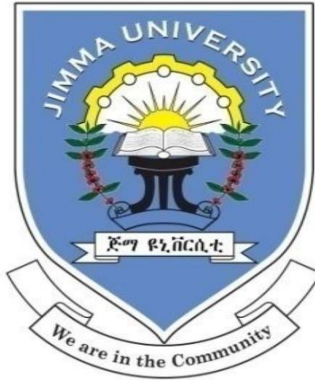




JIMMA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
JIMMA INSTITUTE OF TECHNOLOGY
FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING
HIGHWAY ENGINEERING STREAM

**Performance Evaluation of Natural Gravel mixed with Calcium Chloride for
Unpaved Road Surfacing**

A Final Thesis Submitted to the School of Graduate Studies of Jimma University in Partial
Fulfillment of the Requirements for the Degree of Master of Science in Highway Engineering

By

Tamrat Mekonnen

August, 2024
Jimma, Ethiopia

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Co-Advisor: Mr. Basha Fayissa (MSc)

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DECLARATION

I the undersigned, declare that this thesis entitled “**Performance Evaluation of Natural Gravel mixed with calcium chloride for unpaved road surfacing**” is my original work and has not been presented by other person for the award of any degree in this or any other University. All sources of materials used for this thesis have been duly acknowledged.

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ABSTRACT

A wide range of granular materials resulting from the weathering of rocks can be used as road base materials. In Ethiopia, there are many Kilometers of unpaved roads in federal and regional road networks, as well as access roads to mining sites and other natural resources. Dust is generated on unpaved road networks that pollute the environment, and the loss of fines associated with road dust contributes to increased gravel loss and the need for frequent maintenance. Hence, this research aims to evaluate the performance of natural gravel mixed with calcium chloride (CaCl_2) as a stabilizer for unpaved road surfacing. For this research, Natural Gravel samples were collected from an open borrow pit and an Anhydrous CaCl_2 stabilizer was obtained from the market. In this research experimental laboratory work was employed. The engineering properties of natural gravel were investigated in the laboratory. Different percentages of CaCl_2 in increasing percentages as 2%, 4%, 6%, 8%, and 10% were added to the specimen by the dry weight of natural gravel in order to evaluate its performance. For performance evaluation, tests carried out include grain size analysis, specific gravity, moisture absorption, Atterberg limits, linear shrinkage, compaction test, UCS, and CBR according to AASHTO, ASTM, and other relevant standards.

The natural gravel was classified A-2-7 (0) as per the AASHTO soil classification system and GC (Clayey Gravel) as per USCS. The hygroscopicity or moisture absorption capacity of the fine grained part of the natural gravel is increased from 1.2 to 9.45% with increased amount of CaCl_2 up to 10%. The test results indicated that the plastic index decreased from 17 to 4% and similarly linear shrinkage decreased from 9.2 to 2.7% with an increased ratio of CaCl_2 up to 10%. It was noted that with increased content of up to 10% of CaCl_2 in the mixture, the value of MDD is increased from 1.640 to 1.795g/cm³ and that of OMC is decreased from 13.7 to 10.1%. Also, the CBR value is increased from 26 to 48% and the CBR swell is decreased from 1.21 to 0.20% with an increased amount of CaCl_2 in the mixture up to 10%. The UCS value increased from 210.37 to 286.34KN/m² with increased amount up to 4% CaCl_2 and decreased with a further increase of CaCl_2 content.

It was found that 4% CaCl_2 is an optimum amount that is recommended to be used for effective stabilization of natural clayey gravel material, which could improve both its plasticity and strength requirements for unpaved road surfacing construction.

Key Words: Natural gravel, unpaved road, Gravel loss, Performance, Chemical Stabilization, Calcium chloride

TABLE OF CONTENT

DECLARATION.....	I
ACKNOWLEDGMENTS	II
ABSTRACT.....	III
TABLE OF CONTENT.....	IV
LIST OF TABLE	VIII
LIST OF FIGURE.....	IX
ACRONYMS	X
CHAPTER ONE	1
INTRODUCTION	1
1.1. Background	1
1.2. Statement of the Problem	3
1.3. Research questions	4
1.4. Objective	4
1.4.1. General Objective	4
1.4.2. Specific Objectives	4
1.5. Significance of the study	4
1.6. Scope of the study	5
1.7. Limitations of the study.....	5
CHAPTER TWO.....	6
LITERATURE REVIEW	6
2.1. Introduction	6
2.2. Unpaved Roads	8
2.3. Material Requirements for Natural Gravels	9
2.3.1. General.....	9
2.3.2. Particle Size Distribution and Shape	10
2.3.3. Plasticity Index	12
2.3.4. Moisture Absorption.....	13
2.3.5. Density, Strength and Durability	13
2.3.6. Natural Gravels Base for Low Volumes Road	14

2.3.7. Material Requirements for Gravel Wearing Course.....	17
2.4. Material Stabilization	20
2.4.1. Materials to be stabilized.....	20
2.4.2. Chemical Stabilization.....	21
2.4.3. Calcium Chloride.....	23
2.4.4. Chemically Stabilised Natural Gravel Base	26
2.5. Laboratory tests	27
CHAPTER THREE	28
MATERIALS AND METHODS.....	28
3.1. Study Area.....	28
3.2. Study Design	29
3.3. Study Procedure	30
3.4. Study Variables	30
3.5. Population.....	30
3.6. Sample collection techniques	30
3.7. Sources of Data	30
3.8. Instruments used.....	31
3.9. Data Collection Process	31
3.10. Materials collection	31
3.10.1. Natural Gravel	31
3.10.2. Calcium Chloride.....	32
3.11. Sample preparation.....	33
3.12. Experimental setup.....	33
3.13. Laboratory tests	34
3.13.1. Grain size analysis.....	35
3.13.2. Specific gravity.....	35
3.13.3. Moisture absorption.....	35
3.13.4. Atterberg limits.....	38
3.13.5. Linear shrinkage	39
3.13.6. Soil classification.....	40

3.13.7. Compaction test	40
3.13.8. Unconfined compressive strength	41
3.13.9. California Bearing Ratio and Swell	42
CHAPTER FOUR.....	43
RESULTS AND DISCUSSION	43
4.1. Introduction	43
4.2. Properties of Materials	43
4.2.1. Properties of Calcium Chloride	43
4.2.2. Properties of untreated natural gravel.....	45
4.2.2.1. Grain size analysis of natural gravel	45
4.2.2.2. Specific gravity of natural gravel.....	48
4.2.2.3. Moisture absorption of natural gravel.....	48
4.2.2.4. Atterberg limits of natural gravel.....	50
4.2.2.5. Linear shrinkage of natural gravel	51
4.2.2.6. Soil classification of natural gravel.....	54
4.2.2.7. Compaction characteristics of natural gravel.....	54
4.2.2.8. Unconfined compressive strength of natural gravel	55
4.2.2.9. Soaked California Bearing Ratio and Swell of natural gravel	55
4.3. Laboratory test results of stabilized natural gravel	56
4.3.1. The effect of Calcium Chloride on Moisture Absorption.....	56
4.3.2. The effect of Calcium Chloride on Atterberg Limits	58
4.3.3. The effect of Calcium Chloride on Linear Shrinkage	61
4.3.4. The effect of Calcium Chloride on Moisture density relationships.....	63
4.3.5. The effect of Calcium Chloride on Unconfined Compressive Strength.....	66
4.3.6. The effect of Calcium Chloride on CBR and Swell	68
CHAPTER FIVE	72
CONCLUSIONS AND RECOMMENDATIONS	72
5.1. Conclusions	72
5.2. Recommendations	74
REFERENCES	75

APPENDIX A: Grain Size Distribution Test Analysis Data	78
APPENDIX B: Specific Gravity Test Analysis Data	79
APPENDIX C: Moisture Absorption Test Analysis Data	80
APPENDIX D: Atterberg Limits Test Analysis Data	83
APPENDIX E: Linear Shrinkage Test Analysis Data	85
APPENDIX F: Soil Classification System Tables.....	87
APPENDIX G: Compaction Test Analysis Data.....	88
APPENDIX H: Unconfined Compressive Strength Test Analysis Data	94
APPENDIX I: California Bearing Ratio Test Analysis Data	95

LIST OF TABLE

Table 2.1: Ethiopian Road Network by Surface Type (2020) [24].....	9
Table 2.2: Recommended PSD for Natural Gravels for Road Base Materials (GB2, GB3) [25]	11
Table 2.3: Types of soils based on plasticity index [27]	13
Table 2.4: Particle size distribution for natural gravel base [25].....	14
Table 2.5: Plasticity requirements for natural gravel road base materials [26]	16
Table 2.6: Plasticity requirements for natural gravel subbase [25,26]	17
Table 2.7: Tanzanian and Ugandan specification for unsealed roads [29]	18
Table 2.8: Recommended material specifications for unsealed rural roads [26].....	19
Table 2.9: Recommended material specifications for unsealed urban roads [26]	20
Table 2.10: Recommended wearing coarse properties – South Africa [20]	20
Table 2.11: Properties of Calcium Chloride Hydrates and Calcium Chloride [30].....	25
Table 2.12: Solubility of calcium chloride in water [30].....	26
Table 2.13: Chemically Stabilized Natural Gravels Road Base Material [25]	26
Table 3.1: Properties of Calcium Chloride used as per specified on the package	32
Table 3.2: Laboratory tests as per standards	34
Table 4.1: Calcium chloride chemical composition and specification	43
Table 4.2: Physical properties of calcium chloride.....	44
Table 4.3: Engineering properties of untreated natural gravel	45
Table 4.4: PSD result of natural gravel and specification requirement of GWC [23].....	47
Table 4.5: Grading parameters value from PSD analysis versus specification requirement	48
Table 4.6: Specific gravity of the natural gravel.....	48
Table 4.7: Atterberg limits of NG sample and its plasticity modulus value	50
Table 4.8: Linear shrinkage of untreated natural gravel sample.....	52
Table 4.9: Shrinkage product value of natural gravel versus specification for unsealed roads....	53
Table 4.10: Calcium chloride effect on moisture absorption of natural gravel	56
Table 4.11: Calcium chloride effect on Atterbeg limits of natural gravel	58
Table 4.12: Calcium chloride effect on shrinkage product from PI and LS correlation.....	61
Table 4.13: Calcium chloride effect on linear shrinkage of natural gravel	62
Table 4.14: Calcium chloride effect on compaction characteristics of natural gravel.....	63
Table 4.15: Calcium chloride effect on unconfined compressive strength of natural gravel	66
Table 4.16: Calcium chloride effect on CBR and CBR swell of natural gravel	69

LIST OF FIGURE

Figure 2.1: Climatic N-Value map for Ethiopia [21].....	15
Figure 2.2: Material quality zones [21].....	18
Figure 3.1: Location map of study area (source https://www.google.com/maps/place/Gelan)....	28
Figure 3.2: Flow chart of study methods	29
Figure 3.3: Natural gravel sample collection	31
Figure 3.4: Anhydrous Calcium Chloride in powder form	32
Figure 3.5: Sample preparation for the laboratory test	33
Figure 3.6 (a): Moisture absorption/hygroscopicity test	36
Figure 3.6 (b): Moisture absorption/hygroscopicity test, after 24 Hours	37
Figure 3.6 (c): Moisture absorption/hygroscopicity test, after 7 days	37
Figure 3.7: Atterberg limits determination	38
Figure 3.8: Linear shrinkage test	39
Figure 3.9: Compaction test.....	40
Figure 3.10: Unconfined compression test	41
Figure 3.11: CBR test procedures	42
Figure 4.1: Moisture absorption of calcium chloride.....	44
Figure 4.2: PSD of natural gravel versus requirement as per ERA specification.....	46
Figure 4.3: Moisture absorption of natural gravel sample	50
Figure 4.4: Natural gravel material quality zone, performance and material properties	53
Figure 4.5: Dry density-moisture relationship curve for untreated natural gravel	54
Figure 4.6: CBR and swell value test result of untreated natural gravel	55
Figure 4.7: Moisture absorption of NG for different percent of CaCl ₂ within 7 days	58
Figure 4.8: Plasticity index of NG for different percentage of CaCl ₂ additive	59
Figure 4.9: Linear shrinkage of NG for different percentage of CaCl ₂ additive	63
Figure 4.10: Dry density and moisture relationship of NG treated with CaCl ₂ additive.....	64
Figure 4.11: Effect of calcium chloride on maximum dry density of NG	65
Figure 4.12: Effect of calcium chloride on optimum moisture content of NG	65
Figure 4.13: UCS of natural gravel treated with CaCl ₂ additive	67
Figure 4.14: CBR of NG treated with CaCl ₂ additive at 10, 30 and 65 number of blows	70
Figure 4.15: CBR value at 95% MDD for natural gravel treated with CaCl ₂ additive	71
Figure 4.16: CBR swell value for natural gravel treated with CaCl ₂ additive	71

ACRONYMS

AASHTO	American Association Of Highway And Transportation Officials
ASTM	American Society For Testing And Materials
BS	British Standard
CBR	California Bearing Ratio
ERA	Ethiopian Roads Authority
GB	Granular Base material
GC	Clayey Gravel
G_c	Grading coefficient
GM	Grading Modulus
GWC	Gravel Wearing Course
I_o	Oversize index
LL	Liquid Limit
LS	Linear Shrinkage
MDD	Maximum Dry Density
NG	Natural Gravel
OMC	Optimum Moisture Content
PI	Plastic Index
PL	Plastic Limit
PSD	Particle Size Distribution
PM	Plasticity Modulus
RH	Relative Humidity
RRAs	Regional Road Authorities
Sp	Shrinkage product
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System

CHAPTER ONE

INTRODUCTION

1.1. Background

Around the world there are millions of kilometers of unpaved (unsealed or gravel roads) in road networks that are managed by numerous different agencies. Unacceptable levels of dust, poor riding quality and impassability in wet weather often result from inappropriate, unsustainable maintenance and gravel replacement practices. Although it is acknowledged that these unpaved roads are fundamental to national, state, and local economies, many of the practices currently used to manage them leave much to be desired since procedures for best-practice gravel selection, construction, and maintenance; programs for dust control (fines preservation), stabilization, maintenance, and gravel replacement optimization; and consideration of low-cost upgrading all remain largely overlooked. Unpaved road management practice in many agencies worldwide is often limited to scheduling grader maintenance and periodic re-graveling, with intervals often dictated more by the availability of funds and public complaints, than by a systems approach [1].

Land transport systems, especially roads, play an important role in economic and social development. The lowest traffic and rural roads are important roads for some industries and factories, farmers, and stockbreeders; they used for transporting raw materials, products and used for gravel surface layer. These roads can also considered as the lowest level of facilities and most governments provide a cover for these roads in order to provide better services for the villagers. One of these methods is the use of calcium chloride and magnesium chloride solution in roads and passages to reduce dust. Due to the availability of these minerals in the desert, there is the ability to use these materials to avoid the costs imposed on the transportation system, as well as to protect the environment and sustainable development of roads [2].

Unpaved roads in Ethiopia require a treatment mechanism by which the sub-base of the road will give sufficient service about bearing capacity and resisting deformability of surface by moving traffic loads. Therefore, it needs to apply stabilization methods to strengthen and increase the durability of unpaved road [3].

In-place stabilization of properly graded aggregate with chloride additives is cost-effective and provides performance and intangible benefits. Stabilization provides a higher standard of road

surface performance by improving ride quality and reducing dust, corrugations (wash boarding), and raveling (loose aggregate). Other intangible benefits include reduced sedimentation in streams, reduced aggregate resource depletion, reduced health hazards from dust, and increased road-user safety [4].

Calcium chloride is an inorganic salt, which is a byproduct of sodium carbonate production [5]. The use of calcium chloride in place of lime, as calcium chloride is easier to make calcium charged supernatant than lime. A recent study indicated that CaCl_2 could be an effective alternative to conventional lime used due to its ready dissolvability in water and supply adequate calcium ions for exchange reactions. Calcium chloride is a more known since it can easily change into calcium charged supernatant than lime and helps in ready cation exchange reactions [6].

Being hygroscopic (moisture absorbing) and deliquescent (moisture retaining), it is able to absorb moisture from the surrounding environment and convert itself into the liquid form. Its ability to wet a dry soil prevents dust-forming particles from becoming airborne [7]. This also promotes an increase in density and capillary tension of fines on the surfaces of the materials, thereby resulting in enhanced inter-particulate bonding [8]. Calcium chloride stabilization significantly improves road-surfacing performance. Stabilization is much less expensive than attempting to obtain similar performance by more frequent road blading [9].

Many additives such as cementitious, bituminous, chemical, mechanical, biological, and proprietary blends routinely used in the improvement of material properties of poor soils and aggregates ranging from highly expansive clays to granular materials. Whereas the benefits of some of these additives are accounted in pavement design and lifecycle processes despite some industry guidance, the benefit of Calcium Chloride (CaCl_2) is not in consideration during design [10].

This study investigated the effect of calcium chloride as stabilizing agent for unpaved road base construction with the aim of determining the optimum mix ratio for the improved engineering properties of natural gravel. It proved feasible and it would lead to reduced cost of unpaved road construction and maintenance [4,9]. In addition, it ensures a safety of the road user and wellbeing of surrounding environment. It preserves the natural landscape by avoiding a need of utilizing more gravel borrow pits and protect natural gravel from depleting [4].

1.2. Statement of the Problem

Because of the low volume traffic and the remoteness of most unpaved roads, the paving of these roads is a hard and expensive task that remains unrealistic. Roads covered with granular materials called unpaved roads appear to be the best solution and thus will remain common. Considering that, security in the transportation industry is a growing concern and considering the industry's concern for increasing its profit-earning capacity, the management of this kind of road is not an easy task [11]. Although these unpaved roads are fundamental to national, state, and local economies, many of the practices currently used to manage them leave much to be desired since procedures for best-practice gravel selection, construction, and maintenance; programs for dust control (fines preservation), stabilization, maintenance, and gravel replacement optimization; and consideration of low-cost upgrading all remain largely overlooked. Unpaved road management practice in many agencies worldwide is often limited to scheduling grader maintenance and periodic re-graveling, with intervals often dictated more by the availability of funds and public complaints, than by a systems approach [1].

Unpaved roads are presently designed with very little scientific input and are constructed from the nearest available material. Unpaved roads demand constant maintenance to arrest damage by both traffic and the environment. Re-graveling is usually needed after only one or two years' service, putting considerable strain on local finance, manpower and natural resources [3].

In Ethiopia, although unpaved road pavement maintenance costs a public body, attention has not given to improve the gravel road performance by using stabilization during construction. Mostly, it relies on conventional method, which is periodically re-graveling, or blading with grader. During its service period, the gravel road emits a large quantity of dust from gravel loss due to traffic volumes, which affects the health of road users and has negative impact on well-being of nearby environment. Therefore, it needs to find an alternative stabilization mechanism for increasing the performance of the unpaved road with a minimum impact on the environment. The purpose of this study was to determine the effect of Calcium Chloride additive on natural gravels by laboratory investigation for using in unpaved road construction and maintenance.

1.3. Research questions

1. What are the physical properties of natural gravel and calcium chloride?
2. What is the performance of natural gravel mixed with different percent of calcium chloride?
3. What is the optimum percent of calcium chloride needed to improve the performance of natural gravel?

1.4. Objective

1.4.1. General Objective

The main objective of this study would be to investigate the effect of Calcium Chloride as a stabilizing agent on the performance of natural gravel used for unpaved road base construction.

1.4.2. Specific Objectives

The specific objectives of the study were

1. To determine the physical properties of natural gravel and calcium chloride
2. To evaluate the performance of natural gravel mixed with different percent of calcium chloride.
3. To determine the optimum percent of calcium chloride needed to improve the performance of natural gravel for unpaved road surfacing.

1.5. Significance of the study

Around the world, there are many kilometers of unpaved road networks constructed that need frequent re-gravelling due to the loss of wearing gravel by segregation and as dust particles, which is costly. The re-graveling needs sources of gravel borrow pit, which depletes the natural resource, and the dust generated from unpaved roads causes the health problem of the road users and has negative impact on surrounding environment. The stabilization alternative is required to use the proximately available natural gravel by improving its engineering properties as per required specification, which improves its performance, increase durability, saves maintenance cost and minimize dust pollution. Therefore, this study on calcium chloride effect as a stabilizing agent of natural gravel for unpaved roads proves that this stabilization could be best alternative of stabilization technique for construction and maintenance of unpaved road network. The study

verified some of the previous researches on Calcium Chloride as a stabilizing agent for road base construction. Other researchers will use the findings as a reference for further research.

1.6. Scope of the study

This study covered the chemical stabilization of natural gravel used in unpaved road surfacing, using Calcium Chloride of different mix proportion on natural gravel sample by conducting laboratory tests. Anhydrous CaCl_2 as stabilizer obtained from the chemical items distributor agency in the local market. Representative sample of natural gravel from open borrow pit were collected. The gravel samples were first air-dried. The tests conducted in accordance with ASTM and AASHTO testing methods. In order to achieve the objective of the research, the laboratory tests such as grain size analysis, specific gravity, moisture absorption, Atterberg limits, linear shrinkage, compaction, UCS and CBR tests were conducted. The study presented the laboratory test results that indicated the effect of CaCl_2 as a chemical stabilizing agent on performance of natural gravel for unpaved road surfacing. The study compared the results with relevant specifications and previous studies from which conclusion and recommendation drawn and forwarded.

1.7. Limitations of the study

This study was limited to its allocated budget and laboratory experience in Ethiopia. The study was done only on one type sample from one borrow material source. The dust suppressing effect of calcium chloride additive was not verified by laboratory test. In addition, the cost analysis for using calcium chloride as stabilizer was not done.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Many countries have large unsealed road networks, which are essential for business efficiency, social connectedness, and community safety [12]. Unpaved roads are the major component of the road network in most developing countries and comprise a significant portion of the network even in highly developed countries such as the United States [13]. These roads are maintained at considerable cost mainly through blading and re-gravelling [12]. It is unlikely that the overall percentage of unpaved roads will decrease significantly in the foreseeable future and techniques for improving the unpaved road networks are thus becoming increasingly important [13]. Typically, in Ethiopia low volume roads are unpaved with a gravel or earth wearing surface. Very few are in good condition and can provide the level of all-weather access that is required. Budgets for the improvement and maintenance of these roads are constrained. In facing the challenge of improving the low volume road network, the application of the conventional planning, design, construction and maintenance philosophies used for higher traffic roads is unlikely to provide an optimal solution [14].

The use of chemical treatments for improving unpaved road performance was first reported in 1907. The first documented research study on the benefits of calcium chloride in road maintenance was published in 1932. Since that time, there has been continual publication of papers documenting the performance of chemical treatments. Unfortunately, the majority of these studies have not considered the benefits (i.e., savings in gravel replacement and grader maintenance) of repeat treatments over the longer term, in line with the pavement preservation approach [1]. Calcium Chloride stabilization significantly improves road-surfacing performance. Ancillary benefits also accrue to road users, including fewer accidents, reduced vehicle maintenance, fewer delays, and improved air quality. Stabilization is much less expensive than attempting to obtain similar performance by more frequent road blading [9].

Two types of chlorides have been used for dust palliatives, magnesium chloride and calcium chloride. Ideal surfacing material for chlorides is between 10 and 20 percent passing the 75 μm sieve. An effective dust palliative is dependent on its interaction with the surface material under site-specific climatic conditions, traffic, and road geometry. Over the years the Forest Service

has successfully used a variety of dust palliatives. Based on the previous experience and cost, the use of dust palliative is considered [15]. A significant problem is when dust suppressing agents are used on gravel roads is that they tend to leach during rainfall. Chloride was prone to transport upwards by means of capillary rise, and therefore, it showed a more effective performance against leaching for a long period. Ions of calcium chloride seemed to flocculate clay particles, which probably prevents them from leaching [16].

Unpaved roads make up a significant portion of the rural and urban road network, and by promoting access; this network is one of the key factors contributing to economic growth. However, travelling along unpaved roads will not always assured because of their low standards, poor riding quality, impassability in wet weather, and the danger in the quantity of dust that is generated by moving vehicles and wind. This dustiness of unpaved roads reduces visibility and hinders traffic safety. Many unpaved roads do not have the ideal range and distribution of particle sizes to give a good load-bearing capacity when wet (coarser particles) or sufficient plastic capability (clay) when dry to prevent material from breaking loose. All unpaved roads, when dry, suffer from surface abrasion loss resulting in dust because the adhesion between the particles is reduced. The loss of road construction material also leads to the formation of ruts and potholes that could collect/retain water and this may decrease the natural durability and strength properties of the unpaved road system, making the road uncomfortable and dangerous to drive on [17].

Each year, most low-volume road agencies maintain thousands of miles of unpaved aggregate surfaced roads by surface blading. Blading is a costly activity which is done frequently and lasts a short time on heavily traveled roads. Road surface conditions can deteriorate so rapidly that blading is often recognized as an ineffective but politically necessary activity. Blading also contributes to the increase of stream sediments and contamination and to loss and breakdown of expensive aggregate surfacing. When used correctly, road surface stabilization with magnesium chloride and calcium chloride materials reduces blading significantly, increases road quality, and saves money. These two chlorides absorb moisture from the air and retain the moisture because they are deliquescent and hygroscopic. They promote an increase in density and capillary tension of fines in aggregate surfacing that helps bond the materials together [4]. Any increase in the strength of the material compared with untreated material could help reduce the amount of dusting and surface wear on the road surface [18].

Treatments with dust suppressants and stabilization agents respectively reduce dust and improve the mechanical characteristics of an unpaved road. Some stabilization agents may also act in both ways. Most of the studies concerning unpaved road treatment are made in a specific context [11]. Even though unpaved roads represent a large proportion of a road network, few research studies have been conducted on the design and maintenance challenges encountered on these types of roads in comparison to proportion of work being conducted on paved roads, mainly because traffic volumes are generally fairly low. However, traffic can also be very intense in terms of axle loads, especially on natural resource access roads. Stabilization agents are widely used to improve bearing capacity and reduce dust lifting to prevent excessive maintenance and air quality problems [19].

2.2. Unpaved Roads

Unsealed roads are defined as roads which are formed and covered with a granular (gravel) wearing course surface. They are also referred to as unpaved or gravel roads [20]. A gravel road consists of a wearing course and a structural layer (base) which covers the in situ material [21]. Gravel roads have a designed layer of imported material, which is typically constructed to a specified standard and width providing an all-weather surface. The performance of a gravel surface is based on material quality, the location of the road and the traffic volume using the road [22]. Unpaved road could be in rural, urban and mine access area. Mine haul roads are unsealed, but carry much higher axle loads than public unsealed roads [20]. Over 70 per cent of the road network in sub-Saharan Africa and most rural roads in other less developed regions of the world remain unpaved. In some countries in Africa, unpaved roads comprise over 90 per cent of the road network. High proportions of roads networks in many Asian countries are also unpaved [23].

