively become more corrosive.

Another trend that can be readily noticed in the data is that, for the five soil samples that were tested at a given concentration of TDS, the resistivity decreased as the amount of alternative water added was increased. For example, for IH-30 soil, when ocean water having 35,000 ppm of TDS was added in increments of 5%, 10%, 15% and 19% by weight, the final resistivity values recorded were 325, 225, 165 and 150 ohm-cm. This direct relationship is consistent for all the soils samples tested in this investigation. These observations confirmed prior literature citations which stated that soil resistivity decreases as the level of soluble salts, TDS, in the water increases (Edgar, 1989). The results of this investigation also indicate that when both the TDS concentration in the alternative water and the amount of that water used in construction were increased, the resistivity decreased.

For the five experimental soils used in this investigation, the variation of soil electrical resistivity is depicted in Figures 5.2 to 5.6. In these figures, soil resistivity is plotted as a function of different alternative water content and for different TDS concentrations measured in the alternative water. The following trends can be seen in data plotted in these figures: (a) coarse granular soil with smaller percent fines shows greater sensitivity than soils with higher fines content, (b) the largest drop in resistivity occurs with the first increment of water; subsequent resistivity drops are smaller.

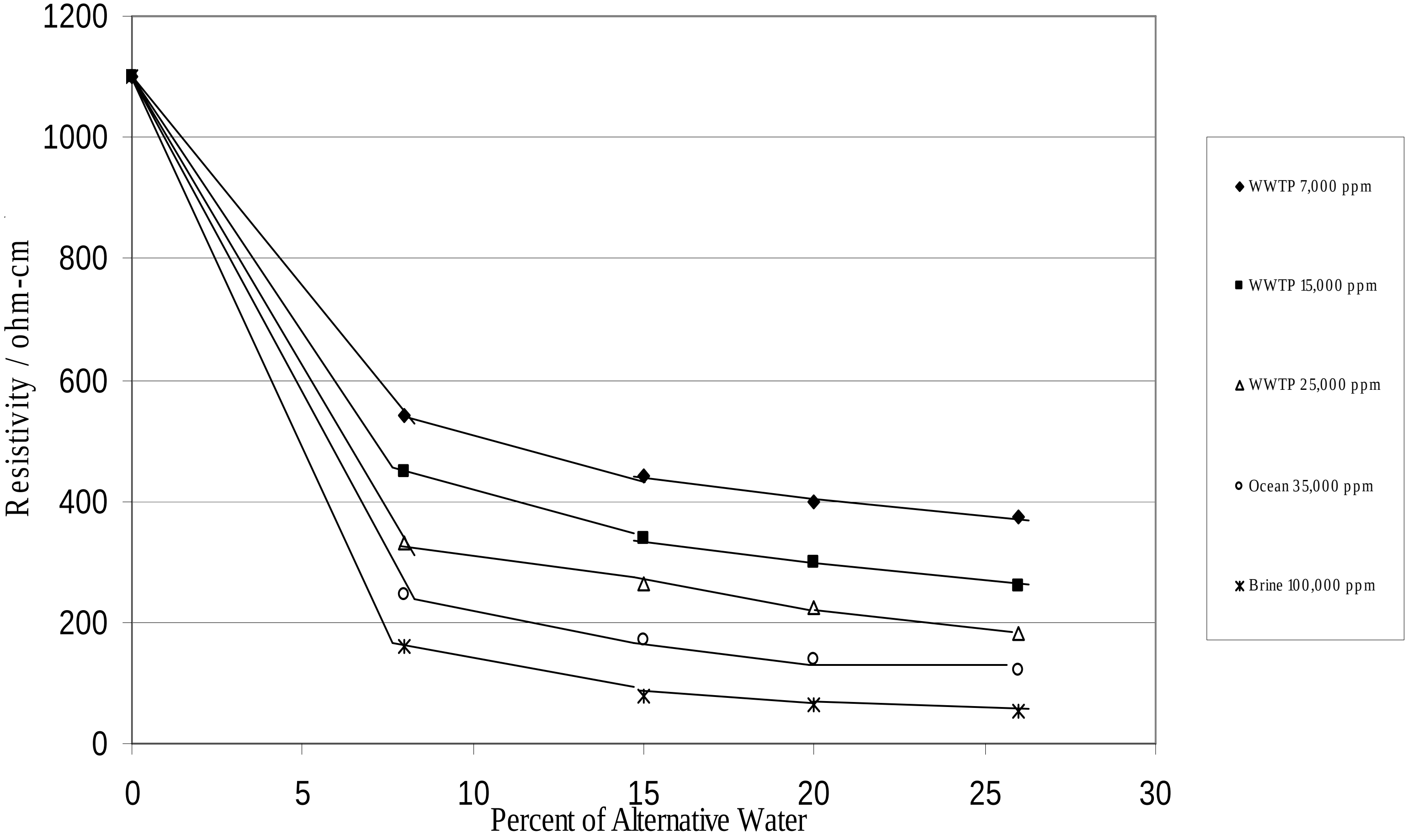


Figure 5.2 Variation of Soil Resistivity with Construction Water for SH121

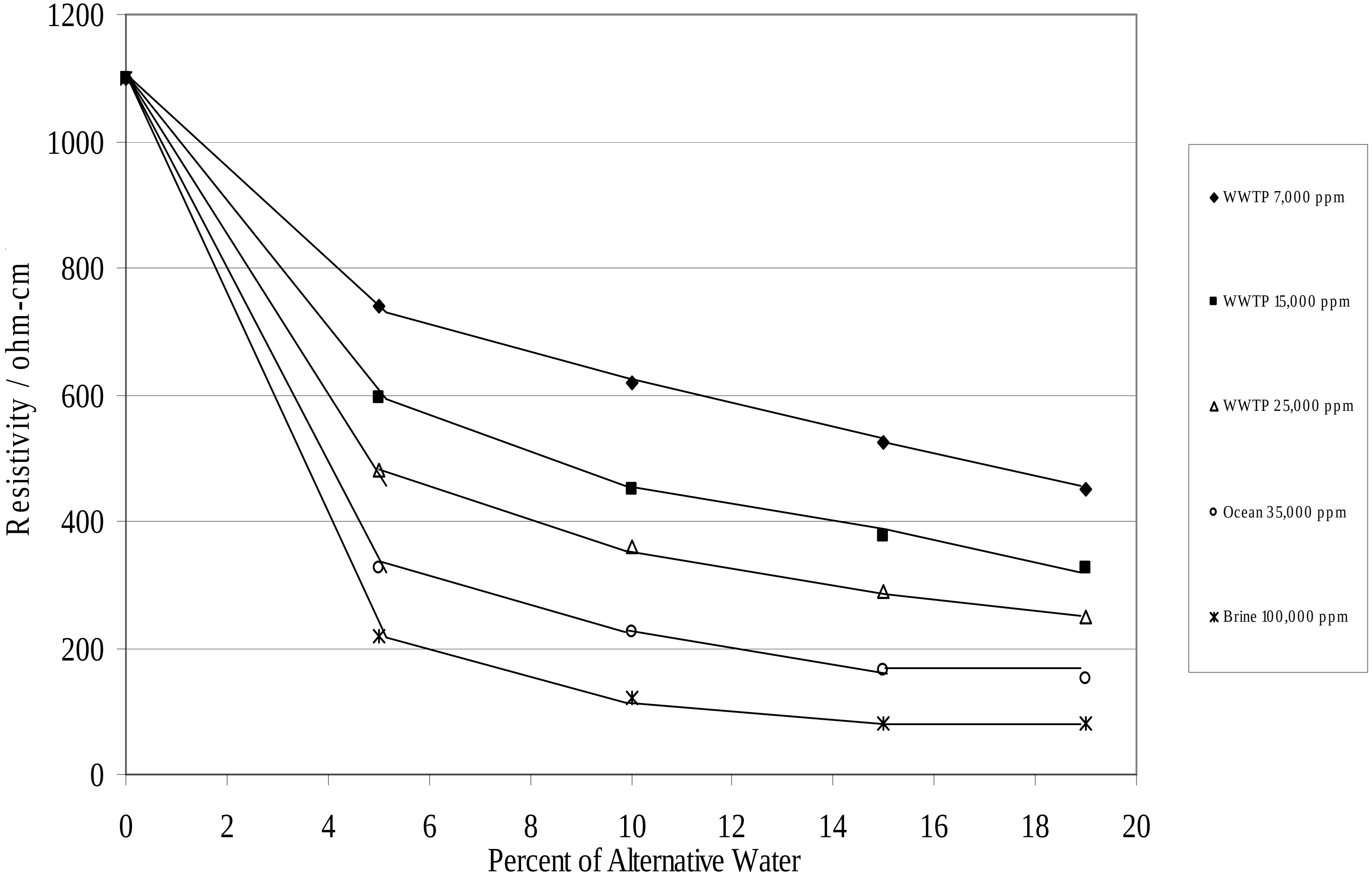


Figure 5.3 Variation of Soil Resistivity with Construction Water for IH30

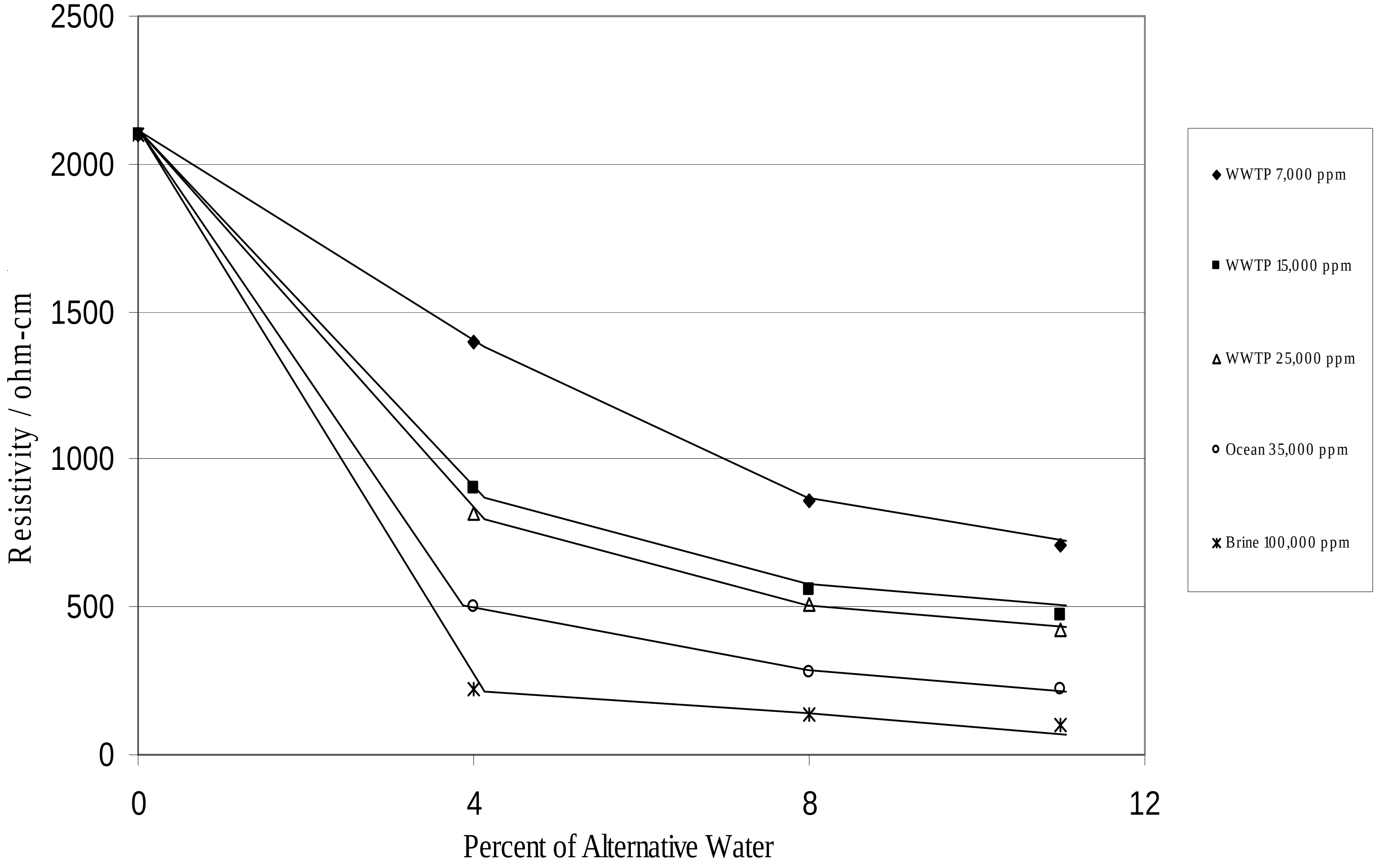


Figure 5.4 Variation of Soil Resistivity with Construction Water for Odessa Flexbase

