AN INVESTIGATION ON THE IMPACT OF LIME VARIATIONS TO THE GEOTECHNICAL PROPERTIES OF VARIOUS SOIL SAMPLES OF DIFFERENT pH RANGES

By

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DECLARATION

I, Phakamani Humphrey Bhengu, hereby declare that this dissertation, except where indicated in the text, is my own work and has not been submitted in part, or in whole, at any other University or University of Technology, and that it's only prior publication was in the form of conference papers and journal articles which are listed in Appendix B.

This research on an investigation on the impact of lime variations to the geotechnical properties of various soil samples of different pH ranges was conducted in KwaZulu Natal, South Africa, and registered at the Durban University of Technology under the supervision of Professor Dhiren Allopi.

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ABSTRACT

When geotechnical engineers design structures, the designs are based on the assumption that specified quality levels will be achieved for each soil layer below. This is accomplished by ensuring that each layer resists shearing and avoids excessive elastic deformations (Jawad *et al*., 2014). When the quality of each level of soil layer is increased, the soil's ability to distribute the load over the greater area is generally increased enough to permit the reduction in the required thickness of the soil and surface layers. Many methods can be adopted in order to achieve quality levels when trying to improve the soil strength (Azadegan, Jafari and Li, 2012). One method entails the application of lime in various concentrations to soil as a soil stabilisation process.

Soil stabilisation is the alteration of soil to enhance its geotechnical properties. These properties include particle size distribution, plasticity and liquid limit, linear shrinkage, Optimum Moisture Content (OMC), Maximum Dry Density (MDD) and California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) of the soil samples.

This research examines the use of lime variations to stabilise soil in order to improve the geotechnical properties of various soil samples. The soil samples had different pH ranges due to diverse mineralogical and microstructural composition. Further, this research was inspired by the paucity of published research on the topic. Over recent years, very little research on soil stabilisation has focused on the impact of lime variations on the soil geotechnical properties towards effective soil stabilisation of soil of diverse pH ranges.

To conduct the research, approximately 3900 kg of soil was collected for laboratory testing purposes. A series of laboratory tests were conducted, including consistency limits, OMC, MDD, CBR and UCS. These tests were all done in compliance with the Technical Methods for Highways Part 1 (TMH1) of South Africa, with particular emphasis on methods A1, A2, A3, A4, A7, A9 and A14 (Department of Transport, 1986a), supplemented by the pavement engineering manual by the South African National Roads Agency (SANRAL) (2013). Mineralogical tests were conducted by applying x-ray diffraction (X-RD) and scanning electron microscopy (SEM) for better understanding of the microstructure of soil samples. This was to enhance the interpretation of the physical behaviour of the soil samples. Properties partially covered in this research in a form of a literature review are as follows: texture, structure, porousness, organic matter, colour, soil-depth and soil-temperature.

In terms of plasticity properties (Atterberg limits), findings of the study confirmed that many of the important engineering and mineralogical properties of soil can be enhanced by the addition of lime. The application of lime led to a reduction in plasticity of both the acidic and alkaline soil samples. The reduction mentioned above occurred due to the decrease in the thickness of the layer of the soil particles that were treated. Further, from the analysis carried out, it was found that the treatment of the soil samples with lime content increased the pH of all the samples. The changes were as a result of the changes in the chemical properties (i.e. cation exchange) and the composition of the samples due to their chemical reactions with the lime additive. This is a substantial pH increase compared to the pH of natural soil (untreated soil samples).

Regarding MDD and OMC, the six soil samples displayed maximum dry densities ranging from 1500 kg/m³ to 1940 kg/m³ and optimum moisture contents ranging from 14 % to 29 %. Lime content at range of 4 % to 8 % indicated the highest density of the stabilised soil samples. The densities of the soil samples showed a slight increase at the lime content of 10 %. However, for almost all samples, the results showed that further addition of lime decreases the density and increases moisture content. Based on the results, it was discovered that the MDD is achieved at 2075 kg/m³ and at 22 % of OMC for alkaline soil sample 6 when treated with lime content of 4 %. The above implies that maximum cohesion and maximum friction are achieved at pH = 8.68. For other soil samples, the MDD decreased with increase in number of days for each of the pH conditions. This indicated that the particles of the soil samples tested were being disintegrated. This reduction in the density of the soil had an impact on the strength of the soil. Typical example for the latter is alkaline soil sample 4 of pH = 9.20, with an MDD of 1591.53 kg/m³ at 18 % of OMC.

The CBR for treated soil samples compacted at 25 compactive efforts recorded lower CBR values compared to the soil samples compacted at 55 compactive efforts. Alkaline soil sample 6 of pH = 8.68 indicated constant increase in CBR for respective penetration depths of 2.54 mm, 5.08 mm and 7.62 mm. The constant increase in CBR for alkaline soil sample 6 compacted at 55 compactive efforts was a direct indication of the principal chemical reactions that took place during the lime-soil stabilisation process.

In order to investigate the effect of pH on shear strength of treated soil, UCS geotechnical properties of the soil samples of different pH values (i.e. pH = 4.02, 4.92, 5.55, 9.20, 8.27 and 8.68 for sample 1 to 6 respectively) were determined using the UCS machine. Based on the results of UCS strength tests, it was found that the UCS geotechnical properties increased considerably if the soil had a high pH (pH = 8.68 for alkaline soil sample soil 6 and pH = 8.27 for alkaline soil sample 5). At an alkaline pH, the increasing of ionic strength favoured face-to-face aggregation of the soil samples. The UCS geotechnical properties decreased considerably when the pH values were less than pH = 8. This was particularly evident for acidic soil samples one of pH = 4.02, soil sample 2 of pH = 4.92 and soil sample 3 of pH = 5.55.

The soil pH had no significant or direct impact on the microstructural studies of the soil tested, but the microstructural properties analysis helped ascertain which elements were found in the soil. Tests used were X-RD, SEM and energy dispersive x-ray spectroscopy (EDS/EDX). The elements found were magnesium (Mg), potassium (K), calcium (Ca), titanium (Ti), iron (Fe), aluminium (Al), silicon (Si) oxygen (O) and carbon (C). Some of the soil elements found and evaluated were significantly influenced by the usage of lime. The findings of X-RD, SEM were influenced by the source of the soil.

Other contributory factors that impacted negatively the geotechnical properties of the soil tested related to the loss of the cementitious elements in both the acidic (pH < 7) and alkaline (pH > 7) soil samples. Therefore, the conclusions and recommendations include the following but are not limited to: the need for a more effective approach to reviewing designs and construction procedures for soil stabilisation; the need to achieve minimisation of carbonation to suit the intended results; and the need to take into account the pH of the soil when designing structures.

DEDICATION

I would like to express my wholehearted thanks to my family and friends for the generous support they have provided to me throughout my entire life and particularly through the process of pursuing my master’s degree. Because of their unconditional love and prayers, I have had the chance to complete this dissertation.

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TABLE OF CONTENTS

ABSTRACT iii

DEDICATION vi

ACKNOWLEDGEMENTS vii

TABLE OF CONTENTS viii

LIST OF FIGURES xii

LIST OF TABLES xv

LIST OF APPENDICES xvi

LIST OF EQUATIONS xvii

LIST OF ABBREVIATIONS xviii

CHAPTER 1 1

- 1.1 Background of the study 1
- 1.2 History and evolution of lime-soil stabilisation 2
- 1.3 Lime-soil stabilisation 3
  - 1.3.1 Chemical reactions in lime treated soil 4
- 1.4 The problem statement 5
  - 1.4.1 Previous research work 6
- 1.5 Main aim of the study 6
- 1.6 Study scope and delimitations 7
- 1.7 Importance of the study 7
- 1.8 Brief description of the research design 8
  - 1.8.1 Research methodology 8
  - 1.8.2 Instruments used in the creation of data 8
  - 1.8.3 Brief procedure of the research methodology 8
- 1.9 Structure of the dissertation 9

CHAPTER 2 10

- 2.1 Introduction: Soil stabilisation in general 10

2.2 Thermal soil stabilisation 11
2.3 Mechanical soil stabilisation 12
2.4 Electrical soil stabilisation 13
2.5 Chemical soil stabilisation 13
  2.5.1 By-products soil stabilisers 15
  2.5.2 Non-traditional soil stabilisers 15
  2.5.3 Traditional soil stabilisers 17
  2.5.4. Lime 17
    2.5.4.1 Production process of lime 18
    2.5.4.2 Lime-soil stabilisation 19
    2.5.4.3 Chemistry of lime-soil stabilisation 19
    2.5.4.4 The effect of pH on lime-soil stabilisation 23
CHAPTER 3 24
3.1 Sieve analysis 25
  3.1.1 Materials and equipment 25
  3.1.2 Methodology 25
3.2 Atterberg limits tests 26
  3.2.1 Materials and equipment 26
  3.2.2 Methodology 27
3.3 Maximum dry density and optimum moisture content 28
  3.3.1 Materials and equipment 28
  3.3.2 Methodology 29
3.4 Curing/Soaking-for CBR penetration 30
  3.4.1 Materials and equipment 30
  3.4.2 Methodology 30
3.5 CBR Penetration 31
  3.5.1 Materials and equipment 31

3.5.2 Methodology 31

3.6 Unconfined compressive strength 32

3.6.1 Materials and equipment 32

3.6.2 Methodology 32

3.7 X-ray diffraction 33

3.7.1 Materials and equipment 33

3.7.2 Methodology 34

3.8 SEM and EDS/EDX scans 34

3.8.1 Materials and equipment 34

3.8.2 Methodology 35

CHAPTER 4 36

4.1 Index properties of soil samples 36

4.2 Engineering properties of the soil samples 39

4.2.1 Maximum dry density and optimum moisture content 39

4.2.2 California Bearing Ratio penetration 43

4.2.2.1 Acidic soil samples-CBR results (samples 1, 2 & 3) 56

4.2.2.2 Alkaline soil samples-CBR results (samples 4, 5 & 6) 61

4.2.3 Soil swelling properties 66

4.2.3.1 Less swelling of the soil samples 66

4.2.3.2 More swelling of the soil samples 67

4.2.4 Unconfined compressive strength results 67

4.2.4.1 UCS at 2 % of lime content for all soil samples 69

4.2.4.2 UCS at 4 % of lime content for all soil samples 69

4.2.4.3 UCS at 6 % of lime content for all soil samples 70

4.2.4.4 UCS at 8 % of lime content for all soil samples 70

4.2.4.5 UCS at 10 % of lime content for all soil samples 71

4.2.5 Microstructural properties 72

4.2.5.1 X-ray diffraction 72
4.2.5.2 Scanning electron microscope (SEM) & EDS/EDX 79
4.2.6 Loss of cementitious elements– Carbonation 93
4.2.6.1 The effect of carbonation on UCS 93
4.2.6.2 The effect of carbonation on CBR 93
4.2.6.3 The effect of carbonation on, SEM and EDS/EDX.............................. 94
4.2.7 The effect of lime stabilisation on the pH of soil.. 94
CHAPTER 5 96
5.1 Conclusions 96
5.1.1 Atterberg limits... 96
5.1.2 Maximum dry density and optimum moisture content 97
5.1.3 California bearing ratio.. 97
5.1.4 Soil swelling properties 99
5.1.5 Unconfined compressive strength... 99
5.1.6 Microstructural properties 100
5.1.7 Carbonation 100
5.1.8 Soil pH 100
5.2 Future recommendations 101
5.2.1 Atterberg limits... 101
5.2.2 Maximum dry density and optimum moisture content 102
5.2.3 California bearing ratio.. 102
5.2.4 Swelling of the soil 103
5.2.5 Unconfined compressive strength... 103
5.2.6 Soil pH 104
REFERENCES... 105
APPENDICES 113