The total extent of the classified road network of Ethiopia in 2020 was 144,027 km, and in terms of road surface type the total classified network was made up by 88% of gravel roads and 12% of asphalt roads [24].

One of the biggest disadvantages of gravel roads is dust that is imposed to them on the vehicle transportation time [2]. Dust is the fine material released from the road surface under the wheels of moving vehicles and the turbulence caused by vehicles. Silt-sized particles (2 - 75 μm) are the predominant elements in dust and the quantity of dust generated by a vehicle is a function of its

aerodynamic shape, speed of travel and the surfacing material properties [13]. Inhabitants that live near gravel roads surface problems such as dust that is settled on their houses and cars and this decrease their life quality. Dust can also have undesirable effects on the air and environment quality and reduce safety (visibility disturbance) for the drivers. In order to control dust in gravel roads, local organizations use dust stabilizers on their roads that are usually calcium chloride and magnesium chloride [2].

Table 2.1: Ethiopian Road Network by Surface Type (2020) [24]

Administration	Surface Type (km)			Road Condition (%)		
	Gravel	Asphalt	Total	Good	Fair	Poor
ERA	13,361	15,338	28,699	22	40	38
RRAs	35,806	0	35,806	30	20	50
Municipalities	24,416	1,282	25,698	24	30	46
Community/Woredas	53,824	0	53,824	18	37	45
Total	127,407	16,620	144,027	20	38	42
	88%	12%				

2.3. Material Requirements for Natural Gravels

2.3.1. General

A wide range of materials including lateritic, calcareous and quartzitic gravels; river gravels; boulders and other transported gravels; or granular materials resulting from the weathering of rocks can be used successfully as road base materials. The material shall be of such a nature that it can be readily excavated, transported, spread and compacted without segregation [25].

Lateritic road base gravels: Lateritic gravels occur in the west and northwestern parts of Ethiopia in the Guraghe, Jimma, Wollega and Gojam highlands. A large number of factors control how a particular type of laterite is developed and the material tends to exhibit both vertical and lateral variability within a deep and irregular weathering profile. The behaviour of lateritic materials in pavement structures depends mainly on their particle size characteristics, the nature and strength of the gravel sized particles, the degree of compaction as well as traffic and environmental conditions. The most important requirements for a laterite to show good field performance are that the material is well graded with a high content of hard, or quartz particles with adequate fines content. However, when judging the gradation of a lateritic gravel, it is important to assess its composition to decide if separate specific gravity determinations of the fines and coarse

fractions should be made. For example, for nodular laterites, the coarse fraction is iron-rich whilst the fine fraction is kaolinite. Thus, if there is a significant difference in the specific gravities of the coarse and fine fractions, the grading should be calculated by use of both volume and mass proportions [26].

Basic igneous rock (including basaltic and doleritic gravels): These materials occur extensively in Ethiopia and their more widespread use could result in significant savings provided the characteristics of the material are good enough to serve as a road base material. However, more research work is required before these materials can be used with confidence. In drier climatic areas, the materials can be used unmodified up to a maximum plasticity index of 10. However, it is suggested that the materials should not be used in wet areas unless chemically modified. Engineers need to use considerable judgement, experience and information from other roads in the area to utilize these materials successfully. Risks must be identified and controlled [26].

Cinder gravels: Volcanic cinder gravels are pyroclastic materials associated with recent volcanic activity. Such materials occur extensively in Ethiopia, characteristically as straight-sided cone-shaped hills which frequently have large concave depressions in their tops or sides where mixtures of solids and gases were released during the formation of the cone. Cinders vary in color often within the same cone and may be red, brown, grey or black. The cinder particles also vary in size from large irregularly shaped lumps 50 cm in size, to sand silt sizes. In some cases, however, particles may be uniform with the largest size not exceeding 3 cm in diameter. Other characteristic features of cinders are their lightweight, their rough vesicular surface and their high porosity. An advantage of cinders as a road construction material is the relative ease with which they dug from the quarry; a mechanical shovel or hand tools are usually adequate for their extraction although occasionally a bulldozer may be required. However, despite their extensive occurrence in Ethiopia, cinders have used for road construction only to a limited extent [26].

2.3.2. Particle Size Distribution and Shape

The particle size distribution should be approximately parallel with the grading envelope, to ensure that the material has maximum mechanical stability, in the grading limits shown in Table 5205/1 when determined in accordance with the requirements of AASHTO T-27. The mass of material passing the 0.075 mm sieve shall be determined in accordance with the requirements of AASHTO T-11. Table 5205/1 of ERA 2013 [25] contains three recommended particle size

distributions for suitable materials corresponding to maximum nominal sizes of 37.5 mm, 20 mm for un-stabilized base material and 37.5 mm nominal size for chemically stabilized material. In Table 2.2, road base material GB2 represented crushed weathered rock, gravel or boulders, and GB3 represented natural coarsely graded granular material, including processed and modified gravels.

Table 2.2: Recommended PSD for Natural Gravels for Road Base Materials (GB2, GB3) [25]

ISO Test sieve (mm)	Percentage by mass passing		
	Natural Gravel		Chemically stabilized
	37.5 mm	20 mm	37.5 mm
50	100	-	100
37.5	80 - 100	100	80 - 100
19	60 – 80	80 - 100	60 - 100
9.5	45 - 65	55 - 80	-
4.75	30 - 50	40 - 60	30 - 80
2.00	20 – 40	30 - 50	20 - 63
0.425	10 - 25	12 - 27	10 - 41
0.075	5 - 15	5 - 15	5 - 20

To meet the requirements consistently, screening and crushing of the larger sizes may be required. The fraction coarser than 10 mm should consist of more than 40 per cent of particles with angular, irregular or crushed faces. The mixing of materials from different sources may be warranted in order to achieve the required grading and surface finish. This may involve adding fine or coarse materials or combinations of the two. The flakiness index shall not exceed 30% when determined in accordance with BS 812 Part 105-1990 [25].

To obtain a material with high bearing capacity, the air void content must be as low as possible. If the content of fine material is too low, there is a risk that the gravel road will be subjected to raveling because the fine material binds larger particles. However, if the content of fine material is too high, there is a risk that the gravel road will be smeary and slippery when wet, sensitive to deformations, and dusty when dry. On the basis of theoretical knowledge and experience from practice, the content of fine material within a gravel wearing course should be between 8–15% by weight, as defined by the Swedish Road Administration [16].

The effectiveness of CaCl_2 treatment can be influenced by weather conditions and the particle size distribution of the road's indigenous aggregate. In the optimum moisture content (MC) condition, the best performance for well graded, non-plastic, and plastic soils, the minus 200 mesh (75 μm) content in the composite needs to be from 12% to 18% and 8% to 12%, respectively [8].

2.3.3. Plasticity Index

Plasticity index (PI) is the numerical difference of the liquid and plastic limits of the soil and indicates the range of moisture content through which the soil remains plastic [7]. The plasticity requirement varies depending on the traffic level and climate [26]. The fine fraction of granular base GB2 and GB3 material for high traffic level shall have a maximum Plasticity Index of 6 when determined in accordance with AASHTO T-90. If the PI approaches the upper limit of six, it is desirable that the fines content (passing 0.425 mm sieve) be restricted to the lower end of the range. To ensure this, a maximum Plasticity Modulus (PM) of 120 is recommended.

Where, $\text{PM} = \text{PI} \times (\text{percentage passing the } 0.425 \text{ mm sieve})$.

The addition of low percentages of hydrated lime or cement to reduce the PI to acceptable limits without satisfying the Initial Consumption of Stabilizer (SANS 30001 GR-57) of the material and creating a stable chemically stabilized material shall not be allowed unless approved by the Engineer. The minimum Grading Modulus for material once placed and compacted on the road shall be for natural material 2.00, and for material to be chemically stabilized 1.75 [25].

The plasticity index is used in soil classification and in various correlations with other soil properties as a basic soil characteristic. Based on the plasticity index, the soils were classified by Atterberg, shows the correlations between the plasticity index, soil type, degree of plasticity and degree of cohesiveness. The plasticity index of a soil increases linearly with the percentage of the clay sized fraction. Plasticity depends on grain size of soil. With the increase of sand content plasticity index of soil decreases, which might be due to decrease of inter molecular attraction force. Due to decrease of attraction force, liquid limit of the soil decreases and accordingly plasticity index decreases. But as the clay content increases inter molecular attraction force increases and liquid limit increases [27].

Table 2.3: Types of soils based on plasticity index [27]

Plasticity index (%)	Soil type	Degree of plasticity	Degree of cohesiveness
0	Sand	Non-plastic	Non-cohesive
Less than 7	Silt	Low plastic	Partly cohesive
7 - 17	Silt clay	Medium plastic	Cohesive
Greater than 17	Clay	High plastic	Highly cohesive

2.3.4. Moisture Absorption

Hygroscopic moisture content of fine-grained soil represents the water adsorbed by the negatively charged clay platelets when the oven-dried soil is exposed to an atmosphere with different levels of humidity, which is a variable. Increase in the relative humidity of the surrounding environment will increase the corresponding hygroscopic moisture content. It reaches a maximum at relative humidity 100%. It is easy to create an environment with relative humidity 100%, which requires the use of only distilled water [28].

The addition of calcium chloride to soil increases the absorption of soil moisture and soil will be wet but test conditions are of high importance in the effect of calcium chloride salt on soil such that if the test is not performed under suitable conditions, there would be a difference of about 80% between the results [2].

2.3.5. Density, Strength and Durability

When used as a road base, the material should be compacted to a density equal to or greater than that specified in 5208(b) of the maximum dry density achieved using the AASHTO T-180 D method. When compacted in the laboratory to 98% of Modified AASHTO density, the material should have a minimum CBR of 80% after four days immersion in water (ASTM D 1883). The durability of certain natural gravel base materials are known to be susceptible to disintegration in service and production of plastic fines which could be detrimental to the performance of the road [25].

The California bearing ratio (CBR) value, of the stabilized soils is an important parameter in assessing its suitability for use as a road construction material. The use of grain size distribution and Atterberg limits alone were not sufficient in meeting the requirements of materials for road construction use because such materials behave differently under different moisture and density conditions. The CBR is used to establish the material's shear strength and this could possibly

explain why UCS and CBR have consistent and similar trend. The CBR soaked test indicate the materials (possibly worst condition) post-compaction behavior, which means when wetted (and in due course soaked or saturated) [5].

2.3.6. Natural Gravels Base for Low Volumes Road

Wider ranges of materials are suitable for the base for low volume roads and are dependent on traffic categories and climate. The quality of material used shall be controlled by the design CBR at a minimum of 98% modified AASHTO density. The grading envelopes for road base for low volume roads as per ERA Standard Technical Specification are shown in Table 2.4. Envelope A varies depending whether the nominal maximum particle size is 37.5mm, 20mm or 10mm. A requirement of five to ten percent retained on successive sieves may be specified at higher traffic (greater than 0.3 Mesa) to prevent excessive loss in stability. Envelope C extends the upper limit of envelope B to allow the use of sandy materials, but its use is not permitted in wet climates. Envelope D is similar to gravel wearing course specification, and shall be used for very low traffic volumes. The grading is specified only in terms of the grading modulus (GM) and can be used in both wet and dry climates [25].

Table 2.4: Particle size distribution for natural gravel base [25]

ISO Test Sieve size (mm)	Per cent by mass of total aggregate passing test sieve				
	Envelope A			Envelope B	Envelope C
	Nominal maximum particle size				
	37.5mm	20mm	10mm		
50	100	-	-	100	-
37.5	80 - 100	100	-	80 - 100	-
19	55 - 95	80 - 100	100	55 - 100	-
9.5	40 - 80	55 - 85	60 - 100	40 - 100	-
4.75	30 - 65	30 - 65	45 - 80	30 - 80	-
2.00	20 - 50	20 - 50	35 - 75	20 - 70	20 - 100
1.00	-	-	-	-	-
425µm	8 - 30	12 - 30	12 - 45	8 - 45	8 - 80
300µm	-	-	-	-	-
75µm	5 - 20	5 - 20	5 - 20	5 - 20	5 - 30
Envelope D 1.65 < GM < 2.65					

The climatic descriptor which is used for the pavement design catalogs is the Weinert 'N' value. N-values less than 4 apply to a climate that is seasonally tropical and wet (the Kolla, Woina Dega, Dega, and Wurch regions of Ethiopia), whereas N-values greater than 4 apply to a climate that is arid, semiarid or dry (the Bereha region of Ethiopia). A map of equivalent N-values for Ethiopia is shown in Figure 2.1 and provides the means of placing a road in the appropriate climatic zone for design purposes [21].

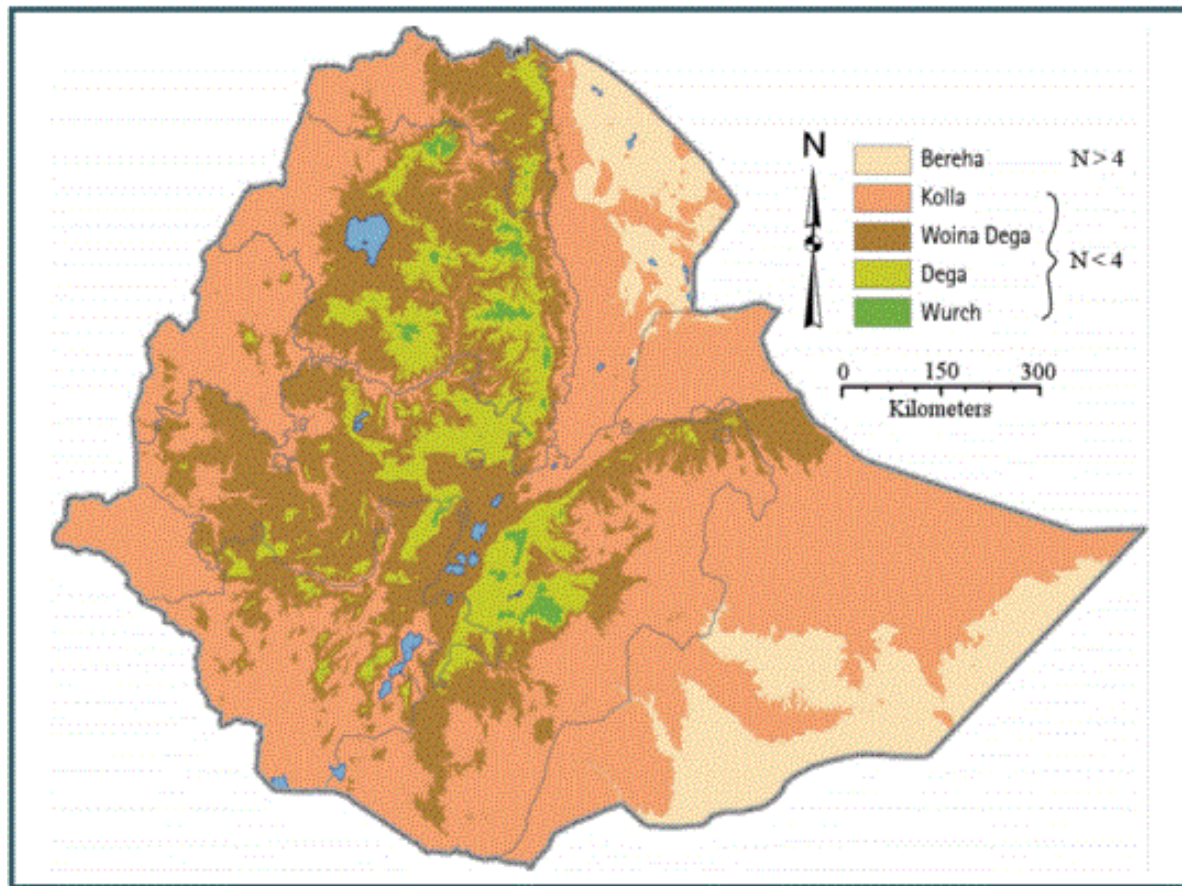


Figure 2.1: Climatic N-Value map for Ethiopia [21]

The plasticity requirement varies depending on the traffic level and climate as per Ethiopian Design Manual For Low Volume Roads shown in Table 2.5. A maximum plasticity index of 6 has been retained for higher traffic levels and also on weaker subgrades. For designs in dry environments the plasticity modulus for each traffic and subgrade class can be increased depending on the crown height and whether unsealed or sealed shoulders are used. In drier climatic areas ($N > 4$), the natural gravel materials can be used unmodified as a road base up to a

maximum plasticity index of 10. However, it is suggested that the materials should not be used in wet areas unless chemically modified [26].

Table 2.5: Plasticity requirements for natural gravel road base materials [26]

Subgrade Class ⁴	Property of base	Traffic Class (mesas)				
		LV1	LV2	LV3	LV4	LV5
		<0.01	0.01-0.1	0.1-0.3	0.3-0.5	0.5-1.0
S2	I _p	<12	<9	<6	<6	<6
	PM	<400	<150	<120	<90	<90
	Grading	B	B	A ⁽⁵⁾	A ⁽⁵⁾	A ⁽⁵⁾
S3	I _p	<15	<12	<9	<6	<6
	PM	<550	<250	<180	<90	<90
	Grading	C ⁽¹⁾	B	B	A ⁽⁵⁾	A ⁽⁵⁾
S4	I _p	Note ⁽²⁾	<12	<12	<9	<9
	PM	<800	<320	<300	<200	<90
	Grading	D ⁽³⁾	B	B	B	A ⁽⁵⁾
S5	I _p	Note ⁽²⁾	<15	<12	<12	<9
	PM	-	<400	<350	<250	<150
	Grading	D ⁽³⁾	B	B	B	A ⁽⁵⁾
S6	I _p	Note ⁽²⁾	<15	<15	<12	<9
	PM	-	<550	<500	<300	<180
	Grading	D ⁽³⁾	C ⁽¹⁾	B	B	A ⁽⁵⁾

Notes:

1. Grading 'C' is not permitted in wet environments or climates (N<4); grading 'B' is the minimum requirement
2. Maximum I_p = 8 x GM
3. Grading 'D' is based on the grading modulus 1.65 < GM < 2.65
4. All base materials are natural gravels; Subgrades are non-expansive
5. Envelope A varies depending on whether the nominal maximum particle size is 37.5, 20 or 10mm [26].

Table 2.6: Plasticity requirements for natural gravel subbase [25,26]

Climate	Typical Annual Rainfall (mm)	Liquid limit	Plasticity index	Linear shrinkage
Moist tropical and wet tropical (N<4)	>1000	< 35	< 6	< 3
Seasonally wet tropical (N<4)	>500	< 45	< 12	< 6
Arid and semi-arid(N>4)	<500	< 55	< 20	< 10

2.3.7. Material Requirements for Gravel Wearing Course

Ideally, the wearing course material should be durable and of consistent quality to ensure, it wears evenly. The desirable characteristics of such a material are good skid resistance, smooth riding characteristics, cohesive properties, resistance to raveling and scouring, wet and dry stability, low permeability, load spreading ability.

Gravel loss is the single most important reason why gravel roads are expensive in whole life cost terms and often unsustainable, especially when traffic levels increase. Reducing gravel loss by selecting better quality gravels or modifying the properties of poorer quality materials is one way of reducing long-term costs [26].

The specifications identify the most suitable materials in terms of two basic soil parameters, Shrinkage Product and Grading Coefficient, which are determined from particle size distribution and linear Shrinkage. For the range of materials likely to be used for gravel wearing course, the plasticity index can be assumed to be 2 x linear shrinkage. The linear shrinkage (shrinkage product) is recommended as it is based on one relatively simple test which has good precision limits in the shrinkage ranges of acceptable gravel wearing course material [21].

Performance related specifications for wearing course materials have been developed for southern Africa based on extensive sampling, testing and monitoring of a large number of test sections. These specifications have been successfully implemented in a number of African countries and are considered to be generally applicable to the Ethiopian environment [26].

The Tanzanian and Ugandan specifications are essentially the same, defining the limits as shown in Table 2.7. Differences in test techniques from those used during the development of the specifications have resulted in transferability problems between countries [29].

Table 2.7: Tanzanian and Ugandan specification for unsealed roads [29]

Property	Tanzania	Uganda
Shrinkage Product	120 - 400	120 - 400
Grading Coefficient	16 - 34	16 - 34

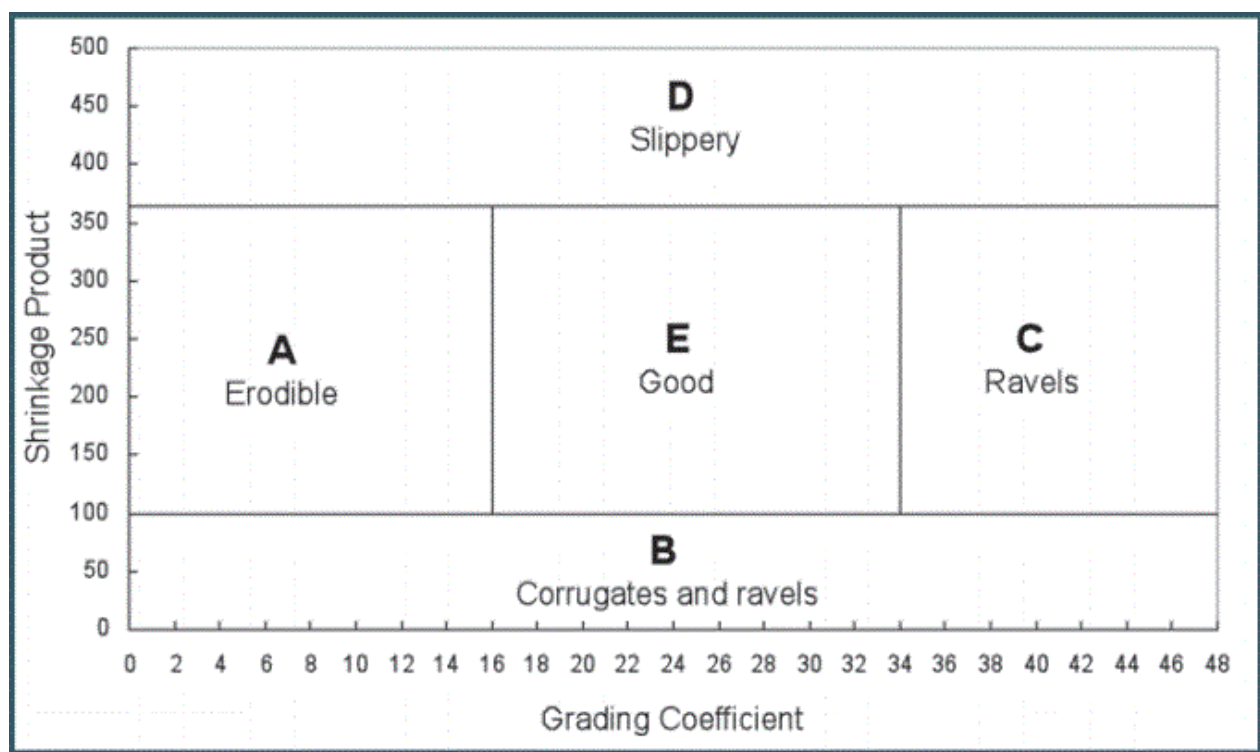


Figure 2.2: Material quality zones [21]

The material quality zones define material quality in relation to their anticipated in-service performance [26]. The characteristics of materials in each zone are as follows:

A: Materials in this area generally perform satisfactorily but are finely graded and particularly prone to erosion. They should be avoided if possible, especially on steep grades and sections with steep cross-falls and super-elevations. Roads constructed from these materials require

frequent periodic labour intensive maintenance over short lengths and have high gravel losses due to erosion.

B: These materials generally lack cohesion and are highly susceptible to the formation of loose material (ravelling) and corrugations. Regular maintenance is necessary if these materials are used and the road roughness is to be restricted to reasonable levels.

C: Materials in this zone generally comprise fine, gap-graded gravels lacking adequate cohesion, resulting in ravelling and the production of loose material.

D: Materials with a shrinkage product in excess of 365 tend to be slippery when wet.

E: Materials in this zone perform well in general, provided the oversize material is restricted to the recommended limits [21].

As per indicated in Ethiopian Roads Authority Design Manual for Low Volume Roads [26] the recommended material specifications for gravel roads in rural areas and for urban areas are presented in Table 2.8 and Table 2.9, respectively. The recommended material specifications for unsealed rural roads presented in [29] is the same with the one presented in [21,26].

Table 2.8: Recommended material specifications for unsealed rural roads [26]

Property	Specification Requirement
Maximum size (mm)	37.5
Oversize index (Io)	$\leq 5 \%$
Shrinkage product (Sp)	100 – 365 (max. of 240 preferable)
Grading coefficient (Gc)	16 – 34
Soaked CBR (@95% Mod AASHTO compaction)	$\geq 15 \%$
Treton impact value (%)	20 – 65
Io = Oversize index (per cent retained on 37.5 mm sieve Sp = Linear shrinkage x per cent passing 0.425 mm sieve Gc = (Per cent passing 26.5 mm – per cent passing 2.0 mm) x per cent passing 4.75mm)/100	

Table 2.9: Recommended material specifications for unsealed urban roads [26]

Property	Specification Requirement
Maximum size (mm)	37.5
Oversize index (Io)	0
Shrinkage product (Sp)	100 – 240
Grading coefficient (Gc)	16 – 34
Soaked CBR@95%	≥ 15 %
Treton impact value (%)	20 – 65

Table 2.10: Recommended wearing coarse properties – South Africa [20]

Property	South Africa					
	Rural roads		Urban roads		Haul roads	
	Min	Max	Min	Max	Min	Max
CBR (4 day soaked) in %	15	-	15	-	40	-
Max size (mm)	37.5	-	37.5	-	75	-
Shrinkage product (Sp)	100	365	100	240	100	365
Grading coefficient (Gc)	16	34	16	34	16	34

2.4. Material Stabilization

Stabilization is a process of blending and mixing materials with a soil or aggregate when the strength or other properties such as gradation, workability, or plasticity of the in-place soil do not meet the desired or required levels for a design [10]. The engineering properties of material for the construction of the roadbed and/or subgrade, sub-base and road base shall improved by the addition of a chemical stabilizing agent, or by the mechanical modification of the material by mixing various materials, or by treating the material with a bituminous stabilizing agent [25].

2.4.1. Materials to be stabilized

Stabilized material is any naturally occurring cohesive or non-cohesive soil or processed material, in which the properties permanently improved by the process of stabilization to comply with the requirements of the Specification for the relevant materials for roadbed and/or subgrade,

sub-base and road base. Materials considered for stabilization shall have a minimum grading coefficient of uniformity of five [25].

Road Bed and/or Sub-grade Stabilization: Sub-grade stabilization is used to establish a dryer construction platform in wet soils to facilitate the compaction of the upper layers; and to strengthen a weak soil and restrict the volume change potential of a highly plastic (expansive) or compressible soil.