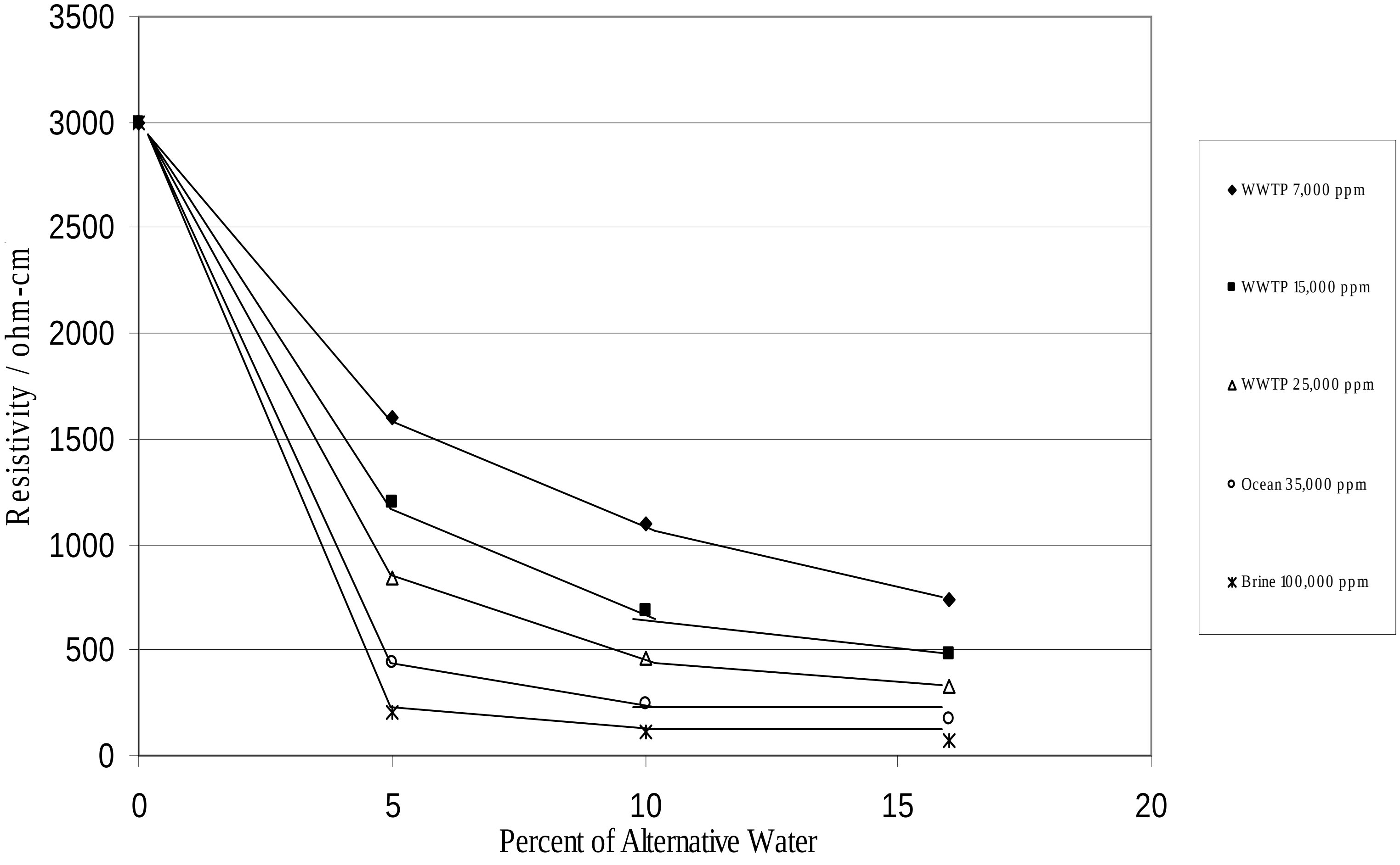


Figure 5.5 Variation of Soil Resistivity with Construction Water for Lubbock Flexbase

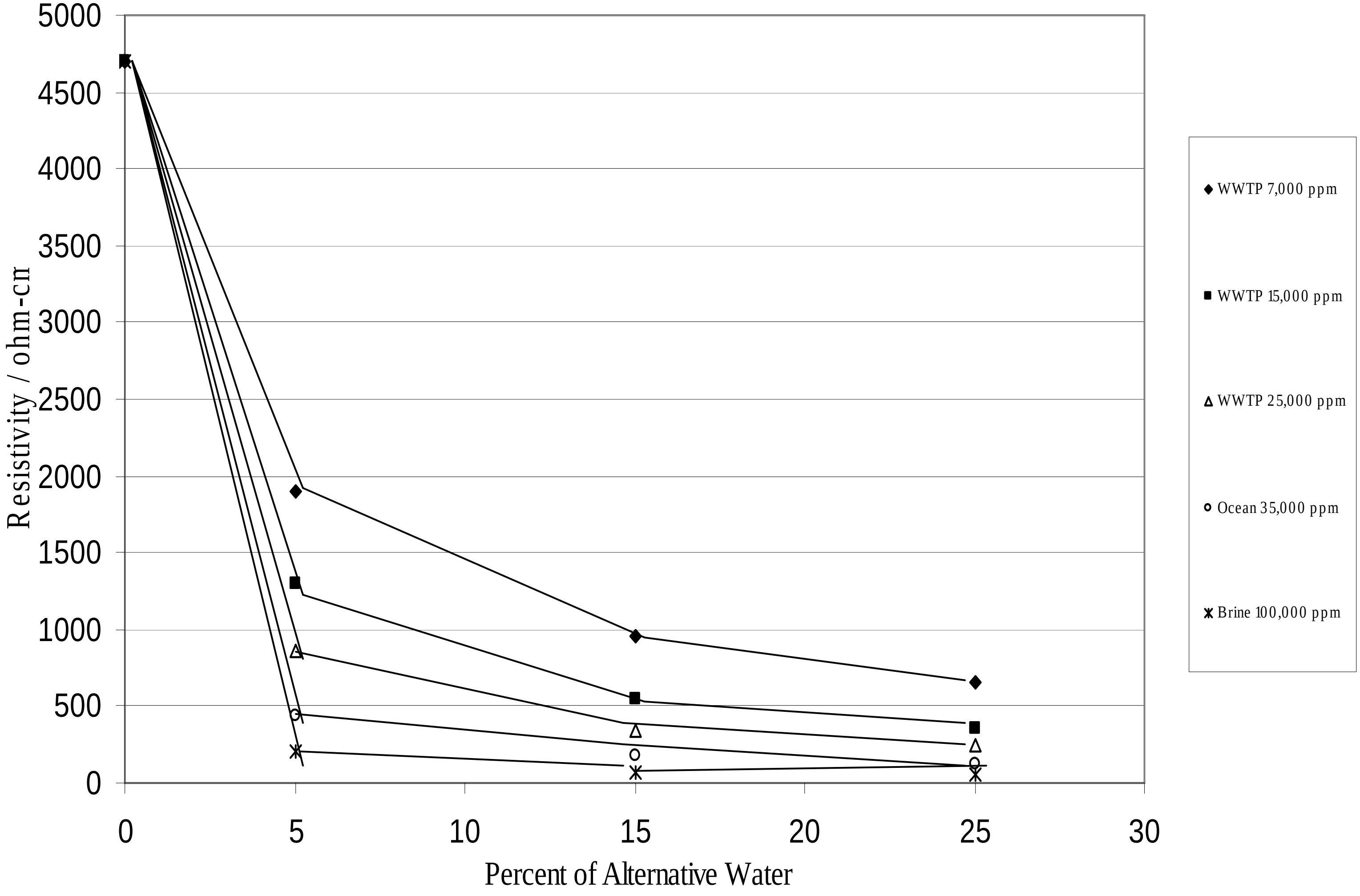


Figure 5.6 Variation of Soil Resistivity with Construction Water for Concrete Sand

Table 5.8 Percent Water Added and Decrease in Soil Resistivity

Soil Name	Waste Water From Treatment Plant			Ocean Water	Brine Water
	7,000 ppm TDS	15,000ppm TDS	25,000 ppm TDS	35,000 ppm TDS	100,000 ppm TDS
SH-121 (Dallas)	26% (725)	26% (840)	26% (920)	26% (980)	26% (1046)
	20% (700)	20% (800)	20% (875)	20% (960)	20% (1036)
	15% (660)	15% (760)	15% (835)	15% (930)	15% (1021)
	8% (560)	8% (650)	8% (770)	8% (855)	8% (940)
IH-30 (Dallas)	19% (650)	19% (775)	19% (850)	19% (950)	19% (1019.5)
	15% (575)	15% (725)	15% (810)	15% (935)	15% (1019)
	10% (480)	10% (650)	10% (740)	10% (875)	10% (980)
	5% (360)	5% (505)	5% (620)	5% (775)	5% (880)
Flexbase (Odessa)	11% (1390)	11% (1630)	11% (1680)	11% (1880)	11% (2002)
	8% (1240)	8% (1540)	8% (1590)	8% (1820)	8% (1965)
	4% (700)	4% (1200)	4% (1280)	4% (1595)	4% (1875)
Flexbase (Lubbock)	16% (2260)	16% (2520)	16% (2670)	16% (2830)	16% (2929)
	10% (1900)	10% (2310)	10% (2540)	10% (2750)	10% (2885)
	5% (1400)	5% (1800)	5% (2160)	5% (2555)	5% (2790)
Concrete Sand	25% (4050)	25% (4340)	25% (4455)	25% (4575)	25% (4648.5)
	15% (3750)	15% (4155)	15% (4355)	15% (4520)	15% (4627.5)
	5% (2800)	5% (3400)	5% (3840)	5% (4260)	5% (4500)

Note- The values outside parenthesis represent the percent water added while values within parenthesis represent change in soil resistivity (ohm-cm) as a result of adding water

5.3.2 Prediction of Change in Soil Resistivity

The soil resistivity testing conducted in this research included 5 different soil types and 5 different wastewater compositions. For each soil type and for each wastewater, tests were repeated for different water content increments. The resulting database consisted of 85 data points (Table 5.8). These data were then used as the basis for development of a model that can predict the change in soil resistivity that can be expected when wastewater of known composition is added to it.

As a first step in the development of the model, data presented were plotted again as shown in Figure 5.7. In this plot, each data series represents one soil type. In other words, data obtained from all of the tests that were conducted on one soil type with the 5 different wastewater compositions were combined into a single data series. This was done by calculating the product of percent wastewater mixed with soil and the total dissolved mineral content in the wastewater (i.e. $\Delta w \cdot TDS$) and using it as the x-variable. The change is soil resistivity, $\Delta\rho$ that occurs with increasing ($\Delta w \cdot TDS$) can be represented by the following functional form:

$$\Delta\rho = \rho_0 \frac{\omega^n}{\omega^n + a} \qquad (5.1)$$

where: $\Delta\rho$ = change in resistivity (ohm-cm)
ρ_0 = initial soil resistivity (ohm-cm)
ω = $\Delta w \cdot TDS$, amount of soluble mineral added from wastewater
n = exponent to be determined by curve-fitting data
a = constant to be determined by curve fitting data

The above functional form was selected because it was capable of accurately mimicking the trends observed in the data. For example, when $\omega = \Delta w \cdot TDS = 0$, then $\Delta\rho = 0$. Similarly, when $\omega = \Delta w \cdot TDS \to \infty$, then $\Delta\rho \to \rho_0$. In other words, if the amount of soluble mineral added to soil is very large, then the resistivity of the soil approaches zero. This is precisely the same trend that was seen in the experimental data.

In the next step, the “a” and “n” parameters for each soil were determined by regression analyses (Table 5.8).

Table 5.9 Constant, a and Exponent, n for the 5 Soil Types Tested

Soil Type	Constant, *a*	Exponent, *n*	R^2-value
SH-121 (Dallas)	1994.3	0.695	0.997
IH-30 (Dallas)	2211.1	0.692	0.995
Flexbase (Odessa)	2413.5	0.750	0.996
Flexbase (Lubbock)	2687.0	0.781	0.995
Concrete Sand	2591.0	0.817	0.982

The extremely high R^2-values (0.982-0.997) shown in Table 5.8 above confirm the fact that Eq. (5.1) is an appropriate form of equation to be used to describe the relationship between $\Delta\rho$ and ω.

The results obtained from above analyses yield a set of regression equations that could serve as predictive models for each of the soils types tested. These models will not be useful in predicting changes in resistivity that would occur in any other soil. To make such prediction it is necessary to develop a more generalized model.

Therefore, in the next step, further analyses were conducted to develop relationships between the constant *a* and exponent *n* and more fundamental soil properties. Review of *a* and *n* parameters clearly show that both of these parameters decrease in magnitude for more fine-grained soils with higher plasticity. Therefore, it was determined that regression analysis should be performed to develop regression equations with *a* and *n* as dependent variables and percent fines and plasticity index as independent variables. The regression equations and the R^2-values obtained are shown below:

$$n = 0.821 - 0.0016F - 0.0035(PI) + 4.42x10^{-5}(F \cdot PI) \qquad (5.2)$$

$R^2 = 0.959$

$$a = 26267.0 + 2.814F - 16.14(PI) - 0.146(F \cdot PI) \qquad (5.3)$$

$R^2 = 0.890$

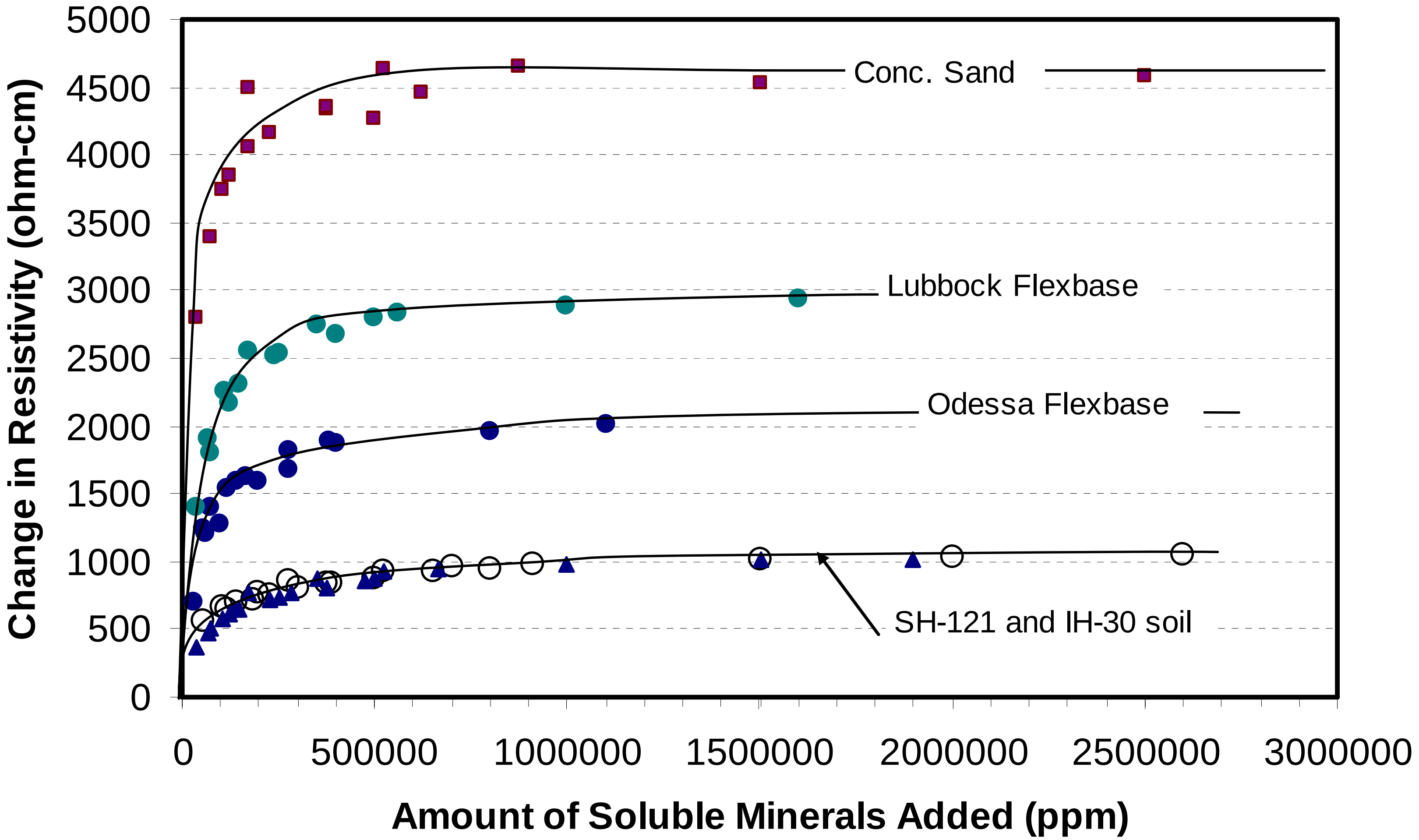
The generalized soil resistivity prediction model would thus include two separate steps in its calculation. In the first step, the constant *a* and exponent *n* are calculated for the particular soil using Equations (5.2) and (5.3). In the second step, the change in resistivity will be calculated using *a* and *n* in Eq (5.1).