LIST OF FIGURES

Figure 1: Flow chart of a vertical shaft kiln during the lime production process........ 19

Figure 2: The schematic representation of the agglomeration process during lime-soil stabilisation 21

Figure 3: (a) Soil particles being air dried prior to riffling and sieve analysis tests; (b) Apparatus utilised for riffling and sieve analysis test on soil 25

Figure 4: (a) Fine material, material less than 0.425 mm used for Atterberg test; (b) Apparatus utilised for the Atterberg limit tests 26

Figure 5: (a) Soil being air dried prior to maximum dry density and moisture content determination. (b) Apparatus utilised for compaction of the soil for MDD and OMC. (c) Air dried soil sample after sieving through a 19 mm sieve size for maximum dry density and optimum moisture content determination. 28

Figure 6: (a) Soil treated with different lime content confined in Proctor steel moulds prior to the curing and soaking processes. (b) Rectangle extra heavy duty tanks 30

Figure 7: (a) Soil treated with different lime content prior to CBR penetration test. (b) CBR machine for penetration test on compacted layer of soil (treated)............. 31

Figure 8: (a) Lime treated soil samples prior to the unconfined compressive strength test. (b) CBR machine during the unconfined compressive strength test 32

Figure 9: (a) Fine material, material less than 0.425 mm used for X-RD analysis. (b) Diffractometer machine used for minerals identification 33

Figure 10: (a) Fine material less than 0.425 mm used for SEM analysis. (b) SEM machine 34

Figure 11: Particle size distribution curves for soil samples 1 to 6 38

Figure 12: CBR penetration curves for sample 1 at lime contents of 2 %, 4 % & 6 % cured for 7 days 44

Figure 13: CBR penetration curves for sample 1 at lime contents of 8 % & 10 % cured for 7 days 45

Figure 14: CBR penetration curves for sample 2 at lime contents of 2 %, 4 % & 6 % cured for 7 days 46

Figure 15: CBR penetration curves for sample 2 at lime contents of 8 % & 10 % cured for 7 days 47

Figure 16: CBR penetration curves for sample 3 at lime contents of 2 %, 4 % & 6 % cured for 7 days 48
Figure 17: CBR penetration curves for sample 3 at lime contents of 8 % & 10 % cured for 7 days 49
Figure 18: CBR penetration curves for sample 4 at lime contents of 2 %, 4 % & 6 % cured for 7 days 50
Figure 19: CBR penetration curves for sample 4 at lime contents of 8 % & 10 % cured for 7 days 51
Figure 20: CBR penetration curves for sample 5 at lime contents of 2 %, 4 % & 6 % cured for 7 days 52
Figure 21: CBR penetration curves for sample 5 at lime contents of 8 % & 10 % cured for 7 days 53
Figure 22: CBR penetration curves for sample 6 at lime contents of 2 %, 4 % & 6 % cured for 7 days 54
Figure 23: CBR penetration curves for sample 6 at lime contents of 8 % & 10 % cured for 7 days 55
Figure 24: Unconfined Compressive Strength (UCS) for soil samples 1 to 6 68
Figure 25: Sample 1 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively 73
Figure 26: Sample 2 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively 74
Figure 27: Sample 3 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively 75
Figure 28: Sample 4 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively 76
Figure 29: Sample 5 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively 77
Figure 30: Sample 6 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively 78
Figure 31: (a1), (a2) and (a3): Sample 1 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 1 EDS/EDX area 1 images respectively 81
Figure 32: (a1) and (a2): Sample 1 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 1 EDS/EDX area 1 images respectively 82

Figure 33: (a1), (a2) and (a3): Sample 2 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 2 EDS/EDX area 1 images respectively 83
Figure 34: (a1) and (a2): Sample 2 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 2 EDS/EDX area 1 images respectively 84
Figure 35: (a1), (a2) and (a3): Sample 3 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 3 EDS/EDX area 1 images respectively 85
Figure 36: (a1) and (a2): Sample 3 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 3 EDS/EDX area 1 images respectively 86
Figure 37: (a1), (a2) and (a3): Sample 4 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 4 EDS/EDX area 1 images respectively 87
Figure 38: (a1) and (a2): Sample 4 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 4 EDS/EDX area 1 images respectively 88
Figure 39: (a1), (a2) and (a3): Sample 5 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 5 EDS/EDX area 1 images respectively 89
Figure 40: (a1) and (a2): Sample 5 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 5 EDS/EDX area 1 images respectively 90
Figure 41: (a1), (a2) and (a3): Sample 6 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 6 EDS/EDX area 1 images respectively 91
Figure 42: (a1) and (a2): Sample 6 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 6 EDS/EDX area 1 images respectively 92

LIST OF TABLES

Table 1: Index properties of the soil and soil pH 36
Table 2: Maximum dry density* and optimum moisture content of lime treated six soil samples 39

LIST OF APPENDICES

Appendix A: Locality plans: Soil sampling 113
Appendix B: List of publications and conference proceedings 117
Appendix C: CBR penetration graphs 118
Appendix D: SEM, EDS/EDX micrographs…………………………………..…..148
Appendix E: Editing certificate……………………………………………………..178

LIST OF EQUATIONS

Equation 1: $Ca(OH)_2 + SiO_2 = CaO\text{-}SiO_2\text{-}H_2O$……………………………………………...4

Equation 2: $Ca(OH)_2 + Al_2O_3 = CaO\text{-}Al_2O_3\text{-}H_2O$………………………………………..……4

Equation 3: $CaCO_3 + \text{Heat} \rightarrow CaO + CO_2$………………………………………..………..18

Equation 4: $CaO + H_2O \rightarrow Ca\,(OH)_2 + \text{Heat}$……………………………………..……..18

Equation 5: $CaO + H_2O \rightarrow Ca\,(OH)_2$…………………………………………………….…20

Equation 6: $Ca(OH)_2 \rightarrow C + 2(OH)^{-}$………..……………………………………………20

Equation 7: $C+2(OH)^{-} + SiO_2 \rightarrow$ CSH silica gel………………………………………...20

Equation 8: $C+2(OH)^{-} + Al2O_3 \rightarrow$ CAH alumina gel…………………………………...20

LIST OF ABBREVIATIONS

CBR- California Bearing Ratio

CKD-Cement Kiln Dust

EKG- Electro Kinetic Geosynthetics

EKS- Electro-Kinetic Stabilisation

LKD- Lime Kiln Dust

MDD- Maximum Dry Density

OMC- Optimum Moisture Content

SEM- Scanning Electron Microscopy

TMH1- Technical Methods for Highways Part 1

UCS- Unconfined Compressive Strength

USCS- The Unified Soils Classification System

CHAPTER 1

INTRODUCTION

1.1 Background of the study

When geotechnical engineers design structures, the designs are based on the assumption that specified quality will be achieved for each soil layer below the structure. This is achieved by ensuring that each layer of soil resists shearing within the layer, avoids excessive elastic deformations that result in fatigue cracking within the layer or the overlaying layer and is prevented from excessive permanent deformation through densification properties (Jawad *et al*., 2014). When the quality of each of the soil layers is increased, the overall ability of the soil to distribute the load over a greater area is generally increased enough to permit a reduction in the required thickness of the soil and surface layers. There are many methods that may be adopted in order to achieve this quality (Azadegan, Jafari and Li, 2012). One of the methods entails the application of lime to soil using the soil stabilisation process.

Soil stabilisation is the alteration of soil to enhance its geotechnical properties. These properties include particle size distribution, plasticity and liquid limit, linear shrinkage, Optimum Moisture Content (OMC), Maximum Dry Density (MDD), California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS) of the soil samples (Miles and Brown, 2003).

Zwissler, Oommen and Vitton (2014), define soil stabilisation (including lime-soil stabilisation) as the process of maximising the suitability of soil for a given construction. Through the use of lime for soil stabilisation purposes, soil is treated to varying degrees, dependent upon the objective of the stabilisation. This varies by project. In South Africa, construction projects normally utilise lime for road pavement soil stabilisation or building structures. The long-term performance of these road pavement structures or building structures is significantly affected by the stability of the underlying soil layers. The underlying layers of the soil alone may not provide the support required to achieve an acceptable performance due to a number of factors. Stabilisation of soil using lime is a globally recognised method utilised to improve strength and durability properties of the soil. This research studied the use of various proportions of lime to stabilise soil in order to improve the strength properties of different soil samples of different pH ranges with diverse mineralogical and microstructural composition. There is a paucity of research output on this topic, particularly regarding the impact of lime on the variation of soil geotechnical properties of different soil samples of different pH ranges. The scope of previous studies on lime soil stabilisation has mainly been based on (but not limited to) the type of stabiliser used to stabilise soil, the specific type of soil to be stabilised, recommended soil stabilisation practices and design procedures for lime soil stabilisation (Little, 1995).

In conducting the research, the researchers' primary aim was to investigate and analyse the impact of lime variations within defined geotechnical properties and different pH ranges. For this research, approximately 3900 kg of soil was collected for laboratory testing purposes. The series of laboratory tests conducted included particle size distribution, Atterberg limits, OMC, MDD, curing/soaking, CBR and UCS tests. These tests were all done in compliance with the Technical Methods for Highways Part 1 (TMH1) of South Africa, with particular emphasis on methods A1, A2, A3, A4, A7, A9 and A14 (Department of Transport , 1986a). Also used for the research was Chapter 3 of the South African National Roads Agency's (SANRAL's) materials testing manual for South African pavements (South African National Roads Agency[SANRAL)], 2013). Mineralogical tests were also conducted, by applying x-ray diffraction (X-RD) and scanning electron microscopy (SEM) for better understanding of the microstructure of soil samples. The reason for the mineralogical tests was to enhance the interpretation of the physical behaviour of the soil samples.

This chapter provides an overview of lime-soil stabilisation processes and practices used globally, particularly in the construction and maintenance of a broadly diverse range of structures.