Sub-base and Road Base Stabilization: The stabilization of materials for use as sub-base and road base shall provide a permanent improvement to the un-stabilized materials to meet the requirements [25].

Unpaved/ Gravel Wearing Course: Travel along unpaved roads is not always assured, because of their low standards, poor riding quality, impassability in wet weather, and the danger in the quantity of dust that is generated by moving vehicles and wind [17]. Obtaining materials that comply with the necessary grading (particle size distribution-PSD) and plasticity specifications for gravel wearing course in Ethiopia can be difficult. Many of the natural gravels tend to be coarsely graded and relatively non plastic and the use of such materials results in very high roughness levels and high rates of gravel loss in service and, in the final analysis, very high life-cycle costs.

Gravel loss is the single most important reason why gravel roads are expensive in whole life cost terms and often unsustainable, especially when traffic levels increase. Reducing gravel loss by selecting better quality gravels or modifying the properties of poorer quality materials is one way of reducing long-term costs [26].

2.4.2. Chemical Stabilization

Stabilization agents such as cement and lime are commonly used chemical stabilization techniques in improving road-base construction material. Other chemical stabilizing agents such as fly ash; cement/lime-slag mixtures using ground-granulated blast-furnace slag; and Portland fly-ash cement shall use if specified in the Particular Specifications if it is approved or instructed by the Engineer. The stabilized layer shall protect against rapid drying out for at least seven days following completion of the layer [25].

- Application of Stabilizing Agent: After preparation of the layer of soil or gravel, the stabilizing agent shall be spread uniformly over the full width of the layer by means of an

approved type of mechanical spreader at the prescribed rate of application in a continuous operation, or it may be spread by hand.

- **Mixing in of Stabilizing Agent:** Immediately after the stabilizing agent has been spread, it shall be thoroughly mixed with the material for the full depth of treatment. Care shall be exercised not to disturb the underlying compacted layer, nor to mix the agent below the desired depth. Mixing shall be continued and repeated as often as may be required to ensure a uniform mix of the soil or gravel and stabilising agent over the full width and depth of material to be treated and until the resulting mixture is homogeneous and of uniform appearance throughout.
- **Watering:** Immediately after the stabilising agent has been properly mixed with the material, the moisture content of the mixture shall be determined and the required amount of water. The amount of water to be added shall be sufficient to bring the mixed material to the optimum moisture content for the compaction equipment used and the minimum density required in the respective requirements for sub grade, sub-bases and bases.
- **Compaction:** The Compaction provisions of the respective Divisions for sub grade, sub-bases and bases shall apply. During compaction, loss of moisture through evaporation shall be corrected by further light applications of water. At the completion of the primary compaction, the surface shall be cut to the finished level and all cuttings removed from the surface before final rolling. Final rolling shall be done with equipment that will give a smooth surface conforming to the surface tolerance specified. The minimum compaction requirements shall be as specified for the particular layer in the Specification
- **Curing of stabilized Work:** The stabilised layer shall be protected against rapid drying out for at least seven days following completion of the layer. The stabilised layer shall be kept continuously wet for seven days by an effective fog spraying system that will not damage the surface of the layer or by any other system approved by the Engineer. During this period the application of water shall be so controlled that it will not unduly wet the layer but at the same time will not allow the layer to dry out [25].

Calcium Chloride is a common chemical additive known for its ability to regulate moisture [10]. Calcium chloride stabilization should be considered for roads in the following conditions: aggregate surfacing replacement costs are high, road blading frequency is high, a high standard

of a road surface performance is needed, the road is located in a dry climate and experiences the traditional problems of raveling, dust, or washboarding [9].

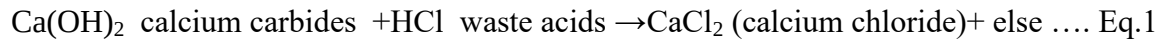
When used in road surface and base stabilization, CaCl_2 , being hygroscopic and deliquescent, absorbs moisture from the air and retains it, thus minimizing dust erosion because of wind and traffic. This also promotes an increase in density and capillary tension of fines on the surfaces of the materials, thereby resulting in enhanced interparticulate bonding [8].

2.4.3. Calcium Chloride

Calcium chloride (CaCl_2) is an inorganic salt, which is a byproduct of sodium carbonate production [18]. It is a typical ionic halide and is a solid at room temperature. Its molecular weight is 110.98 g/mol and its melting point is 772 °C. Calcium chloride, being very soluble, can serve as a source of calcium ions in a solution, unlike many other calcium compounds, which are insoluble. Calcium chloride is one of the most versatile of the basic chemicals. It has been produced commercially for over 100 years. The properties and characteristics of CaCl_2 make it useful in a large number of applications. It has several common applications such as brine for refrigeration plants, ice and dust control on roads, and in concrete. The anhydrous salt is also widely used as a desiccant, where it will absorb so much water that it will eventually dissolve in its own crystal lattice water (water of hydration). It can be produced directly from limestone, but large amounts are also produced as a by-product of the “Solvay Process” (which is a process to produce soda ash from brine). Because of its hygroscopic nature, the anhydrous form must be kept in tightly sealed containers. Because the anhydrous salt is strongly hygroscopic, air or other gases can be channeled through a column of calcium chloride to remove moisture [30].

The solid calcium chloride has high water-absorbing performance. At a relative humidity of 95%, solid CaCl_2 can absorb 16.6 times its weight of water. Even in a relatively low humidity environment of 30%, it can absorb almost equal to its own weight water. In addition, calcium chloride dissociates into Ca^{2+} ions in the presence of water, which will lead to ion exchange reactions with Na^+ and K^+ ions initially adsorbed on the clay particle surface. As a result, the thickness of double diffusion layer (DDL) of soil particles shall reduce and soil particle aggregates will form. Consequently, the soil plasticity will decrease and strength will increase [31].

Solid CaCl_2 shall obtain from the industrial wastes, calcium carbides, which are byproducts of acetylene factory. Currently in China, these calcium carbides are usually open stocked without any covering material, which has caused serious environmental pollution problem at rain season. However, calcium carbides shall reuse to produce solid CaCl_2 through following chemical reaction:



Here, Ca(OH)_2 is the main component of calcium carbides and HCl is a kind of waste acids produced from iron or steel factory. At this moment, CaCl_2 isn't solid, and it needs heating and drying to be in solid state. By doing so, calcium carbides can reuse and its impact on surrounding environment can reduce. The validity of Eq. 1 can approve in preliminary series of laboratory tests. It found that through chemical reaction as described by Eq. 1, up to 0.85 kg solid CaCl_2 can be obtained from 1 kg calcium carbides, implying that the source of solid calcium carbides could guaranteed in engineering practice [31].

Calcium chloride (CaCl_2) is a simple material produced from natural brine deposits found underground or from the synthetic Solvay process. It is processed into a colorless, odorless liquid, which is the material primarily used for dust control and base stabilization on unpaved roads [32]. Calcium chloride has been used as an additive to accelerate curing durations and to increase the strength of soil-cement mixtures [33].

Calcium chloride stabilization treatment at 1.5% to 2.0% pure chloride improves dense graded aggregate and native surface road performance significantly and can be cost-effective when compared with the combined costs of blading maintenance and aggregate replacement. Stabilization reduces blading maintenance and sedimentation and also leads to decreases in dust, aggregate loss, raveling, and wash boarding. Treatment performance is strongly influenced by weather conditions, traffic volume, and type. The best performance was obtained with aggregates that are well graded with 12% to 18% smaller than No. 200 sieve if non-plastic and from 8% to 12% smaller than No. 200 sieve if plastic [9].

The addition of calcium chloride shrinks and decreases repulsive forces, thus promoting the flocculation of clay particles and dehydrating interlayer zones of expandable clays, which subsequently became gritty or granular. It was indicated that increasing cation concentration or cation valence would result in a decrease in net repulsive forces; hence causing clay particles to flocculate. This behaviour is attributed to the decrease in the thickness of the diffused double

layer as the salt content increased. Therefore, it could be said that the CaCl_2 content tends to reduce the thickness of the diffuse double layer and flocculate the clay particles, resulting in a reduction in liquid limit, plastic limit and plasticity index of clay thus having a significant effect. The improvement in the compaction parameters with the addition of CaCl_2 may be attributed to the cation exchange between mineral layers. Under the influence of dynamic compaction, the clay particles become more oriented and the compacted dry unit weight increases with the increase in salt content [5].

The use of Calcium Chloride can decrease dust lifting up to 70% and maintenance costs up to 46% [19].

Calcium Chloride is classified as Solid (S) and Liquid (L). Concentrations of Type S and Type L Calcium Chloride shall be expressed as the percentage of the total. The concentrations of Type L Calcium Chloride shall be specified by the purchaser; typical concentrations vary from 30 to 45%. Type S (Solid) Calcium Chloride is graded as: Grade 1, is 77% minimum concentration of either Class A-Flake or Class B-Granular; Grade 2, is 90% minimum concentration of Class A-Flake, Class B-Pellet, Class C-Granular, Class D-Powder; Grade 3, is 94% minimum concentration of Class A-Flake, Class B-Pellet, Class C-Granular, Class D-Powder [34].

Table 2.11: Properties of Calcium Chloride Hydrates and Calcium Chloride [30]

Property	$\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	$\text{CaCl}_2 \cdot 4\text{H}_2\text{O}$	$\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$	$\text{CaCl}_2 \cdot \text{H}_2\text{O}$	CaCl_2
Composition (% CaCl_2)	50.66	60.63	75.49	86.03	100
Molecular weight	219.09	183.05	147.02	129	110.99
Melting point ($^{\circ}\text{C}$)	29.9	45.3	176	187	773
Melting point (F)	85.8	113.5	349	369	1424
Boiling point ² ($^{\circ}\text{C}$)	-	-	174	183	1935
Boiling point (F)	-	-	345	361	3515
Density at 25 $^{\circ}\text{C}$ (77 F), g/cm^3	1.71	1.83	1.85	2.24	2.16
Heat of fusion (cal/g)	50	39	21	32	61.5
Heat of fusion (Btu/lb)	90	70	38	58	110.6
Heat of solution ³ in H_2O (cal/g) (to infinite dilution) (Btu/lb)	17.2	-14.2	-72.8	-96.8	-176.2
Heat of formation ³ at 25 $^{\circ}\text{C}$ (77 F), kcal/mol	-623.3	-480.3	-335.58	-265.49	-190.10
Heat capacity at 25 $^{\circ}\text{C}$ (77 F), cal/g $^{\circ}\text{C}$ or Btu/lb F	0.34	0.32	0.28	0.20	0.16

Table 2.12: Solubility of calcium chloride in water [30]

		g/100 ml of water							
Substance	Formula	0°C	10°C	15°C	20°C	30°C	50°C	70°C	90°C
Calcium chloride	CaCl ₂	59.5	64.7	74.5	100	128	137	147	159

2.4.4. Chemically Stabilised Natural Gravel Base

ERA (2013) [25] stated the requirements for chemically stabilized natural gravel materials using stabilizers such as Ordinary Portland cement, Portland Blast-Furnace Cement, Lime, fly-ash, cement/lime-slag mixtures using ground granulated blast-furnace slag, and Portland fly-ash cement such that the natural gravel meeting grading requirements.

The main objective of chemical stabilisation on unpaved road material, as explained by researchers, is to maintain the characteristics of the material, favourable from the aspects of the given engineering target, regardless of the moisture in its environment. As a result of chemical stabilisation, the bearing capacity and strength of the unpaved road material should be increased; and water-tightness, resistance to erosion and other properties should also be improved [17].

Table 2.13: Chemically Stabilized Natural Gravels Road Base Material [25]

Material before treatment			Grading to be within the limits shown in Table 5205/1
PI after treatment			Slightly plastic or non-plastic
Unconfined Compressive Strength (MPa)	100% Mod AASHTO density	Minimum	1.5
		Maximum	3.0
	97% Mod AASHTO density	Minimum	1.0
		Maximum	2.0
Indirect tensile Strength – 100% mod AASHTO density (kPa)			250
Stabiliser content			Initial Consumption of Stabiliser (SANS 3001 GR-57) + 1%
Wet/Dry durability using the mechanical brush test to SANA 3001 GR 56			< 8% loss
Carbonated UCS strength			N/A If the ICL requirement is satisfied, carbonation of stabilized layers is unlikely

Chemical additives used for strength improvement are referred to as stabilisers or additives, and for dust suppression are referred to as dust palliatives [17]. Use of calcium chloride as a dust palliative is well known. Its ability to wet a dry soil prevents dust-forming particles such as fly ash from becoming airborne. Calcium chloride treatment provides the additional benefits of reducing the plasticity index (PI) of a soil and, in turn, improves its workability and increases the strength of the roadbed mixture [7].

The key benefit of the use of CaCl_2 is that it allows for optimum aggregate interlock by penetrating into the aggregate structure and coating its particles, improving compaction during construction, which is already known to provide cost savings to gravel surfaced roads. The benefits in the use of CaCl_2 on road rehabilitation projects include better material workability during construction; less use of water for compaction; higher compaction levels; and a general sense of better performing projects [10].

2.5. Laboratory tests

Laboratory studies on natural gravel treated with different percentage of calcium chloride (CaCl_2) by dry weight of soil was carried out to establish the soil improving potential. Tests to be carried out include grain size analysis, moisture absorption, Atterberg limits, linear shrinkage, compaction characteristics (maximum dry density, MDD and optimum moisture content, OMC), strength characteristics (unconfined compressive strength, UCS and California bearing ratio, CBR) of materials were investigated separately in order to know the natural properties of materials as per relevant code of standard [25,26,34,36].

Several classifications systems have been developed to categorize granular materials and soils based on the material properties, primarily particle size distribution, and plasticity. The most widely used classifications systems are the AASHTO Soil Classification System [34] and the Unified Soil Classification System (USCS) [36]. The AASHTO system classifies soils in eight groups (from A-1 to A-8) based essentially on particle size distribution and plasticity. In the USCS classification material is categorized based on particle size distribution (G if gravel, S if sand, M if silts, and C if clays, W if well-graded, P if poorly graded) and plasticity [12].

CHAPTER THREE

MATERIALS AND METHODS

3.1. Study Area

Natural gravel samples were collected from location near Gelan Town, in the Akaki woreda of Oromia Special Zone Surrounding Finfinne, in Oromia Regional State, Ethiopia. Its geographical coordinates is $8^{\circ} 49' 36.21''$ N, $38^{\circ} 51' 33.59''$ E shown in Figure 3.1. Anhydrous CaCl_2 as stabilizer was obtained from the chemical items distributor agency in Addis Ababa.

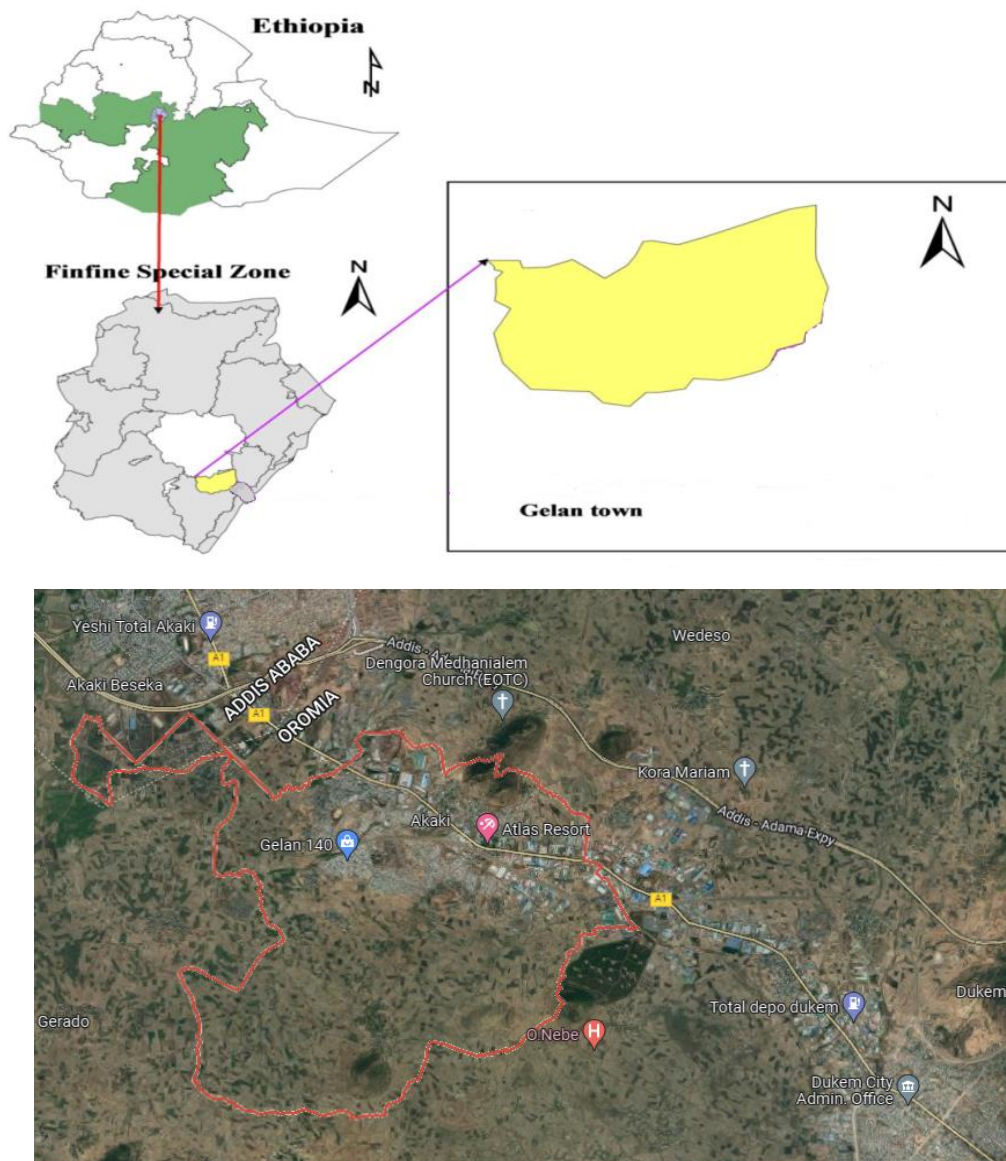


Figure 3.1: Location map of study area (source <https://www.google.com/maps/place/Gelan>)

3.2. Study Design

This research was designed to answer the research questions and to meet its objectives based on experimental study that was conducted in the laboratory. The first step was sample collection. The next step was laboratory tests on un-stabilized natural gravel and the stabilized one. The outcomes were analyzed, interpreted and then properties of natural gravel and its performances after stabilization was determined, from which conclusion and recommendation were finally made.

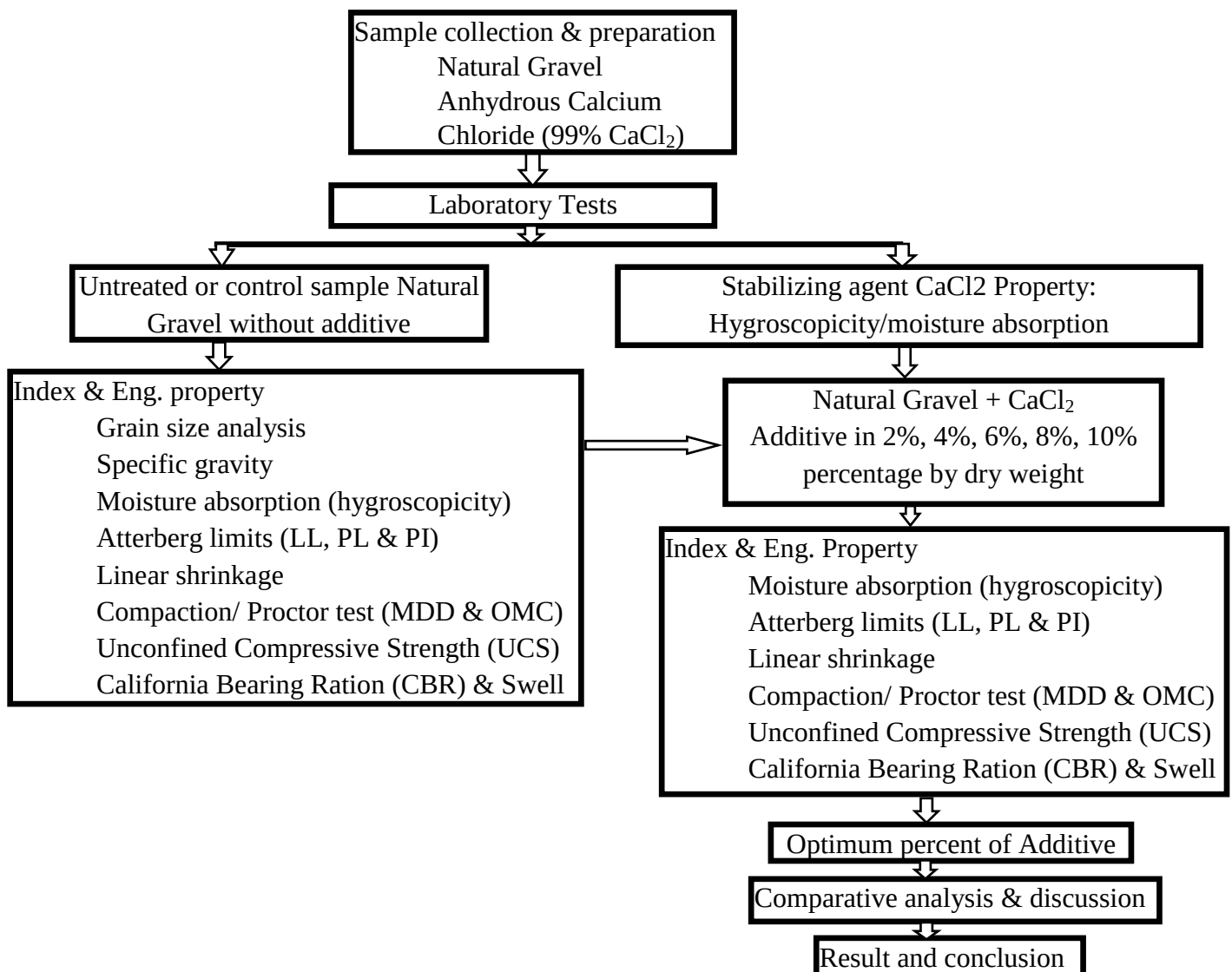


Figure 3.2: Flow chart of study methods

3.3. Study Procedure

The procedure utilized throughout the conduct of this research study were as follows: Continuous review of related literatures on methods of stabilization, types of stabilizers and properties of calcium chloride includes articles, reference books, research papers, standards specifications like ERA, AASHTO and ASTM. Necessary data collection, organization, comparison and analysis were obtained, and then subsequently compared the results with previous literature and standard specifications. Conclusion and recommendation were made based on the results.

3.4. Study Variables

The study variables, which consist in the research, contained both independent and dependent variables. The dependent variable was performance of natural gravel stabilized with calcium chloride for unpaved road base construction.

The independent variables were Index and Engineering properties of natural gravel samples including Particle Size Distribution, Specific Gravity, Moisture Absorption, Atterberg Limits, Linear Shrinkage, MDD, OMC, UCS, CBR and CBR swell, and Dosage of stabilizing agent (Calcium Chloride) contents.

3.5. Population

The population of this research was the natural gravel of the selected study area of Gelan town, and anhydrous calcium chloride.

3.6. Sample collection techniques

The sampling technique used for this research was a purposive sampling, which is non-probability method. This sampling technique was proposed based on the information that to determine the experimental investigation on suitability of the natural gravel for unpaved road base construction. For sample preparation, quartering and weighting technique was used.

3.7. Sources of Data

Both primary and secondary data sources were used. The primary sources of data for this study were laboratory experimental outputs and secondary data were collected from different standards, journals, books and websites.

3.8. Instruments used

The following instruments and software were used for this study: sampling bags, shovel, manual hand auger equipment, vehicle for sample transport, laboratory equipment, and digital camera for documentation, MS word and Excel to analyze laboratory data.

3.9. Data Collection Process

In order to attain the purpose of this research work, ethical considerations before start any data collection, a formal letter was obtained from Jimma institute of Technology.

Quantitative and qualitative data were utilized based on the necessary input parameters for the analysis by comparing them with AASHTO, ASTM and ERA manuals. The data collection process included field visual inspection, sampling, and laboratory tests. Finally, the results from laboratory tests were compared with standard specifications.

3.10. Materials collection

3.10.1. Natural Gravel

The natural gravel sample were collected by observation purposely from open borrow pit which was located near Gelan Town, in the Akaki woreda of Oromia Special Zone surrounding Finfinne, in Oromia Regional State of Ethiopia. According to procedures outlined on AASHTO and ERA manuals [34,35], a 300 kilograms disturbed sample of natural gravel was collected as shown in Figure 3.3.



Figure 3.3: Natural gravel sample collection

3.10.2. Calcium Chloride

The calcium chloride used in this study was obtained from a chemical store market, in Addis Ababa. The industrial grade calcium chloride of specified 99% minimum assay in crystal/powder form, 16 kilograms packed in plastic jar of each 500 grams were taken. As per AASHTO Manual [34], Calcium Chloride used for this study is classified as Solid, Grade 3, and Class D-Powder. Properties of calcium chloride as per specified on the package and as per indicated on [3,6,29] is presented in Table 3.1.