The final resistivity, ρ_f of the soil can be calculated in the following manner.

$$\rho_f = \rho_0 - \rho_0 \frac{\omega^n}{\omega^n + a}$$

$$\rho_f = \rho_0 \frac{a}{\omega^n + a} \qquad (5.4)$$

Figure 5.8 shows a comparison between measured $\Delta\rho$ and $\Delta\rho$ calculated using the proposed methodology. The corresponding R^2-value is 0.993.



5.7 Change in Soil Resistivity versus Amount of Soluble Minerals Added

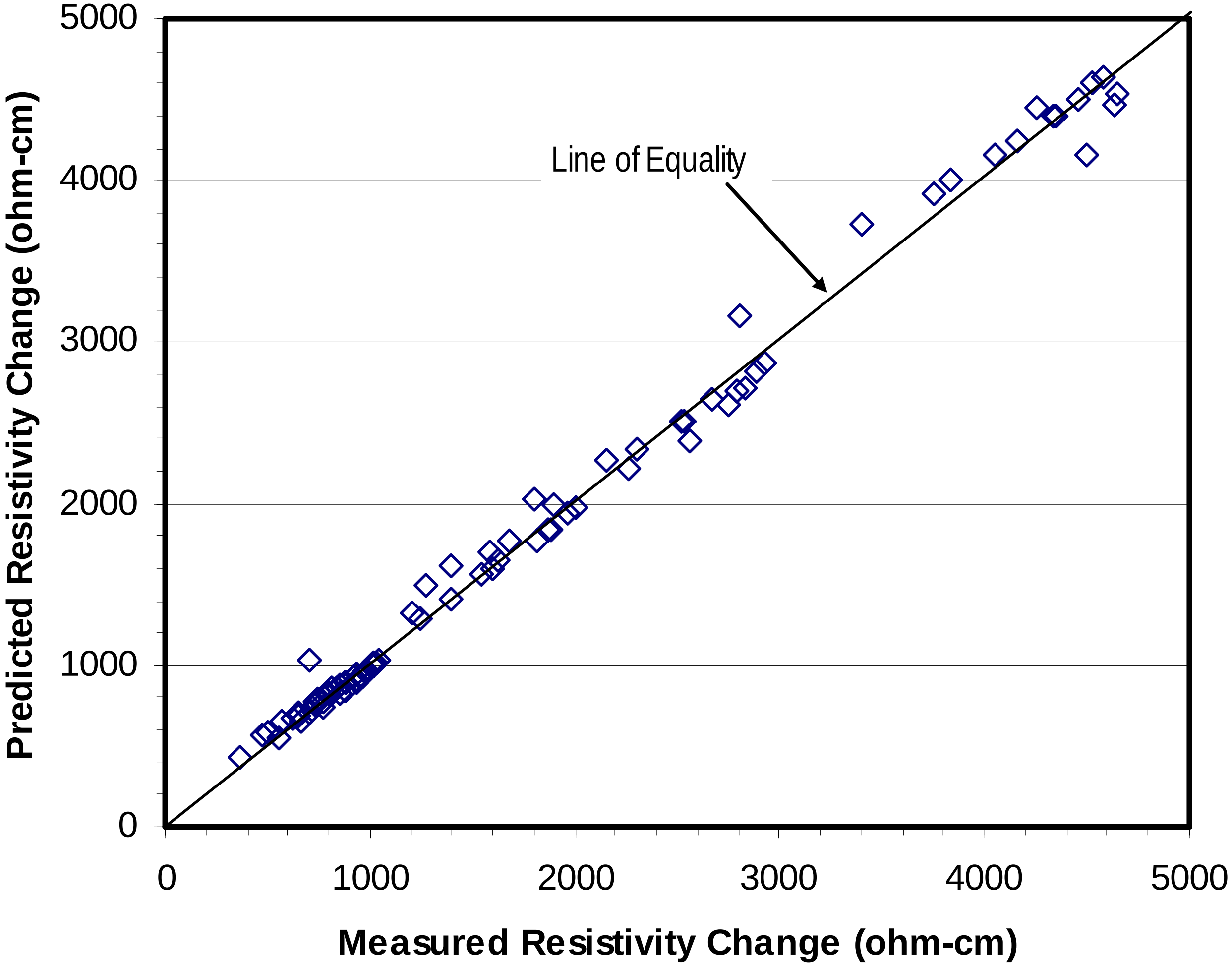


Figure 5.8 Change in Soil Resistivity; Comparison between Predicted versus Measured

5.3.3 Soil pH Data

5.3.3.1 Baseline Soil pH

The baseline soil pH values obtained from tests conducted in accordance with Tex-128-E are given in Table 5.9. These data reflect the pH values of the five soils before construction water was added. The pH level is the other soil parameter that is used in conjunction with resistivity for assessing its corrosive potential.

Table 5.10 Soil pH Values Before Adding Construction Water

Soil	pH
SH 121	8.1
IH 30	7.5
Flexbase (Odessa)	8.6
Flexbase (Lubbock)	9.0
Concrete Sand	10.6

For soil to be classified as non-corrosive, TxDOT specifications require that the soil pH remain with the range between 5.5 and 10.0. The experimental results presented in Table 5.9 indicate that the pH values of four out of the five soils are within the specified TxDOT range. Only the pH value of concrete sand, which was measured as 10.6, exceeded the upper limit of 10.0, but only by a narrow margin. Therefore, the initial pH values of the soils were assumed to be within the approved range, and the soils were not considered to be corrosive based on their measured pH level.

Palmer (1990) states that soil pH values outside the range of 4.5 to 8 are associated most commonly with contaminated soils. Hence, if the soils used for construction are not heavily contaminated, then it is most probable that their pH values will remain within the range specified by TxDOT. Palmer (1990) also reports that usually eastern marshy soils have low pH values. Low pH soil readings could be mitigated by using protective coatings, cathodic protection, alkalizing agents, and crushed limestone as a buffering backfill.

5.3.4 Soil Sulfate and Chloride Levels

When the electrical resistivity of a given soil sample is between 1,500 and 3,000 ohm-cm, it still cannot be designated a non-corrosive soil. Such soils may only be considered to be non-corrosive when their sulfate concentration is below 200 ppm and the chloride content of the soil is less than 100 ppm. In this investigation the sulfate and chloride concentrations levels for the experimental soil samples were tested. Test results are available for only four of the five soil samples; SH-121, IH-30, Odessa flexbase, and Lubbock flexbase. Sulfate and chloride concentrations were not determined for the Concrete Sand soil sample.

5.3.4.1 Baseline Soil Sulfate and Chloride Concentration Levels

Concentration levels of sulfate and chloride ions in the five test soils were measured prior to the addition of any construction water. The results are given in Table 5.10. Since the resistivity of the Concrete Sand sample was determined to be 4,700 ohm-cm before the addition any construction water, which is well above established threshold limit of 3,000 ohm-cm, the sulfate and chloride concentrations in Concrete Sand would have no effect on its corrosion characteristics.

The experimental test results given in Table 5.10 confirm that before any construction water was added the sulfate and chloride concentrations were below 200 ppm and 100 ppm respectively for soil samples SH-121, IH-30 and Lubbock flexbase. Sulfate and chloride concentrations below these threshold levels indicate that the corrosion potential of these soils is low. Therefore, even though the resistivity of Lubbock flexbase soil was equal to the threshold limit of 3,000 ohm-cm before adding construction water, its132 ppm sulfate concentration was less than the 200 ppm threshold limit while the 40 ppm chloride level was less than its threshold of 100 ppm. Therefore, the corrosion potential of the Lubbock flexbase soil sample can also be considered to be low.

Table 5.11 Soil Sulfate and Chloride Values Before the Addition of Construction Water

Soil	Sulfate Content/(mg/kg)	Chloride Content/(mg/kg)
SH 121	49	19
IH 30	58	38
Odessa Flexbase	302	81
Lubbock Flexbase	132	40

The Odessa flexbase soil had an initial resistivity of 2,100 ohm-cm, which was within the 1,500 to 3,000 ohm-cm range. Therefore, Odessa flexbase soils can only be considered non-corrosive if their in situ sulfate and chloride concentration levels are below the established threshold limits. Table 5.10 indicates that the measured sulfate and chloride ion concentration levels were 302 ppm and 81 ppm respectively for the Odessa flexbase soil sample. Although its chloride level was less than the established threshold of 100 ppm, its sulfate content was higher than the 200 ppm sulfate threshold. Hence, the Odessa flexbase soil was considered to be a potentially corrosive soil.

Before any construction water was added, the resistance of soil samples SH-121 and IH-30 were both determined to be 1,100 ohm-cm, which is less than the established 1,500 ohm-cm standard. Therefore, both soil samples were considered to be potentially corrosive regardless of their sulfate and chloride ion content. However, Table 5.10 lists their sulfate and chloride content at below the threshold values. Had their resistivity values been within the 1,500 and 3,000 ohm-cm range, then these soils too could have been classified as soils with low corrosion potential.

5.3.4.2 Impact of Construction Water on Soil Sulfate and Chloride

Samples of WWTP water with sulfate concentrations of 1,000, 1,500 and 3,000 ppm were prepared for this series of tests. The sulfate concentrations used with the ocean and brine waters were 2,700 and 5,000 ppm respectively. Similarly, the chloride concentration for WWTP was established at 500 ppm, while the chloride concentrations of ocean and brine waters were set at 2,700 and 5,000 ppm respectively. The compositions of these water samples were given in Table 4.9 and 4.10. The soils were treated with various amounts of simulated wastewater and then tested for sulfate and chloride contents using TxDOT test procedure Tex-620-J. The data collected are given in Table 5.11.

Table 5.12 Soil Sulfate and Chloride Values after Adding Construction Water

Soil Name	Water Content	Sulfate Concentration (ppm)					Chloride Concentration (ppm)		
		WWTP			Ocean	Brine	WWTP	Ocean	Brine
		1000	1500	3000	2700	5000	500	18,000	65,800
SH 121	15%	149	173	418	306	613	78	2688	11243
	20 %	200	220	514	422	846	111	3295	15179
	25 %	238	319	647	589	1231	121	4817	20704
IH 30	10 %	149	180	317	292	442	87	1761	6469
	15 %	201	242	455	417	648	120	2575	10334
	19 %	241	259	575	522	820	133	3839	12805
Flexbase Odessa	4 %	325	368	381	394	543	106	785	3020
	8 %	349	425	485	501	699	123	1551	5977
	11 %	375	431	567	660	841	136	2477	8338
Flexbase Lubbock	5 %	157	191	308	271	319	53	1012	3245
	10 %	193	253	424	366	492	76	1968	6618
	16 %	219	298	557	451	666	92	2972	10306

From the results shown in Table 5.11, it is evident that sulfates and chlorides in treatment water can significantly influence the total soil sulfate and chloride levels in soil. Although a few of the data points were below the 200 ppm threshold level, the majority exceeded 200 ppm. Similarly, it was observed that except for a few readings, most of the soil chloride concentrations exceeded the established chloride threshold of 100 ppm. Hence, if alternative water resources having similar concentrations of sulfates and chlorides are used in road construction operations, then any soil used in construction and having an initial soil resistivity between 1500 and 3000 ohm-cm will most probably become designated a corrosive soil when mixed with the alternative water.

5.4 Influence of Construction Water Quality on Sulfate Heave Potential in Stabilized Soil

As discussed in the preceding section, soil sulfate levels have important implications in terms of determining the corrosive potential of soils. Additionally, it is known that high levels of soil sulfate can create potential sulfate heave problems in soils that are stabilized with calcium based stabilizers. This section focuses on this latter issue.

5.4.1 Soil Sulfate Data

Experimental values for the soil sulfate content values were back-calculated from the sulfate assays on soil filtrate using Ion Chromatography. These values are referred to as the measured soil sulfate contents. Estimated values of sulfate levels in the final treated soil were also obtained based on the background sulfate in the soil and the amount of simulated water added and its sulfate concentration. The experimentally measured sulfate levels were then correlated with the estimated sulfate content values for all the samples tested. This correlation should aid in the development of a relationship between the initial and final soil sulfate content when the amount of added simulated water and its sulfate concentration are known.

The soil sulfate content obtained with and without treating the soils with the simulated water are shown in the following tables for each soil which was tested with multiple weight percentages of simulated construction water. The tables indicate the measured and the estimated sulfate content followed by a column that gives the calculated ratio of the measured to the predicted values.