Before commencing the topic of soil stabilisation (using lime as the stabilising agent), it may be helpful to review the basics of soil stabilisation. A brief description of the history and the evolution of several associated concepts are therefore offered in the following sub-section.

1.2 History and evolution of lime-soil stabilisation

The necessity of improving the geotechnical properties of soil has been recognised for as long as construction has existed. Many ancient cultures, including the Chinese, Romans and Incas, utilised various techniques to improve soil stability. Some of these were so effective that many of the buildings and roadways they constructed still stand to this day (Zwissler, Oommen and Vitton, 2014).

The modern era of soil stabilisation began in the United States during the 1960s with noticeable growth despite general shortages of aggregate and petroleum resources. These were poor economic times and there were some major global market disruptions. Soil stabilisation then fell out of favour, mainly due to faulty application techniques and misunderstandings. More recently, soil stabilisation has once again become a favoured practice.

In South Africa, various innovative green soil stabilisation products have been formulated, particularly for pavement layers (Imbabi, Carrigan, and McKenna, 2012). These products have environmentally friendly formulations that utilise less non-renewable materials. They create less greenhouse gas in their manufacturing process and reduce the need for landfill sites.

1.3 Lime-soil stabilisation

Almost all construction is built with or upon soil. For many years it has been common practice that when unsuitable construction conditions are encountered one of the following options becomes a solution to overcome the impact of unstable soil. These include (but are not limited to) the following:

- Finding new construction sites.
- Redesigning of structures by design engineers so that they can be constructed on poor soil.
- Removing of poor soil and replacing it with good soil.
- Improving the geotechnical properties of the soil.

Cravens *et al*. (2006) write that finding new construction sites and redesigning a structure so that it can be constructed on poor soil after considering the alternatives can prove to be impractical. As a consequence, there have recently been more improvements in technology. Removal of top soil and replacement with good soil is the most commonly adopted modern strategy. However due to further new technological innovations and inventions, more recently the focus has been mainly on improving the soil’s geotechnical properties. This is either *in situ* or using imported soil.

Modern improved soil geotechnical properties are achieved through the process of soil stabilisation using many additives with lime being just one of them.

Lime, for lime stabilisation, is one of the additives widely used in stabilisation of fine grained soil. Various forms of lime such as hydrated high-calcium lime ($Ca\ (OH)_2$), monohydrated dolomitic lime ($Ca(OH)_2$–MgO), and dolomitic quicklime (CaO-MgO) have been successfully utilised for stabilisation for many years. One of the family compounds (quicklime [Calcium Oxide]), is delivered in the form of coarse-grained powder. It reacts quickly with water producing hydrated or slaked lime, generating heat and volume change as illustrated by the following chemical formula: ($CaO+H_2O= Ca(OH)_2$ + 65.3kj/mol. It contributes to the strength of soil by enabling the creation of cementation between soil particles.

1.3.1 Chemical reactions in lime treated soil

As pointed by Jawad *et al*. (2014), several reactions occur when lime is added to soil in the presence of water. The reactions are termed cation exchange, flocculation-agglomeration, carbonation, and pozzolanic reaction. Cation exchange and flocculation-agglomeration reactions occur immediately after mixing. These reactions cause immediate changes in the strength, plasticity index, and workability of soil (Ika Putra, 2014). Carbonation is a reaction of carbon dioxide with lime in open air or voids in the soil. The process forms a relatively weak cementing agent (Hall, Najim and Keikhaei Dehdezi, 2012). Cementation caused by carbonation on a soil surface results in a rapid initial increase in strength. Pozzolanic reaction occurs between lime, silica and alumina – particularly in clay – and produces cementing material including calcium-silicate-hydrates and calcium alumina hydrates (Little, 1995). In the long term pozzolanic reactions result in the solidification of the soil as can be shown by Equations 1 and 2:

$Ca\ (OH)_2 + SiO_2 = CaO\text{-}SiO_2\text{-}H_2O$ Equation 1

Calcium hydroxide + Silicon dioxide = Calcium oxide –Silicon dioxide – water

$Ca\ (OH)_2 + Al_2O_3 = CaO\text{-}Al_2O_3\text{-}H_2O$ Equation 2

Calcium hydroxide + Aluminium oxide = Calcium oxide – Aluminium oxide – water

1.4 The problem statement

The optimum functioning of the soil is impacted by the physical, chemical and microstructural properties it possesses. One of the chemical properties of soil is the degree of acidity and alkalinity, that is to say, pH. The pH of soil can be interpreted in many ways. According to Addy, Green and Herron, (2004), the pH of soil is the measure of acidity or alkalinity in the soil resulting from the substances constituting the soil. Soil pH is one of the most common analyses of soil and is measured on a scale of 0-14.

This research was largely and primarily inspired by the use of lime variations to stabilise soil in order to improve the geotechnical properties of various soil types of different pH levels. Further to this, the research is influenced by limited academic writing on the topic. One of the reasons for the latter relates to soil pH being a chemical property which is mainly associated with agricultural or crop production and not with the structural stability of the soil (McCall, 1980; Haynes and Naidu, 1998; McCauley, Jones and Jacobsen, 2009). The above mentioned on its own (if not considered) may have implications in designs of structures, structural stability or integrity, the optimal resource utilisation and even environmental degradation.

For an example, if not documented and addressed, the paucity of information might pose problems in structural stability and integrity both short and long term of soil since other soils are salt affected, that’s all due to chemical composition, with soil pH being one of the components. Soils of salt–affected due to chemical composition may contain elevated concentrations of potassium and/or magnesium, which may affect the levels of soluble and exchangeable cations, and lead to soil structural deterioration due to clay dispersion and swelling, hence the problems in designs on soils, problems in structural stability or integrity and even environmental degradation.

If not documented and addressed, the paucity of information might pose problems on optimal resource utilisation since certain areas of soil of poor quality can be found when constructing structures not only due to geotechnical properties but also due to chemical properties (e.g. soil pH). In order to build on it, the soil must be altered. This can be done by means of stabilization or modification of the soil or one can replace the poor quality soil with good quality soil. This soil improvements or replacement of the soil might have an impact on the construction cost therefore one should consider various options like the cost of stabilization versus the replacement of the poor quality soil.

1.4.1 Previous research work

Over recent years, many studies have been conducted on lime-soil stabilisation. However, very few comment on soil pH in relation to the effective stabilisation of soil. The scope of previous studies on stabilisation has mainly been based on the types of stabiliser used to stabilise soil, the specific type of soil to be stabilised, recommended soil stabilisation practices and design procedures for soil-lime stabilisation (McCall, 1980; Novak and Bandak, 1994; Al-Mukhtar, Khattab and Alcover, 2012; Salem, El-Kady and Abd-Elbaset, 2016). Most published research exploring and commenting on soil properties when trying to modify the soil's geotechnical properties or chemical and physical parameters do not contain in-depth information on the role that the soil's pH has on the stabilisation or modification of the chemical or physical parameters.

1.5 Main aim of the study

The main aim of this study was to investigate the impact variations in lime concentration have on the geotechnical properties of various soil samples of different pH ranges. This research will assist in ascertaining whether the variations in the concentration of lime impacts on soil, either positively or negatively, taking into consideration the pH of the soil treated.

This aim of the research was achieved through the adoption of five specific objectives, namely:

1. To identify acidic and alkaline soil by means of conducting soil tests. The study utilised field and in-house pH testing equipment.
2. To determine the geotechnical properties of the different lime-soil-mixtures. These were particle size distribution, plastic and liquid limit of the samples, linear shrinkage, Optimum Moisture Content (OMC), Maximum Dry Density (MDD), California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS).
3. To determine the different lime-soil-mixtures for mineralogical and microscopic properties. These were done using x-ray diffraction (X-RD) and scanning electron microscopy (SEM) and EDS/EDX.

4. To evaluate and rate the strength development of lime-soil-mixtures and quantify the impact of lime concentration variations for soil samples of different pH readings considering soil stabilisation.
5. To develop an effective remedial or improvement strategy in terms of recommendations to be implemented so as contribute to the current practices used to stabilise soil.

1.6 Study scope and delimitations

In engineering terms, soil stabilisation is a generic term for any physical, chemical, biological, or combined method(s) of changing natural soil to meet an engineering purpose. Several methods of improving the behaviour of soil exist. These include thermal, mechanical, electrical and chemical methods. The chemical method of stabilising soil uses agents such as fly ash, bitumen and lime. This is not an exhaustive list and there are other agents. For this research, particular emphasis was placed on the chemical form of stabilising soil, particularly considering the use of lime. The lime used in this research was hydrated lime. However, various other methods of stabilising soil are discussed in the literature review, with the intention of establishing a knowledge base for this study.

1.7 Importance of the study

The use of lime plays a crucial role in advancing the performance of the soil in many ways. From an engineering perspective, the long-term performance of any construction project depends on the soundness of the underlying soil. Weak and unstable soil can create significant problems to the road pavement layers and building structures built upon it. Structures must be built based on proper design and proper construction methods (National Lime Association, 2004).

In addition to the above, lime helps neutralise the acidity of soil. Lime is typically composed primarily of calcium carbonate. The application of carbonates is the preferred tool for raising low pH of soils, particularly in farm fields. One main factor determining the speed of neutralisation of the soil is the volume of carbonates in the material and the speed of the reaction of the carbonates to neutralise the soil.

This research is important in that, on completion, the principal researcher seeks to use the experimental data, analyses, interpretations, conclusions and recommendations to contribute towards the current practices adopted to stabilise soil of different pH ranges. It is also believed that the results can assist construction contractors in developing project bids, planning jobs, and conducting construction activities. Besides these uses, the study has relevance for engineers preparing lime stabilisation construction specifications, project inspectors and for civil engineering students studying in the geotechnical engineering or construction material fields.

1.8 Brief description of the research design

1.8.1 Research methodology

The research undertaken used a quantitative research methodology, conducted in an indoor laboratory setting. The data was collected from lime-treated soil samples with the intention of measuring variables involving soil stabilisation, taking into account the impact of soil pH.

1.8.2 Instruments used in the creation of data

By virtue of this largely being quantitative research, the creation of data was through laboratory experiments using specific apparatus. The experiment was conducted in a laboratory facility with specified controlled conditions.

Scientific instruments in the form of equipment and apparatus were used to conduct the experiments. The equipment included the following: sieve shaker, liquid limit device apparatus, plastic limit device apparatus, linear shrinkage trough apparatus, mechanical compacting machine, curing tanks, CBR penetration machine and thermostatic ovens. These instruments were used for scientific measurements as they were specifically designed and constructed for this purpose.

1.8.3 Brief procedure of the research methodology

The research methodology entailed the collection of numerical data derived form of soil samples, the objective being to quantify and measure the impact of lime variations on soil strength. In achieving the objectives of the research, and to carry out the methodology successfully, soil samples from various locations were collected. A series of soil laboratory tests were performed. These included pH tests, particle size distribution, plastic and liquid limit, linear shrinkage, OMC, MDD, curing, soaking, CBR, UCS.X-RD and SEM and EDS/EDX tests were also conducted.