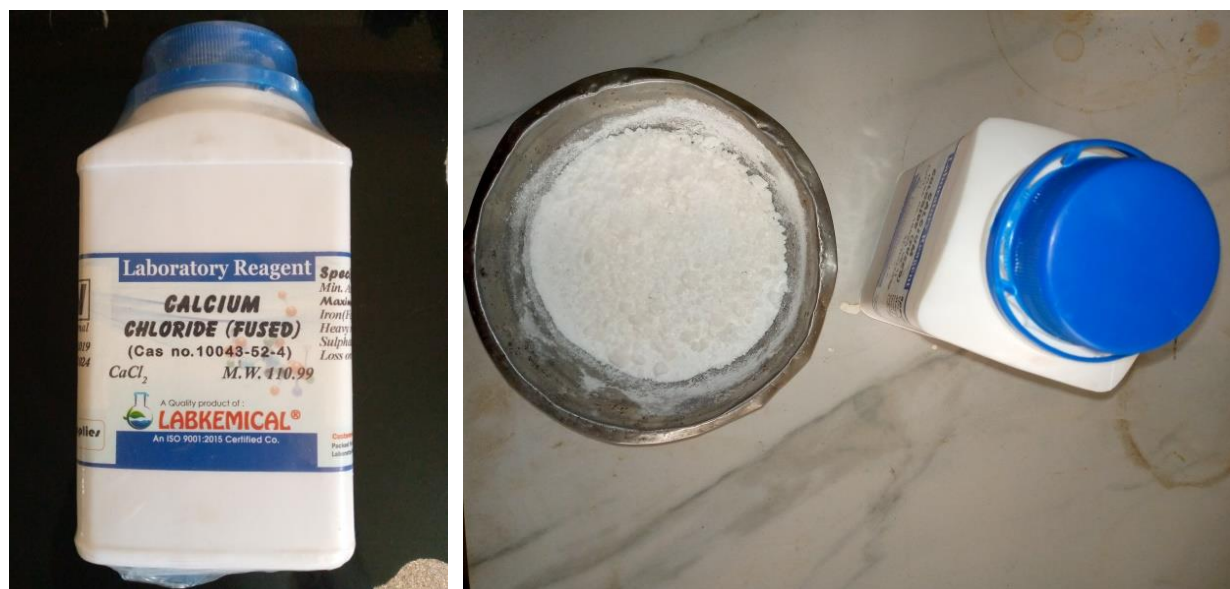


Figure 3.4: Anhydrous Calcium Chloride in powder form

Table 3.1: Properties of Calcium Chloride used as per specified on the package

Physical property	Result
Molar mass (g/mol)	110.99
Appearance	White powder
Minimum assay (%)	99
Iron (Fe) maximum impurity (%)	0.002
Heavy metal (Pb) maximum impurity (%)	0.002
Sulphate (SO_4) maximum impurity (%)	0.05
Loss on drying (%)	10
Boiling point ($^{\circ}C$)	1935
Density (g/cm ³)	2.15
Soluble in	Water

3.11. Sample preparation

The natural gravel sample collected from the field was prepared for laboratory tests using the procedure outlined in AASHTO T87 and AASHTO T248. The natural gravel sample was dried thoroughly in air. The representative sample to perform the laboratory tests was obtained by splitting on canvas. The aggregation of natural gravel was done by a rubber covered hammer, adequately pulverized and then sieve analysis was conducted. Sieving was done into three groups. The first group was natural gravel sample passing 0.425mm sieve for Atterberg limit, the second group 2.00mm sieve was for specific gravity, and the third group was natural gravel sample passing 19 mm for compaction and California bearing ratio.



Figure 3.5: Sample preparation for the laboratory test

3.12. Experimental setup

First, the index and engineering properties of natural gravel were determined. Then, dried natural gravel sample and calcium chloride in different percentage (2%, 4%, 6% and 8%) were mixed together in proportion of by weight. These percentages were selected to suit for comparison and evaluation purpose with previous studies used as references. Laboratory tests were conducted on natural gravel stabilized with different percentage of calcium chloride to determine the effect on index properties, compaction characteristics and strength properties. Tests that were carried out include Moisture absorption (hygroscopicity), Atterberg limits, Linear shrinkage, compaction

characteristics (maximum dry density, MDD and optimum moisture content, OMC), strength characteristics (unconfined compressive strength, UCS and California bearing ratio, CBR).

Then, laboratory tests data were analyzed and interpreted that the effects of calcium chloride additive on natural gravel performances as unpaved road surfacing was addressed. The optimum stabilizing ratio for maximum improvement of the engineering properties of the natural gravel was evaluated and the result from the laboratory test was compared with the standards and specifications of AASHTO and ERA. Finally, the research findings and recommendations were expressed based on the laboratory test results.

3.13. Laboratory tests

The laboratory tests were undertaken as per relevant code of standard procedures referenced to ERA, AASHTO and ASTM standards. The conducted laboratory tests were Grain Size Analysis, Specific Gravity, Moisture absorption (hygroscopicity), Atterberg Limits (LL, PL, PI), Linear shrinkage, Proctor compaction test (MDD, OMC), Unconfined Compressive Strength (UCS), and California Bearing Ratio (CBR) and Swell.

Table 3.2: Laboratory tests as per standards

Laboratory test	Test method
Grain Size Analysis	AASHTO T27
Specific Gravity	AASHTO T100
Moisture absorption (hygroscopicity)	AASHTO T265
Atterberg Limits (LL, PL, PI)	AASHTO T89, T90
Linear shrinkage	SANS 3001-GR10, as per ERA requirement [25]
Soil classification	AASHTO M145, ASTM D2487
Proctor compaction test (MDD, OMC)	AASHTO T180
Unconfined Compressive Strength (UCS)	AASHTO T208 (ASTM D2166)
California Bearing Ratio (CBR) and Swell	AASHTO T193

3.13.1. Grain size analysis

For the grain size analysis, the method AASHTO T27 was used. This test was performed to determine the particle size distribution of fine and coarse aggregates by sieving. A weighed sample of dry natural gravel was separated through a series of sieves of progressively smaller openings for determination of particle size distribution.

3.13.2. Specific gravity

The specific gravity test was conducted on the natural gravel in accordance with AASHTO T100 testing procedure. This test method covers the determination of the specific gravity of soils using a volumetric flask for material passing a 4.75 mm sieve. The specific gravity is the ratio of the mass of a unit of volume of a material with a stated temperature to the mass of the same volume of gas free distilled water at a stated temperature.

3.13.3. Moisture absorption

In this test for determining the hygroscopic moisture content and moisture absorption capacity or hygroscopicity of the finer portion of the natural gravel sample under study, the way of calculation of moisture content determination stated on AASHTO T265 was used. As stated in AASHTO T88 test method, the hygroscopic moisture content is the moisture contained in air dried particles that shall be expressed as a percentage of the mass of the oven dried soil [34]. Also, as per defined in [28], hygroscopic moisture content of fine-grained soil represents the water adsorbed by the negatively charged clay platelets when the oven-dried soil is exposed to an atmosphere with different levels of humidity, which is a variable. As per stated in [28], hygroscopic moisture content has been linked with many clay mineralogical parameters in predictive geotechnical engineering. However, there appears to be no standard codal provisions to quantify this property.

In this study, the air dried sample was used for determining the hygroscopic moisture content of the fine grained portion of untreated natural gravel material as per defined in [34], and the oven dried sample was used for determining the hygroscopicity or moisture absorption capacity when exposed to atmosphere for treated and untreated sample as per stated in [28]. The oven dried sample was chosen as a controlling point for evaluating the moisture absorption, since the oven drying will make the moisture content null. Because, the air dried sample may have different hygroscopic moisture content in different atmosphere of varying relative humidity and

temperature. Moisture absorbing capacity is influenced by the temperature and relative humidity of the environment [7].

As understood from previous studies, hygroscopicity is the moisture absorption capacity of the material. By using methods stated in [2,28], the moisture absorption capacity or the hygroscopicity of fine grained portion of natural gravel passing 0.425mm sieve, exposed to ambient moisture at approximately 100% relative humidity, was determined on increasing time intervals from 24 Hours to 7 days. A quantity of 20 – 30 grams of oven dried natural gravel portion passed 0.425mm sieve were placed and spread in stainless steel cup. These cups containing the oven dried samples, with their lids removed, were placed on the platform inside a desiccator containing distilled water at its bottom, and the lid of the desiccator was closed. The masses of these cups with the fine grained portion of natural gravel were measured at 24 hours elapsed times for consecutive 7 days, and the increase in amount of moisture absorption were recorded.



Figure 3.6 (a): Moisture absorption/hygroscopicity test



Figure 3.6 (b): Moisture absorption/hygroscopicity test, after 24 Hours



Figure 3.6 (c): Moisture absorption/hygroscopicity test, after 7 days

3.13.4. Atterberg limits

The Atterberg limits are a simple measure of the critical water fillings of a fine-grained soil [2]. The test procedure adapted for the determination of liquid limit, plastic limit and plasticity index for both untreated and treated natural gravel sample was in accordance with AASHTO T89 and T90 respectively. Representative samples of fine portion of natural gravel were subjected to Atterberg limits testing to determine its consistency. An Atterberg limits device was used to determine the liquid limit of the natural gravel using the portion passing through a 475 μm sieve. The liquid limit was determined by using the Casagrande apparatus. The plastic limit of each sample was determined by using fine portion of natural gravel passing through a 475 μm sieve and rolling 3-mm diameter threads until they began to crack. The plasticity index was then computed for each sample based on the liquid and plastic limit obtained.



Figure 3.7: Atterberg limits determination

3.13.5. Linear shrinkage

Linear shrinkage test followed SANS 3001-GR10, as per ERA requirement [25], and covers the determination of total linear shrinkage from linear measurement on a standard bar of length 150 mm with a semicircular section of diameter 25 mm, the groove filled by a soil of the fraction passing 0.425 mm test sieve, originally having the moisture content of the liquid limit. The linear shrinkage was determined as the change in length of a bar sample of fine portion of natural gravel passed 0.425mm sieve when dried from about its liquid limit, expressed as a percentage of the initial length.



Figure 3.8: Linear shrinkage test

3.13.6. Soil classification

The sampled natural gravel was classified using the AASHTO Soil Classification System AASHTO M145, and USCS Soil Classification system ASTM D2487. For classifying the material, both methods utilize the test results of the grain size distribution and Atterberg limits. The standard tables or charts of the respective specification were used to classify the natural gravel material sample.

3.13.7. Compaction test

This test was done to determine the maximum dry density (MDD) and optimum moisture content (OMC) of the material. In this study, AASHTO T180 was used for compaction tests on the natural gravel and various percentages of a mixture of calcium chloride added to the natural gravel.



Figure 3.9: Compaction test

3.13.8. Unconfined compressive strength

The significance of this test is to quickly obtain the approximate compressive strength of soils that possess sufficient cohesion to permit testing in the unconfined state. For this study AASHTO T208 was used to determine compressive strength of the fine portion of natural gravel passing 0.425mm sieve, compacted to optimum moisture content and maximum dry density in a cylindrical mold of diameter 38mm and height 76mm. Cylindrical specimens were axially loaded in unconfined condition at axial strain rate 0.5 to 2percent/min. In this test method, unconfined compressive strength is taken as the maximum load attained per unit area or the load per unit area at 15 percent axial strain, whichever is secured first during the performance of a test.



Figure 3.10: Unconfined compression test

3.13.9. California Bearing Ratio and Swell

The CBR is expressed by force exerted by the plunger and the depth of its penetration into the specimen; it is aimed at determining the relationship between force and penetration. A three point CBR test at 10, 30 and 65 blows were conducted according to AASHTO T193 and the CBR values at 95% MDD was determined. The CBR test indirectly measures the shearing resistance of a soil under controlled moisture and density conditions. The CBR is obtained as the ratio of load required to affect a certain depth of penetration of a standard penetration piston into a compacted specimen of the soil at some water content and density to the standard load required to obtain the same depth of penetration on a standard sample of crushed stone.



Figure 3.11: CBR test procedures

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

This chapter presents test results, analysis and discussion of all experimental work that were performed on untreated and treated natural gravel sample with calcium chloride as stabilizer. First, properties of untreated natural gravel were examined, then the effect of stabilizer on moisture absorption, Atterberg limits, linear shrinkage, compaction characteristics, unconfined compressive strength, CBR and swell values were investigated by varying the percentage of stabilizer from 2% to 10%, by 2% increment and compared with untreated natural gravel engineering properties. Then, the effect of calcium chloride stabilizer on the properties of treated natural gravel was compared and contrasted with standard specification manuals.

4.2. Properties of Materials

4.2.1. Properties of Calcium Chloride

The chemical composition and specification of anhydrous calcium chloride used in this study was presented in Table 4.1. For calcium chloride used in this study, the concentration of other impurities, those compounds other than water and chlorides, was 0.054%. For calcium chloride product concentration greater than 90.5%, this level of impurities meet the requirement of AASHTO M144 standard.

Table 4.1: Calcium chloride chemical composition and specification

Chemical composition	Result (%)	Specification (%)	Remark
Minimum assay, CaCl ₂ (%)	99	94 minimum, for Grade 3 Powder	In range
Iron maximum impurity (%)	0.002	1 maximum other impurities, those compounds other than NaCl, KCl, MgCl ₂ , H ₂ O, Ca(OH) ₂	In range
Heavy metal maximum impurity (%)	0.002		
Sulphate maximum impurity (%)	0.05		

The physical properties of calcium chloride as per presented in [3,6,29] was shown in Table 4.2.

Table 4.2: Physical properties of calcium chloride

Physical properties	Result (%)
Appearance	White powder
Molar mass (g/mol)	110.99
Melting point (°C)	773
Boiling point (°C)	1935
Density (g/cm ³)	2.15
Solubility in water	Freely soluble

The result of moisture absorption or hygroscopicity test conducted on calcium chloride for 7 consecutive days of exposure to approximately 100 percent relative humidity in desiccator, filled with distilled water, was presented in Figure 4.1. The moisture absorption of calcium chloride under controlled relative humidity, from the first day to the seventh day was recorded that it increased from 16 to 97%. In one week time, the calcium chloride absorbed moisture amount as much as its weight from the environment of approximately 100% relative humidity, and it was observed that the specimen changed to aqueous solution. As stated in [6], solid calcium chloride has high water absorbing performance, which was verified in this study. This means that calcium chloride attracts and absorbs water.

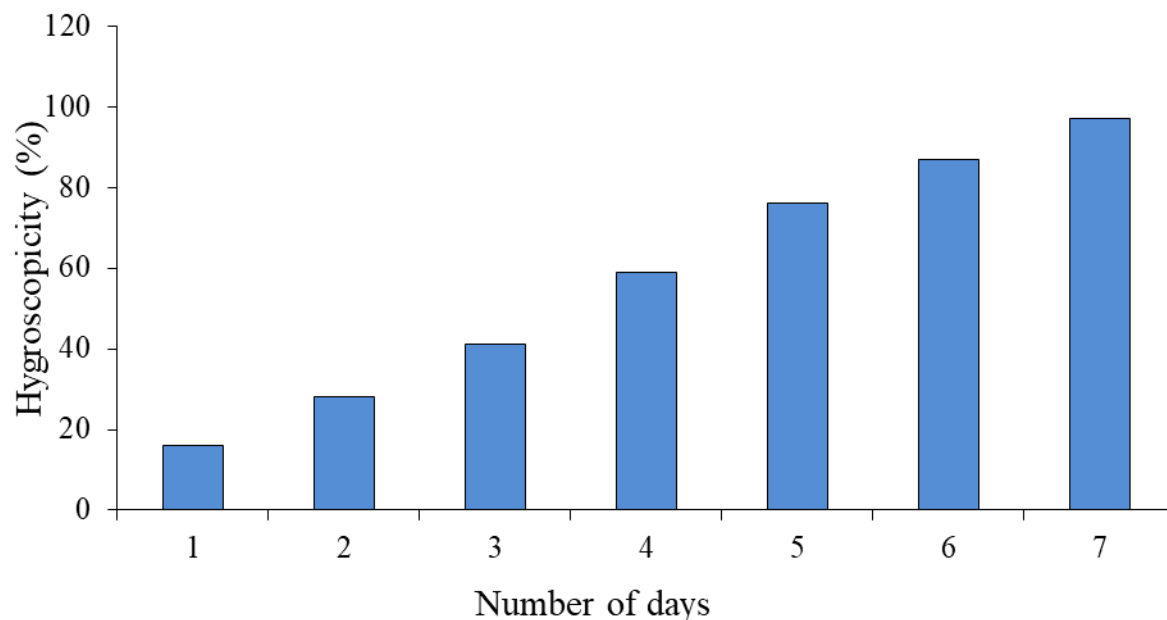


Figure 4.1: Moisture absorption of calcium chloride

4.2.2. Properties of untreated natural gravel

The engineering properties of the untreated natural gravel obtained from conducted laboratory tests were presented in Table 4.3.

Table 4.3: Engineering properties of untreated natural gravel

Physical property	Laboratory result
Percent passing No. 200 Sieve, 0.075mm (%)	13
Percent passing 0.425mm Sieve (%)	30
Specific Gravity	2.66
Hygroscopic moisture content (%)	0.81
Plastic Index (%)	17
Linear shrinkage (%)	9.2
Soil classification AASHTO	A-2-7 (0)
Soil classification USCS	GC (Clayey Gravel)
Maximum dry density, MDD (g/cm ³)	1.64
Optimum moisture condition, OMC	13.7
Unconfined Compressive Strength, UCS (KN/m ²)	210.37
Soaked CBR value at 95% MDD (%)	26.0
CBR swell (%)	1.21

4.2.2.1. Grain size analysis of natural gravel

Grain size analysis provides the grain size distributions, and it was required in classifying the natural gravel material. The sieve analysis was used to determine the grain size distribution curve of soil samples by passing them through a stack of sieves of decreasing mesh opening sizes and by measuring the weight retained on each sieve. The sieve analysis was applied to the soil fraction larger than 0.075mm by method AASHTO T27. The particle size analysis results in comparison with ERA specification [25] shown in Table 2.2 for recommended particle size distribution of natural gravel to be chemically stabilized was depicted in Figure 4.2. The detailed grain size analysis data were attached in Appendix A.

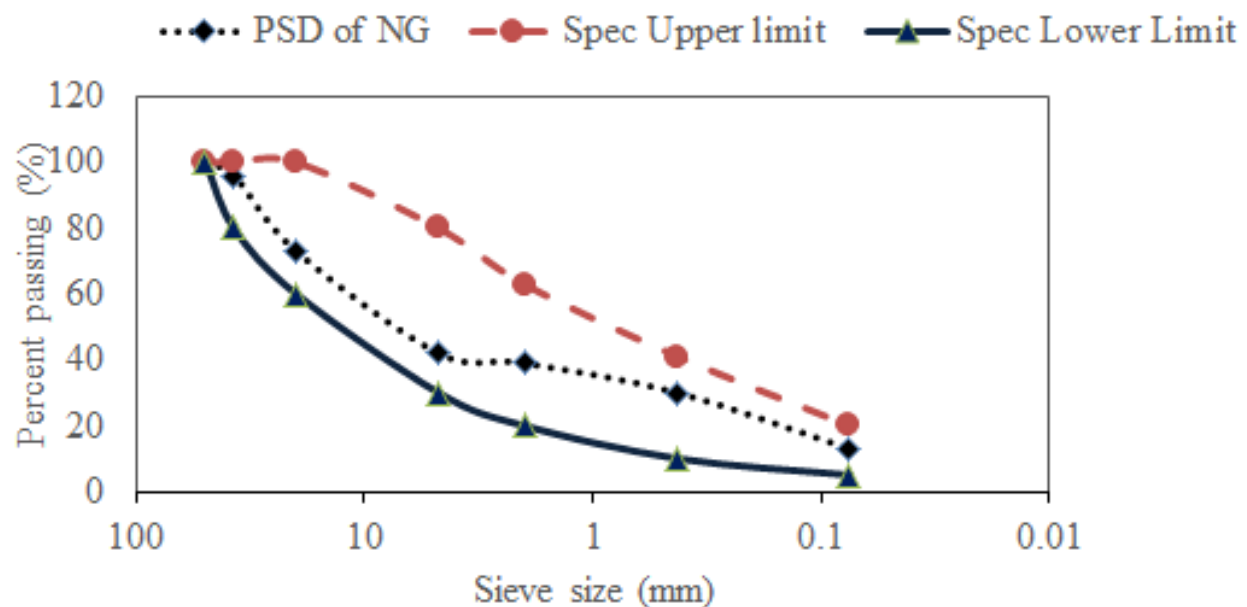


Table 4.4: PSD result of natural gravel and specification requirement of GWC [23]

Sieve size (mm)	Percent Passing (%)	Specification (%)	Remark
50	100	-	-
37.5	96	-	-
26.5	88	100	It is coarser
20	73	85 - 100	It is coarser
12.5	69	-	-
10	50	65 - 100	It is coarser
4.75	42	55 - 85	It is coarser
2	39	20 - 60	In the range
1.18	38	-	-
0.425	30	25 - 45	In the range
0.15	17	-	-
0.075	13	10 - 25	In the range

As presented above on Table 4.4, in comparison with PSD requirement for gravel wearing coarse material as [23] from Australian Road Research Board, the grain size distribution of the natural gravel under study for sieves size from 4.75mm to 26.5mm indicated that it is coarser than the requirement, and for sieves size from 2mm to 0.075mm indicated that it is within the requirement range.

When categorized as per ERA design manual for low volume roads [26], the result of PSD analysis of natural gravel were 13% of silt and clay less than 0.075 mm grain size, 26% of sand 0.075 - 2.0 mm grain size and 56% of gravel 2.0 - 37.5 mm grain size.

The parameters for characterizing the grading of natural gravel material obtained from grain size analysis result were presented in Table 4.5.

Table 4.5: Grading parameters value from PSD analysis versus specification requirement

Grading Parameters from PSD analysis	Result	Specification	Source	Remark
Grading modulus, GM	2.2	1.65 – 2.65	Table 2.4, ERA [25]	In the range
Maximum size (mm)	37.5	37.5	Table 2.8, ERA [25]	Fulfilled
Oversize index, I_o (%)	4.3	Less than or equal to 5%	Table 2.8, ERA [25]	In the range
Grading coefficient, G_c	20	16 - 34	ERA [25]	In the range

4.2.2.2. Specific gravity of natural gravel

Specific gravity which is the measure of heaviness of the soil particles was determined by the method AASHTO T100 using a natural gravel sample passing 4.75mm sieve. The laboratory test result of specific gravity was presented in Table 4.6 and the laboratory data analysis was attached in Appendix B. In this study, the specific gravity of natural gravel was used to construct a formula for calculating the required amount of calcium chloride additive while application on site, based on recommended ratio.

Table 4.6: Specific gravity of the natural gravel

Sample	NG passing 4.75mm		
Specific gravity, G_s at 20 °C in 3 trials	2.66	2.67	2.65
Average specific gravity, G_s at 20°C	2.66		

4.2.2.3. Moisture absorption of natural gravel

In this study, the hygroscopic moisture content was determined, and expressed as moisture contained in air dried sample; and on the other hand the hygroscopicity was determined as a moisture absorption capacity of the material when exposed to the atmosphere. The result was presented in Figure 4.3, and the detailed laboratory data was shown in Appendix C.

Hygroscopic moisture content of finer portion of natural gravel passing 0.425mm sieve was determined, which was calculated as ratios of moisture in air dried sample and an oven dried sample; the result was 0.81%. In this study, for measuring the relative humidity and temperature the Digital Thermo-Hygrometer was used. The atmosphere in which the sample air dried had an average relative humidity of 66% and an average temperature of 20°C. To determine the hygroscopicity of the material or the moisture absorption capacity from the atmosphere, the oven dried fine grained portion of the natural gravel passing 0.425mm sieve was exposed to controlled moisture of approximately uniform relative humidity of 100%, and then the hygroscopicity was determined on increasing consecutive time intervals from 24 Hours to 7 days. The test temperature was between 18 and 21°C.

The result hygroscopicity test conducted on natural gravel for 7 consecutive days of exposure to approximately 100% relative humidity, in desiccator filled with distilled water, was presented in Figure 4.3. The moisture absorption of calcium chloride under controlled relative humidity, from the first day to the seventh day was recorded that it increased from 0 to 1.2%. At fifth day exposure, the natural gravel material absorbed 0.8% moisture from the atmosphere which is nearly equal to the hygroscopic moisture content of the material. In one week time, it was recorded that the fine grained portion of the natural gravel absorbed 1.2% moisture from the environment of approximately 100 percent relative humidity. When this absorbed moisture of 1.2% added to the adsorbed moisture or hygroscopic moisture of 0.81%, it results in 2.01%. From this result, it could be deduced that the air dried material exposed to an atmosphere of a high relative humidity would contain moisture of 2.01% and more.

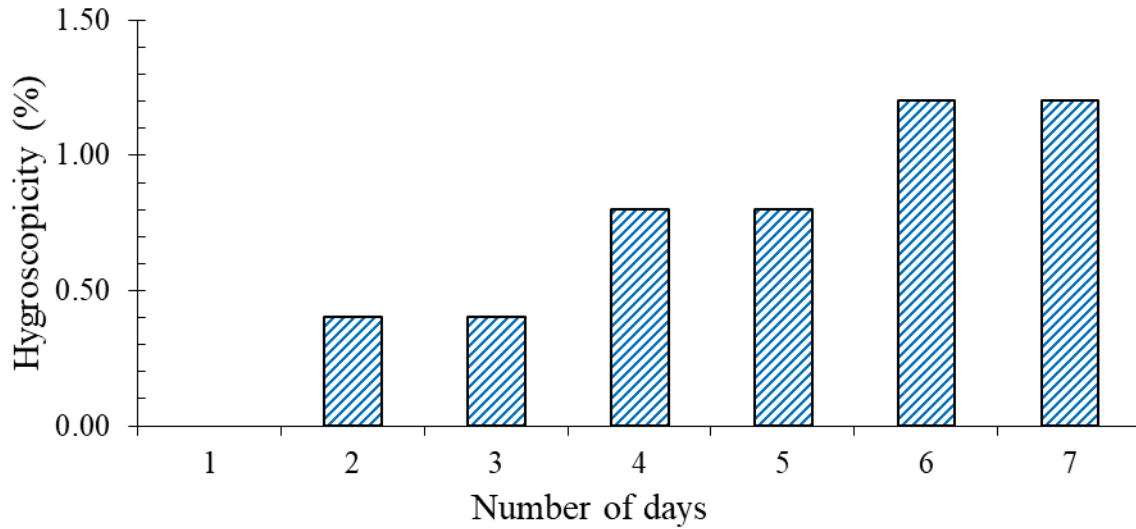


Figure 4.3: Moisture absorption of natural gravel sample

4.2.2.4. Atterberg limits of natural gravel

Following the AASHTO T89 and T90 procedure, the liquid limit, plastic limit and plastic index of the natural gravel sample were determined as presented in Table 4.7. The laboratory data analysis of atterbeg limits were given in Appendix D.

Table 4.7: Atterberg limits of NG sample and its plasticity modulus value

Sample	Atterbeg limits (%)		
	LL	PL	PI
Natural Gravel material	48	31	17

The Plasticity modulus (PM) which is expressed as a product of plasticity index value and percentage passing 0.425mm sieve [25], was calculated from plastic index value and percentage passing the 0.425mm sieve presented in Table 4.3, and the PM value of 510 obtained. According to ERA specification [25], the natural gravel base material for high traffic level shall have a maximum plasticity index of 6 %, and to ensure this a maximum plasticity modulus (PM) of 120 is recommended. For the natural gravel material in this study from its fine content value of 30% passing 0.425mm sieve, and from ERA manual recommended value of 120 maximum plasticity modulus, the plasticity index value should be reduced to 4% to fulfill the criteria of natural gravel base for high traffic road.

According to [4], the plastic index range from 2 to 9% is preferred for gravel wearing course material that has gradation of 12 to 15% passing 0.075mm sieve. When compared to plasticity requirement specified in [4], the plastic index 17% is out of range specified from 2 to 9%, which is not acceptable.