5.4.2 Predictive Model for Increase in Soil Sulfate Content

A simple, additive equation was developed to predict the final soil sulfate content of a soil following treatment with alternative water containing sulfate. The equation is:

$$C_f = C_i + \Delta w(C_w) \qquad (5.5)$$

where, C_f denotes the final soil sulfate content

C_i is initial soil sulfate content of untreated soil

C_w is sulfate level in the alternative water source

Δw is the water content of the alternative water source added.

Figure 5.9 is a plot of the estimated versus the measured sulfate levels of the soil samples treated with alternative construction water. This comparison shows that the simple additive model given by Eq.(5.5) is capable of providing a reasonably good estimate of the final soil sulfate content. It is also apparent that larger deviations occur at high sulfate contents and such deviations were greater for soils containing high clay content, such as SH-121 and IH30. These deviations were attributed to the removal of sulfate ions by the clayey particles in the soil during the filtration process, which is done prior to the determination of sulfate content using ion chromatography.

Table 5.13 Sulfate Content Data for SH121 Soil

Sulfate Content of Untreated Soil (ppm)	Sulfate Conc. In Water Added (ppm)	Percent Water Added	Volume of Filtrate (ml)	Sulfate Conc. In Filtrate (ppm)	Sulfate Content in Treated Soil (ppm)	Predicted Sulfate Content (ppm)	Measured/ Predicted Ratio
48.9	1000	15	124	36.0	149	199	0.748
48.9	1000	20	133	45.2	200	249	0.805
48.9	1000	25	101	70.8	238	299	0.797
48.9	1500	15	137	37.9	173	274	0.631
48.9	1500	20	82	80.5	220	349	0.631
48.9	1500	25	114	83.9	319	424	0.752
48.9	3000	15	162	77.4	418	499	0.838
48.9	3000	20	162	95.1	514	649	0.792
48.9	3000	25	202	96.1	647	799	0.810
48.9	5000	15	162	113.5	613	799	0.767
48.9	5000	20	165	153.7	846	1049	0.806
48.9	5000	25	166	222.4	1230	1299	0.947
48.9	2700	15	160	57.5	306	454	0.675
48.9	2700	20	158	80.2	422	589	0.717
48.9	2700	25	168	105.2	589	724	0.814

Table 5.14 Sulfate Content Data for IH30 Soil

Sulfate Content of Untreated Soil (ppm)	Sulfate Conc. In Water Added (ppm)	Percent Water Added	Volume of Filtrate (ml)	Sulfate Conc. In Filtrate (ppm)	Sulfate Content in Treated Soil (ppm)	Predicted Sulfate Content (ppm)	Measured/ Predicted Ratio
58.2	1000	10	93	48.0	149	158	0.940
58.2	1000	15	149	40.4	201	208	0.965
58.2	1000	19	143	50.6	241	248	0.973
58.2	1500	10	128	42.2	180	208	0.866
58.2	1500	15	146	49.8	242	283	0.855
58.2	1500	19	115	67.6	259	343	0.755
58.2	3000	10	136	70.0	317	358	0.886
58.2	3000	15	166	82.1	455	508	0.894
58.2	3000	19	152	113	575	628	0.915
58.2	5000	10	170	77.9	442	558	0.791
58.2	5000	15	173	112	648	808	0.802
58.2	5000	19	156	158	820	1010	0.814
58.2	2700	10	165	53.1	292	328	0.890
58.2	2700	15	166	75.3	417	463	0.900
58.2	2700	19	167	93.7	522	571	0.914

Table 5.15 Sulfate Content Data for Odessa Flexbase Soil

Sulfate Content of Untreated Soil (ppm)	Sulfate Conc. In Water Added (ppm)	Percent Water Added	Volume of Filtrate (ml)	Sulfate Conc. In Filtrate (ppm)	Sulfate Content in Treated Soil (ppm)	Predicted Sulfate Content (ppm)	Measured/ Predicted Ratio
302	1000	4	96	101	325	342	0.949
302	1000	8	104	101	349	382	0.913
302	1000	11	108	104	375	412	0.909
302	1500	4	160	68.9	368	362	1.015
302	1500	8	186	68.5	425	422	1.006
302	1500	11	185	70.0	432	467	0.924
302	3000	4	158	72.4	381	422	0.903
302	3000	8	172	84.6	485	542	0.895
302	3000	11	180	94.6	568	632	0.898
302	5000	4	170	95.8	543	502	1.081
302	5000	8	181	116	700	702	0.996
302	5000	11	191	132	841	852	0.987
302	2700	4	170	69.6	395	410	0.962
302	2700	8	176	85.5	501	518	0.968
302	2700	11	182	109	660	599	1.102

Table 5.16 Sulfate Content Data for Lubbock Flexbase Soil

Sulfate Content of Untreated Soil (ppm)	Sulfate Conc. In Water Added (ppm)	Percent Water Added	Volume of Filtrate (ml)	Sulfate Conc. In Filtrate (ppm)	Sulfate Content in Treated Soil (ppm)	Predicted Sulfate Content (ppm)	Measured/ Predicted Ratio
132	1000	5	130	36.3	157	182	0.863
132	1000	10	150	38.6	193	232	0.832
132	1000	16	153	43.0	219	292	0.750
132	1500	5	166	34.6	191	207	0.924
132	1500	10	174	43.6	253	282	0.897
132	1500	16	168	53.2	297	372	0.800
132	3000	5	171	54.0	307	282	1.090
132	3000	10	184	69.2	424	432	0.982
132	3000	16	181	92.3	557	612	0.910
132	5000	5	189	50.6	319	382	0.835
132	5000	10	188	78.6	492	632	0.779
132	5000	16	180	111	666	932	0.714
132	2700	5	181	44.9	271	267	1.014
132	2700	10	179	61.3	366	402	0.910
132	2700	16	187	72.4	451	564	0.800

Table 5.17 Sulfate Content Data for Lubbock Embankment Soil

Sulfate Content of Untreated Soil (ppm)	Sulfate Conc. In Water Added (ppm)	Percent Water Added	Volume of Filtrate (ml)	Sulfate Conc. In Filtrate (ppm)	Sulfate Content in Treated Soil (ppm)	Predicted Sulfate Content (ppm)	Measured/ Predicted Ratio
29.4	1000	4	136	13.3	60.3	70	0.869
29.4	1000	8	141	18.9	88.8	109	0.812
29.4	1000	11	117	29.6	115	139	0.828
29.4	1500	4	142	15.5	73.5	89	0.822
29.4	1500	8	146	25.5	124	149	0.830
29.4	1500	11	139	35.6	165	194	0.848
29.4	3000	4	160	24.3	130	149	0.868
29.4	3000	8	166	42.5	235	269	0.874
29.4	3000	11	155	60.2	311	359	0.866
29.4	5000	4	132	44.6	196	229	0.857
29.4	5000	8	138	82.9	381	429	0.888
29.4	5000	11	134	112.3	502	579	0.866
29.4	2700	4	170	20.6	117	137	0.852
29.4	2700	8	177	35.8	211	245	0.862
29.4	2700	11	165	53.6	295	326	0.903

In Tables 5.12 through 5.16, the last column gives the measured: predicted sulfate content ratios. The average of all the ratios calculated was 0.87. In nearly all cases, the measured/predicted ratio was less than unity. This indicates that, over the range of sulfate contents tested in this test program (i.e. sulfate content < 1000 ppm), the additive model will provide an estimate of the upper limit of final soil sulfate content in the soil. Therefore, the model can be used in the preliminary screening of candidate water sources with good confidence.

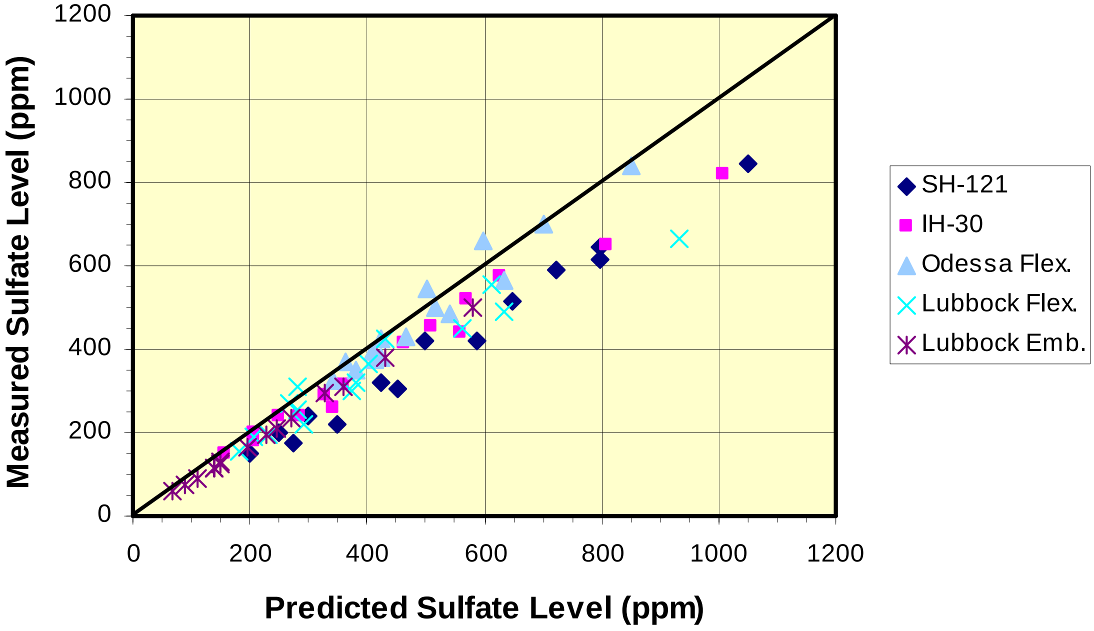


Figure 5.9 Measured versus Predicted Sulfate Levels

The following example illustrates the use of the model. Assume that the initial sulfate level of a soil is 500 ppm, the percentage of alternative water to be added is 5%, and the concentration of sulfate in water is 1000 ppm. Then the final sulfate level in the soil after adding the specified amount of alternative water would then be equal to 500ppm + (0.05)(1000ppm) or 550 ppm. In most cases, the amount of sulfate added to soil through the water will be quite small. Thus, the final soil sulfate level in soil is largely controlled by the amount of sulfate that was present in the soil initially rather than by the amounts added through alternative water. However, if the soil being stabilized is a borderline material in terms of its sulfate content, then there is a chance that the threshold sulfate levels will be exceeded as a result of adding alternative water.

5.5 Influence of Construction Water Quality on Soil Dispersion

Soil dispersivity was addressed in two ways: 1).by SAR (Sodium Adsorption Ratio), and by 2) Double Hydrometer Dispersion Test (ASTM D 4221). The double hydrometer dispersion test was performed in order to corroborate the SAR test results.

5.5.1 Sodium Adsorption Ratio (SAR) Data

The initial SAR data for the soil samples without any alternative construction water was determined first. Then the measurements were repeated after the soil had been combined with various amounts of simulated construction water that represented waste water from treatment plants, WWTP, ocean water, and brine water. Data reflecting these test results are given in Tables 5.17 through 5.19.

The final SAR values of the soil samples that were treated with WWTP and ocean water were invariant in comparison to their initial values. The addition of WWTP derived construction water did not appear to increase the treated soil SAR levels, but the addition of ocean water increased the SAR level of the soil by a slight amount at least 50 percent of the time. Significant changes were recorded, however, following soil treatments that involved the addition of brine water. Specifically, the soils' SAR levels were found to be significantly higher every time brine water was added.

The data indicate that most of the SAR values were elevated, ranging from about 12 to 34.9 together except for a few outliers. Gerber and Harmse (1987) reported that SAR values exceeding 10 are indicative of a dispersive soil, 6-10 are representative of intermediate dispersive soil, and soil SAR levels less than 6 indicate a non-dispersive soil. Therefore, it can be expected that the soil samples treated with brine water would show dispersive behavior.

5.5.2 Double Hydrometer Dispersion Test Data

To corroborate the SAR observations, the double hydrometer test described in ASTM D 4221 was conducted on four of the test soils prior to their treatment with simulated construction water. In all cases the soil dispersion values were zero. The soils were then tested using the double hydrometer approach after treatment with each of the simulated alternative construction water. Once again the soil dispersion values were null. One final sample of synthetic construction water was used to treat the soil samples. This water had a Na^+ concentration of 10,000 ppm and a $[(Na^+)/ (Ca^{2+} + Mg^{2+})]$ ratio of 150. This experiment was performed to ensure that the sodium concentration level was significantly elevated relative to the Ca^{2+} and Mg^{2+} cations. This high sodium concentration still produced a soil dispersion value of zero. Table 5.20 shows the null readings obtained for the double hydrometer tests on the five soils. The hydrometer results confirm that even with high experimental SAR values, the soils being tested show no dispersion. Thus, the results from the double hydrometer tests fail to confirm the findings from SAR tests. Because of the contradictory results obtained from the two test series a definite conclusion cannot be reached about the significance of alternative water composition on dispersion potential of soils.