1.9 Structure of the dissertation

The dissertation has been divided into five chapters which are summarised below.

Chapter 1: Introduction

The chapter deals mainly with the rational background, problem statement, objectives of the dissertation and scope of the research methodology as well as the structure of the research. The chapter gives a preview as to how the study was designed and sets out significant points of the research dissertation.

Chapter 2: Literature review

The chapter reviews the relevant literature and recent published work relating to the research topic. Substantive findings are reviewed as well as theoretical and methodological contributions.

Chapter 3: Research materials, equipment and methodology

Materials, equipment used and the methodologies adopted are described in this chapter. The chapter presents detailed procedures of all laboratory tests conducted to achieve the objectives of the research and discusses their limits and accuracy.

Chapter 4: Results and discussion

The analysis of the test results in the form of tables and figures are presented in this chapter. The chapter presents the results of all experimental work performed on raw and lime soil samples, and discusses the results.

Chapter 5: Conclusion and recommendations

The conclusion of the research and recommendations are provided in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction: Soil stabilisation in general

The concept of soil stabilisation dates back 5000 years. McDowell *et al*. (1959) reported that stabilised earth roads were utilised in ancient Mesopotamia and Egypt. The Greeks and the Romans utilised lime-soil mixtures to improve the strength of soil (Liu, Pemberton and Indraratna, 2010). Kézdi (1979) mentioned that the first experiments on soil stabilisation were conducted in the United States of America (USA) with sand or clay mixtures around 1906. In the 20th century, especially in the thirties, soil stabilisation relevant to road construction was applied in Europe. Vosteen, and Schellschmidt, (2003) and Otoko and Precious, (2014) reported that in Germany the utilisation of lime or cement for the stabilisation of pavement bases was investigated and developed into practical construction procedures. In South Africa, lime has many uses, with the main applications being treatment associated with the gold, uranium, iron, steel, water treatment, agriculture and soil stabilisation (Douglas, 1969).

This chapter summarises available literature, recent works and information pertaining to the use of lime for soil stabilisation. The chapter presents a literature review which is an examination of and comment on the existing written knowledge-base and includes substantive findings as well as theoretical and methodological contributions. Initially the study examines literature on the phenomenon of soil stabilisation, and thereafter focusses on the chemical stabilisation of soil, using lime as the primary soil stabilising agent. The information presented in this review has been obtained solely from materials published in English or translated into English. The intention is that this review will serve to both guide and stimulate further investigations into the concept of soil stabilisation, particularly by means of lime treatment.

In this chapter, literature from a number of scientific and engineering disciplines has been investigated. These disciplines include soil mechanics, geology, mineralogy, soil physics and soil chemistry.

Over the years, engineers, particularly geotechnical engineers, have tried different methods to stabilise soil that is subject to fluctuations in strength and stiffness properties. These properties are a function of fluctuations in moisture content (Little, 1995). Generally, soil stabilisation is achieved by thermal, mechanical, electrical or chemical methods (Little, 1995). For completeness, the above mentioned methods of stabilisation are briefly discussed below with the intention of providing a broad understanding of the mechanism of soil stabilisation as a whole.

In general:

- Thermal soil stabilisation can be described as the method of burning soil particles (normally at 600°C) with the intention of dehydrating and fusing soil particles (Kulkarni, 1975; Bayasan *et al*., 2008).
- Mechanical soil stabilisation includes compaction, fibrous and other non-biodegradable reinforcement of geo materials to improve the strength of soil (Jones, Lamont-Black and Glendinning, 2011; White *et al*., 2013).
- Electrical soil stabilisation entails the application of direct electrical current to the soil (Kestler, 2009).
- Chemical soil stabilisation relates to the method of improving the soils' strength properties, achieved by mixing chemicals such as cement, fly ash, bitumen, lime or a combination of these materials with soil to form a strong composite material (Kestler, 2009).

The geotechnical properties of problematic, weak, soft fine-grained, expansive soil or soil not suitable for construction purposes can be improved by applying any of the abovementioned methods, after due consideration of the applicability of each process. Each method depends on the availability of materials, method preference, weather, specifications and other influences, to improve and treat the geotechnical properties of the soil.

2.2 Thermal soil stabilisation

The most common methods for improving the geotechnical properties of soil are the addition of cement, lime, bitumen and combinations of stabilising agents. However, in permafrost areas, the most common method is thermal soil stabilisation. This method includes freezing of thawed soil and cooling of permafrost. It is known for its effectiveness in providing stable support for buildings and structures in cold permafrost regions (Bayasan *et al*., 2008). Permafrost regions are defined as perennially frozen ground remaining at or below 0°C for a year or more (Munroe *et al*., 2007).

Thermal soil stabilisation is derived from heating and freezing of soil particles to achieve the desired purposes (Kulkarni, 1975; Filimonov and Vaganova, 2013). The necessity for using the method is mostly brought about by adverse climate conditions in cold regions which can create many problems during building construction. Due to the natural resources that are now being extensively exploited, many settlements and industrial facilities are being built on permafrost in regions such as Russia, Serbia and others.

In South Africa, such a method, particularly for road construction is impractical. This is due to the weather patterns in most regions of the country, skills associated with the usage of the method as well as the availability of resources.

2.3 Mechanical soil stabilisation

In mechanical soil stabilisation, different categories of soil are mixed together. These are used as aggregates and binders; the aggregates being sand and gravel with the binders being clay and silty soil. When these are mixed to the desired composition, a soil composite stratum showing the required cohesion and friction is obtained. This becomes mechanically stable when properly placed and compacted. The method relies heavily on physical processes to stabilise the soil (Jones *et al*., 2011; White *et al*., 2013).

With mechanical soil stabilisation, soil is rolled to lower the volume, thus increasing the density. This is done through the application of heavy machinery in order to improve the grading or decrease the plasticity of the original material. Machines such as large soil compactors with vibrating steel drums are often used for this purpose. However, over-compaction of soil by machinery is a danger and should be given careful consideration. Over compaction leads to aggregates getting crushed in which case the soil loses its desired geotechnical properties.

2.4 Electrical soil stabilisation

In recent years, major settling or tilting of buildings, bridges, pavement layers and road embankments as well as the instability of some dam walls have occurred in various parts of the world. Many attempts have been made to mitigate such adverse changes (Tajudin and Azhar, 2012). Typical methods of stabilising soil (i.e. thermal, mechanical and chemical stabilisation) are not generally suitable for stabilising soil beneath existing structures, hence the development of Electrokinetic Soil Stabilising (EKS) (Shrestha *et al*., 2016).

There are several definitions of EKS (Gray and Schlocker, 1969; Eid *et al*., 2000; Castillo, García-Delgadob and Rivero, 2012; Tajudin and Azhar, 2012; Jayasekera, 2015). Panjaitan *et al*. (2012) define EKS as a process in which the provision of an electric potential causes an electric current to move between two electrodes embedded in a medium. Alternatively, EKS can be defined as a process that separates and extracts heavy metals, radionuclides and organic contaminants from saturated or partially saturated soil, sludge, and sediments (Shenbagavalli and Mahimairaja, 2010). In general, EKS relates to the application of direct current to soil using electrodes with the intention of improving the soil strength through dewatering and consolidation (Tajudin and Azhar, 2012).

The first EKS phenomenon was observed at the beginning of the 19th century, when Reuss applied a direct current to a clay and water mixture (Linsha and Praseeja, 2015). However, scientists Helmholtz and Smoluchowski were the first to propose a theory dealing with the electro-osmotic velocity of a fluid and zeta potential under an imposed electric gradient (Wall, 2010; Azhar *et al.*, 2017).

2.5 Chemical soil stabilisation

One method of improving the geotechnical properties of soil is by the addition of chemicals. The necessity for chemical soil stabilisation may be a result of in-situ subgrades which often do not provide the support required to achieve acceptable soil performance under traffic loading, and for other environmental reasons.

Chemical soil stabilisation has been described as the alteration of the soil's geotechnical properties by chemical means in order to enhance its engineering qualities (Jawad *et al*., 2014). The technique is generally cost effective. For example, the cost of transportation and processing of the stabilising agent or additive (such as lime) to treat an in-place soil material is often more economical than importing aggregate of the same thickness as the base course, particularly for road construction activities.

In South Africa, the stabilisation of highways and other pavement soil layers is a very widely adopted process. Diverse recommendations and standards for highway series exist. In particular there is TRH13: Cementitious stabilisers in road construction (Department of Transport, 1986b), and TRH14: Guidelines for road construction materials (Department of Transport, 1986c), and TRH4: Structural design of flexible pavements for interurban and rural roads (Department of Transport, 1996c).

Chemical soil stabilisation has been used for many centuries (Holt, 2010). The Romans were one of the first societies to utilise a chemical soil stabilisation method. During that time weak soil was mixed with pozzolana (volcanic ash containing alumina and silica) and lime to improve its bearing capacity. This ultimately led to modern day treatment of soil which started in the late 1950s in the United States of America, where weak clay soil was treated with hydrated lime. The development and improvement of construction methods since the 1950s has seen significant use of the method globally. The United States of America, France, Australia, New Zealand, South Africa, the United Kingdom, Germany and Sweden are just some of the countries using the method.

Better quality soil is produced when chemical soil stabilisation is used compared to other methods. Manette, Oyawa and Nyomboi (2014) assessed the changes in soil when stabilised with lime. Findings of their study revealed one or more of the following effects and benefits:

- Increase in strength;
- Reduction in soil permeability;
- Increase in the durability of the soils; and
- Less shrinkage and expansion.

Chemical soil stabilising agents are broadly divided into three groups: by-products soil stabilisers, non-traditional soil stabilisers and traditional soil stabilisers (Dhanoa, Chopra and Pathak, 2014), and are discussed below.

2.5.1 By-products soil stabilisers

Among soil stabilising agents derived from by-products normally utilised for soil stabilisation, lime kiln dust (LKD) and cement kiln dust (CKD) are prominent. These are by-products resulting respectively from the production of lime and cement. The properties of these by-products depend primarily on the source of the materials and the production process of the materials (Jones *et al*., 2011).

Little (1995) writes that LKD products contain 30 % to 40 % lime, while CKD generally contains between about 30 % to 40 % of calcium oxide and about 20 % to 25 % pozzolanic material. This indicates that when soil is stabilised with either one of the above by-products, the strength varies depending, amongst other factors, on the behaviour of the soil as a result of content of the stabiliser, as opposed to the soil being stabilised with the original soil agents. Besides being utilised for construction related works, by-products used in soil stabilisation have other applications. This includes agriculture and waste stabilisation.