As per ERA design manual [26], plasticity requirement of natural gravel for road base material presented in Table 2.5, maximum plastic index for natural gravel under study was calculated from grading modulus (GM) value presented in Table 4.5, which became 18%. Therefore, as per ERA manual [26], the plasticity index obtained from laboratory test which was 17% is near upper boundary of plasticity requirement of natural gravel base, for the low traffic volume and non-expansive subgrade roads. As per ERA design manual [26], a maximum plasticity index of 6 has been retained for higher traffic levels and also on weaker subgrades. In addition, ERA manual stated that a natural gravel material of plastic index up to 10% can be used in drier climatic areas and, it suggested that the material should not be used in wet areas unless chemically modified.

When evaluated as per ERA manual [25] and [26], the untreated natural gravel in this study with a plastic index value 17%, plasticity modulus value 510, and grading modulus value 2.2 could be used for base material for low traffic class of LV1 (Mesa less than 0.01) and strong subgrade class from S4, S5 and S6, in dry climate. This material could not be used in wet climatic areas, unless chemically treated.

The test result showed that the natural gravel in this study is not suitable for unpaved road base and surfacing, in all-weather, medium to high traffic, and weak subgrade road. Hence, the natural gravel material should be treated chemically to reduce its plastic index value to 6% and less, in order to be used as road base and surfacing material in high traffic and weak subgrade road, in all-weather. In addition, the plastic index should be reduced to 10% and less in order to be used as road base material in high traffic and weak subgrade road in dry areas.

4.2.2.5. Linear shrinkage of natural gravel

The linear shrinkage test was conducted on the fine grained portion of untreated natural gravel that passed 0.425mm sieve, by SANS 3001-GR10 as per ERA requirement [25], and the result was presented in Table 4.8 and data of analysis were given in Appendix E. The shrinkage

product which is expressed as a product of linear shrinkage and percentage passing 0.425mm sieve was determined.

Table 4.8: Linear shrinkage of untreated natural gravel sample

Sample	NG passing 0.425mm		
Linear shrinkage (%), in 3 trials	9.3	9.2	9.2
Average Linear shrinkage, LS (%)	9.2		

As stated in [1] and ERA design manual for low volume roads [21], for the range of materials likely to be used for gravel wearing course, the plasticity index can be assumed to be two times linear shrinkage. The determined linear shrinkage and plastic index value from laboratory test analysis were 9.2% and 17%, respectively. These values indicated that the ratio of plastic index to linear shrinkage is 1.85 which is slightly less than two. The correlation of linear shrinkage and plastic index assumed made by [21] is nearly fulfilled. Therefore, to use this material as a road base or gravel wearing course, the value of linear shrinkage deduced from plasticity index requirement of 6% indicated that the linear shrinkage should be reduced to less than 4%.

As stated in [12] and [20], the recommended linear shrinkage value for gravel wearing course material by different standards ranges from 2 to 8%. The natural gravel material in this study did not fulfill the linear shrinkage value requirement of GWC material evaluated against relevant standards.

The calculated shrinkage product value which is a product of Linear shrinkage and per cent passing 0.425 mm sieve was calculated for the untreated natural gravel, presented in Table 4.9 and evaluated in comparison with different specification requirements.

According to ERA design manual [21], material quality zones showed in Figure 2.2, the quality zone of natural gravel material in this study was obtained by sketching the vertical line from grading coefficient axis and horizontal line from shrinkage product axis, that the result laid in upper left Zone E, as presented in Figure 4.4. As per [21], materials in Zone E perform well in general. As described in [20], material Zone E is good which comprises well-graded soil aggregate mixes with sufficient plasticity to bind aggregate fractions into a hard wearing tight surface. Higher fines content can produce a dusty surface.

Table 4.9: Shrinkage product value of natural gravel versus specification for unsealed roads

Parameter	Value	Specification requirement	Standard specification used	Remark
Shrinkage Product, Sp	276	100 – 365 (maximum of 240vpreferable)	Table 2.8, rural roads, ERA [26] & South Africa [20]	In the range
		100 - 240	Table 2.9, urban roads, ERA [26] & South Africa [20]	Not satisfied, Above limit
		120 - 400	Table 2.7 Tanzania & Uganda [29]	In the range

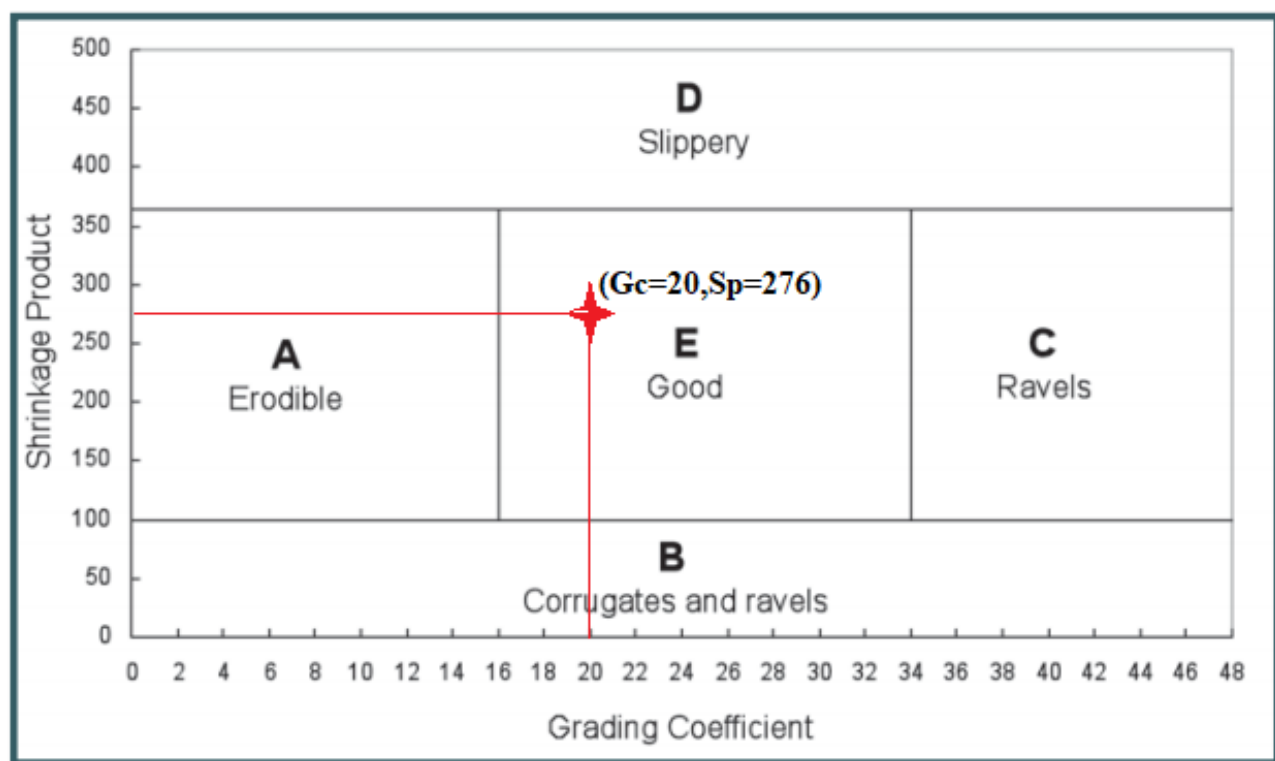


Figure 4.4: Natural gravel material quality zone, performance and material properties

4.2.2.6. Soil classification of natural gravel

The sampled natural gravel was classified using the AASHTO Soil Classification System AASHTO M145, and USCS Soil Classification system ASTM D2487. Using the grain size distribution and Atterberg limits test results, the natural gravel was classified A-2-7 (0) as per AASHTO soil classification system and GC (Clayey Gravel) as per USCS. The standard tables used for soil classification of the respective methods were shown in Appendix F.

As per AASHTO soil classification system material of subgroup A-2-7 includes gravel and sand with silt contents, and the finer portion contains plastic clay.

4.2.2.7. Compaction characteristics of natural gravel

To determine the maximum dry density (MDD) and optimum moisture content (OMC) of the untreated natural gravel sample, a modified compaction test was conducted according to AASHTO T180. The untreated natural gravel sample has a maximum dry density and optimum moisture content of 1.64g/cm^3 and 13.7%, respectively. The dry density-moisture relationship curve was presented in Figure 4.5. The detailed data for compaction test analysis was given in Appendix G.

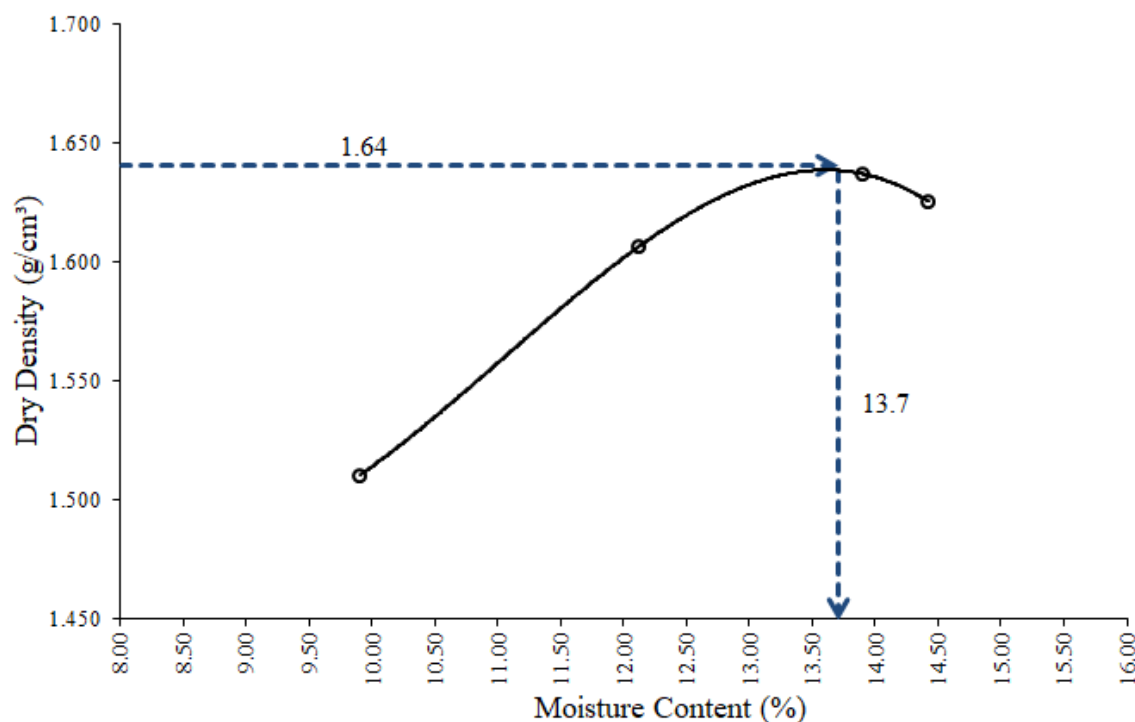


Figure 4.5: Dry density-moisture relationship curve for untreated natural gravel

4.2.2.8. Unconfined compressive strength of natural gravel

The unconfined compressive strength (UCS) of untreated natural gravel was determined using test procedure AASHTO T208 (ASTM D2166). The laboratory test was conducted on the fine grained portion of natural gravel passing 0.425mm sieve, compacted to optimum moisture content and maximum dry density, and the UCS result obtained was 210.37KN/m². The laboratory data for analysis was given in Appendix H.

4.2.2.9. Soaked California Bearing Ratio and Swell of natural gravel

A three point CBR test at 10, 30 and 65 blows were conducted on untreated natural gravel sample according to AASHTO T193 test procedure and the CBR values at 95% MDD was determined. The CBR value and swell of untreated natural gravel obtained were 26.0% and 1.21% respectively. The results were shown in Figure 4.6 and the detailed CBR and swell laboratory data analysis were presented in Appendix I.

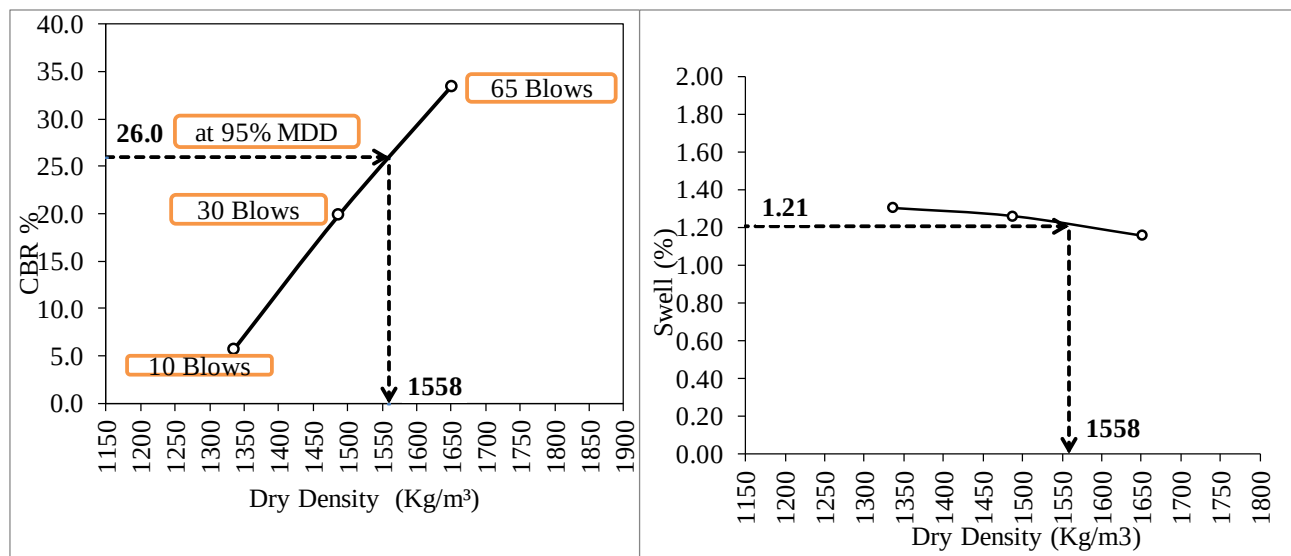


Figure 4.6: CBR and swell value test result of untreated natural gravel

4.3. Laboratory test results of stabilized natural gravel

4.3.1. The effect of Calcium Chloride on Moisture Absorption

The effect of calcium chloride addition in varying proportions with natural gravel had been studied and the variation in hygroscopicity for various mix ratios was observed. For comparison purpose, the hygroscopicity of untreated natural gravel, calcium chloride, and the treated natural gravel with different percentage of additive were summarized and presented in Table 4.10 and depicted in Figure 4.7.

Table 4.10: Calcium chloride effect on moisture absorption of natural gravel

Number of days of exposure	Hygroscopicity or Moisture Absorption (%)						
	NG	NG+2% CaCl ₂	NG+4% CaCl ₂	NG+6% CaCl ₂	NG+8% CaCl ₂	NG+10% CaCl ₂	Calcium chloride (CaCl ₂)
1	0.00	0.78	1.15	1.89	2.22	2.55	16.00
2	0.40	1.18	1.54	2.64	3.70	4.00	28.00
3	0.40	1.57	2.31	3.40	4.81	5.45	41.00
4	0.80	1.96	3.08	4.53	6.30	6.91	59.00
5	0.80	2.35	3.85	5.66	7.78	8.00	76.00
6	1.20	2.75	4.23	6.04	8.52	9.09	87.00
7	1.20	2.75	4.23	6.79	8.89	9.45	97.00

As shown in Figure 4.7, the moisture absorption of natural gravel increased with increasing percentage of calcium chloride from 0% to 10%, by 2% increase, observed for each day elapsed, for seven consecutive days. From the trend of moisture absorption result of treated natural gravel, the rate with which moisture absorbed increased with the amount of calcium chloride added. The amount of moisture absorption for treatment with 2% and 4% became unchanged after sixth day; whereas for treatment amount of 6, 8 and 10% the amount of moisture absorption showed increasing value up to seventh day, however with decreasing rate after fifth day. It was observed that, the addition of 2% CaCl₂ increased the moisture absorption of NG by nearly 3 times, 4% CaCl₂ by nearly 4 times, 6% CaCl₂ by nearly 6 times, 8% CaCl₂ by nearly 9 times, and 10% CaCl₂ by nearly 10 times. From this trend, it could be deduced that 1% addition of calcium

chloride would approximately result in 100% increase in moisture absorption of natural gravel of the type investigated in this study, which means the material classified as clayey gravel (GC) and the material classified as A-2-7 subgroup.

According to [2], there is a direct relation between the moisture absorption and CaCl_2 increase. It was also observed in [8], that the addition of CaCl_2 increased the moisture content of the mixtures because of its hygroscopic property. When the result of this study compared to previous studies, even though the amount of the result obtained differed, which could be due to different laboratory circumstances, the effect of calcium chloride on moisture absorption capacity of the mixture was similar, which is increasing.

Calcium chloride plays the role of dust control on unsealed low volume traffic road and even some higher volume roads [7]. For this reason, CaCl_2 is most commonly utilized for dust suppression in unbound road surfacing applications with additional proven benefits of reduced surface aggregate loss, reduced grading maintenance which results in annual material and maintenance savings [10]. As testified by [11], from field study, the calcium chloride was seen that it is an excellent hygroscopic product that helps to retain a lot of moisture in the granular material at the surface of the road. Referring to previous studies and its hygroscopic property confirmed by laboratory test during this study, it could be assured that the calcium chloride would help the gravel wearing course material to absorb and retain moisture from the surrounding environment, which in turn reduces dust emission from the road surface. In this study, the dust suppressing effect of calcium chloride additive was not verified by laboratory test; it was deduced from its moisture absorbing capacity and the fact that the moisture avoids dust.

As per findings by [16], Chloride is transported downward through the soil by leaching water and upward by means of capillary rise; and then attested that the optimal percentage of fine material for minimal chloride leaching is 10 to 16% by weight. In comparison with recommendation by [16], for the fine portion amount of the material to be stabilized, the result of the grain size analysis of natural gravel in this research as indicated in Table 4.3 was 13% for fine material passing 0.075mm sieve, which fulfills the grading requirement to minimize the leaching problem.

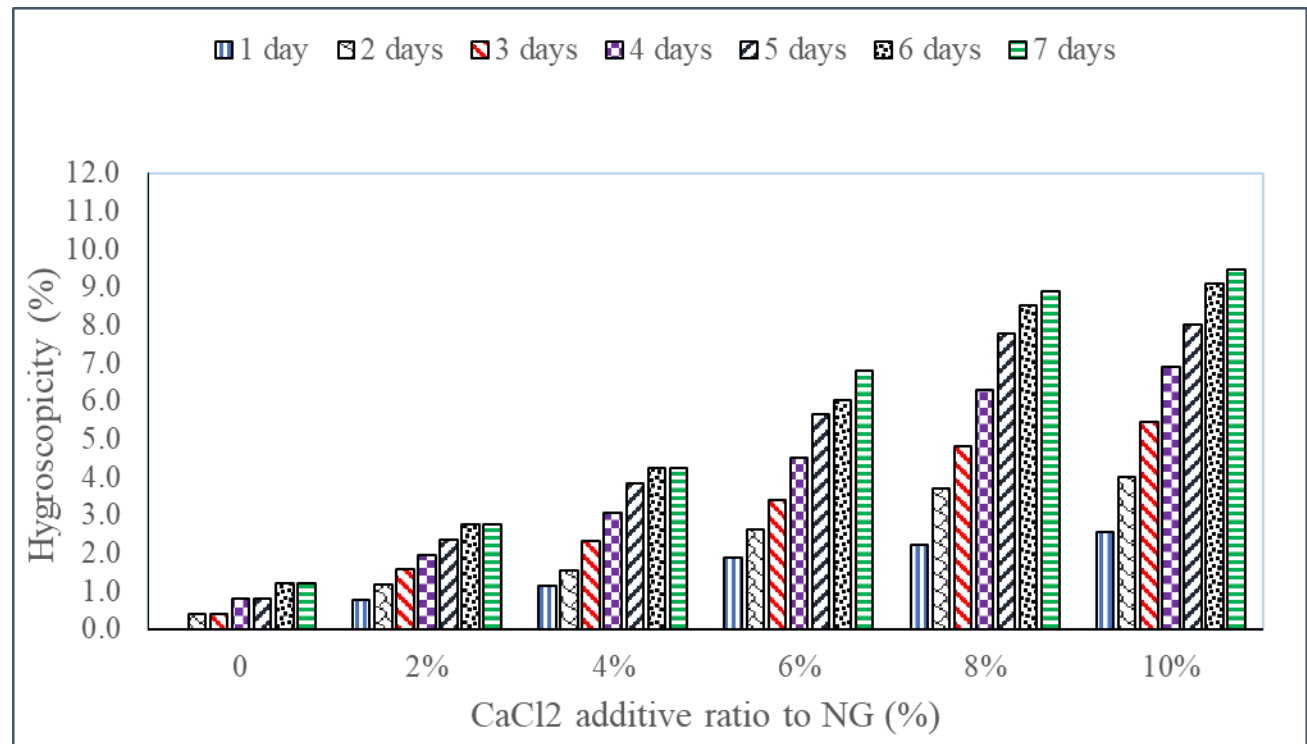


Figure 4.7: Moisture absorption of NG for different percent of CaCl₂ within 7 days

4.3.2. The effect of Calcium Chloride on Atterberg Limits

The effect of calcium chloride addition in varying proportion with natural gravel on Atterberg limits had been studied, and the variation in consistency limit for various additive mix-ratio were presented in Table 4.11.

Table 4.11: Calcium chloride effect on Atterbeg limits of natural gravel

Mix ratio of natural gravel with CaCl ₂	Atterberg limits		
	Liquid Limit (%)	Plastic Limit (%)	Plastic Index (%)
NG	48	31	17
NG+2% CaCl ₂	40	31	9
NG+4% CaCl ₂	36	29	7
NG+6% CaCl ₂	34	29	5
NG+8% CaCl ₂	31	27	4
NG+10% CaCl ₂	31	27	4

As observed from laboratory test result, as percentage of calcium chloride increased from 2% to 8% the liquid limit value decreased, and no change observed for increase of CaCl_2 from 8% to 10%. Similar result was observed for the plastic limit; it decreased with an increased percentage of CaCl_2 . As a result, the value of the plasticity index was decreased as a percentage of CaCl_2 increased. For addition of 2% CaCl_2 the PI value of untreated natural gravel material decreased from 17% to 9%, which is a decrease of 45 percent. For addition of 4% CaCl_2 the PI value of untreated NG decreased from 17% to 7%, which is a decrease of 60 percent. Similarly, 6% CaCl_2 addition resulted in decrease of PI from 17% to 5% and, 8% addition CaCl_2 resulted in decrease of PI from 17% to 4%; a decrease of 68 and 75 percent were observed, respectively. The addition of CaCl_2 by 10% showed similar result with addition of CaCl_2 by 8%. As described above, an addition of CaCl_2 from 2% to 8% showed a decreasing value for the PI, and a further increase of CaCl_2 from 8% to 10% did not result in change of PI.

As presented in Figure 4.8, the plastic index of natural gravel were decreased with increasing percentage of calcium chloride from 0% to 8%, and remained uniform from 8% to 10% of additive.

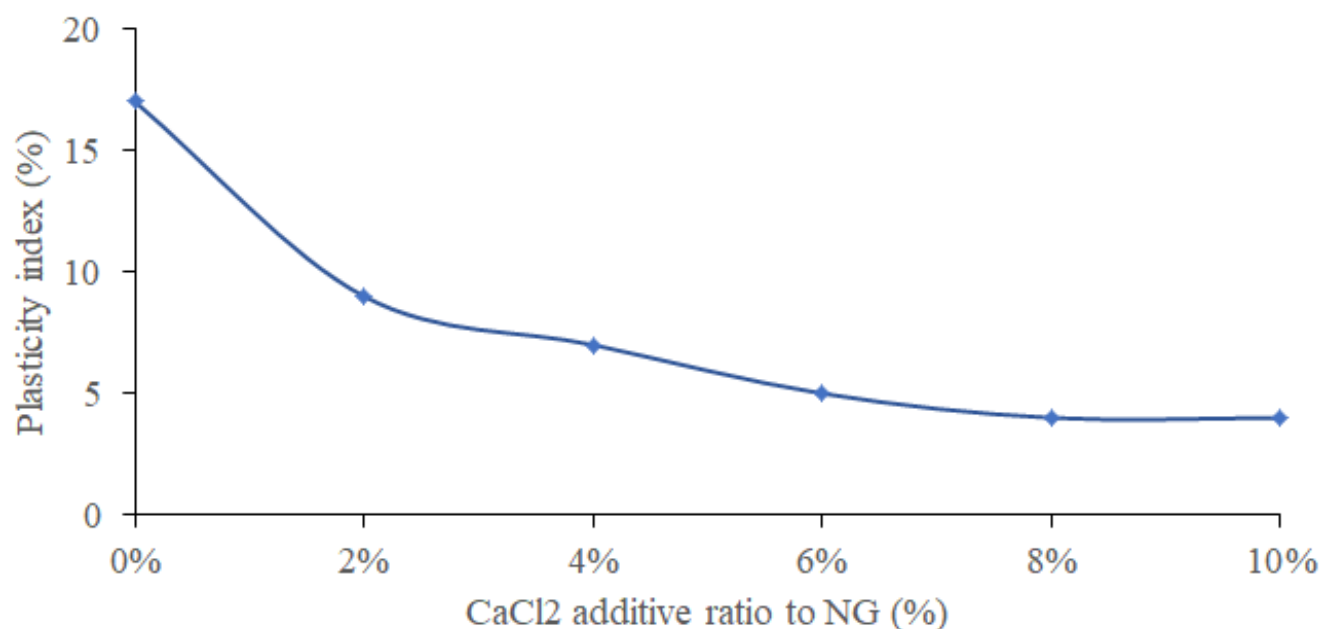


Figure 4.8: Plasticity index of NG for different percentage of CaCl_2 additive

According to [2,5,6], there is a reverse proportion between calcium chloride percentage and the plastic limit and liquid and plastic index of soil and adding calcium chloride salt to soil reduces the plastic limit and liquid limit. Similarly, as per investigated in [7], the addition of calcium chloride reduced the PI of the material tested. The effect of calcium chloride on plasticity of the natural gravel obtained by laboratory investigation in this study resembled with the results in previous studies.

According to [4], the plastic index range from 2 to 9% is preferred for gravel wearing course material. When compared with plasticity requirement in [4], the plastic index of treated natural gravel by the calcium chloride of 2% by weight could satisfy the maximum limit, and the addition of calcium chloride by 4, 6, 8 and 10% resulted in PI results 7, 5, 4 and 4%, respectively. These values of PI are in a range of plasticity requirement for gravel wearing course stated in [4].