Table 5.18 SAR Results for Each Soil Treated with WWTP

Soil Name	Soil Properties	Initial Soil SAR	With WWTP				
			Concentration in Water (ppm)			Final Soil SAR	Change in SAR
			Na^+	Ca^{2+}	Mg^{2+}		
SH=121	93% Fines PI = 31 OMC=26%	12.50	2984.22	57.94	40.1	3.81	-8.69
IH-30	73% Fines PI = 21 OMC=19%	11.50	2984.22	57.94	40.1	5.24	-6.26
Lubbock Flexbase	24% Fines PI = 8 OMC=16%	14.20	2984.22	57.94	40.1	8.33	-5.87
Lubbock Embankment	11% Fines PI = 11 OMC=11%	16.30	2984.22	57.94	40.1	6.96	-9.34

Table 5.19 SAR Results for Each Soil Treated with Ocean Water

Soil Name	Soil Properties	Initial Soil SAR	With Ocean Water				
			Concentration in Water (ppm)			Final Soil SAR	Change in SAR
			Na^{+}	Ca^{2+}	Mg^{2+}		
SH-121	93% Fines PI = 31 OMC=26%	12.50	10758.75	410.81	1291.37	10.80	-1.70
IH-30	73% Fines PI = 21 OMC=19%	11.50	10758.75	410.81	1291.37	11.80	0.30
Lubbock Flexbase	24% Fines PI = 8 OMC=16%	14.20	10758.75	410.81	1291.37	15.40	1.20
Lubbock Embankment	11% Fines PI = 11 OMC=11%	16.30	10758.75	410.81	1291.37	11.90	-4.40

Table 5.20 SAR Results for Each Soil Treated with Brine Water

Soil Name	Soil Properties	Initial Soil SAR	With Brine Water				
			Concentration in Water (ppm)			Final Soil SAR	Change in SAR
			Na^+	Ca^{2+}	Mg^{2+}		
SH-121	93% Fines PI = 31 OMC=26%	12.50	48826.07	10198.2	1973.05	27.30	14.80
IH-30	73% Fines PI = 21 OMC=19%	11.50	48826.07	10198.2	1973.05	30.80	19.30
Lubbock Flexbase	24% Fines PI = 8 OMC=16%	14.20	48826.07	10198.2	1973.05	34.90	20.70
Lubbock Embankment	11% Fines PI = 11 OMC=11%	16.30	48826.07	10198.2	1973.05	24.60	8.30

Table 5.21 Dispersion Values (Double Hydrometer Test) for Each Soil

Soil	Soil Properties	No Construction Water (Before)	WWTP (3000ppm)	Percent Change with WWTP (%)	Ocean Water	Percent Change with Ocean Water (%)	Brine Water		Percent Change with Brine Water (10,000ppm) (%)	Percent Change with Brine Water (50,000ppm) (%)	Optimum Moisture Content (%)
					Fairly High TDS, Fairly High Na+		High SAR, Low TDS (10,000ppm)	High SAR, High TDS (50,000ppm)			
SH-121	93% Fines	0	0	0.0	0	0.0	0	0	0.0	0.0	26
	PI = 31										
IH-30	73% Fines	0	0	0.0	0	0.0	0	0	0.0	0.0	19
	PI = 21										
Lubbock Flexbase	24% Fines	0	0	0.0	0	0.0	0	0	0.0	0.0	16
	PI = 8										
Lubbock Embankment	11% Fines	0	0	0.0	0	0.0	0	0	0.0	0.0	11
	PI = 11										

5.6 Influence of Construction Water Quality on Soil Index Properties

5.6.1 Atterberg Limit Test Data

Atterberg limits were determined using the ASTM D 4318 test procedure for each of the four soils: IH-30, SH-121, Lubbock Embankment, and Lubbock Flexbase. These tests were performed both before and after construction water was added. The Atterberg limits included a liquid limit (LL), a plastic limit (PL), and the plasticity index (PI). The experimental results are presented in Tables 5.21 to 5.25.

Table 5.22 Atterberg Limits for Soils without Simulated Waste Water

Soil	Liquid Limit	Plastic Limit	Plasticity Index
IH-30	42	21	21
SH-121	64	33	31
Lubbock Embankment	27	15	12
Lubbock Flexbase	26	18	8

Table 5.23 Atterberg Limits for Soils Treated with Brine Water (10,000 ppm)

Soil	Liquid Limit	Plastic Limit	Plasticity Index
IH-30	41	21	20
SH-121	63	34	29
Lubbock Embankment	28	16	12
Lubbock Flexbase	26	19	7

Table 5.24 Atterberg Limits for Soils Treated with Brine Water (50,000 ppm)

Soil	Liquid Limit	Plastic Limit	Plasticity Index
IH-30	41	23	18
SH-121	64	35	29
Lubbock Embankment	27	15	12
Lubbock Flexbase	27	19	8

Table 5.25 Atterberg Limits for Soils Treated with WWTP*

Soil	Liquid Limit	Plastic Limit	Plasticity Index
IH-30	40	21	19
SH-121	63	34	29
Lubbock Embankment	28	16	12
Lubbock Flexbase	27	18	9

*Simulated Waste Water from Treatment Plants

Table 5.26 Atterberg Limits for Soils Treated with Ocean Water

Soil	Liquid Limit	Plastic Limit	Plasticity Index
IH-30	39	20	19
SH-121	64	35	29
Lubbock Embankment	28	18	10
Lubbock Flexbase	26	18	8

The percentage change in PI for the test soils after treatment with simulated construction water remained fairly small. Moreover, the changes that were observed were nearly always negative, which indicated that PI levels were reduced following mixing with the construction water. Therefore, it is reasonable conclude that alternative water would not have any adverse impact on Atterberg Limits of soils.

5.6.2 Bar Linear Shrinkage Test Data

The shrinkage test, Tex-107-E; Determination of Bar Linear Shrinkage of Soils, was used to assess the shrinkage potential of the soils and alternative construction water used in this investigation. None of the soils posed any shrinkage problems, since they all exhibited bar linear shrinkage values greater than 2. The Texas Department of Transportation indicates that bar linear shrinkage values for construction soils should be greater than or equal to 2. Table 5.27 gives the experimental results of bar linear shrinkage tests performed in this investigation.

5.6.3 Expansion Index Test Data

The standard, ASTM D 4829 Expansion Index Test, was used to assess the potential expansion of the soils before and after treatment with construction water.

Results from expansion index tests on soils after treatment with simulated construction water did not reveal any defined pattern. Therefore little could be deciphered from these experimental results apart from the observation that the vast majority of the soils that were tested remained essentially within the same potential expansion range. It was concluded, therefore, that the most typical sources of alternative construction water would have no appreciable effect on the tested soils or other similar soils used in engineered construction. Table 5.28 gives the experimental results of the expansion index (EI) tests.

However, it should be noted that none of the soils tested were marginal in terms of their potential for expansive behavior. Therefore, it may not be advisable to extrapolate the above conclusion to soils that have high expansion potential.

Table 5.27 Variation of Plasticity Index (PI) with Simulated Water Treatment of Soils

Soil	PI without Simulated Water	PI with Brine (10,000ppm)	Percent Change with Brine (10,000ppm)	PI with Brine (50,000ppm)	Percent Change with Brine (50,000ppm)	PI with WWTP	Percent Change with WWTP	PI with Ocean Water	Percent Change with Ocean Water
IH-30	21	20	-4.76	18	-14.29	19	-9.52	19	-9.52
SH-121	31	29	-6.45	29	-6.45	29	-6.45	29	-6.45
Lubbock Embankment	12	12	0.00	12	0.00	12	0.00	10	-16.67
Lubbock Flexbase	8	7	-12.50	8	0.00	9	12.50	8	0.00

Table 5.28 Bar Linear Shrinkage Values for Each Soil

Soil	Soil Properties	No Construction Water (Before)	WWTP (3000ppm)	Percent Change with WWTP (%)	Ocean Water	Percent Change with Ocean Water (%)	Brine Water		Percent Change with Brine Water (10,000ppm) (%)	Percent Change with Brine Water (50,000ppm) (%)	Optimum Moisture Content (%)
					Fairly High TDS, Fairly High Na+		High SAR, Low TDS (10,000ppm)	High SAR, High TDS (50,000ppm)			
SH-121	93% Fines PI = 31	20	21	5.0	21	5.0	22	21	10.0	5.0	26
IH-30	73% Fines PI = 21	14	14	0.0	10	-28.6	13	14	-7.1	0.0	19
Lubbock Flexbase	24% Fines PI = 8	10	9	-10.0	11	10.0	10	13	0.0	30.0	16
Lubbock Embankment	11% Fines PI = 11	6	8	33.3	9	50.0	10	9	66.7	50.0	11

Table 5.29 Expansion Index (EI*) Values for Each Soil Tested

Soil	Soil Properties	No Construction Water (Before)	WWTP (3000ppm)	Percent Change with WWTP (%)	Ocean Water	Percent Change with Ocean Water (%)	Brine Water		Percent Change with Brine Water (10,000ppm) (%)	Percent Change with Brine Water (50,000ppm) (%)	Optimum Moisture Content (%)
					Fairly High TDS, Fairly High Na+		High SAR, Low TDS (10,000ppm)	High SAR, High TDS (50,000ppm)			
SH-121	93% Fines PI = 31	90	73	-18.9	61	-32.2	88	91	-2.2	1.1	26
IH-30	73% Fines PI = 21	57	63	10.5	46	-19.3	70	80	22.8	40.4	19
Lubbock Flexbase	24% Fines PI = 8	0	0	0.0	0	0.0	2	5	0.0	500.0	16
Lubbock Embankment	11% Fines	13	0	-100.0	7	-46.2	11	9	-15.4	-30.8	11

*EI	Potential Expansion	*EI	Potential Expansion
0-20	Very Low	91-130	High
21-50	Low	>130	Very High
51-90	Medium		

CHAPTER VI

DECISION MATRIX

6.1 OVERVIEW

The final major task in this research project involved the development of a decision matrix that TxDOT engineers could use when making decisions with respect to suitability of various alternative water sources for specific construction applications. As mentioned earlier, such decisions will be based on a number of considerations. (a) Is there any regulatory control on the use of a specific alternative water source? If so, what permit process should be followed? (b) Is there potential adverse effect on the health and safety of the public or the workers, (c) Is there potential for environmental damage from the use of alternative water? (d) How would the water composition impact material properties and performance of the constructed facility?

The decision matrix to qualify (or disqualify) a given water source for a specific application is presented in the form of a series of flow charts. These flow charts are divided into two separate categories; Stage I decision matrices and Stage II decision matrices. Stage I decision matrices incorporate requirements (a), (b) and (c) and are organized according to water source. Stage II decision matrices deal with requirement (d), i.e. potential impact on material properties and performance. These flow charts are organized by construction application.

6.2 STAGE I DECISION MATRICES

Stage I Decision Matrix performs necessary checks to ensure that requirements (a), (b), and (c) are satisfied. As a first step, it will inform the user if it is necessary to obtain formal approval prior to the use of water from a given alternative water source. When such approval is required, it will identify the appropriate permitting agency and the procedures to be followed. For example, the reuse of effluent from municipal wastewater treatment plants requires a permit from the Texas Commission on Environmental Quality (TCEQ). Similarly, produced water reuse requires a permit from the Texas Railroad Commission. These permitting requirements and procedures were explained in Chapter II. On the other hand, there are no known permit requirements for impaired surface water or for ocean water. However, disposal of unused water may require permits form either or both of TCEQ and the RRC but these are not addressed in this research effort.

The second important issue that Stage I decision matrix is designed to address is the health and safety of the public and the construction workers. Fortunately, there are established guidelines that specifically address this concern. The criteria to be used for effluent from municipal wastewater treatment plants were presented in Tables 2.2 and 2.3. Similar guidelines are not specified in regulation for impaired surface water. However, it can be readily noted that the potentially harmful constituents in the two types of alternative water sources are the same. Therefore, it is prudent to use the criteria specified in Tables 2.2 and 2.3 for impaired surface water as well. Figure 6.2: Stage I Decision Matrix for impaired surface water was developed accordingly. The list of available impaired surface water sources is available from CWA 305 B report. The impaired surface water discharged into natural water bodies must exceed the total maximum daily loads of contaminants permitted by TCEQ TMDL program for that site in accordance to section 305B of Clean Water Act. Location and quality of produced brine water sources is available from USGS produced water database. Permits to transport, use, and dispose the brine water must be obtained from RRC and TCEQ on a case by case basis

For a number of reasons, figures representing Stage I decision matrix do not explicitly address concerns with respect to potential environmental damage. First, when taken as a percentage of the total, the amounts of construction water that are added and mixed with soil material in typical construction operations are quite small. Secondly, in nearly all cases (with possible exception of vegetative watering), the use of alternative water will be limited to a single application of water rather than repeated applications. Furthermore, the quality and quantity of water that could be incorporated into soil will be controlled based on material property and performance considerations. These limits will be more stringent than any limit that will be imposed based on environmental damage considerations. Thus, the environmental damage considerations have been addressed in the above decision matrix indirectly.

However, in some situations environmental damage considerations may govern. One such situation arises when there is unused, surplus water at the jobsite after a project had been completed. Because of its poor quality, any leftover alternative water from construction cannot be released into the environment arbitrarily. Their disposal must be done according to guidelines provided by Clean Water Act , 30 TAC 307, 16 TAC 3.8

Figures 6.1 through 6.4 include Stage I Decision Matrices for the 4 types of alternative water sources.