2.5.2 Non-traditional soil stabilisers

A variety of non-traditional soil and aggregate stabilisers are presently available on the market. Non-traditional soil stabilisation additives are commercially available chemical and liquid agents designed to enhance the properties of materials such as soil. These products are diverse in their composition and the manner in which they interact with soil.

Kestler (2009) details guidelines relating to the selection of aggregate and native-surfaced low-volume roads and points out that the market is becoming increasingly populated by alternative non-traditional stabilisation products. These include, for example, concentrated liquid stabilisers and waste by-products. This is because most traditional chemical stabilising agents requite lengthy cure times and large quantities of additive required to attain the desired strength. This is also because of the adverse chemical reactions found in a few traditional chemical stabilising agents.

The non-traditional stabilisers can be grouped into eight categories:

1. Chlorides (chlorides, salts, calcium chloride, magnesium chloride, sodium chloride) (Monlux and Mitchell, 2006; Abood, Kasa and Chik, 2007).
2. Clay additives (filler, bentonite, montmorillonite).

3. Electrolyte emulsions (electrolyte stabilisers, ionic stabilisers, electrochemical stabilisers, acids) (Lim *et al*., 2014).
4. Enzymatic emulsions (enzymatic emulsions, enzymes) (Stan and Ciobanu, 2012).
5. Lignosulfonates (lignosulfonates, lignin, lignin sulphate, lignin sulphides) (Vinod, Mahamud and Indraratna, 2012).
6. Synthetic-polymer emulsions (synthetic-polymer emulsions, polyvinyl acetate, and vinyl acrylic) (Orts *et al*., 2007).
7. Tree-resin emulsions (tree-resin emulsions, tall-oil emulsions, pine-tar emulsions) (Lim *et al*., 2014).
8. Ionic soil stabilisers (a water soluble chemical used in the construction of all types of road utilising in-situ materials) (Alhassan and Olaniyi, 2013).

Abood, Kasa and Chik (2007), point out that one of the benefits of adding one of the above non-traditional soil stabilising agents is an improvement in the strength of the soil. The authors conducted a study to investigate the effect of adding different chloride compounds. Findings revealed that an increase in the percentage of each of the chloride compounds resulted in an increase in the maximum dry density and decrease in the optimum moisture content and the unconfined compressive strength.

Mgangira (2009) examined the identification of the effects of enzymes on soil using a laboratory experiment. The findings of their study were that the unconfined compressive strength results showed mixed effects on the soil strength. There was approximately a 50 % increase in strength when the concentration level of the two enzyme-based stabilisers was increased and the soil aged after treatment. The evaluation was made after the samples were left to cure in plastic bags for 7, 14 and 28 days.

Rauch, Katz and Liljestrand (2003) conducted a study to evaluate non-traditional soil and aggregate stabilisers using proprietary chemical products. The researchers found that the ionic soil stabiliser showed no significant changes in clay mineralogy. However, they did list certain positive effects of such agents, including:

- The experimental results entailing the enzyme stabiliser identified polyethylene glycol as the principal ingredient to be used as a protein/enzyme deactivator.

- Clay treated with the high application ratios of enzyme soil stabiliser experienced interlayer expansion.

Tingle *et al*. (2004) argue that many of these non-traditional soil stabilisation agents are relatively immature, and little is known regarding their interaction with geotechnical materials and their fundamental stabilisation mechanisms. Hence more future research work is required to understand them better, particularly in the context of road soil stabilisation.

2.5.3 Traditional soil stabilisers

Traditional stabilisers generally rely on pozzolanic reactions to modify or stabilise soil (Aprile and Lorandi, 2012). Among the traditional stabilisers, lime and cement are the most routinely utilised. Flexible pavements are a popular construction method in many parts of South Africa. These are mostly layers of soil stabilised using either lime or cement, particularly lime. For example, more than 80 % of the pavements in Gauteng province and surrounding provinces (KwaZulu Natal, Free State, Mpumalanga, North West, Western Cape, Northern Cape, Eastern Cape and Limpopo) are constructed using this type of construction (Ventura, 2003). This dissertation constantly refers to lime as the preferred method of improving the geotechnical properties in most parts of the world, including South Africa. This is not only considering its performance when mixed with moist soil, but also because it is a material that can perform many functions at a reasonable cost.

2.5.4. Lime

The history of the utilisation of lime dates back many years. The earliest archaeological evidence for lime burning is a kiln found in Mesopotamia dating 2450 BC (National Lime Association, 2004). Initially lime was utilised worldwide for masonry and plaster work. This continued until the end of the 19th century, thereafter other stabilisers were developed. Today, lime is utilised widely for soil stabilisation, particularly for road construction throughout the world (Little, 1995).

Lime is a material that is reactive in the presence of moisture and is created from limestone. Lime, as referred to in this dissertation, comes in many configurations and different authors define it in different ways, depending on the requirements and intended final use of the product (National Lime Association, 2004; Schwab *et al.*; Hall, Najim and Dehdezi, 2012). The limestone with which we are concerned can be defined briefly as any rock constituted mostly of calcium carbonate ($CaCO_3$). These rocks are composed of more than 50 % carbonate minerals, generally the minerals calcite (pure $CaCO_3$) or dolomite (calcium-magnesium carbonate, CaMg [CO3]2) or both. Their intended use is the forming of hydrated lime, quicklime or lime slurry.

2.5.4.1 Production process of lime

Companies such as Idwala Lime, Pretoria Portland Cement, and PBD Lime in South Africa are, responsible for the production of lime. The process includes mining, crushing, screening, burning, and milling. The common final products emanating from the production of lime are hydrated lime, quicklime and lime slurry (calcium hydroxide). The derivation of many different varieties of lime is very complex and requires that high purity limestone be used during production. In this document, the term limestone covers any rock consisting mostly of calcium carbonate. The composition of these rocks is approximately 50 % carbonate minerals, with calcite or dolomite being the most common minerals. The process of transforming limestone to lime follows a carefully planned and well controlled process which consists of four sub-processes, namely, quarrying or mining, stone preparation, calcining and hydration (Little, 1995). During the manufacturing process, heating limestone at elevated temperatures produces quicklime. Figure 1 and Equation 3 make reference to the above. The latter (i.e. equation) specifies that, limestone is heated to produce quicklime with carbon dioxide produced as a by-product.

$$CaCO_3 + \text{Heat} \rightarrow CaO + CO_2 \qquad \text{Equation 3}$$

Calcium carbonate + heat → Calcium oxide + Carbon dioxide

Hydrated lime primarily and extensively is used for road construction (Parsons, Kneebone and Milburn, 2004). The formation follows a hydration process which transforms quicklime into hydrated lime. Equation 4 indicates that when water is added to quicklime, hydrated lime is produced with the creation of heat as a by-product.

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat} \qquad \text{Equation 4}$$

Calcium oxide + water → Calcium hydroxide + heat

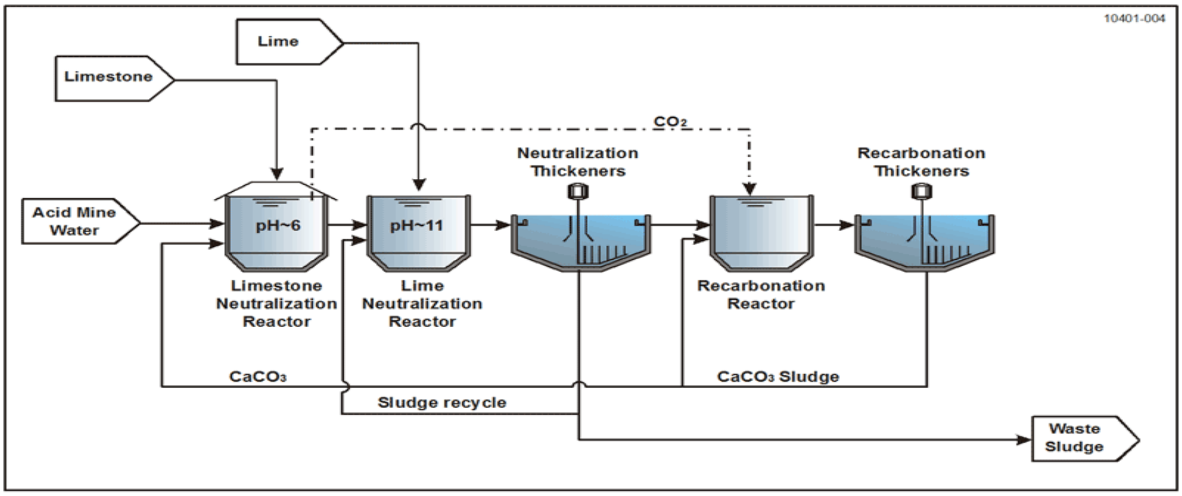


Figure 1: Flow chart of a vertical shaft kiln during the lime production process

Source: (National Lime Association, 2004)

2.5.4.2 Lime-soil stabilisation

The term lime-soil stabilisation applies primarily when lime is introduced to soil that is reactive and this creates long-term strength development through pozzolanic reaction (National Lime Association, 2004). The reaction produces stable calcium silicate hydrates and calcium aluminium hydrates when calcium from the lime reacts with the aluminates and silicates solubilised from the clay. For short term purposes, lime is also the perfect medium for the modification of the geotechnical properties of the soil, with short term benefits achieved through compaction. Lime helps to dry out wet areas, bridge across underlying spongy sub soil, and provide working platforms for the subsequent construction (Little, 1995). Although the lime modification process is primarily aimed at construction expediency, additional effects such as long-term improvement of stiffness or strengthening by pozzolanic and carbonation cementation reactions can be expected (Jung & Bobet 2008).

2.5.4.3 Chemistry of lime-soil stabilisation

The technique of soil stabilisation utilising lime, particularly hydrated lime, can be broadly classified into four different processes. These are referred to as lime-soil stabilisation reactions or lime-soil chemistry (Jawad *et al*., 2014). Lime-soil reactions are complex and entail primarily, secondary and tertiary process. These reactions are: cation exchange, flocculation and agglomeration, lime carbonation, and pozzolanic reaction (Aprile and Lorandi 2012; Mallela, Quintus and Smith, 2004).

According to Aldaood, Bouasker and Al-Mukhtar (2014a), the principal chemical reactions that take place during lime-soil stabilisation can be summarised by the following chemical reaction equations (Equations 5 to 8):

$CaO + H_2O \rightarrow Ca\ (OH)_2$ Equation 5

Calcium oxide + water → Calcium hydroxide

$Ca(OH)_2 \rightarrow C + 2(OH)^{-}$ Equation 6

Calcium hydroxide → Carbon + hydroxide

$C+2(OH)^{-} + SiO_2 \rightarrow$ CSH silica gel Equation 7

Carbon + hydroxide + Silicon dioxide → Calcium silicate hydrate

$C+2(OH)^{-} + Al2O_3 \rightarrow$ CAH alumina gel Equation 8

Carbon + hydroxide + Aluminium oxide → Calcium aluminate Hydrates

All four processes mentioned above are described in greater detailed below.