As per ERA design manual [26], a maximum plasticity index of 6% has been recommended for higher traffic levels and also on weaker subgrades; a natural gravel material of plastic index up to 10% can be used in drier climatic areas and, it suggested that the material should not be used in wet areas unless chemically modified. The calcium chloride addition by 6 to 10% resulted in PI of 5% to 4%; therefore, when compared with ERA specification requirement, the addition of calcium chloride by 6 to 10% in weight, to a clayey gravel material or a gravel material of subgroup A-2-7 could satisfy for a road of high traffic and weak subgrade, as well as could be used in wet climate area. For the road in a drier climate, to keep a maximum PI value of 10%, an addition of calcium chloride by 2% could be enough to satisfy the plasticity requirement of clayey gravel. ERA specification [25] as shown in Table 2.13, PI chemically treated natural gravel road base material should be slightly plastic or non-plastic; for this requirement, the addition of calcium chloride by 4% to 8% would satisfy.

As per stated in ERA design manual for low volume roads, for the range of materials likely to be used for gravel wearing course, the plasticity index can be assumed to be two times linear shrinkage [21]. From the correlation of plasticity index and linear shrinkage stated in [21], the value of linear shrinkage estimated from plastic index was presented in Table 4.12. For evaluation purpose against specifications, the shrinkage product was calculated from estimated linear shrinkage by correlation from PI.

Table 4.12: Calcium chloride effect on shrinkage product from PI and LS correlation

Linear shrinkage (LS) and shrinkage product (Sp) calculated from Plastic index (PI) by correlation						
Mix ratio	NG	NG+2% CaCl₂	NG+4% CaCl₂	NG+6% CaCl₂	NG+8% CaCl₂	NG+10% CaCl₂
PI from laboratory test (%)	17	9	7	5	4	4
LS estimated from correlation, LS=PI/2 (%)	8.5	4.5	3.5	2.5	2	2
Shrinkage product, Sp (%)	255	135	105	75	60	60

According to ERA design manual [21], material quality zones showed in Figure 2.2, the quality zone of natural gravel material in this study treated with calcium chloride from 2% to 4% resulted in shrinkage product value greater than 100, which when read with a grading coefficient value (G_c) value 20 obtained from natural gravel PSD analysis, resulted in Zone E considered as good material. Addition of calcium chloride 6% to 10% resulted in shrinkage product value less than 100 which laid in Zone B, considered as a material which ravel and corrugates.

When compared with different specifications and studies, for different conditions of weather, subgrade strength and traffic volume, the addition of calcium chloride from 2 to 6% would modify the plastic index of natural clayey gravel to be used for gravel wearing course and road base material.

4.3.3. The effect of Calcium Chloride on Linear Shrinkage

The effect of calcium chloride addition in varying proportion with natural gravel had been studied, and the variation in linear shrinkage for various additive mix-ratio were presented in Table 4.13.

Table 4.13: Calcium chloride effect on linear shrinkage of natural gravel

Mix ratio of NG and CaCl₂	NG	NG+2% CaCl₂	NG+4% CaCl₂	NG+6% CaCl₂	NG+8% CaCl₂	NG+10% CaCl₂
Linear shrinkage, LS (%)	9.2	5.5	4.4	3.6	2.9	2.7
Shrinkage product, Sp=LS x percent passing 0.425mm sieve	276	165	132	108	87	81

As observed from laboratory test result, as percentage of calcium chloride increased from 2% to 10%, the linear shrinkage value decreased. For addition of 2% CaCl₂ the LS value of untreated natural gravel material decreased from 9.2% to 5.5%, which is a decrease of 40 percent. For addition of 4% CaCl₂ the LS of untreated NG decreased from 9.2% to 4.4%, which is a decrease of 52 percent. In a similar way, for 6, 8 and 10% CaCl₂ addition resulted in a decrease of LS of untreated natural gravel by 61, 68 and 71 percent, respectively. It was seen that the decreasing value was in a decreasing rate. As described above, an addition of CaCl₂ from 2% to 10% showed a decreasing value for the LS, and small change in LS value was observed for addition of CaCl₂ from 8% to 10%. The effect of CaCl₂ on the linear shrinkage of natural gravel was depicted in Figure 4.9.

When compared to a recommended linear shrinkage value for gravel wearing course material by different standards, which ranges from 2 to 8%, as stated in [12,20], the effect of CaCl₂ addition from 2% to 10% in this study resulted in a range of a target value for clayey gravel material and a material classified as A-2-7 subgroup.

When compared to ERA specification [26] as presented in Table 2.8 and Table 2.9, which requires the Sp value from 100 to 365 for gravel wearing coarse of rural roads and from 100 to 240 for urban unpaved roads, an addition of CaCl₂ from 2% to 6% resulted in Sp within requirement range; however, for CaCl₂ of 8% and 10% the Sp value was below 100 and did not fulfill the requirement as per ERA specification.

When compared to Sp requirement for unsealed roads [29] for Tanzania and Uganda as presented in Table 2.8, which requires the Sp value from 100 to 365 for gravel wearing coarse of rural roads, an addition of CaCl₂ from 2% to 6% resulted in Sp within requirement range;

however, for CaCl_2 of 8% and 10% the Sp value was below 100 and did not fulfill the requirement as per ERA specification.

Hence, as per comparison with relevant specifications and studies, the addition of calcium chloride from 2 to 6% would modify the linear shrinkage of natural clayey gravel to be used for unpaved road surfacing.

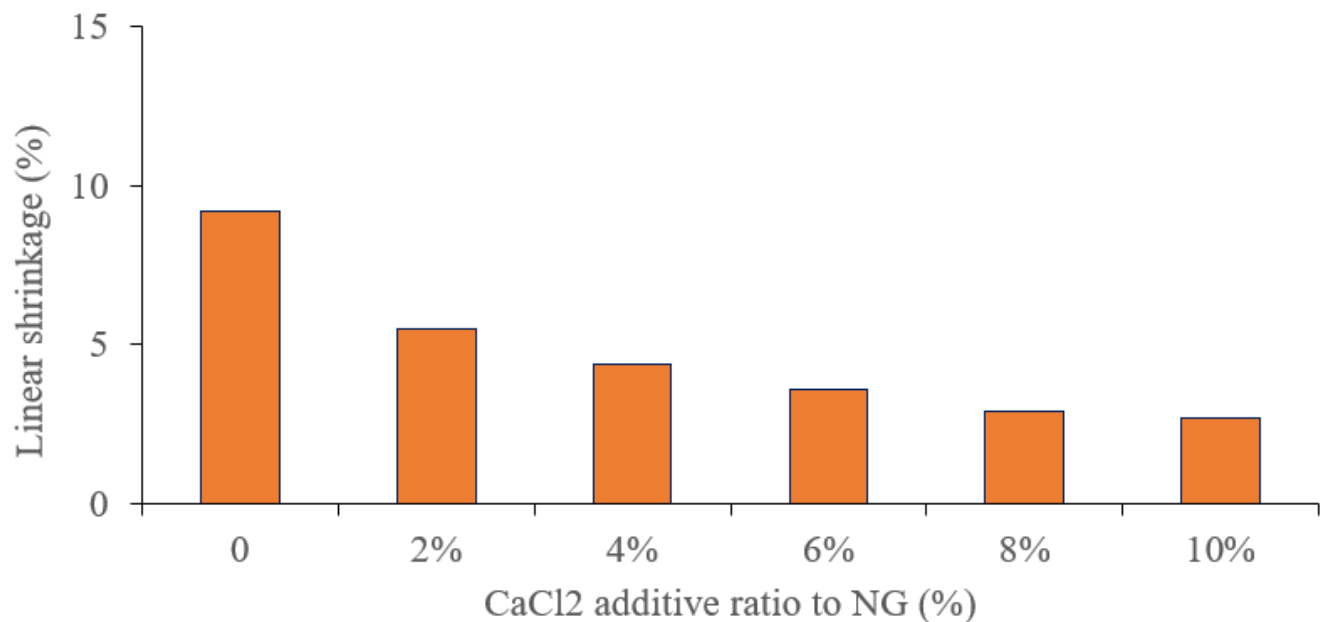


Figure 4.9: Linear shrinkage of NG for different percentage of CaCl_2 additive

4.3.4. The effect of Calcium Chloride on Moisture density relationships

The modified Procter compaction test results of treated natural gravel with calcium chloride were summarized in Table 4.14. For comparison purpose the moisture density curves are plotted and presented in Figure 4.10. The detailed laboratory data analyses were shown in Appendix G.

Table 4.14: Calcium chloride effect on compaction characteristics of natural gravel

Mix ratio of NG and CaCl_2	NG	NG+2% CaCl_2	NG+4% CaCl_2	NG+6% CaCl_2	NG+8% CaCl_2	NG+10% CaCl_2
MDD (g/cm^3)	1.640	1.680	1.715	1.780	1.790	1.795
OMC (%)	13.70	12.80	10.90	10.30	10.10	10.10

As observed from laboratory test result, as a percentage of calcium chloride increased from 2% to 10%, the value of maximum dry density (MDD) increased and the optimum moisture content (OMC) decreased.

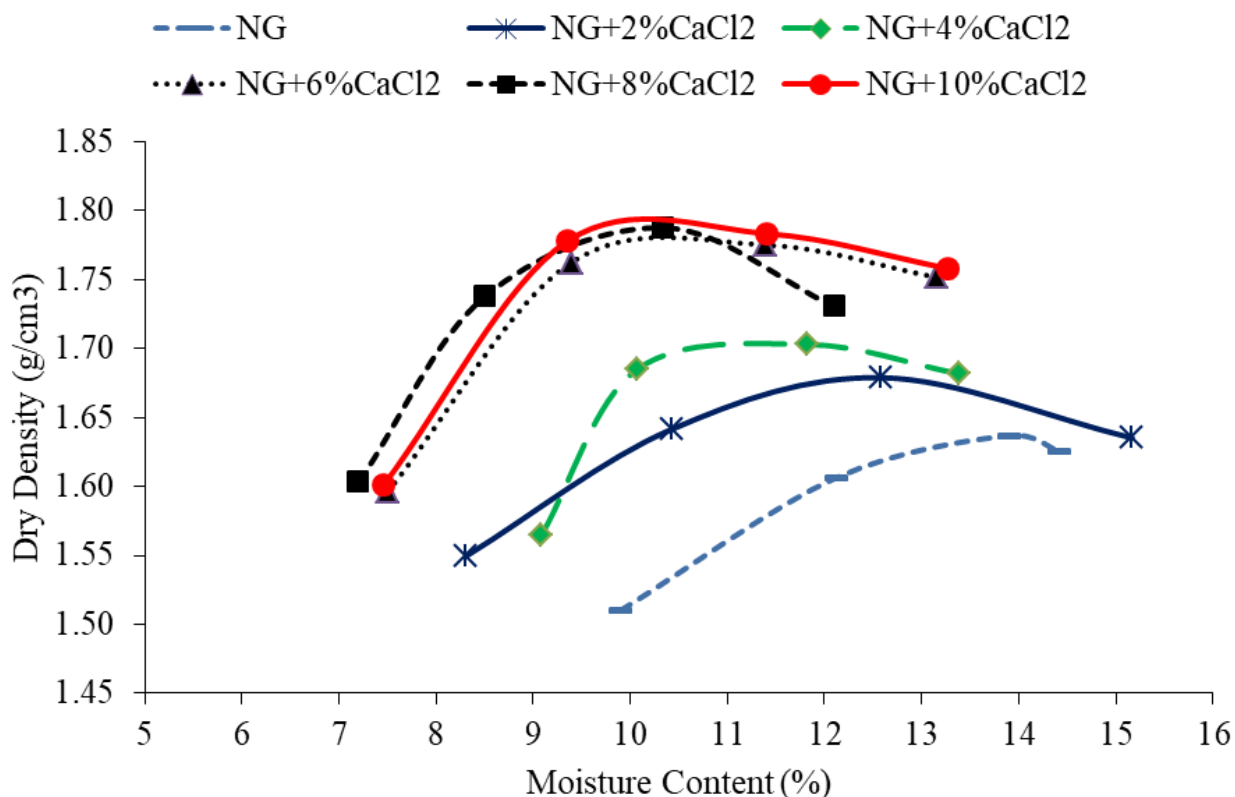


Figure 4.10: Dry density and moisture relationship of NG treated with CaCl_2 additive

For the illustration purpose the effect of calcium chloride on maximum dry density and the optimum moisture content was separately presented in Figure 4.11 and Figure 4.12.

For addition of 2% CaCl_2 the MDD value of untreated NG material increased from 1.640g/cm^3 to 1.680g/cm^3 , which is an increase of 2.44 percent. For 4% CaCl_2 the MDD of untreated NG increased from 1.680g/cm^3 to 1.715g/cm^3 , which is an increase of 4.57 percent. Similarly, for 6, 8 and 10% CaCl_2 addition resulted in an increase of MDD of untreated NG by 8.54, 9.15 and 9.45 percent, respectively. The rate of change of increase for MDD was faster for addition of additive from 2% to 6%, and slower for 6% to 10% additive.

For addition of 2% CaCl_2 the OMC value of untreated NG material decreased from 13.7% to 12.8%, which is a decrease of 7 percent. For 4% CaCl_2 the OMC of untreated NG decreased

from 13.7% to 10.9%, which is a decrease of 20 percent. Similarly, for 6 and 8% CaCl_2 addition resulted in a decrease of OMC of untreated NG by 25 and 26 percent, respectively. A further increase of additive from 8 to 10% did not result in a change of OMC.

From the observed effect of CaCl_2 on compaction characteristics of NG the use of additive from 4 to 6% by weight would result in a significant increase in MDD and decrease in OMC.

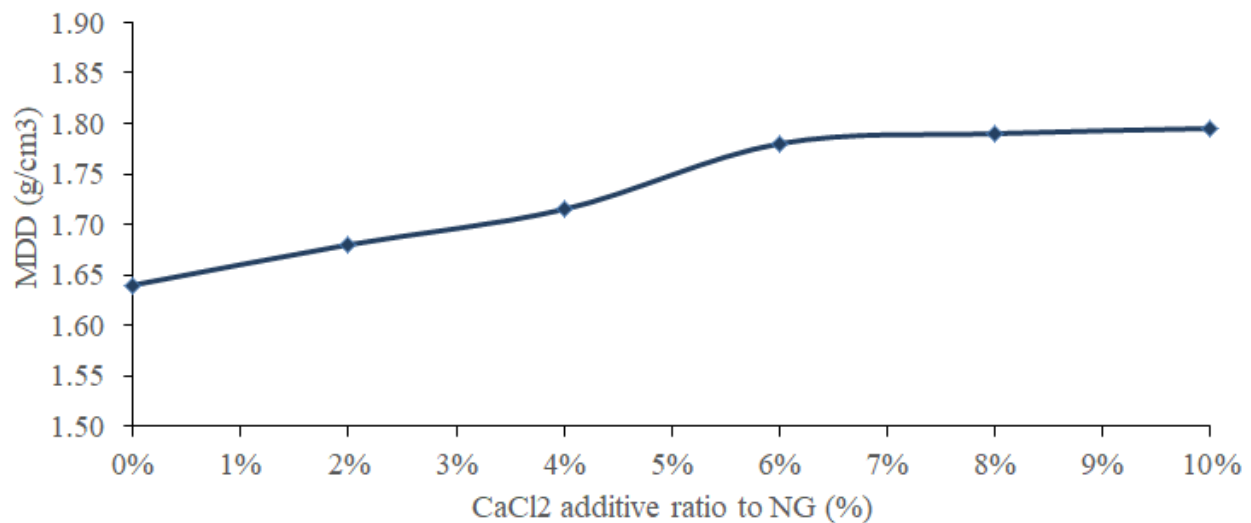


Figure 4.11: Effect of calcium chloride on maximum dry density of NG

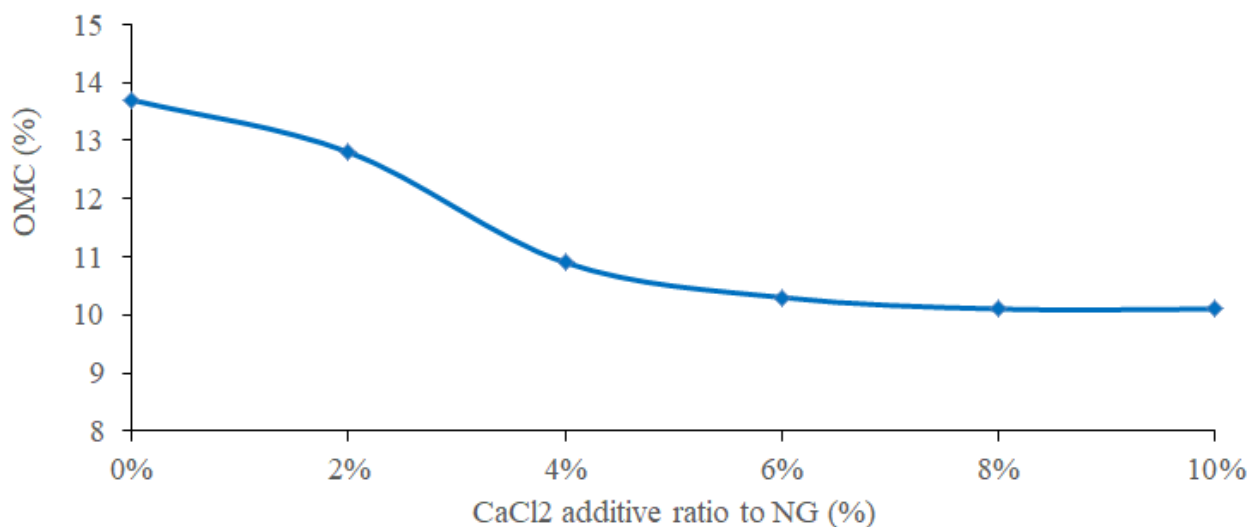


Figure 4.12: Effect of calcium chloride on optimum moisture content of NG

As per previous studies [5,6], an increase in CaCl_2 content leads to an increase in a dry density and decrease in optimum moisture content, which result in a greater strength. According to [32], the research and field tests have shown that adding the proper amount of calcium chloride to the road base aggregate results in a greater density in the aggregate than would be achieved by the use of water alone. A calcium chloride has a stronger moisture film which enhances the lubrication effect with less moisture. The aggregate components can then slide together easily as they are mechanically compacted. In addition, it was stated in by [32], that calcium chloride hygroscopic qualities, along with its ability to lower the vapor pressure of water, work to inhibit evaporation and therefore help to maintain optimum moisture. In this study, in comparison with previous studies, the effect of calcium chloride on compaction characteristics was verified.

4.3.5. The effect of Calcium Chloride on Unconfined Compressive Strength

The effect of calcium chloride addition in varying proportion with natural gravel had been studied, and the variation in unconfined compressive strength for various additive mix-ratio were presented in Table 4.15 and depicted in Figure 4.13. To determine effect of calcium chloride on unconfined compressive strength of the natural gravel, the calcium chloride were added in different percentage by weight to the fine portion of natural gravel passing 0.425mm sieve, compacted to approximately optimum moisture content and maximum dry density in a cylindrical mold of diameter 38mm and height 76mm. Then, for curing purpose, the prepared specimens with different ratios of CaCl_2 additive were placed in a plastic bag along with a damp sponge, for 4 days. The number of curing days was selected from previous studies experience [5,6,8,31,33], which mostly ranges from 1 to 28days.

Table 4.15: Calcium chloride effect on unconfined compressive strength of natural gravel

Mix ratio of NG and CaCl_2	NG	NG+2% CaCl_2	NG+4% CaCl_2	NG+6% CaCl_2	NG+8% CaCl_2	NG+10% CaCl_2
UCS (KN/m^2)	210.37	251.28	286.34	245.43	233.75	216.21

For addition of 2% CaCl_2 the UCS value of untreated NG material increased from 210.37 to 251.28 KN/m^2 , which is an increase of 19 percent. For 4% CaCl_2 the UCS of untreated NG increased from 251.28 KN/m^2 to 286.34 KN/m^2 , which is an increase of 36 percent. Similarly, for 6, 8 and 10% CaCl_2 addition resulted in an increase of UCS of untreated NG by 17, 11 and 3 percent, respectively. The UCS of natural gravel was increasing with increasing percentage of calcium chloride from 0% to 4%, and attained maximum value at 4% which was 286.34 KN/m^2 , an increase of 36 percent when compared to UCS of untreated material. Then, UCS value was decreasing for mix ratio from 6% to 10%. The value of UCS at Calcium chloride mix ratio of 6%, 8% and 10% were less than the value of UCS at 2% mix ratio, and still greater than UCS of untreated natural gravel. From this result, it could be concluded that the UCS value attain its maximum value near 4% mix ratio, and still UCS for mix ratio from 2% to 10% is better than untreated natural gravel, with the value at 10% nearly equal to the UCS for untreated sample. From this trend, it could be deduced that further increase of CaCl_2 after 10% may result in decrease of UCS below untreated value, but need further study with more than 10% ratio. From this study, the optimum content of CaCl_2 to be used for improvement of UCS of clayey gravel was found to be near 4%.

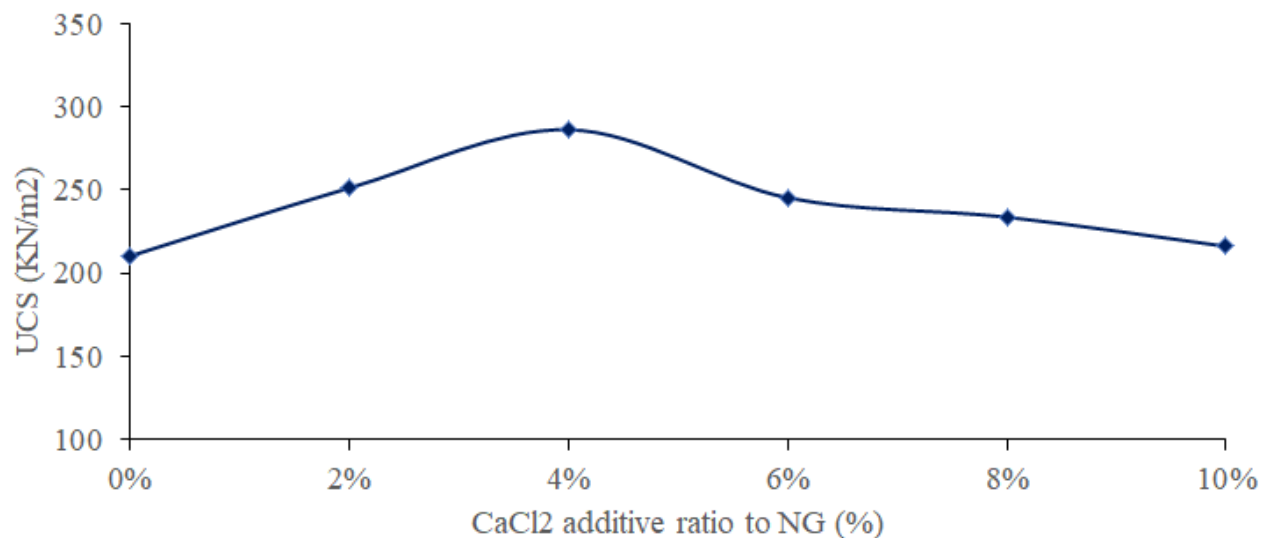


Figure 4.13: UCS of natural gravel treated with CaCl_2 additive

As stated in [5], the increase of calcium chloride up to 8% gives rise to an increase in unconfined compressive strength of natural soil. The increase in UCS values can be attributed to cation exchange at the surface of clay particles and intercalation whereby ions of CaCl_2 enters into the interconnected spaces of clay mineral structure, thus bringing about significant modification in clay behavior. The addition of CaCl_2 salt to the soil causes an increase in the ion concentration of the pore water with attendant reduction in the double layer thickness and this, in turn, causes a reduction in the antiparticles repulsion and an increase in the attraction, resulting in the increase in cohesion of the soil– CaCl_2 mixtures [5]. According to [6], the UCS of the stabilized expansive soil is increasing with increase in percentage of CaCl_2 added to the soil, with a significant increase up to 5% additive beyond which UCS value decreased. Also as described by [8], CaCl_2 results in increased and accelerated gains in strength.

Comparing with ERA specification [25] requirement as showed in Table 2.13, the chemically stabilized natural gravels road base material should have UCS value from 1.0Mpa to 2.0Mpa. The maximum value of UCS obtained in this study was for addition of 4% CaCl_2 , which was 286.34KN/m^2 or 0.286MPa, which is less than the minimum requirement for road base course material. For the gravel wearing coarse material ERA specification and other relevant specifications has not set value requirement in terms of UCS.

In comparison with previous studies, the effect of calcium chloride on unconfined compressive strength of fine grained portion of natural clayey gravel observed in this study showed similar trend, with a variance in amount of a result due to different condition of laboratory investigation and material property under investigation.

4.3.6. The effect of Calcium Chloride on CBR and Swell

The CBR value was determined after prepared samples had been soaked in water for 96 Hours. In this test, in addition to the requirement of test procedure, soaking acts as a means of curing for the treated samples with calcium chloride. The soaked CBR test result of the natural gravel samples treated with different percentage of calcium chloride was presented in Table 4.16 and illustrated in Figure 4.14.

Table 4.16: Calcium chloride effect on CBR and CBR swell of natural gravel

Mix ratio of NG with CaCl ₂	CBR value (%)						CBR at 95%MDD (%)	CBR swell (%)
	10 blows		30 blows		65 blows			
	2.54mm	5.08mm	2.54mm	5.08mm	2.54mm	5.08mm		
NG	5.68	5.42	19.88	17.91	33.45	31.25	26.00	1.21
NG+2%	8.21	6.25	22.41	20.41	40.40	37.91	31.00	1.11
NG+4%	18.94	17.91	35.98	33.95	50.50	47.08	43.0	0.80
NG+6%	19.88	18.33	37.24	35.20	53.02	49.58	46.0	0.30
NG+8%	21.78	20.21	38.50	36.24	54.28	51.45	47.0	0.20
NG+10%	24.62	24.16	40.40	37.29	55.55	52.91	48.0	0.20

For the addition of 2% CaCl₂ the CBR value of untreated NG material increased from 26% to 31%, which is an increase of 19 percent. For 4% CaCl₂ the CBR of untreated NG increased from 26% to 43%, which is an increase of 65 percent. Similarly, 6, 8 and 10% CaCl₂ addition resulted in an increase of CBR of untreated NG by 77, 81 and 85 percent, respectively. The rate of change of increase for CBR was faster and showed significant change for addition of additive from 2% to 4% and, slower with no significant change for 4% to 10% additive.

For addition of 2% CaCl₂ the CBR swell value of untreated NG material decreased from 1.21% to 1.11%, which is a decrease of 8 percent. For 4% CaCl₂ the CBR swell of untreated NG decreased from 1.21% to 0.80%, which is a decrease of 34 percent. Similarly, for 6 and 8% CaCl₂ addition resulted in a decrease of CBR swell of untreated NG by 75 and 84 percent, respectively. A further increase of additive from 8 to 10% did not result in a change of CBR swell value. The rate of change of decrease for CBR was faster and showed significant change for addition of additive from 2% to 6% and, slower with no significant change for 6% to 10% additive. An addition of calcium chloride up to 4% to clayey natural gravel had showed a significant improvement on CBR and CBR swell values. From this result, it could be concluded that an addition of calcium chloride additive is directly proportional to CBR value and inversely proportional to CBR swell.