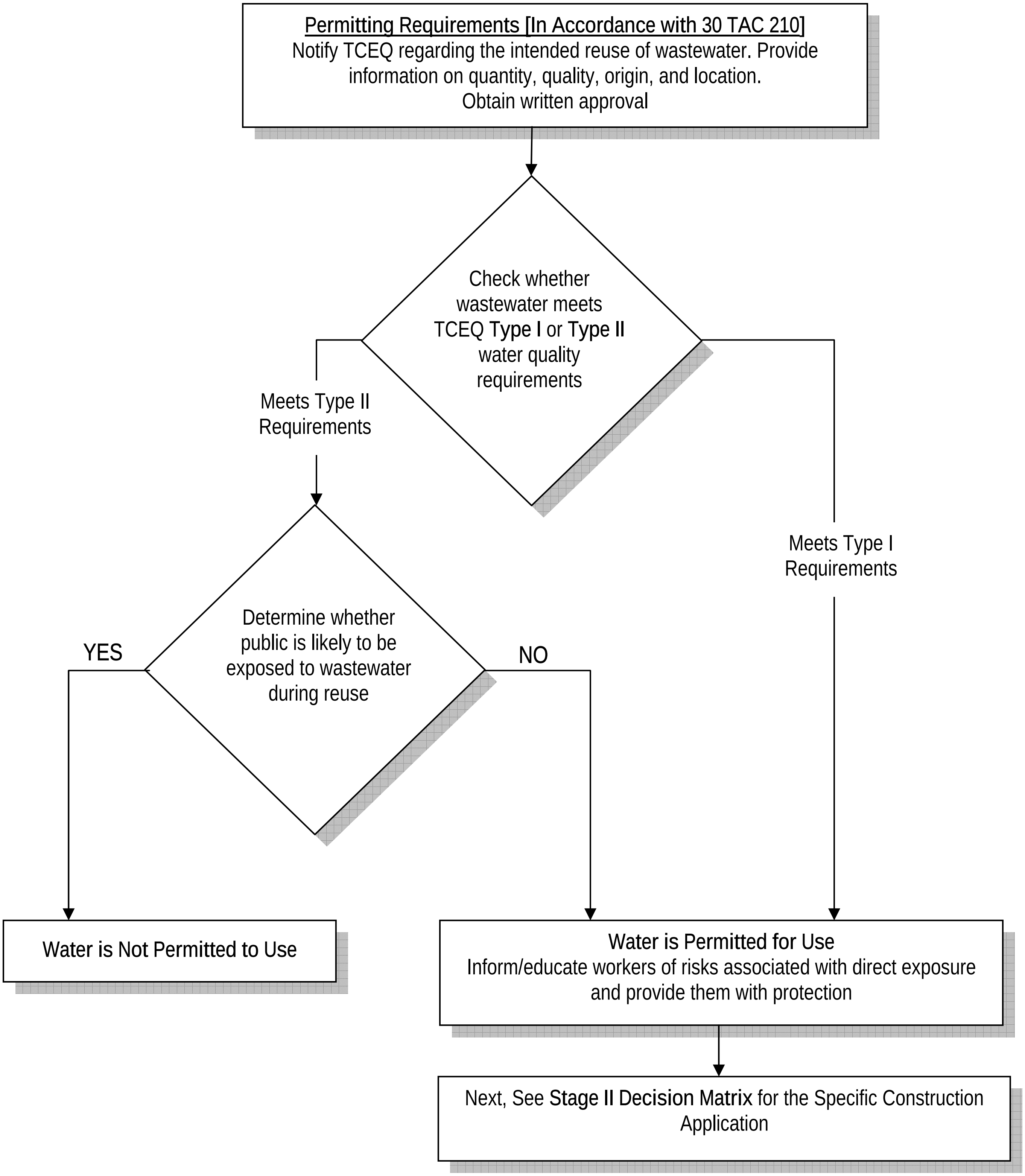


Figure 6.1- Stage I Decision Matrix for Treated Effluent from Municipal Wastewater Treatment Plants

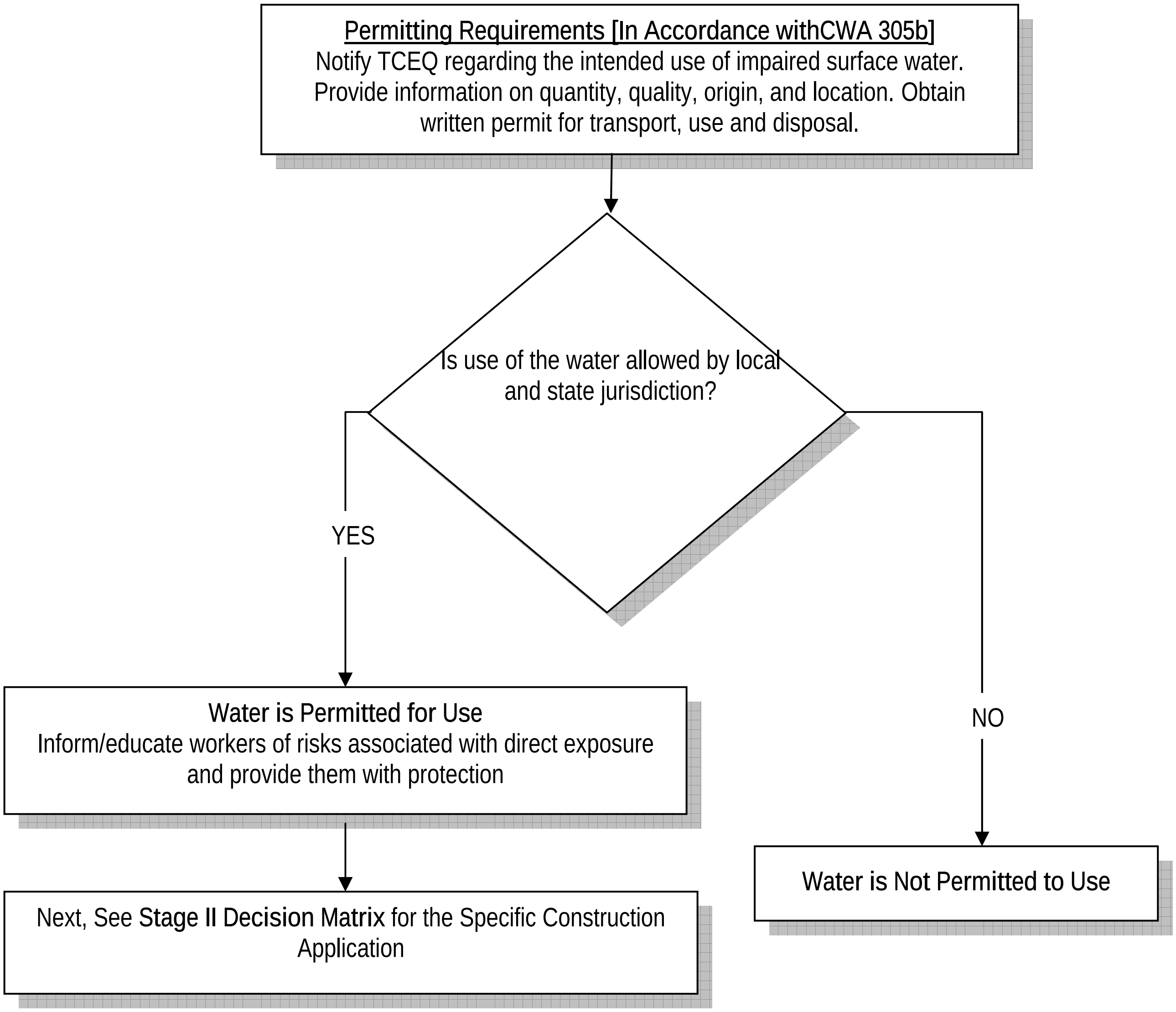


Figure 6.2 - Stage I Decision Matrix for Impaired Surface Water

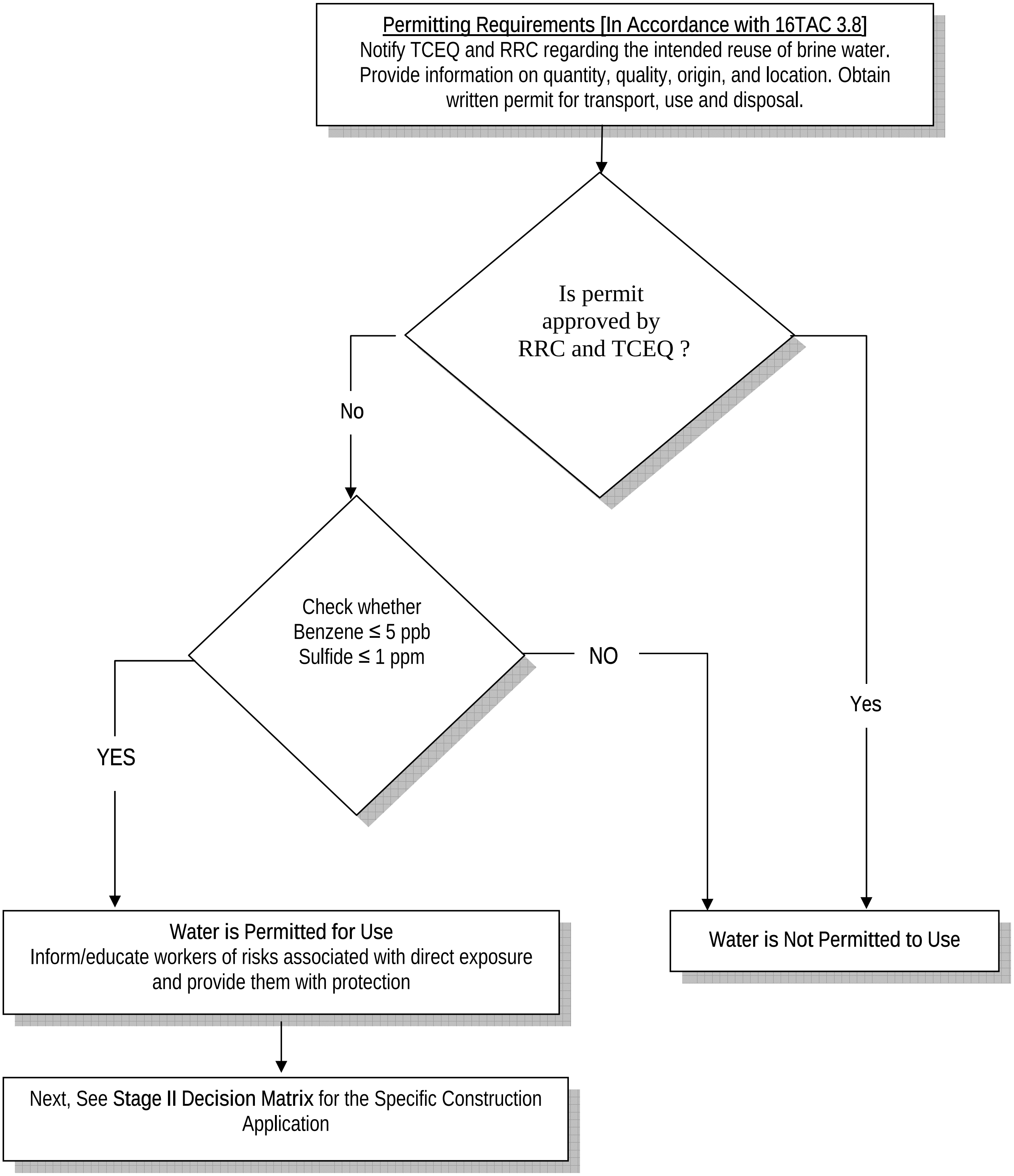


Figure 6.3 - Stage I Decision Matrix for Produced Water

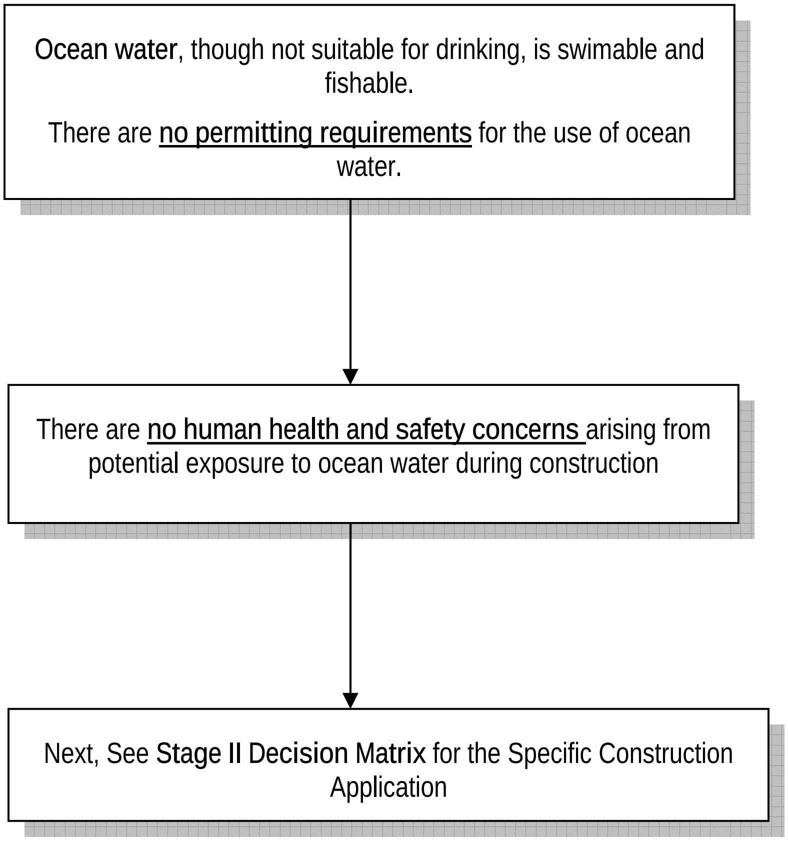


Figure 6.4 - Stage I Decision Matrix for Ocean Water

6.3 STAGE II DECISION MATRIX

Stage II Decision Matrix assists the engineer in determining whether the performance of a constructed facility is likely to be compromised by using water obtained from a given alternative source. Accordingly, the decision with respect to acceptance or rejection of a water source at this stage will be made based on the potential adverse effect that it may have on material properties and performance of the completed structure. Stage II decision matrix is based on the findings from the laboratory tests completed in this research.

Figures that represent Stage II Decision Matrices are organized by construction applications. Sections 6.2.1 through 6.2.4 explain the steps involved in developing the decision matrix in detail.

6.3.1 Compaction of MSE Retaining Wall Backfill

Testing conducted in this research showed that the soil parameter that is most sensitive to the quality of construction water used is its corrosivity. Soil corrosivity is the primary basis for determining the suitability of backfill materials for the construction of MSE retaining walls. MSE walls use galvanized steel strips or grids to reinforce backfill soil. Therefore, the backfill material used must meet the corrosivity limits specified in TxDOT specification Item 423. Corrosivity of the soil is controlled by imposing limits on soil pH, resistivity and chloride and sulfate contents. As discussed in Section 3.4.2, the specific requirements are:

(a) The pH of the backfill soil material shall be from 5.5 to 10.0, as determined by Test Method Tex-128-E.

(b) The resistivity of the backfill soil shall not be less than 3000 ohms-cm as determined by Test Method Tex-129-E. Materials with a resistivity between 1500 and 3000 ohms-cm may be used, provided the chloride content does not exceed 100ppm and the sulfate content does not exceed 200ppm as determined by Tex-620-J.

Test results confirm that there is no risk in pH of the soil backfill exceeding or falling below the specified limits (5.5 to 10.0) as a result of mixing with the soil with water from the sources examined in this study. However, the effect of mixing soil with water with high dissolved mineral content results in a dramatic loss in resistivity.