2.5.4.3.1 Cation exchange

Cation exchange includes the immediate reaction of soil with lime within a few minutes of mixing, resulting in soil with improved texture. Practically, all fine-grained soils display cation exchange and flocculation-agglomeration reactions when treated with lime in the presence of water. The reactions occur quite rapidly when the soil and lime are intimately mixed (Mallela, Quintus and Smith, 2004). According to Aldaood, Bouasker and Al-Mukhtar (2014b), this process relies upon the immediate interaction between the ions associated with the clay particles and the calcium ions of the lime. However, this proposal is opposite to the findings of the laboratory experimental study conducted by Akbulut and Arasan (2010) on the effects of four different additives. These concern the effect of added cement, lime, fly ash, and silica fume, on the cation exchange capacity, pH, zeta potential, and swelling pressure of three expansive soils. The test results indicated that the additives, lime, fly ash and silica fume, reduced the cation exchange capacity of the expansive soil.

2.5.4.3.2 Flocculation and agglomeration

The process, which is called flocculation and agglomeration, generally occurs in a matter of hours (Jawad *et al*., 2014). The addition of lime to a fine-grained soil causes flocculation and agglomeration of the clay fraction. These reactions result in an apparent change in texture, with the clay particles clumping together into larger sized aggregates (Roohbakhshan and Kalantari, 2013). Flocculation and agglomeration are affected by the increased electrolyte content of the pore water and also as a result of ion exchange from the clay to the calcium. The flocculated structure is stabilised through the rapid formation of tetra calcium aluminate hydrate cementing agents that bond the flocculated particles (Figure 2).

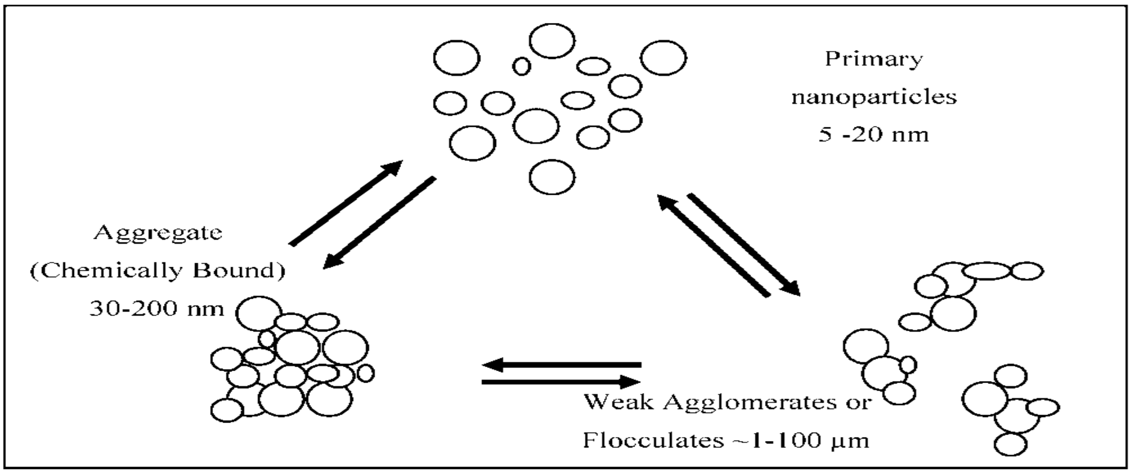


Figure 2: The schematic representation of the agglomeration process during lime-soil stabilisation

Source: (Egerton, 2014)

2.5.4.3.3 Lime carbonation

A number of problems relating to the loss of cementitious content in lime-stabilised soil, particularly due to carbonation, have been reported in South Africa (Netterberg and Paige-Green, 1984; Paige-Green, Netterberg and Sampson, 1990; Paige-Green, 2008). It must however be noted that carbonation is a global problem. The reaction is one of the chemical reactions taking place when lime is mixed with moist soil. As reported by Jung and Bobet (2008), the formation of calcium carbonate when lime stabilised soil is left in the open air is promoted by the phenomenon of carbonation. A carbonation reaction results in the change of calcium hydroxide into calcium carbonate. This is a result of the reaction between calcium hydroxide and atmospheric carbon dioxide gas (Cizer *et al*., 2006).

There have, however, been some initiatives in trying to curb the effects of carbonation. Paige-Green, Netterberg and Sampson (1990) and Paige-Green (2008) have published extensively on carbonation in relation to South African soil. These initiatives include keeping stabilised material as moist as possible, preventing carbonation by minimising the exposure of stabilised materials and improvement in construction practices. An example is compacting sooner with appropriate equipment to get higher soil density and lower permeability as well as improving curing procedures and operations (Paige-Green, Netterberg and Sampson, 1990). Some of the initiatives adopted include reviewing of designs and construction procedures to suit intended results.

2.5.4.3.4 Pozzolanic reactions

The addition of lime to soil promotes pozzolanic reactions and produces new minerals such as calcium aluminate hydrates (Al-Mukhtar, Lasledj and Alcover, 2010). The reactions between lime, water, soil silica and alumina constitute various cementing-type materials and are referred to as pozzolanic reactions (National Lime Association, 2004; Little, 1995; Aldaood, Bouasker and Al-Mukhtar, 2014b). These sources all state that lime-soil stabilisation is associated with the long term effect on the strength of the soil and are time and curing temperature dependant. This implies that the strength of the lime stabilised soil develops either positively or negatively gradually over a long period.

The chemical reactions in soil, both positive and negative, can continue for a very long period of time – even decades – as long as enough lime is present in the soil. This is because such reactions are functions of temperature, the quantity of calcium available, their pH value and the percentage of silica and alumina in the soil (Jawad *et al*., 2014).

The long-term behaviour of samples, as studied by Kavak and Baykal (2012), also supports the validity of the reaction. This study investigated the changes in the micro-fabric of long-term cured lime-stabilised kaolinite clay soil. The authors found that the unconfined compressive strength of lime-stabilised kaolinite increased continuously when compared to that of the natural kaolinite clay samples.

2.5.4.4 The effect of pH on lime-soil stabilisation

Soil science in the form of other properties such as pH is very relevant to soil stabilisation and road infrastructure. The effect of soil pH plays a crucial part in lime soil stabilisation as it depends upon the combination of the individual elements of soil forming factors. These include (amongst others) parent material, time, topography, organisms and climate.

During the use of lime for lime-soil stabilisation, the soil pH increases but possibly not in organic soils which are acidic, unless large and, possibly uneconomic, amounts of lime are added.

It has been reported that during lime soil stabilisation, when adequate quantities of lime and water are added, the pH of the soil quickly increases to above 10.5, which promotes the breakdown of clay particles in the soil structure (National Lime Association, 2004). Soil pH if not attended to, may indirectly present hazards to construction projects. One hazard can be in the form of acidity in the soil. Acidity increases the risk of corroding concrete and steel structures and road furniture or causing land degradation. The risks associated with acidity need to be identified and managed as part of project design, assessment, maintenance and management.

Biggs and Mahony (2004) report that as agricultural production increases, acidity also increases (through unbalanced nitrogen cycling), thus accelerating the corrosion of structures nearby.

From an agricultural perspective, a low pH is usually toxic for plants as this results in poor growth. Lime application raises the pH of the soil to 6 or 7 and also allows for the release of such elements as Mg, P and Mo for use by the plant. This implies that when the pH value increases, the high pH environment then causes a pozzolanic reaction between the free Ca+2 cations and the dissolved silica and alumina (Jawad *et al*., 2014). A high alkaline environment, with a pH greater than 12.4, needs to be maintained to enable the pozzolanic reactions to occur. During the reaction period, the silica and alumina that exist in the soil minerals become soluble and free from the soil when pH exceeds 12.4 (Jawad *et al*., 2014).

CHAPTER 3

RESEARCH MATERIALS, EQUIPMENT AND METHODOLOGY

This chapter describes the research materials, equipment and methodologies used by recounting the various procedures, schemes and algorithms for the research. These include theoretical procedures, experimental setup and approaches to the research.

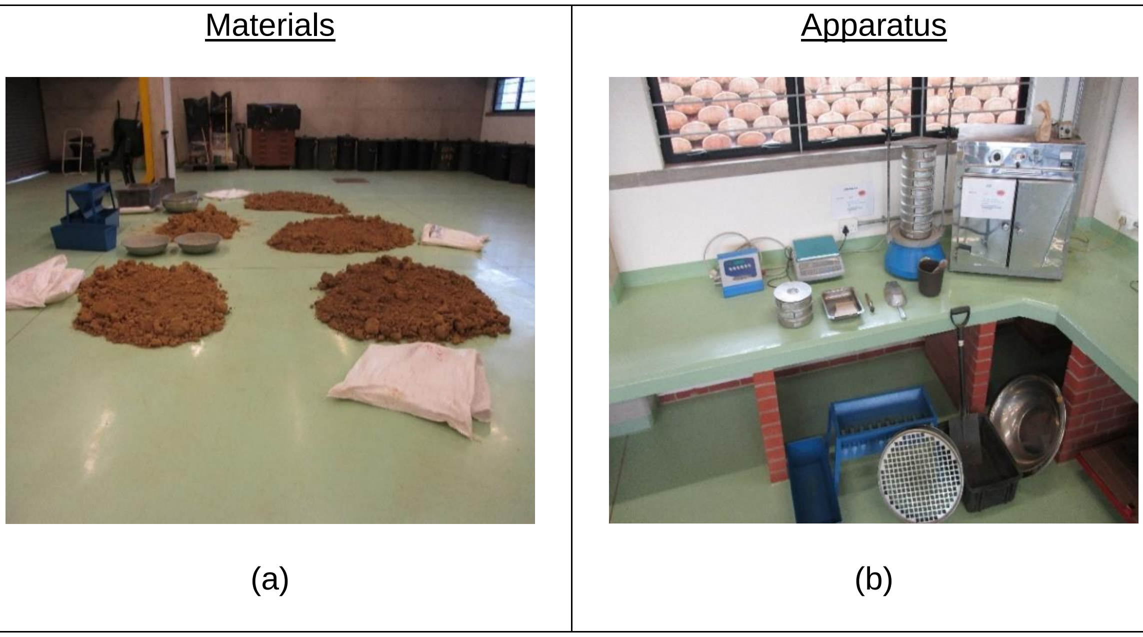
The overall objective of the study was to investigate the impact of addition of lime variations to the geotechnical properties of various soils of different pH ranges. The following laboratory tests were conducted for the research: sieve analysis, liquid limit, plastic limit, linear shrinkage, maximum dry density and optimum moisture content tests, soaking/curing, CBR penetration, and the UCS test. These tests were all done in compliance with the Technical Methods for Highways Part 1 (TMH1) of South Africa, with particular emphasis on methods A1, A2, A3, A4, A7, A9 and A14 (Department of Transport , 1986a). Other complimentary information was drawn from Chapter 3 of the SANRAL materials testing manual for South African pavements (SANRAL, 2013). Mineralogical tests were also conducted by applying X-RD and SEM, EDS/EDX for better understanding of the microstructure of soil samples so as to enhance the interpretation of their physical behaviour.