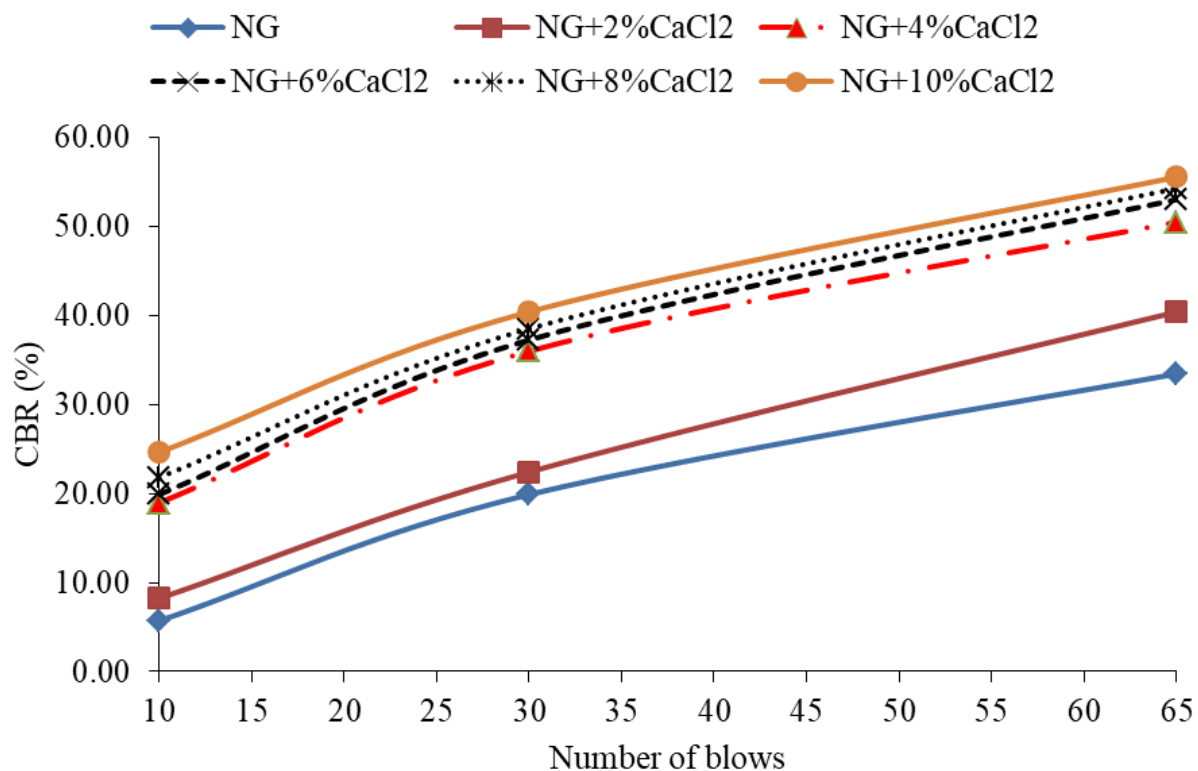


Figure 4.14: CBR of NG treated with CaCl₂ additive at 10, 30 and 65 number of blows

According to [5], the CBR value for soil-calcium chloride mixture was improved up to 4% calcium chloride treatment; and reasoned that the reduction beyond 4% calcium chloride content is as a result of calcium chloride occupying greater percentage of the soil matrix and reduced its strength.

When compared to specifications requirement of CBR for gravel wearing coarse material, the untreated natural gravel material in this study fulfilled the requirement set by ERA specification [26] presented in Table 2.8, and recommended wearing coarse properties for South Africa discussed in [20] presented in Table 2.10; which set the minimum CBR value of 15% for both rural and urban unsealed roads. According to [20], for the haul roads the minimum CBR requirement is 40%. Since the CBR value of untreated NG in this study was 26% it does not fulfill the South Africa specification requirement for haul roads; however, the treated NG with 4% calcium chloride which resulted in CBR value of 43% satisfied the haul road CBR strength requirement.

For illustration purpose, the CBR value at 95% of maximum dry density for different mix ratio were presented in Figure 4.15, and the CBR swell value was presented in Figure 4.16.

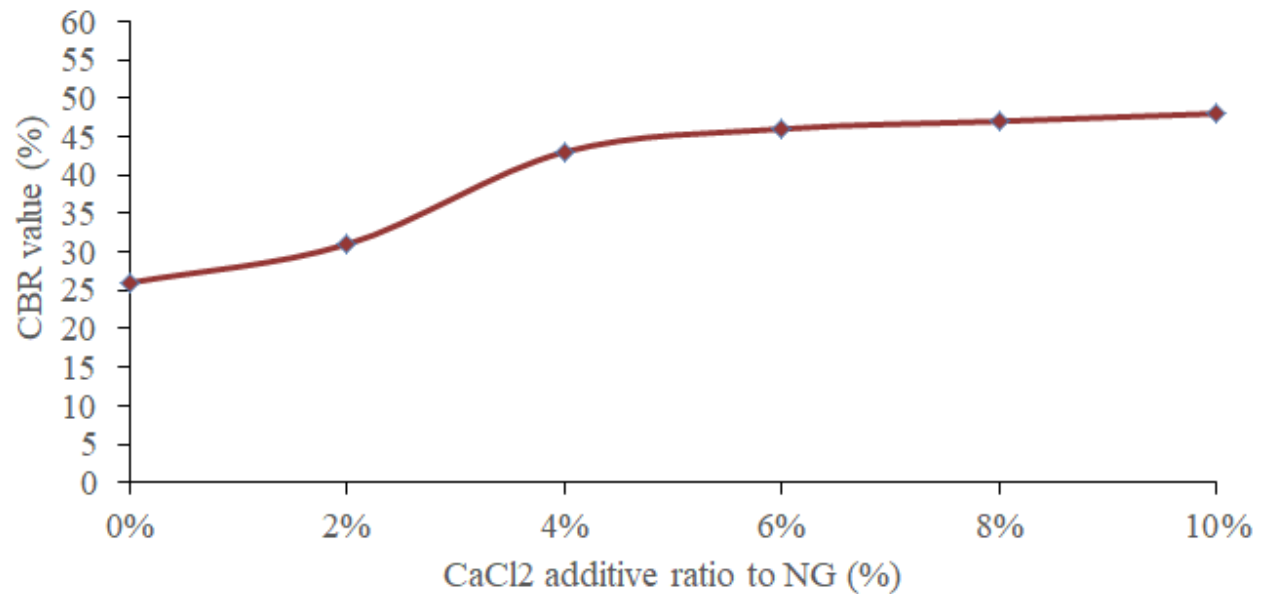


Figure 4.15: CBR value at 95% MDD for natural gravel treated with CaCl₂ additive

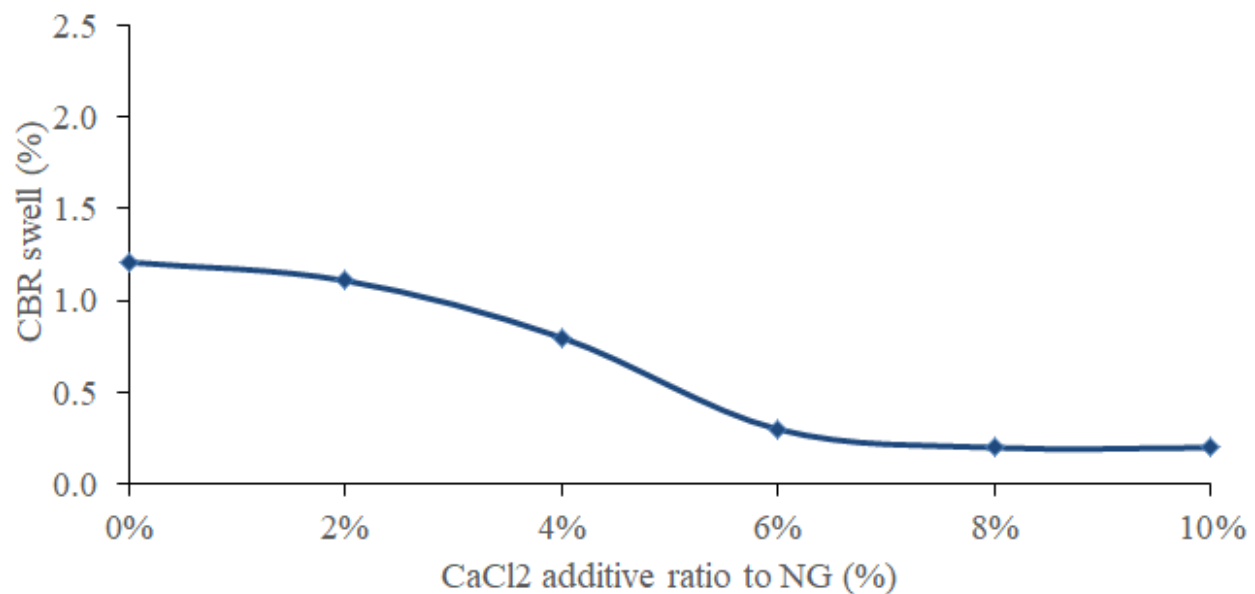


Figure 4.16: CBR swell value for natural gravel treated with CaCl₂ additive

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this study, a laboratory investigation was carried out to determine the effect of calcium chloride as a stabilizing agent on the performance of natural gravel to be used for unpaved road surfacing. The physical properties of natural gravel and calcium chloride additive were determined and discussed. The natural gravel samples were treated with CaCl_2 in concentration of 2%, 4%, 6%, 8% and 10% by dry weight of the material and its effect on different engineering parameters of natural gravel was determined and discussed by comparing with previous studies and relevant specifications. Based on the results obtained from the laboratory investigation the following conclusions were drawn.

- The natural gravel material was classified as A-2-7 (0) based on AASHTO soil classification system and as Clayey Gravel (GC) based on USCS. When evaluated against material quality zone by its shrinkage product (Sp) and grading coefficient (Gc), the material was considered as well graded with sufficient plasticity. It was observed that the natural gravel material investigated was not suitable for unpaved road base and surfacing, in all-weather, medium to high traffic, and weak subgrade road, unless its plasticity and strength property improved.
- The moisture absorption or hygroscopicity property of calcium chloride additive was studied. The moisture absorption of calcium chloride under controlled relative humidity, for seven consecutive days was observed, that its moisture absorption increased from 16 to 97%, and its high moisture absorbing performance was verified. The hygroscopicity of the natural gravel was increased with increasing amount of CaCl_2 in the mixture. Referring to previous studies and its hygroscopic property confirmed by laboratory test result, it could be assured that the calcium chloride would help the gravel wearing course material to absorb and retain moisture from the surrounding environment, which in turn reduces dust emission from the road surface.
- The value of the plasticity index was decreased as a percentage of CaCl_2 increased. It was observed that as percentage of calcium chloride increased from 2 to 8% the liquid limit value decreased, and no change observed for increase of CaCl_2 from 8 to 10%. Similar

result was observed for the plastic limit; it decreased with an increased percentage of CaCl_2 . It was noted that the addition of calcium chloride improved the plasticity of the natural gravel material to fulfill the criteria set by specifications as required.

- The linear shrinkage value decreased, as percentage of calcium chloride increased. When compared to a recommended linear shrinkage value for gravel wearing course material by different standards, it was observed that CaCl_2 addition by 2 to 10% resulted in a range of a target value for clayey gravel material and a material classified as A-2-7 subgroup.
- The value of maximum dry density (MDD) increased and the optimum moisture content (OMC) decreased, with increasing percentage of calcium chloride from 2 to 10%. The rate of change of increase for MDD was faster for addition of CaCl_2 from 2 to 6%, and slower for 6 to 10%. It was observed that a further increase of CaCl_2 from 8 to 10% did not result in a change of OMC. From this result, it was noted that the addition of calcium chloride enhanced the compaction effort with less moisture content.
- The unconfined compressive strength (UCS) of natural gravel was increased with increasing percentage of calcium chloride from 0 to 4%, and attained maximum value at 4%, and then decreased for mix ratio from 6 to 10%. The value of UCS at Calcium chloride mix ratio of 6%, 8% and 10% were less than the value of UCS at 2% mix ratio. It was seen that the optimum content of CaCl_2 to be used for improvement of UCS of clayey gravel was found to be 4%.
- The CBR value increased and the CBR swell decreased, with increasing percentage of calcium chloride from 2 to 10%. The rate of change of increase for CBR was faster and showed significant change for addition of additive from 2 to 4% and, slower with no significant change for 4 to 10% additive. A further increase of additive from 8 to 10% did not result in a change of CBR swell value. An addition of calcium chloride up to 4% to clayey natural gravel had showed a significant improvement on CBR and CBR swell.
- The findings in this study indicated that when evaluated against previous studies, ERA specifications and other relevant standards, the addition of 4% CaCl_2 by dry weight of the natural gravel material was found to be an optimum amount for an effective stabilization in improving both the plasticity and strength requirement of clayey natural gravel to be utilized as unpaved road base and surfacing material. It could be concluded that calcium chloride is an effective chemical stabilizer for unpaved road surface construction.

5.2. Recommendations

The recommendations were forwarded based on the findings of this study and experiences:

- While utilizing the calcium chloride stabilizer, the optimum amount which has a positive effect on all parameters should be used. Increasing a stabilizer above certain limit may have positive effect on some parameters and adverse effect on other parameters.
- The effectiveness of calcium chloride amount to be used depends on climatic condition, traffic level and subgrade strength. Therefore, the Engineers should categorize the traffic class, locate climatic condition and investigate subgrade extension to choose a proper amount of stabilizers. From previous experience, relatively higher amount of calcium chloride is recommended in dry areas and lower amount in wet areas.
- Even though calcium chloride was proved by numerous studies as an effective chemical stabilizer for road base material, particularly unpaved road surfacing, ERA manual of Ethiopia did not include it in its specifications. It is recommendable if it is included in specifications that would authorize an Engineer and builders to consider it during design, construction and maintenance of road base, particularly unpaved road surfacing.
- In this study, the effect of calcium chloride was investigated only on one material type and calcium chloride alone used as stabilizer. In addition, the dust suppressing effect of calcium chloride additive was not verified by laboratory test; it was deduced from its moisture absorbing capacity and from previous studies.
- Further study need:
 - Studying the effectiveness of calcium chloride on different type of natural gravel material or soils with different engineering properties.
 - Investigating the effect of calcium chloride mixing with other additives, or with other locally available material on the properties of natural gravel material or soils.
 - To undertake an experimental investigation on quantifying dust suppressing effect of calcium chloride, or by developing correlation from plasticity and strength parameters.
 - To undertake the field investigation of the effect of calcium chloride on a short segment unpaved road construction project in different climatic zones. This research is recommended at a level of public road administration authorities.
 - The comparative cost analysis for using calcium chloride as stabilizer.

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APPENDIX A: Grain Size Distribution Test Analysis Data

Grain Size Analysis of Natutal Gravel				
Sieve size (mm)	Mass retained (g)	Percent retained (%)	Cumulative percent retained (%)	Percent passing (%)
75	-	0.0	0.0	100
63	-	0.0	0.0	100
50	-	0.0	0.0	100
37.5	288.0	4.3	4.3	96
26.5	536.0	8.0	12.4	88
20	984.0	14.8	27.1	73
12.5	281.0	4.2	31.3	69
10	1,230.0	18.5	49.8	50
4.75	579.0	8.7	58.5	42
2	147.0	2.2	60.7	39
1.18	105.0	1.6	62.3	38
0.425	492.0	7.4	69.6	30
0.15	868.0	13.0	82.7	17
0.075	288.0	4.3	87.0	13
Pan	868.0	13.0	100.0	0
	6,666.0			

APPENDIX B: Specific Gravity Test Analysis Data

Specific Gravity of Natural Gravel

No	Sample	Trial		
		1	2	3
1	Mass Of Empty, Clean Pycnometer (g)	170.40	170.40	170.40
2	Temprature of Pycnometer Contents, (°C)	24	24	24
3	Mass Of Oven Dry Soil (g)	27.75	28.35	28.10
4	Mass Of Pycnometer Fill With Water (g)	398.79	399.45	399.47
5	Mass Of Pycnometer Containing Soil and Water (g)	416.12	417.20	416.97
6	Correction Factor K for Temp. 20°C	0.9991	0.9991	0.9991

APPENDIX C: Moisture Absorption Test Analysis Data

Natural Gravel Material, CaCL ₂ , NG+2%, 4%, 6%, 8%, 10%							
Hygroscopicity (24HR)	Hygroscopicity/Moisture Absorption						
	NG	NG+2%	NG+4%	NG+6%	NG+8%	NG+10%	CaCL ₂
Lid Number	A	B	C	D	E	F	G
Mass of Can (Mc)	10.8	11.3	10.9	11	12.6	11.2	12.9
Mass of moist Sample + Can (M1)	35.80	37.00	37.20	38.00	40.20	39.40	24.50
Mass of Air Dried Sample + Can (M2)	35.80	36.80	36.90	37.50	39.60	38.70	22.90
Mass of Moisture Absorbed, Mm=M1-M2	0.00	0.20	0.30	0.50	0.60	0.70	1.60
Mass of Air Dried Sample, Md=M2-Mc	25.00	25.50	26.00	26.50	27.00	27.50	10.00
Moisture Absorption (Hygroscopicity), wh = Mm/ Md x 100	0.00	0.78	1.15	1.89	2.22	2.55	16.00

Hygroscopicity (48HR)	Hygroscopicity/Moisture Absorption						
	NG	NG+2%	NG+4%	NG+6%	NG+8%	NG+10%	CaCL ₂
Lid Number	A	B	C	D	E	F	G
Mass of Can (Mc)	10.8	11.3	10.9	11	12.6	11.2	12.9
Mass of moist Sample + Can (M1)	35.90	37.10	37.30	38.20	40.60	39.80	25.70
Mass of Air Dried Sample + Can (M2)	35.80	36.80	36.90	37.50	39.60	38.70	22.90
Mass of Moisture Absorbed, Mm=M1-M2	0.10	0.30	0.40	0.70	1.00	1.10	2.80
Mass of Air Dried Sample, Md=M2-Mc	25.00	25.50	26.00	26.50	27.00	27.50	10.00
Moisture Absorption (Hygroscopicity), wh = Mm/ Md x 100	0.40	1.18	1.54	2.64	3.70	4.00	28.00

Hygroscopicity (72HR)	Hygroscopicity/Moisture Absorption						
	NG	NG+2%	NG+4%	NG+6%	NG+8%	NG+10%	CaCL ₂
Lid Number	A	B	C	D	E	F	G
Mass of Can (Mc)	10.8	11.3	10.9	11	12.6	11.2	12.9
Mass of moist Sample + Can (M1)	35.90	37.20	37.50	38.40	40.90	40.20	27.00
Mass of Air Dried Sample + Can (M2)	35.80	36.80	36.90	37.50	39.60	38.70	22.90
Mass of Moisture Absorbed, Mm=M1-M2	0.10	0.40	0.60	0.90	1.30	1.50	4.10
Mass of Air Dried Sample, Md=M2-Mc	25.00	25.50	26.00	26.50	27.00	27.50	10.00
Moisture Absorption (Hygroscopicity), wh = Mm/ Md x 100	0.40	1.57	2.31	3.40	4.81	5.45	41.00

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Hygroscopicity (4Day)	Hygroscopicity/Moisture Absorption						
	NG	NG+2%	NG+4%	NG+6%	NG+8%	NG+10%	CaCL ₂
Lid Number	A	B	C	D	E	F	G
Mass of Can (Mc)	10.8	11.3	10.9	11	12.6	11.2	12.9
Mass of moist Sample + Can (M1)	36.00	37.30	37.70	38.70	41.30	40.60	28.80
Mass of Air Dried Sample + Can (M2)	35.80	36.80	36.90	37.50	39.60	38.70	22.90
Mass of Moisture Absorbed, Mm=M1-M2	0.20	0.50	0.80	1.20	1.70	1.90	5.90
Mass of Air Dried Sample, Md=M2-Mc	25.00	25.50	26.00	26.50	27.00	27.50	10.00
Moisture Absorption (Hygroscopicity), wh = Mm/ Md x 100	0.80	1.96	3.08	4.53	6.30	6.91	59.00

Hygroscopicity (5Day)	Hygroscopicity/Moisture Absorption						
	NG	NG+2%	NG+4%	NG+6%	NG+8%	NG+10%	CaCL ₂
Lid Number	A	B	C	D	E	F	G
Mass of Can (Mc)	10.8	11.3	10.9	11	12.6	11.2	12.9
Mass of moist Sample + Can (M1)	36.00	37.40	37.90	39.00	41.70	40.90	30.50
Mass of Air Dried Sample + Can (M2)	35.80	36.80	36.90	37.50	39.60	38.70	22.90
Mass of Moisture Absorbed, Mm=M1-M2	0.20	0.60	1.00	1.50	2.10	2.20	7.60
Mass of Air Dried Sample, Md=M2-Mc	25.00	25.50	26.00	26.50	27.00	27.50	10.00
Moisture Absorption (Hygroscopicity), wh = Mm/ Md x 100	0.80	2.35	3.85	5.66	7.78	8.00	76.00

Hygroscopicity (6Day)	Hygroscopicity/Moisture Absorption						
	NG	NG+2%	NG+4%	NG+6%	NG+8%	NG+10%	CaCL ₂
Lid Number	A	B	C	D	E	F	G
Mass of Can (Mc)	10.8	11.3	10.9	11	12.6	11.2	12.9
Mass of moist Sample + Can (M1)	36.10	37.50	38.00	39.10	41.90	41.20	31.60
Mass of Air Dried Sample + Can (M2)	35.80	36.80	36.90	37.50	39.60	38.70	22.90
Mass of Moisture Absorbed, Mm=M1-M2	0.30	0.70	1.10	1.60	2.30	2.50	8.70
Mass of Air Dried Sample, Md=M2-Mc	25.00	25.50	26.00	26.50	27.00	27.50	10.00
Moisture Absorption (Hygroscopicity), wh = Mm/ Md x 100	1.20	2.75	4.23	6.04	8.52	9.09	87.00

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Hygroscopicity (7Day)	Hygroscopicity/Moisture Absorption						
	NG	NG+2%	NG+4%	NG+6%	NG+8%	NG+10%	CaCL ₂
Lid Number	A	B	C	D	E	F	G
Mass of Can (Mc)	10.8	11.3	10.9	11	12.6	11.2	12.9
Mass of moist Sample + Can (M1)	36.10	37.50	38.00	39.30	42.00	41.30	32.60
Mass of Air Dried Sample + Can (M2)	35.80	36.80	36.90	37.50	39.60	38.70	22.90
Mass of Moisture Absorbed, Mm=M1-M2	0.30	0.70	1.10	1.80	2.40	2.60	9.70
Mass of Air Dried Sample, Md=M2-Mc	25.00	25.50	26.00	26.50	27.00	27.50	10.00
Moisture Absorption (Hygroscopicity), $w_h = Mm / Md \times 100$	1.20	2.75	4.23	6.79	8.89	9.45	97.00

APPENDIX D: Atterberg Limits Test Analysis Data

Natural Gravel material	Liquid Limit Test				Plastic Limit Test	
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 1	Trial 2
No. of Blows N	34	26	22	18	-----	-----
Mass of Can M_c	31.1	31.1	31.4	31.4	10.8	11.8
Mass of moist Sample + C M_1	47.41	50.85	53.15	56.02	17.96	17.27
Mass of Dried Sample + C M_2	42.73	44.56	45.86	47.36	16.22	16.00
Mass of Moist $M_m = M_1 - M_2$	4.68	6.29	7.29	8.66	1.74	1.27
Mass of Dried Sample $M_d = M_2 - M_c$	11.63	13.46	14.46	15.96	5.42	4.20
Moisture $w = M_m / M_d \times 100$	40.24	46.73	50.41	54.26	32.10	30.24

Natural Gravel material +2% CaCl ₂	Liquid Limit Test				Plastic Limit Test	
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 1	Trial 2
No. of Blows N	36	25	22	18	-----	-----
Mass of Can M_c	31.1	31.1	31.4	31.4	10.8	11.8
Mass of moist Sample + C M_1	50.30	52.71	55.71	58.00	16.63	16.54
Mass of Dried Sample + C M_2	45.80	46.96	48.37	49.08	15.22	15.45
Mass of Moist $M_m = M_1 - M_2$	4.5	5.75	7.34	8.92	1.41	1.09
Mass of Dried Sample $M_d = M_2 - M_c$	14.70	15.86	16.97	17.68	4.42	3.65
Moisture $w = M_m / M_d \times 100$	30.61	36.25	43.25	50.45	31.90	29.86

Natural Gravel material +4% CaCl ₂	Liquid Limit Test				Plastic Limit Test	
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 1	Trial 2
No. of Blows N	37	26	23	17	-----	-----
Mass of Can M_c	31.1	31.1	31.4	31.4	10.8	11.8
Mass of moist Sample + C M_1	52.48	57.99	55.52	56.64	18.78	18.54
Mass of Dried Sample + C M_2	48.11	51.28	48.76	48.63	17.04	16.95
Mass of Moist $M_m = M_1 - M_2$	4.37	6.71	6.76	8.01	1.74	1.59
Mass of Dried Sample $M_d = M_2 - M_c$	17.01	20.18	17.36	17.23	6.24	5.15
Moisture $w = M_m / M_d \times 100$	25.69	33.25	38.94	46.49	27.88	30.87

Natural Gravel material +6% CaCl ₂	Liquid Limit Test				Plastic Limit Test	
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 1	Trial 2
No. of Blows N	38	25	22	18	-----	-----
Mass of Can M_c	31.1	31.1	31.4	31.4	10.8	11.8
Mass of moist Sample + C M_1	60.02	59.47	62.06	56.06	19.87	19.40
Mass of Dried Sample + C M_2	54.25	52.66	53.64	48.74	17.84	17.71
Mass of Moist $M_m = M_1 - M_2$	5.77	6.81	8.42	7.32	2.03	1.69
Mass of Dried Sample $M_d = M_2 - M_c$	23.15	21.56	22.24	17.34	7.04	5.91
Moisture $w = M_m / M_d \times 100$	24.92	31.59	37.86	42.21	28.84	28.60

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Natural Gravel material +8% CaCl ₂	Liquid Limit Test				Plastic Limit Test	
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 1	Trial 2
No. of Blows N	37	26	23	17	-----	-----
Mass of Can M _c	31.1	31.1	31.4	31.4	10.8	11.8
Mass of moist Sample + C M ₁	61.99	64.95	66.54	64.07	19.50	22.28
Mass of Dried Sample + C M ₂	56.32	57.32	57.38	54.87	17.58	20.11
Mass of Moist M _m =M ₁ -M ₂	5.67	7.63	9.16	9.2	1.92	2.17
Mass of Dried Sample M _d =M ₂ -M _c	25.22	26.22	25.98	23.47	6.78	8.31
Moisture w = M _m / M _d x 100	22.48	29.10	35.26	39.20	28.32	26.11