The change in resistivity is a function of the amount of dissolved minerals added to the soil from water as well as properties of the soil (percent fines, plasticity index etc.). The amount of minerals added from water can be quantified in terms of ($\Delta w \cdot TDS$), where Δw represents the percent water added and TDS represent the total dissolved mineral content in the alternative water. The maximum ($\Delta w \cdot TDS$) that any of the 5 soils tested could tolerate before its resistivity dropped below the minimum acceptable value of 1,500 ohm-cm was approximately 35,000ppm. If one assumes that most construction projects would involve the addition of a minimum of 5% water, then the alternative water sources that have TDS > 7,000ppm would be excluded. This would eliminate ocean water and nearly all produced water (i.e. waste brine) sources from consideration. Therefore, in the decision matrix presented, ocean water and produced water sources have been rejected outright. The suitability of municipal wastewater and impaired surface water can be determined by using the model described in Chapter V. The above model is used in the decision matrix as a preliminary screening tool. Such preliminary screening will help in minimizing the amount of testing required.

If the water sample passes the screening criteria, then its suitability must be confirmed by performing appropriate testing. For this purpose, soil samples must be prepared according the procedure outlined in Appendix A and tested using Tex-129-E.

Soil corrosivity criteria also consider Chloride and Sulfate Levels in soils. Accordingly, soil sample must be prepared according to procedures outlined in Appendix A and tested using Tex-620-J.

The Decision Matrix for the qualification of water used in the placement and compaction of MSE Retaining Wall Backfill is presented in Figure 6.5

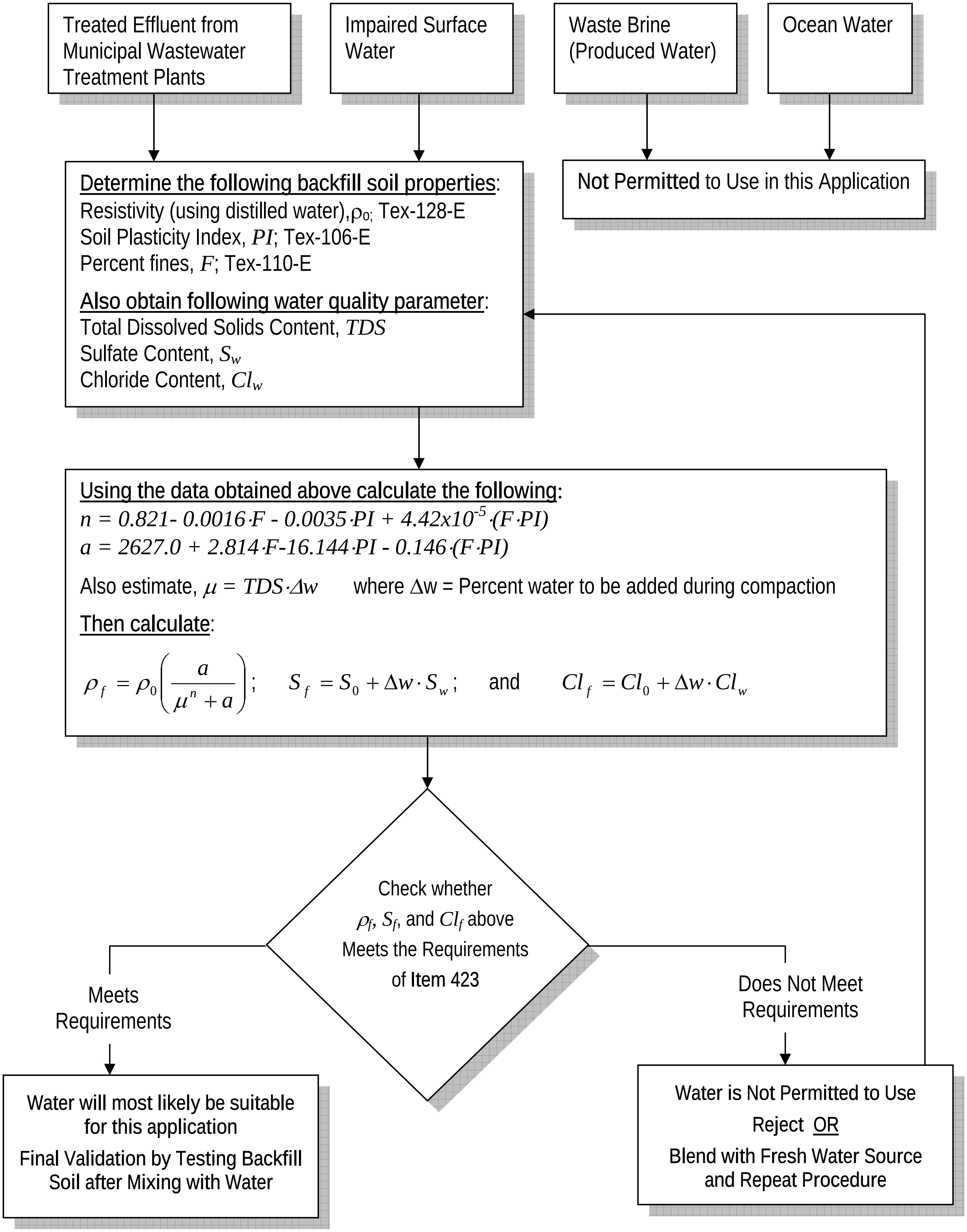


Figure 6.5 - Stage II Decision Matrix for Water Used in the Compaction of MSE Retaining Wall Backfill

6.3.2 Water Used in the Stablization of Subgrades and Bases

Another construction application in which quality or the composition of water can have significant implications is stabilization of subgrades and base courses. In this construction application, the particular concern is with the maximum acceptable level of sulfate in material to be treated with Ca-based stabilizers.

Test results showed that the following simple equation provides a good approximation for the change in sulfate that can occur in soil as a result of adding alternative water:

$$C_f = C_i + \Delta w(C_w)$$

where, C_f denotes the final soil sulfate content
C_i is initial soil sulfate content of untreated soil
C_w is sulfate level in the alternative water source
Δw is the water content of the alternative water source added

This equation can be used as a preliminary check to determine whether water obtained from a particular source with known sulfate content can be used in the stabilization project without significant impact on the risk of sulfate heave due to ettringite formation.

The final soil sulfate content is then compared against specific threshold values to determine whether the corresponding risk of sulfate heave is low, moderate or high. As discussed in Section 3.4.1, sulfate levels within the range 0-2,000ppm are considered to pose low risk, 2,000-5,000ppm is considered to pose moderate risk.

Review of water quality data collected show that the increase in soil sulfate level from addition of alternative water sources, in most cases, will be relatively low. For example, all WWTP water and impaired surface water have less than 3,000ppm sulfate. The majority of brine water sulfate contents fall below this threshold. If the amount of water added to soil is 5%, then the corresponding increase in soil sulfate level is 0.05x3,000 = 150ppm. Thus, any soil with starting sulfate level of 1850ppm or less will not exceed the threshold limit of 2,000ppm because of sulfate added from water. Because of this reason, none of the categories of alternative water has been excluded from consideration due to sulfate concerns.

The final acceptance or rejection of the water source, however, should be based on laboratory test results. Accordingly, sample preparation should be done in accordance with Appendix A and Test Method Tex-620-J conducted to determine whether soil sulfate levels are within acceptable limits.

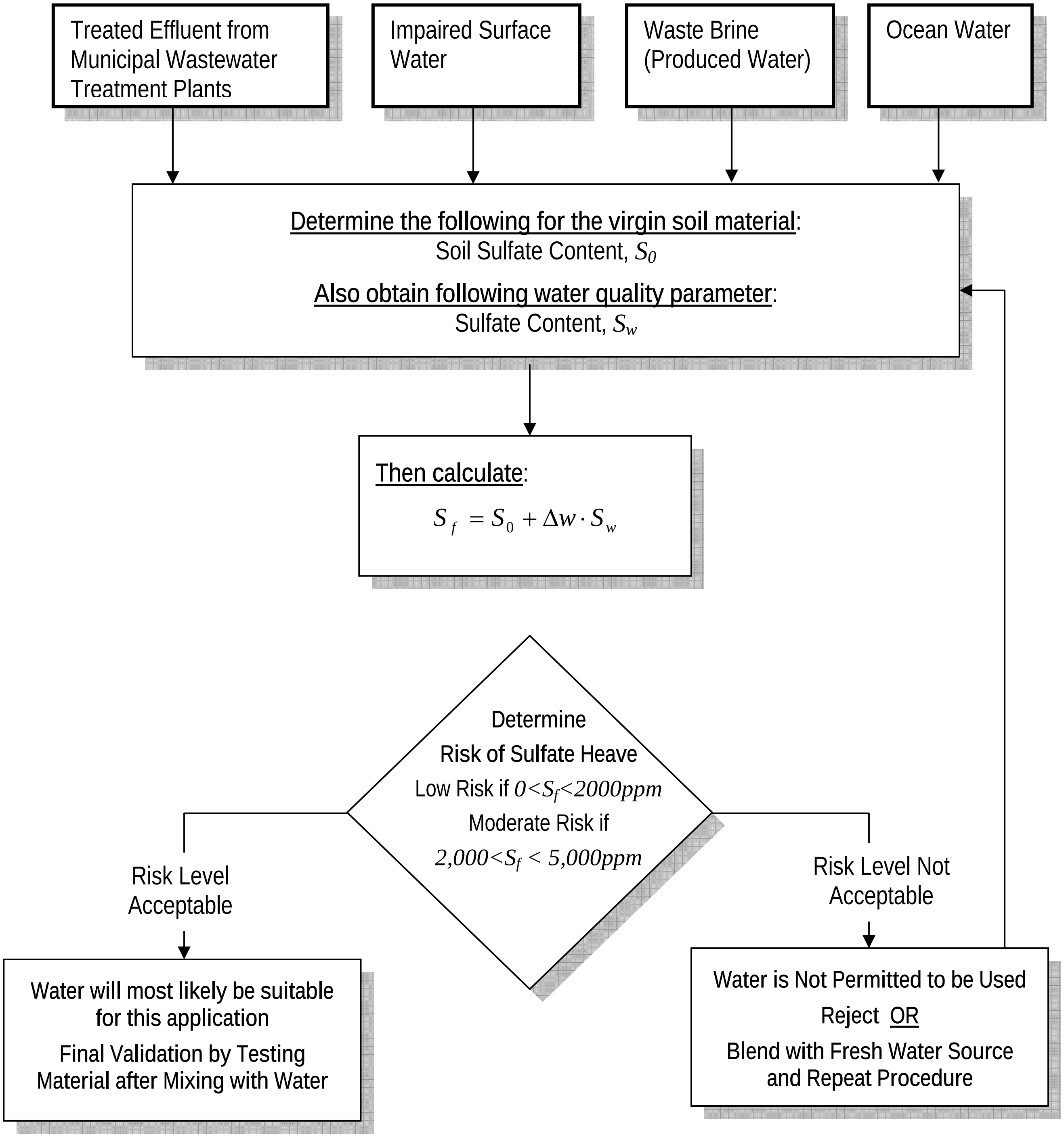


Figure 6.6 - Stage II Decision Matrix for Water Used in the Stabilization of Subgrades, Subbase and Base Courses

6.3.3 Water Used in the Compaction of Subgrades, Embankments and Flexible Bases

This part of the decision matrix applies to all construction operations that involve soil compaction. Many TxDOT specifications that require density control specify compacting soil at water contents not less than optimum values. Typically, water is added to the soil material to bring its moisture content up to its optimum value. Specific concerns related to the use of alternative water in soil compaction included the following:

(a) Will the added water significantly impact shrink/swell potential of the soil?

(b) Will the water increase dispersive potential of the soil?

(c) Will the water alter the soil parameters that are used in the selection of materials, e.g. Atterberg Limits and Bar Linear Shrinkage?

The changes observed in the 5 soils that were tested show that:

(a) Even when treated with water that represented "worst case" condition, the Expansion Index of the tested soils did not exceed an EI value of 90, the threshold value for medium expansion potential.

(b) The soil SAR increased after treatment with alternative water. However, the dispersion potential as determined by the double hydrometer did not show any change.

(c) The changes in soil Atterberg limits and bar linear shrinkage were small and in nearly all cases, showed improvement of those properties rather than degradation.

Based on the above findings, it was determined that preliminary criteria were not necessary for screening out candidate water sources. Therefore, all water sources can be considered for use in this application. The final acceptance of the water should be based on laboratory test results. Accordingly, samples of soil material should be mixed with the alternative water according to the procedure described in Appendix A and then tested using standard TxDOT lab test procedures.

The test results obtained in this research leads to the conclusion that increase in shrink/swell or dispersion potential should not be a concern for most soils. However, it must be pointed out that none of the soils tested were marginal in terms of shrink/swell and dispersion potential. Therefore, it should not be assumed that the conclusion given above is equally valid for soils that exhibit shrink/swell or dispersive behavior. Therefore, it is recommended that alternative water may not be used for these soils until more data becomes available from further research.