To avoid biasness results, random sampling process of the soil samples was adopted. With acidic soils normally found in areas of high rainfall, bags of naturally occurring acidic soil were collected from Umlazi, a township on the east coast of KwaZulu-Natal, South Africa, located south-west of Durban (29°58′S 30°53′E), Scottburgh is a coastal area situated on the mouth of the Mpambanyoni river (30°17′S 30°45′E), Amanzimtoti, (30°03′S 30°53′E, South of Durban in South Africa). The above mentioned areas have acidic soils, this is due rainfall, with average rainfall in these areas being 1009ml. For alkaline soil samples, bags of soil were sampled from Mkuze 27°37′S 32°02′E and Kwalini 28°53′18″S 31°26′54″E both situated in the northern part of the province of KwaZulu Natal in South Africa. Soil samples were taken at minimum adequate depths of 0.5metres, this by examining each soil horizon to that depth. The soil samples for laboratory analyses were typically air dried in preparation for receiving lime for the below stated laboratory tests. The current state or use of the above mentioned sites ranges from site quarries (for road pavements) to agricultural sites. Full details of research materials, equipment and methodologies are provided below.

3.1 Sieve analysis

3.1.1 Materials and equipment

Quantities of soil samples ranging between 1000 g to 2000 g for each of the six soil samples were selected for inclusion in sieve analysis tests. For each of the six soil selected samples, the following equipment was used: riffler with 25 mm openings, 450 mm diameter sieve with 19 mm openings, 530 mm diameter basin, iron mortar and pestle, plastic boxes, stainless steel pans, shovel, drying oven thermostatically capable of maintaining a temperature of 105 °C to 110 °C, scale capable of weighing up to 5 kg to an accuracy of within 1 g, mechanical sieve shaker, scoop, copper wire brush, paper bags and sieves of predetermined aperture sizes (63 mm, 53 mm, 37.5 mm, 26.5 mm, 19 mm, 13.2 mm, 4.75 mm, 2 mm and 0.425 mm). Materials and equipment are illustrated in Figures 3(a) to 3(b).



(a) (b)

Figure 3: (a) Soil particles being air dried prior to riffling and sieve analysis tests; (b) Apparatus utilised for riffling and sieve analysis test on soil

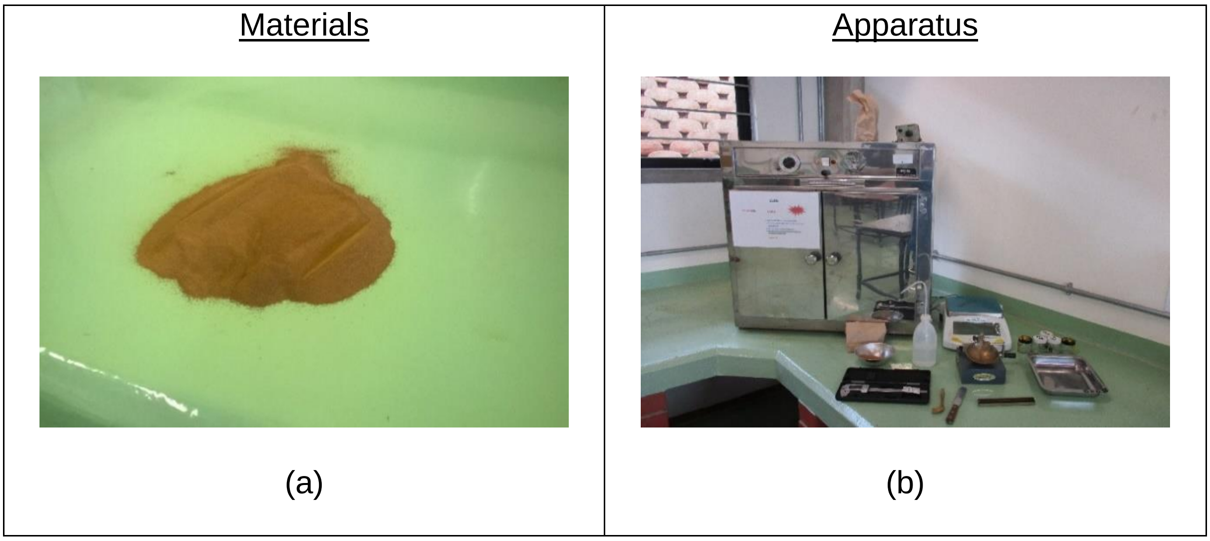
3.1.2 Methodology

The tests were performed with the aim of quantifying the different granular particles contained within the samples. The test started with pouring of soil samples of approximate range of 1000 g to 2000 g into the basin and sieving them through the 19 mm aperture sieve. Large soil aggregations and clods were retained in the process. These were disintegrated in the mortar with the pestle and were eventually added to the material after it passed through the 19 mm aperture sieve. The entire process was conducted so as to divide the soil into three smaller workable representative samples. These were then oven-dried overnight before being split into samples for the actual sieve analysis tests. This process was repeated for the other soil samples. Subsequent to oven drying, the three representative samples were sieved through a nest of sieves using the mechanical sieve shaker. The sieves were placed in order of aperture size: 63 mm, 53 mm, 37.5 mm, 26.5 mm, 19 mm, 13.2 mm, 4.75 mm, 2 mm and 0.425 mm. Subsequent to sieve analysis, the material retained on each sieve was weighed with its mass calculated and recorded.

3.2 Atterberg limits tests

3.2.1 Materials and equipment

For Atterberg limits, only 300 g of the 0.425 mm sieve size portions of oven-dried for each of the soil samples was used from the sieve separation test. The following equipment was used in conducting the Atterberg limits tests: liquid limit device, grooving tool, 100 mm dish, spatula 100 mm long and 20 mm wide, scale capable of weighing up to 3000 g capable of accuracy to within 0.01 g, thermostatically controlled drying-oven capable of maintaining a temperature of between 105 °C and 110 °C, plasticity index bottles, stainless steel pans, squeeze bottle with mixing water, shrinkage troughs, and Vernier calliper for measuring shrinkage of oven dried soil. Figures 4 (a) and 4 (b) illustrate materials and equipment used.



(a) (b)

Figure 4: (a) Fine material, material less than 0.425 mm used for Atterberg test; (b) Apparatus utilised for the Atterberg limit tests

3.2.2 Methodology

Depending on the moisture content of the soil samples, fine soil may exist in liquid, plastic, semi-solid or solid state. Consistency limits occur at the points when the moisture content of the soil passes from one stage to the next stage. The Atterberg tests were aimed at identifying these limits (i.e. limit tests; the liquid limit, the plastic limit and the linear shrinkage of the soils). These tests were conducted in compliance with the South African Technical Methods for Highways Part 1 (TMH1) applying method subsections, A2, A3, and A4 (Department of Transport, 1986a). One hundred and fifty grams of the fine material was weighed with clean water and adequate quantities of lime added to it and mixed with a spatula for a period of 10 minutes. Subsequent to mixing, approximately 75 % of the mixed material was transferred into the bowl of the liquid limit device with a groove cut through the centre of the flattened material using the grooving tool. Blows or vibrations by rotating the handle of the liquid limit device were applied such that varied consistency in following ranges were achieved for each representative fine sample: consistency 28 to 35, consistency 22 to 28 and consistency 15 to 22. On achieving each consistency, a fine soil paste of approximately 150 g was transferred into the PI bottles, weighed and oven-dried for the determination of moisture content.

Left over material from the liquid limit test was utilised for the linear shrinkage test. This soil was filled into the troughs with soil paste which was still in its liquid limit state. The TMH1 recommends that the test be done immediately after the liquid limit test. Linear shrinkage troughs were filled with wet material and were then placed into the oven to dry for shrinkage determination.

Fine soil paste left over from the liquid limit and the linear shrinkage tests was also used for the plastic limit test. Approximately 3 grams of this soil was rolled between the palms of the hands to allow the formation of an ellipsoidal soil shape approximately 3 mm in diameter. The procedure was repeated until the soil crumbled which prevented further formation of the 3 mm thread. Crumbled soil was then transferred to the PI bottles, weighed, and then oven-dried for moisture content determination.

3.3 Maximum dry density and optimum moisture content

3.3.1 Materials and equipment

Approximately 130 kg of each soil sample, one for each concentration of lime, were utilised for this test. The following equipment was used for the test: shovel, plastic boxes, 19 mm aperture sieve size, 530 mm dish, 25 mm opening riffler with pans, 410 mm stainless dishes, scoop, scale capable of 12 kg with an accuracy to within 1 g, thermostatically controlled drying oven capable of maintaining a temperature of 105 ºC to 110 ºC, stainless steel pans, iron mortar and pestle, garden trowel, compaction moulds, compaction machine, 4.75 mm size sieve, 4.536 kg tamper, perforated base plates (for soaking), annular surcharges for soaking, proctor moulds and a tripod with a dial gauge. The material and equipment are illustrated in Figures 5(a) to 5(c).