Natural Gravel material +10% CaCl ₂	Liquid Limit Test				Plastic Limit Test	
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 1	Trial 2
No. of Blows N	36	26	22	18	-----	-----
Mass of Can M _c	31.1	31.1	31.4	31.4	10.8	11.8
Mass of moist Sample + C M ₁	68.60	70.60	66.50	68.60	20.60	21.00
Mass of Dried Sample + C M ₂	61.80	61.90	57.80	58.00	18.60	19.00
Mass of Moist M _m =M ₁ -M ₂	6.8	8.7	8.7	10.6	2	2
Mass of Dried Sample M _d =M ₂ -M _c	30.70	30.80	26.40	26.60	7.80	7.20
Moisture w = M _m / M _d x 100	22.15	28.25	32.95	39.85	25.64	27.78

APPENDIX E: Linear Shrinkage Test Analysis Data

Natural Gravel	Trial 1	Trial 2	Trial 3
Mould No.	1	2	3
Original length of the specimen (Lo) in mm	150	150	150
Length of the oven-dry specimen (L) in mm	136.1	136.3	136.3
Linear Shrinkage (LS) in mm LS=Lo-L	13.9	13.7	13.7
Bar Linear Shrinkage (BLS) in % BLS=LSx0.67	9.3	9.2	9.2
Mean Bar Linear Shrinkage (BLS*) in %	9.2		

Natural Gravel + 2% CaCl₂	Trial 1	Trial 2	Trial 3
Mould No.	1	2	3
Original length of the specimen (Lo) in mm	150	150	150
Length of the oven-dry specimen (L) in mm	141.9	141.7	141.8
Linear Shrinkage (LS) in mm LS=Lo-L	8.1	8.3	8.2
Bar Linear Shrinkage (BLS) in % BLS=LSx0.67	5.4	5.6	5.5
Mean Bar Linear Shrinkage (BLS*) in %	5.5		

Natural Gravel + 4% CaCl₂	Trial 1	Trial 2	Trial 3
Mould No.	1	2	3
Original length of the specimen (Lo) in mm	150	150	150
Length of the oven-dry specimen (L) in mm	143.3	143.5	143.4
Linear Shrinkage (LS) in mm LS=Lo-L	6.7	6.5	6.6
Bar Linear Shrinkage (BLS) in % BLS=LSx0.67	4.5	4.4	4.4
Mean Bar Linear Shrinkage (BLS*) in %	4.4		

Natural Gravel + 6% CaCl₂	Trial 1	Trial 2	Trial 3
Mould No.	1	2	3
Original length of the specimen (Lo) in mm	150	150	150
Length of the oven-dry specimen (L) in mm	144.9	144.6	144.6
Linear Shrinkage (LS) in mm LS=Lo-L	5.1	5.4	5.4
Bar Linear Shrinkage (BLS) in % BLS=LSx0.67	3.4	3.6	3.6
Mean Bar Linear Shrinkage (BLS*) in %	3.6		

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Natural Gravel + 8% CaCl₂	Trial 1	Trial 2	Trial 3
Mould No.	1	2	3
Original length of the specimen (Lo) in mm	150	150	150
Length of the oven-dry specimen (L) in mm	145.8	145.7	145.7
Linear Shrinkage (LS) in mm LS=Lo-L	4.2	4.3	4.3
Bar Linear Shrinkage (BLS) in % BLS=LSx0.67	2.8	2.9	2.9
Mean Bar Linear Shrinkage (BLS*) in %	2.9		

Natural Gravel + 10% CaCl₂	Trial 1	Trial 2	Trial 3
Mould No.	1	2	3
Original length of the specimen (Lo) in mm	150	150	150
Length of the oven-dry specimen (L) in mm	146.1	146.0	146.0
Linear Shrinkage (LS) in mm LS=Lo-L	3.9	4.0	4.0
Bar Linear Shrinkage (BLS) in % BLS=LSx0.67	2.6	2.7	2.7
Mean Bar Linear Shrinkage (BLS*) in %	2.7		

APPENDIX F: Soil Classification System Tables

AASHTO soil classification system AASHTO M145 [34]

General Classification	Granular Materials 35% or less passing the 0.075 mm sieve							Silt-Clay Materials >35% passing the 0.075 mm sieve			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5 A-7-6
Sieve Analysis, % passing											
2.00 mm (No. 10)	50 max	---	---	---	---	---	---	---	---	---	---
0.425 (No. 40)	30 max	50 max	51 max	---	---	---	---	---	---	---	---
0.075 (No. 200)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 0.425 mm (No. 40)											
Liquid limit	---		---	40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min ^a
Usual types of significant constituent materials	stone fragments, gravel and sand		fine sand	silty or clayey gravel and sand				silty soils		clayey soils	
General rating as a subgrade	excellent to good							fair to poor			

USCS Soil Classification system ASTM D2487 [36]

Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests ^A				Soil Classification	
				Group Symbol	Group Name ^B
COARSE-GRAINED SOILS	Gravels (More than 50 % of coarse fraction retained on No. 4 sieve)	Clean Gravels (Less than 5 % fines ^C)	Cu ≥ 4.0 and 1 ≤ Cc ≤ 3.0 ^D	GW	Well-graded gravel ^E
			Cu < 4.0 and/or [Cc < 1 or Cc > 3.0] ^D	GP	Poorly graded gravel ^E
		Gravels with Fines (More than 12 % fines ^C)	Fines classify as ML or MH	GM	Silty gravel ^{E,F,G}
			Fines classify as CL or CH	GC	Clayey gravel ^{E,F,G}
More than 50 % retained on No. 200 sieve	Sands (50 % or more of coarse fraction passes No. 4 sieve)	Clean Sands (Less than 5 % fines ^H)	Cu ≥ 6.0 and 1.0 ≤ Cc ≤ 3.0 ^D	SW	Well-graded sand ^I
			Cu < 6.0 and/or [Cc < 1.0 or Cc > 3.0] ^D	SP	Poorly graded sand ^I
		Sands with Fines (More than 12 % fines ^H)	Fines classify as ML or MH	SM	Silty sand ^{F,G,I}
			Fines classify as CL or CH	SC	Clayey sand ^{F,G,I}
FINE-GRAINED SOILS	Sils and Clays	inorganic	PI > 7 and plots on or above "A" line ^J	CL	Lean clay ^{K,L,M}
			PI < 4 or plots below "A" line ^J	ML	Silt ^{K,L,M}
		organic	Liquid limit – oven dried Liquid limit – not dried < 0.75	OL	Organic clay ^{K,L,M,N} Organic silt ^{K,L,M,O}
50 % or more passes the No. 200 sieve	Sils and Clays	inorganic	PI plots on or above "A" line	CH	Fat clay ^{K,L,M}
			PI plots below "A" line	MH	Elastic silt ^{K,L,M}
		organic	Liquid limit – oven dried Liquid limit – not dried < 0.75	OH	Organic clay ^{K,L,M,P} Organic silt ^{K,L,M,O}
HIGHLY ORGANIC SOILS		Primarily organic matter, dark in color, and organic odor		PT	Peat

APPENDIX G: Compaction Test Analysis Data

Natural Gravel material		Mass of mold + base	Kg=	7145		
		Volume of mold	Kg/m3 =	2124		
TEST DATA						
Moisture %		1	2	3	4	
Mass of wet soil + mould	A (g)	10670	10970	11105	11095	
Mass of mould	B (g)	7145	7145	7145	7145	
Mass of wet soil	C=A-B (g)	3525	3825	3960	3950	
VOLUME OF MOULD	(CC)	2124	2124	2124	2124	
Bulk density	C / V = W	1.660	1.801	1.864	1.860	
Moisture determination container No.		A-1	A-2	A-3	A-4	
Mass of container + wet soil	a (g)	140.9	120.9	107.4	110.9	
mass of container + dry soil	b (g)	131	111.4	98.2	100.2	
Mass of container	d (g)	31.00	33.00	32.00	26.00	
Mass of dry soil	b - d = e (g)	100	78.4	66.2	74.2	
Mass of moisture	a - b = f (g)	9.90	9.50	9.20	10.70	
Moisture content	f/e*100 = m (%)	9.90	12.12	13.90	14.42	
Dry density	W / (100+m) *100 (g/cc)	1.510	1.606	1.637	1.625	

Moisture-Density Relationship

The graph plots Dry Density (g/cm³) on the y-axis (ranging from 1.450 to 1.750) against Moisture Content (%) on the x-axis (ranging from 8.00 to 16.00). A smooth curve is drawn through the data points, showing a peak at 13.7% moisture content and 1.640 g/cm³ dry density. A vertical dashed line with arrows at both ends connects the peak to the x-axis at 13.7. A horizontal dashed line with an arrow at the right end connects the peak to the y-axis at 1.64.

Moisture Content (%)	Dry Density (g/cm³)
9.90	1.510
12.12	1.606
13.90	1.637
14.42	1.625

MAXIMUM DRY DENSITY (g / cc)	1.640
OPTIMUM MOISTURE CONTENT (%)	13.7

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Natural Gravel Material + 2% CaCl2		Mass of mold + base		Kg=	7145	
		Volume of mold		Kg/m3 =	2124	
TEST DATA						
Moisture %		5	6	7	8	
Mass of wet soil + mould	A (g)	10710	10995	11160	11145	
Mass of mould	B (g)	7145	7145	7145	7145	
Mass of wet soil	C=A-B (g)	3565	3850	4015	4000	
VOLUME OF MOULD	(CC)	2124	2124	2124	2124	
Bulk density	C / V = W	1.678	1.813	1.890	1.883	
Moisture determination container No.		E-1	A-2	A-3	E-4	
Mass of container + wet soil	a (g)	159.2	160.8	150.6	161.2	
mass of container + dry soil	b (g)	149.9	149.3	137.9	145.5	
Mass of container	d (g)	38.00	39.00	37.00	42.00	
Mass of dry soil	b - d = e (g)	111.9	110.3	100.9	103.5	
Mass of moisture	a - b = f (g)	9.30	11.50	12.70	15.70	
Moisture content	f/e*100 = m (%)	8.31	10.43	12.59	15.17	
Dry density	W / (100+m) *100 (g/cc)	1.550	1.641	1.679	1.635	

Moisture-Density Relationship

Moisture Content (%)	Dry Density (g/cm³)
8.31	1.550
10.43	1.641
12.59	1.679
15.17	1.635

MAXIMUM DRY DENSITY (g / cc)	1.680
OPTIMUM MOISTURE CONTENT (%)	12.8

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Natural Gravel Material + 4% CaCl2		Mass of mold + base	Kg=	7145		
		Volume of mold	Kg/m3 =	2124		
TEST DATA						
Moisture %		9	10	11	12	
Mass of wet soil + mould	A (g)	10770	11085	11190	11195	
Mass of mould	B (g)	7145	7145	7145	7145	
Mass of wet soil	C=A-B (g)	3625	3940	4045	4050	
VOLUME OF MOULD	(CC)	2124	2124	2124	2124	
Bulk density	C / V = W	1.707	1.855	1.904	1.907	
Moisture determination container No.		B-1	B-2	B-3	B-4	
Mass of container + wet soil	a (g)	160.9	166.6	160.7	167.2	
mass of container + dry soil	b (g)	151	154.6	147.3	151	
Mass of container	d (g)	42.00	35.50	34.00	30.00	
Mass of dry soil	b - d = e (g)	109	119.1	113.3	121	
Mass of moisture	a - b = f (g)	9.90	12.00	13.40	16.20	
Moisture content	f/e*100 = m (%)	9.08	10.08	11.83	13.39	
Dry density	W / (100+m) *100 (g/cc)	1.565	1.685	1.703	1.682	

Moisture-Density Relationship

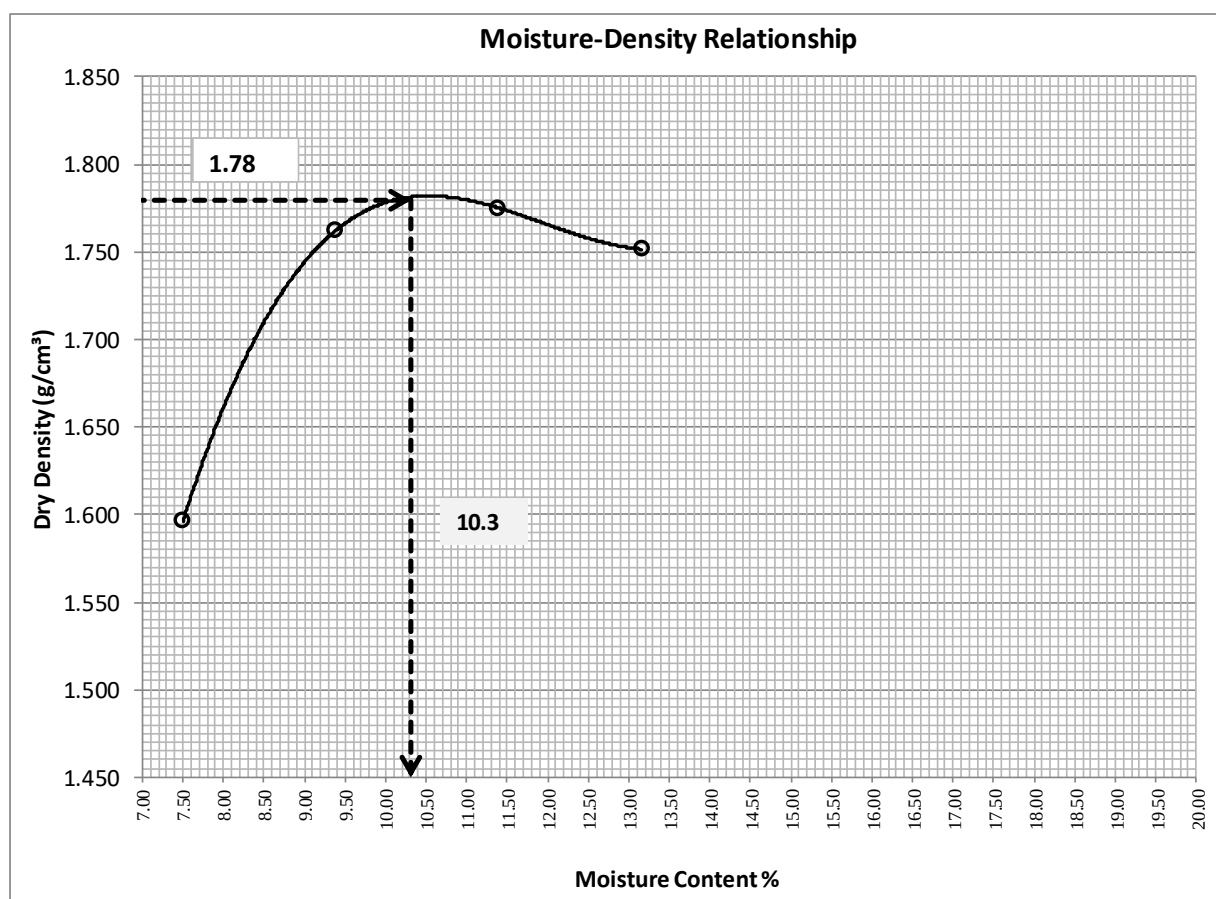
Moisture Content (%)	Dry Density (g/cm³)
9.08	1.565
10.08	1.715
11.83	1.703
13.39	1.682

MAXIMUM DRY DENSITY (g / cc)	1.715
OPTIMUM MOISTURE CONTENT (%)	10.9

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Natural Gravel Material + 6% CaCl₂	Mass of mold + base Kg=	7145
	Volume of mold Kg/m ³ =	2124

TEST DATA						
Moisture %		13	14	15	16	
Mass of wet soil + mould A (g)		10790	11240	11345	11355	
Mass of mould B (g)		7145	7145	7145	7145	
Mass of wet soil C=A-B (g)		3645	4095	4200	4210	
VOLUME OF MOULD (CC)		2124	2124	2124	2124	
Bulk density C / V = W		1.716	1.928	1.977	1.982	
Moisture determination container No.		D-1	D-2	D-3	D-4	
Mass of container + wet soil a (g)		168.8	160.8	169.9	160.4	
mass of container + dry soil b (g)		159.6	150	155.8	145	
Mass of container d (g)		37.00	35.00	32.00	28.00	
Mass of dry soil b - d = e (g)		122.6	115	123.8	117	
Mass of moisture a - b = f (g)		9.20	10.80	14.10	15.40	
Moisture content f/e*100 = m (%)		7.50	9.39	11.39	13.16	
Dry density W / (100+m) *100 (g/cc)		1.596	1.762	1.775	1.752	



MAXIMUM DRY DENSITY (g / cc)	1.780
OPTIMUM MOISTURE CONTENT (%)	10.3

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Natural Gravel Material + 8% CaCl2		Mass of mold + base Kg=		7145		
		Volume of mold Kg/m3 =		2124		
TEST DATA						
Moisture %	17	18	19	20		
Mass of wet soil + mould A (g)	10795	11150	11335	11265		
Mass of mould B (g)	7145	7145	7145	7145		
Mass of wet soil C=A-B (g)	3650	4005	4190	4120		
VOLUME OF MOULD						

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing

Natural Gravel Material + 10% CaCl2		Mass of mold + base Kg=		7145			
		Volume of mold Kg/m3 =		2124			
TEST DATA							
Moisture %		21	22	23	24		
Mass of wet soil + mould A (g)		10800	11275	11365	11375		
Mass of mould B (g)		7145	7145	7145	7145		
Mass of wet soil C=A-B (g)		3655	4130	4220	4230		
VOLUME OF MOULD (CC)		2124	2124	2124	2124		
Bulk density C / V = W		1.721	1.944	1.987	1.992		
Moisture determination container No.		F-1	F-2	F-3	F-4		
Mass of container + wet soil a (g)		167.6	170.6	174.6	158.6		
mass of container + dry soil b (g)		158.6	159	160	143.3		
Mass of container d (g)		38.00	35.00	32.00	28.00		
Mass of dry soil b - d = e (g)		120.6	124	128	115.3		
Mass of moisture a - b = f (g)		9.00	11.60	14.60	15.30		
Moisture content f/e*100 = m (%)		7.46	9.35	11.41	13.27		
Dry density W / (100+m) *100 (g/cc)		1.601	1.778	1.783	1.758		

Moisture-Density Relationship

The graph plots Dry Density (g/cm³) on the y-axis (ranging from 1.450 to 1.850) against Moisture Content (%) on the x-axis (ranging from 7.00 to 20.00). A smooth curve is drawn through five data points. A vertical dashed line from the peak of the curve to the x-axis marks the optimum moisture content at 10.1%. A horizontal dashed line from the peak to the y-axis marks the maximum dry density at 1.795 g/cm³.

Moisture Content (%)	Dry Density (g/cm³)
7.5	1.601
9.5	1.783
10.1	1.795
11.5	1.783
13.3	1.758

MAXIMUM DRY DENSITY (g / cc)	1.795
OPTIMUM MOISTURE CONTENT (%)	10.1

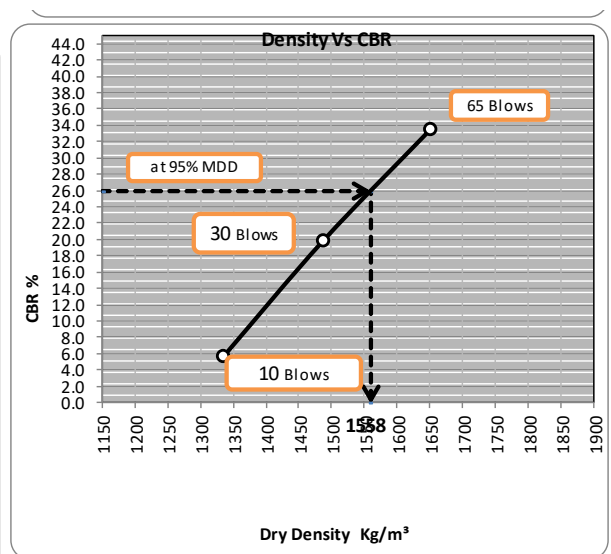
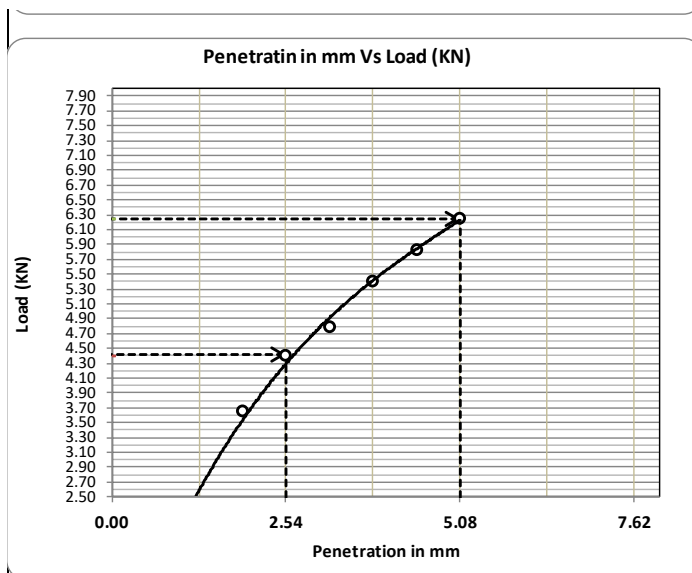
APPENDIX H: Unconfined Compressive Strength Test Analysis Data

Unconfined compressive strength (UCS) test								
No	Sample	Diameter (mm)	Height (mm)	Weight of Soil Sample (kg)	Dial Reading	Ring Factor (N/div)	Unit Weight (kg/m ³)	UCS (kN/m ²)
1	Natural Gravel Material	38	76	0.149	36	6.624	1730	210.37
2	Natural Gravel Material With 2%Calcium Chloride	38	76	0.145	43	6.624	1683	251.28
3	Natural Gravel Material With 4%Calcium Chloride	38	76	0.146	49	6.624	1695	286.34
4	Natural Gravel Material With 6%Calcium	38	76	0.143	42	6.624	1660	245.43
5	Natural Gravel Material With 8%Calcium Chloride	38	76	0.145	40	6.624	1683	233.75
6	Natural Gravel Material With 10%Calcium Chloride	38	76	0.147	37	6.624	1706	216.21

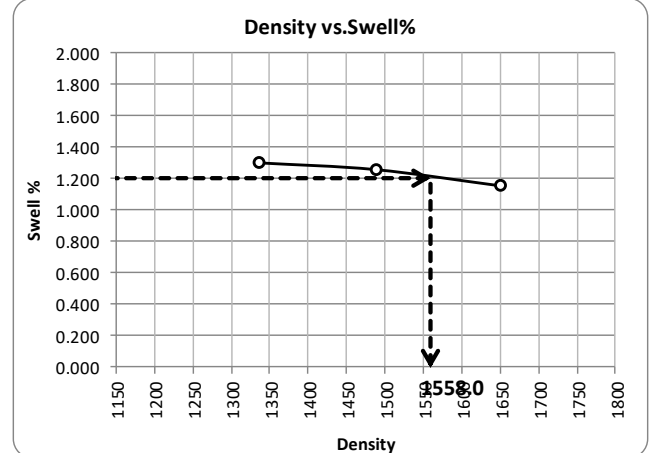
APPENDIX I: California Bearing Ratio Test Analysis Data

CALIFORNIA BEARING RATIO												
Material Type:-			Natural Gravel									
COMPACTION DATA												
COMPACTION DATA				10 Blows		30 Blows		65 Blows		Remarks		
				Before		Before		Before				
Mould No.				M1		G2		M6				
Mass of soil + Mould				g		10450		11230		11800		
Mass Mould				g		7250		7650		7850		
Mass of Soil				g		3200		3580		3950		
Volume of Mould(Specimen)				g		2124		2124		2124		
Wet density of soil				g/cc		1.507		1.685		1.860		
Dry density of soil				g/cc		1.336		1.488		1.651		
MOISTURE CONTENT DATA												
MOISTURE CONTENT DATA				10 Blows		30 Blows		65 Blows		Remarks		
				Before		Before		Before				
Container no.				4		5		7				
Mass of wet soil + Container				g		543.00		532.00		543.00		
Mass of dry soil + Container				g		486.00		475.00		486.00		
Mass of water				g		57.00		57.00		57.00		
Mass of container				g		41		46		36		
Mass of drysoil				g		445.0		429.0		450.0		
Moisture content				%		12.81		13.29		12.67		
PENTERATION DATA												
PENTERATION RATE (1.27mm/min.)										Ring Factor KN/Div 0.04		
10 Blows			CBR%	30 Blows			CBR%	65 Blows			CBR%	Remarks
Pen.mm	Gauge,Div	Load, KN		Pen.mm	Gauge,Div	Load, KN		Pen.mm	Gauge,Div	Load, KN		
0	0.0	0		0.00	0.0	0		0.00	0.0	0		
0.64	4.0	0.17		0.64	16.0	0.67		0.64	33.0	1.37		
1.27	6.0	0.25		1.27	32.0	1.33		1.27	59.0	2.46		
1.91	10.0	0.42		1.91	49.0	2.04		1.91	88.0	3.67		
2.54	18.0	0.75	5.68	2.54	63.0	2.62	19.88	2.54	106.0	4.42	33.45	
3.18	19.0	0.79		3.18	70.0	2.92		3.18	115.0	4.79		
3.81	20.0	0.83		3.81	73.0	3.04		3.81	130.0	5.42		
4.45	23.0	0.96		4.45	80.0	3.33		4.45	140.0	5.83		
5.08	26.0	1.08	5.42	5.08	86.0	3.58	17.91	5.08	150.0	6.25	31.25	
7.62	31.0	1.29		7.62	94.0	3.92		7.62	159.0	6.62		
10.16	37.0	1.54		10.16	104.0	4.33		10.16	167.0	6.96		
Max.Dry Density g/cc			1.640					OMC %			13.7	

Performance Evaluation of Natural Gravel mixed with Calcium Chloride for Unpaved Road Surfacing



Swell				
Number of blows		10	30	65
Guage reading before soaking		0.54	0.69	0.65
Guage reading after soaking		2.05	2.15	1.99
% swell		1.302	1.259	1.155
CBR %	2.54mm	5.68	19.88	33.45
	5.08mm	5.42	17.91	31.25
Load KN	2.54mm	0.75	2.62	4.42
	5.08mm	1.08	3.58	6.25
Dry Density(Kg/m ³)		1336	1488	1651



Standard Load in KN at 2.54 mm	13.2
Standard Load in KN at 5.08 mm	20

Swell %	CBR%
1.21	26.0

95% of MDD	1558
CBR %	26.0