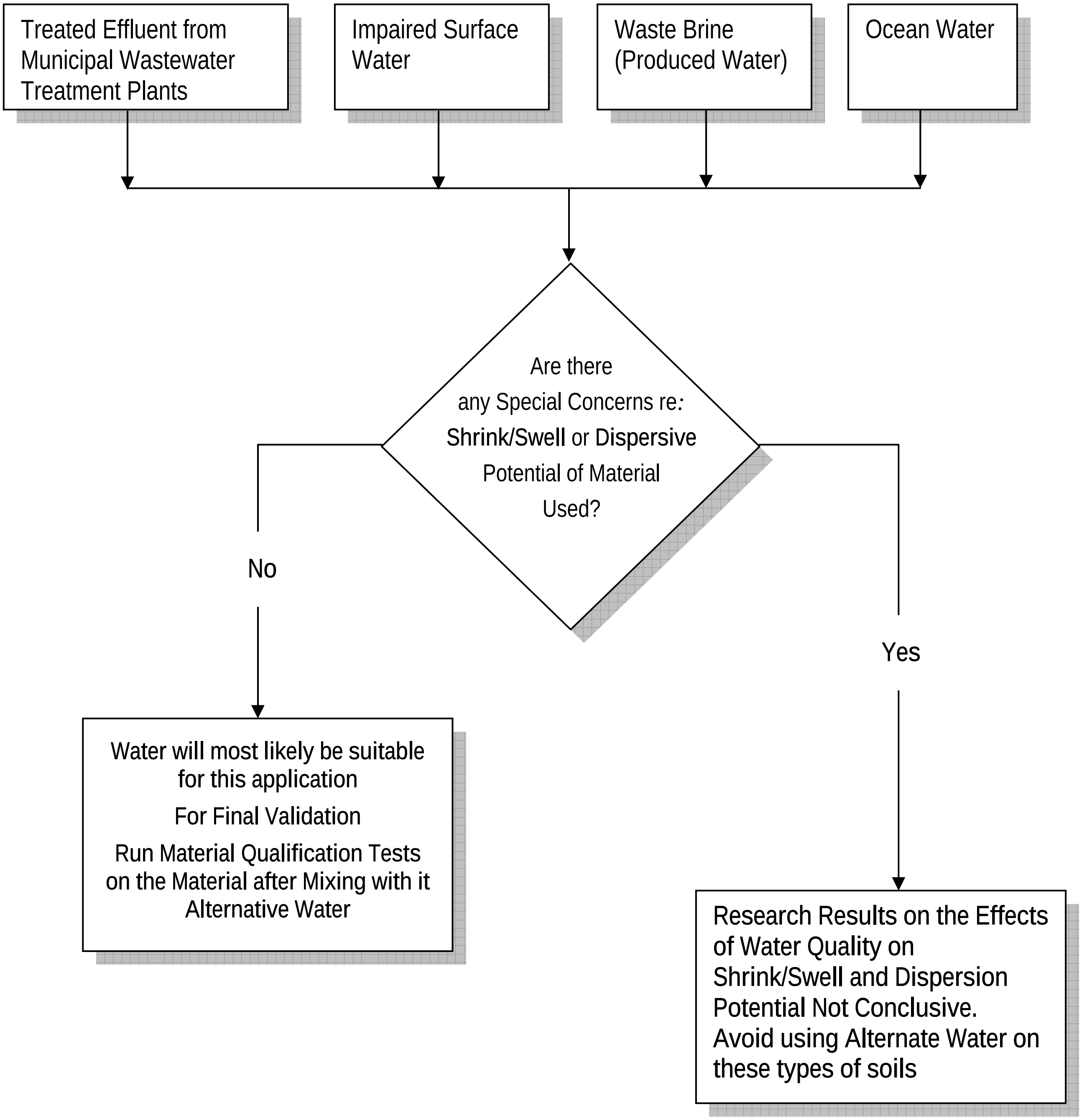


Figure 6.7 - Stage II Decision Matrix for Water Used in the Compaction of Road Subgrades, Flexible Base Courses and Embankment Fill

6.3.4 Water Used in Seeding and Vegetative Watering

Irrigation, as considered in this project, is the application of alternate water through an above ground system to promote and sustain grasses and other plants along the highway or other rights of ways. Alternate water sources can also be used for seeding and sodding operations. Typically, the plants are irrigated by sprinklers or sprayed.

If the sodium level exceeds the threshold value shown in Figure 6.8, it may cause the soil structure to breakdown and may be detrimental to plants. Sodium salts affect the exchangeable cation composition of the soil, while calcium and magnesium act as stabilizing ions balancing the destabilizing effect of sodium ions in regards to the soil structure. The potential effect of sodium on soil properties is indicated by sodium-adsorption ratio (SAR). SAR is expressed as concentration of sodium in water relative to calcium and magnesium ions. Another measure of exchangeable sodium (ESP) value listed in Figure 6.8 is the general value recommended by US salinity laboratory.

EPA recommends a free residual chlorine level of < 1 ppm is safe for most plants grown along the highways. Sulfate is not a concern for irrigation and erosion control as the soil expansion would not cause a problem. If total dissolved solids exceed 2000 ppm (EPA, 1992) then the TDS may be detrimental to plants and grass. The pH of the water must be in the range of 6-9 or it may become corrosive to the soils and/or harmful to the plants.

Most treated effluent water and impaired surface water that are qualified based on health and environmental criteria can be used for this operation. Produced water and the ocean water would not qualify for this operation as the TDS, sodium, and chloride levels in these water sources are typically much higher than the threshold limits suggested in the decision matrix.

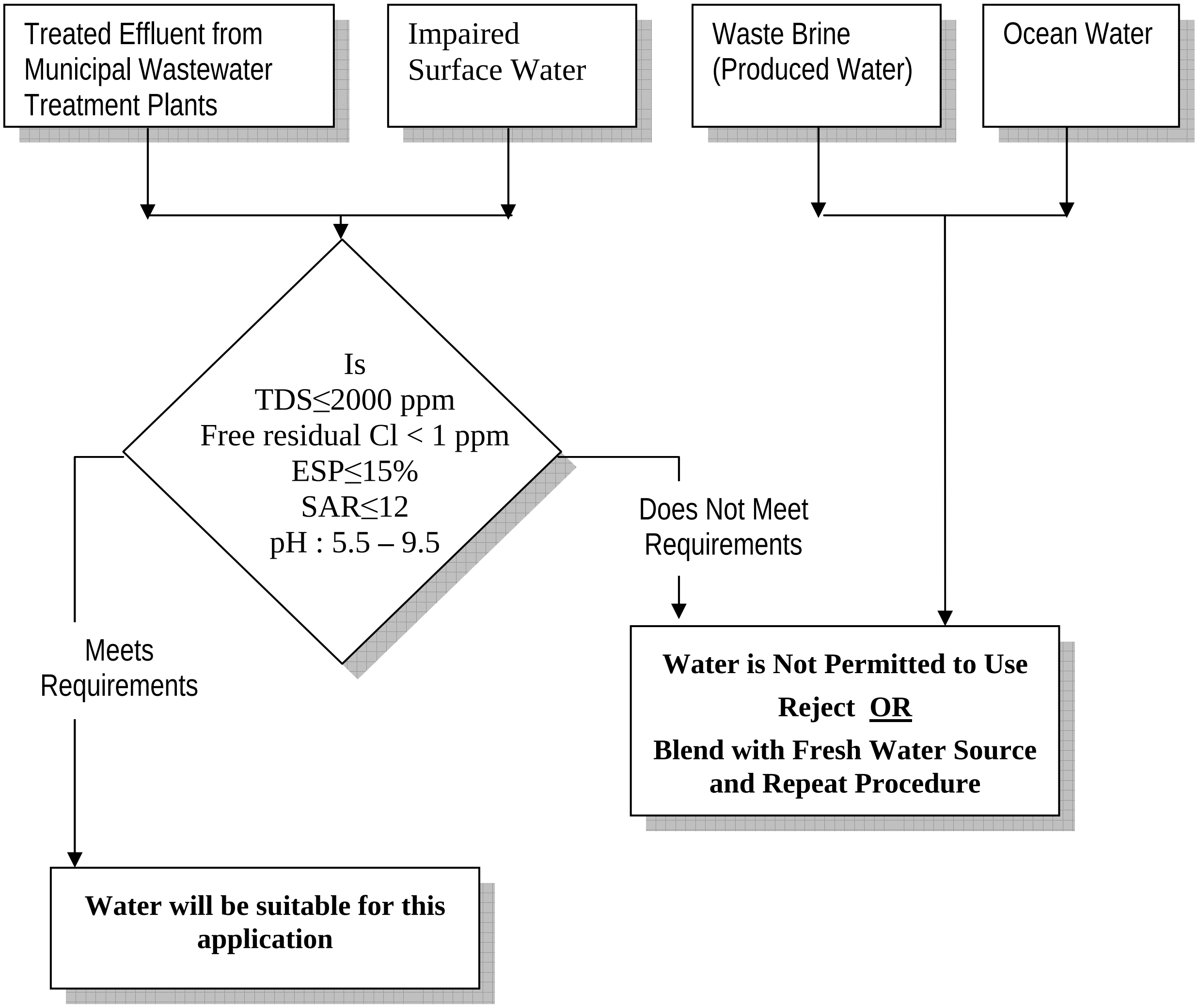


Figure 6.8 - Stage II Decision Matrix for Water Used for Irrigation

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The demand for usable water will continue to increase into the foreseeable future while supplies are generally both finite and currently utilized at near capacity. Even today short term drought conditions can cause the rationing of water. TxDOT requires large quantities of water for construction projects. The ability to use non-potable water sources for some of these applications can have a significant benefit by decreasing the demand for potable water supplies while decreasing the chances of construction delays due to water supply insufficiencies. This project evaluated a subset of alternate water sources (i.e. treated municipal wastewater Type I or II, brine water from oil production, impaired surface and groundwater, and ocean water) for their potential to be used in place of potable water for a number of construction activities (i.e. dust control, vegetative watering, flexible base, embankment, retaining wall). Evaluations focused on regulatory control of water sources, health and safety impacts for workers and the general public, environmental impacts, and impact on material properties and performance of constructed facilities.

Of the alternate waters evaluated wastewater effluent, and impaired surface and groundwater water will generally be of the highest quality in relation to critical attributes impacting construction applications. However, this increased quality also impacts the available (proximity and non-committed) sources which will be an important determinant of their eventual use. Wastewater effluent is generally produced wherever population centers exist. However, in some areas especially where water is scarce wastewater effluent may be dedicated for other usages. Availability of impaired surface waters and groundwater’s is likewise difficult to determine on a broad basis. Water rights can be an issue and should be dealt with on a local basis. Availability of brine and ocean water is mainly a function of access or proximity rather than competition for the source. In general the success of incorporating alternative sources into construction application sin relation to availability, permitting, and access will be a district dependent.

Numerous construction applications were valuated of these some were more sensitive than others in relation to performance impacts. It should be pointed out that potabiility does not equate with acceptability for performance as in some cases potable waters which are currently acceptable for use may not be acceptable for performance standards. Ocean water and brine water will generally only be potentially useable for stabilization (subgrades, subbase, and base courses) and compaction (road subgrades, flexible base courses, and embankment fill). Treated waste water effluent and impaired surface waters are potentially usable for all applications but must be individually evaluated. In most applications it is not possible to only evaluate the water source but the water source soil combination should be addressed as soil properties will play an important role in the eventual usability of alternate waters.

In order to evaluate a given water source a number of models and/or procedures were developed. For instance a model based on sulfate and chloride content and standard soil properties was developed to predict whether specific soil water combination s would be acceptable for retaining wall backfill. In most cases only a few parameters will impact usability (e.g. sulfate for stabilization or sodium and TDS for irrigation). In order to facilitate the evaluation process and use for the models and procedures developed in this research effort detailed decision matrices were created. In some cases insufficient research is available to confidently predict performance (e.g. soils subject to shrink/swell and dispersion concerns) and so use of alternative waters has been discouraged. However, additional research may allow for the selection of tests which would adequately evaluate these combinations. The following is a list of the major conclusions from this research effort.

Significant Conclusions

- Alternative water sources may be designated “non-potable” or “impaired” based on considerations (e.g. presence of disease causing pathogens) that have no relevance to their suitability for use in construction. Therefore, the alternative water sources are not necessarily inferior to water obtained from conventional sources.
- With the exception of ocean water, the variability of composition of all other alternative water sources examined is very high. Therefore, it is difficult to make the acceptance/rejection decisions by the generic water source category. This is possible on a few, rare instances (e.g. brine water sources are excluded from consideration for irrigation). More often, the acceptance/rejection decision require sampling water from the specific source of interest and testing the water or water-soil mixtures.
- The composition of water added to soil materials had significant impact on some soil parameters while it had negligible or no impact on others. The soil parameter that showed the greatest sensitivity to water composition was its resistivity. Resistivity controls the corrosion potential of soils. Therefore, careful evaluation is needed when using of alternative water in construction application where soil corrosion must be controlled.
- The sulfate and chloride levels in soil can also be significantly influenced by any sulfate and chloride that are present in construction water. Once again, this is most important in construction applications where soil corrosion is a concern. This is because the maximum acceptable levels of sulfate and chloride in soil (200ppm and 100ppm respectively) are quite low for a soil to be considered “mildly corrosive.”
- Addition of soluble sulfate from construction water into soil is also a concern when the soil is to be stabilized with Ca-based stabilizers. However, the soil sulfate threshold for low sulfate heave potential is 2000ppm which is much higher than the threshold established based on corrosion considerations. Analyses conducted in this research showed that when sulfate contents in most alternative water sources and the amounts of water typically added during construction are considered, the soluble sulfate contribution from construction would be fairly small. Therefore, as a general rule, use of alternative water is unlikely to make a significant impact on sulfate heave potential of soils. However, it can make a difference in soils that are marginal in terms of sulfate heave potential.

- The other soils parameters that were investigated, soil pH, Atterberg limits, and bar linear shrinkage did not change significantly as a result of mixing the soil with alternative water. Previous other studies have shown drawn similar conclusions with respect the impact of water composition on soil shear strength and compaction characteristics. Therefore, most alternative water sources would qualify for use in dust control, and soil compaction operations associated with embankment and road construction.
- Furthermore, testing conducted in this research did not reveal any appreciable change in soil dispersion or shrink/swell potentials as a result of adding alternative water. However, these two aspects deserve further study before that conclusion can be extended to soils that are marginal with respect to dispersion and shrink/swell potential.

Recommendations

A number of recommendations have been developed from the results of this effort. These are listed and explained below. However, a critical need which should be addressed is to field evaluate these results. Issues which should be addressed in an implementation project not only include the usability of the developed decision tools but confirmation of performance predictions and perhaps most importantly peripheral issues which can not be addressed by research such as permitting, access, transportation, and coordination of construction activities in relation to alternate water sources.

- Launch an implementation project.
    - select several projects,
    - one or two projects to represent each category;
    - compare quality of water from alternative sources versus conventional sources;
    - go through permitting and procurement process;
    - apply decision matrices;
    - set up a plan for monitoring the project; perform cost-benefit analysis;
    - develop an implementation guide for using alternative water sources in TxDOT construction projects.
- Undertake further research to determine impact on water quality on soils that show moderate to high dispersion potential and moderate high shrink/swell potential.