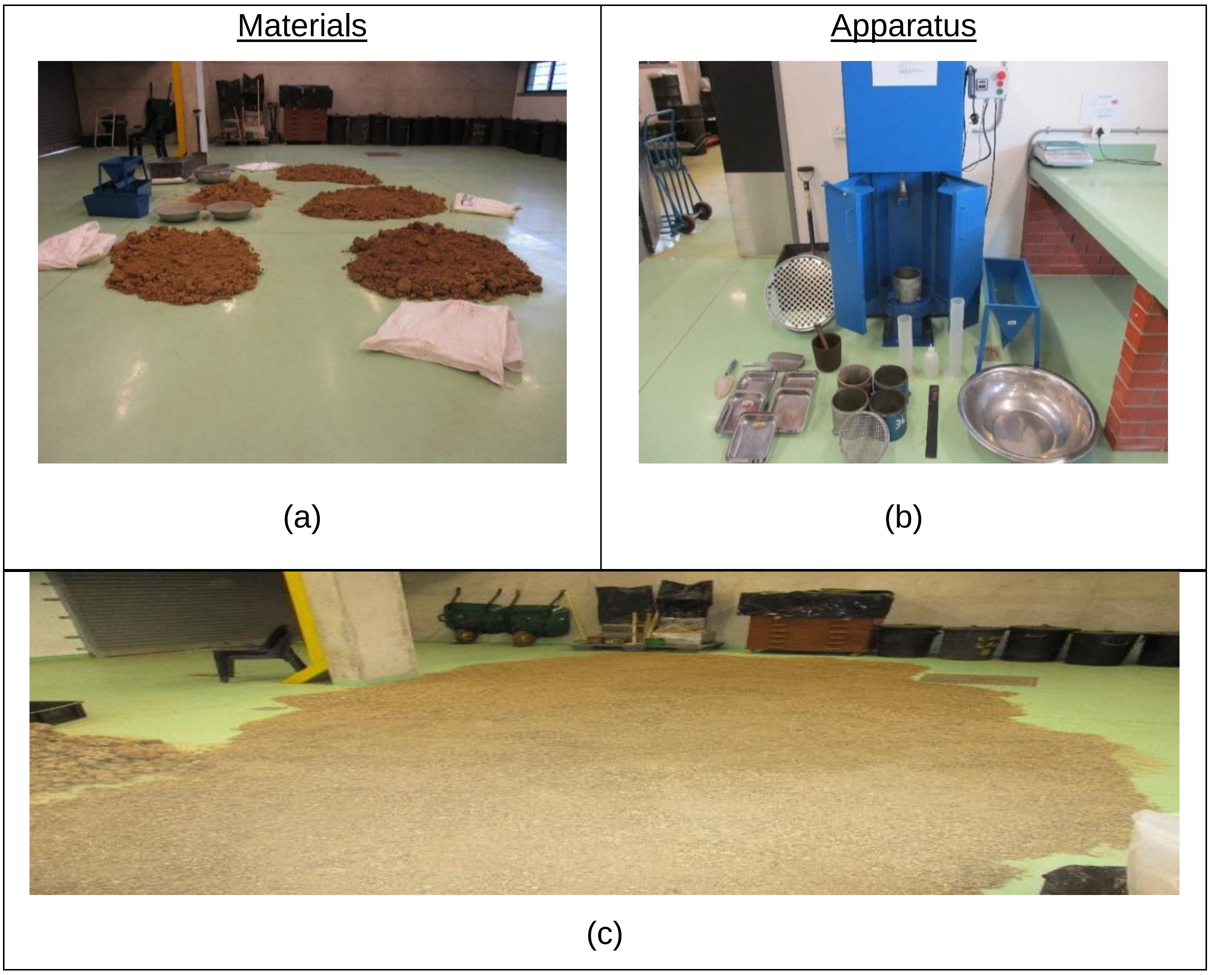


Figure 5: (a) Soil being air dried prior to maximum dry density and moisture content determination. (b) Apparatus utilised for compaction of the soil for MDD and OMC. (c) Air dried soil sample after sieving through a 19 mm sieve size for maximum dry density and optimum moisture content determination.

3.3.2 Methodology

The materials were prepared by splitting each sample in two portions for each pH range. One portion of each sample was prepared for a maximum dry density test and the determination of optimum moisture content. Compaction of each sample used approximately 130 kg, with the second portion being used for the determination of CBR for treated soil with lime contents of 2 %, 4 %, 6 %, 8 % and 10 %. The first portion of the soil was divided into five parts of approximately equal portions of 7 kg and each treated with lime content variations (as described above) by applying the weight method. The five portions were mixed with a pre-determined amount of water. The other four samples were treated similarly, but with different amounts of water used. This was done in order to obtain sufficient optimum moisture content in the soil samples. The soil samples were covered with plastic for 30 min to prevent evaporation whilst enabling proper distribution of moisture within the component particles. The soil was then moulded in the proctor moulds and compacted using the compaction machine with five layers at a compacted effort of 55. During the filling and compaction process, at every second layer of compaction, a representative sample of moist material (approximately 500 g to 1000 g) was taken and put into the oven for moisture content determination. The process was repeated for each level of lime content at 2 %, 4 %, 6 %, 8 % and 10 %.

The second portion of the soil was used for the CBR determination. The process began with mixing of sufficient soil to make four 21 kg soil samples, each with different lime concentration. Subsequent to the process, soil treated with lime was mixed with a pre-determined amount of water to achieve approximately ± 0.3 % of its optimum moisture content in preparing to make three soil samples. The moist soil was then covered with plastic sheet and allowed to stand for 30 min to prevent evaporation, thus promoting the even distribution of moisture within the soil particles. After 30 min, prior to moulding and compaction, two representative samples (each between 500 g and 1000 g) were taken from the moist soil and put into the oven for moisture determination through calculation. The moist soil was then compacted into the three Proctor steel moulds by applying the following compaction efforts: 55 mechanical compactive efforts, then 25 mechanical compactive efforts and finally 55 manual compactive efforts, using the tamping hammer. After compaction, the moulded material was then weighed and massed recorded.

3.4 Curing/Soaking-for CBR penetration

3.4.1 Materials and equipment

The following was the equipment used: plastic tanks with clean water for curing purposes, a dial gauge with a tripod for measuring the swelling of soil samples after being subjected to water, proctor steel moulds, perforated base plates, annular surcharge weights and airtight plastic bags. The material and equipment is illustrated in Figures 6(a) and 6(b) respectively.

Material

Apparatus

(a)

(b)

Figure 6: (a) Soil treated with different lime content confined in Proctor steel moulds prior to the curing and soaking processes. (b) Rectangle extra heavy duty tanks

3.4.2 Methodology

Subsequent to soaking the moulded soil samples in water, moulded soil samples were cured by putting them into an airtight plastic bag for 7 days (for 3 moulded soil), 14 days (for 3 moulded soil) and 28 days (for 3 moulded soil) respectively for each level of lime content and for each type of soil in terms of its pH.

After curing, each of three sets of soil samples that were confined to the proctor steel moulds was then soaked in the curing tank with clean water. This was done by inverting the moulds with compacted moist soil downward and then placing them on the perforated base plates with annular surcharge weights at the top of the moulded material. The moulds with moist material were soaked for four consecutive days to prepare them for CBR penetration testing. The swelling was constantly monitored by the use of the dial gauging tool.

3.5 CBR Penetration

3.5.1 Materials and equipment

The equipment used was a CBR compression testing machine. The material and equipment is illustrated in Figures 7(a) and figure 7(b) respectively. The compression testing machine frame is designed for applications requiring multi-purpose loading systems, with a controlled AC motor driven platen at speeds from 127 mm/min.

Material	Apparatus
 (a)	 (b)

Figure 7: (a) Soil treated with different lime content prior to CBR penetration test. (b) CBR machine for penetration test on compacted layer of soil (treated)

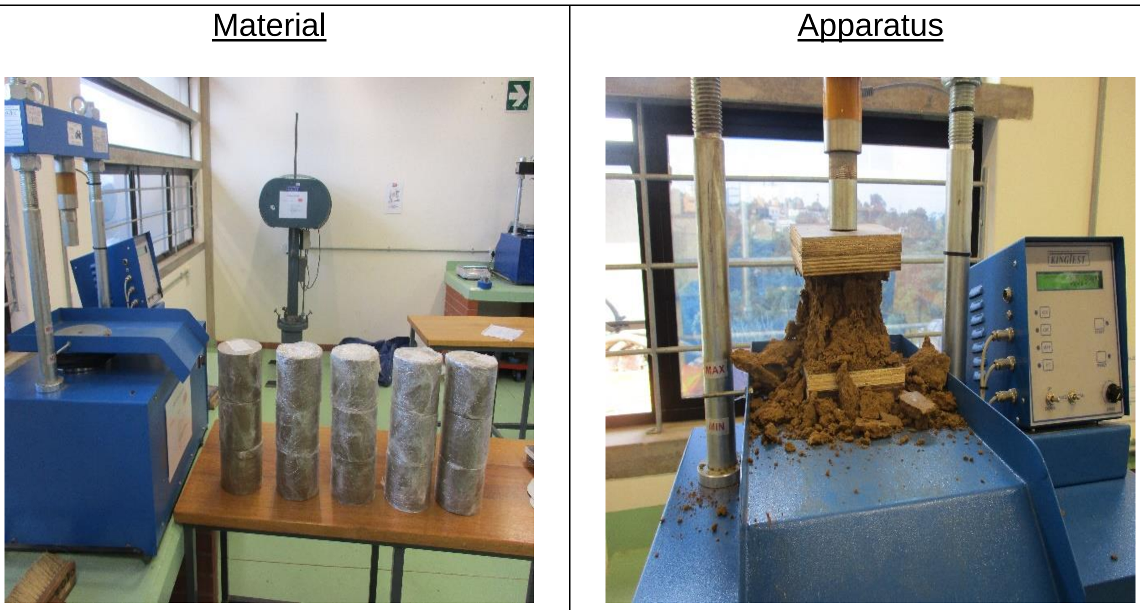
3.5.2 Methodology

After soaking for four days, the moulded soil samples were taken out from the curing tank containing water and allowed to drain for 15 min. The moulds were then placed into the CBR compression machine and a 5.56 kg surcharge was placed on top. The penetration piston was then seated on the soil surface and the load applied to the soil at a constant rate of strain of 1.27 mm/min. The load reading displayed on the CRB compression machine monitor was recorded for every 0.635 mm penetration depth to a depth of 9.525 mm for three samples respectively. The process was repeated for the other samples of each soil type of pH.

3.6 Unconfined compressive strength

3.6.1 Materials and equipment

Materials used were lime, clean water, and 21 kg of soil for each lime concentration and for each type of soil in terms of pH. Equipment used included plastic boxes for mixing, garden trowel, scale, water cylinders, squeeze bottles, stainless steel pans, scoops, split moulds, and air tight plastic CBR machine. Materials and equipment appear in Figures 8(a) and 8(b) respectively.


Material

Apparatus

(a)

(b)

Figure 8: (a) Lime treated soil samples prior to the unconfined compressive strength test. (b) CBR machine during the unconfined compressive strength test

3.6.2 Methodology

Both the CBR penetration test and the unconfined compressive strength test were conducted on the soil. The latter test was conducted to measure the shearing resistance of the soils derived from remoulded specimens. Adequate air dried material (as per method A7 under subsection 3.1 of the TMH1) was prepared and mixed with predetermined amounts of clean mixing water and lime. During the mixing process, portions of the moist materials were taken from the mixing container and put into the container for moisture content determination. Upon mixing and moulding of the treated soil, the split mould was dismantled to allow the treated samples to cure in a room with controlled temperature ranging between 22 ºC to 25 ºC. This included wrapping them with transparent air tight plastic for 7 days, 14 days and 28 days respectively for each sample with different lime content and for each sample type based on its pH. Once the defined curing time was complete, the specimens were removed from the plastic and compressed to total failure using the UCS machine. During the compression process, the axial load was applied onto the soil surface and the unconfined compressive strength was determined and recorded.

3.7 X-ray diffraction

3.7.1 Materials and equipment

The test required the use of 1 g of powdered fine material processed by a diffractometer. Figures 9(a) and figure 9(b) illustrate the material and equipment used. The diffractometer is designed to accommodate X-RD applications in materials research, powder diffraction and high resolution diffraction.

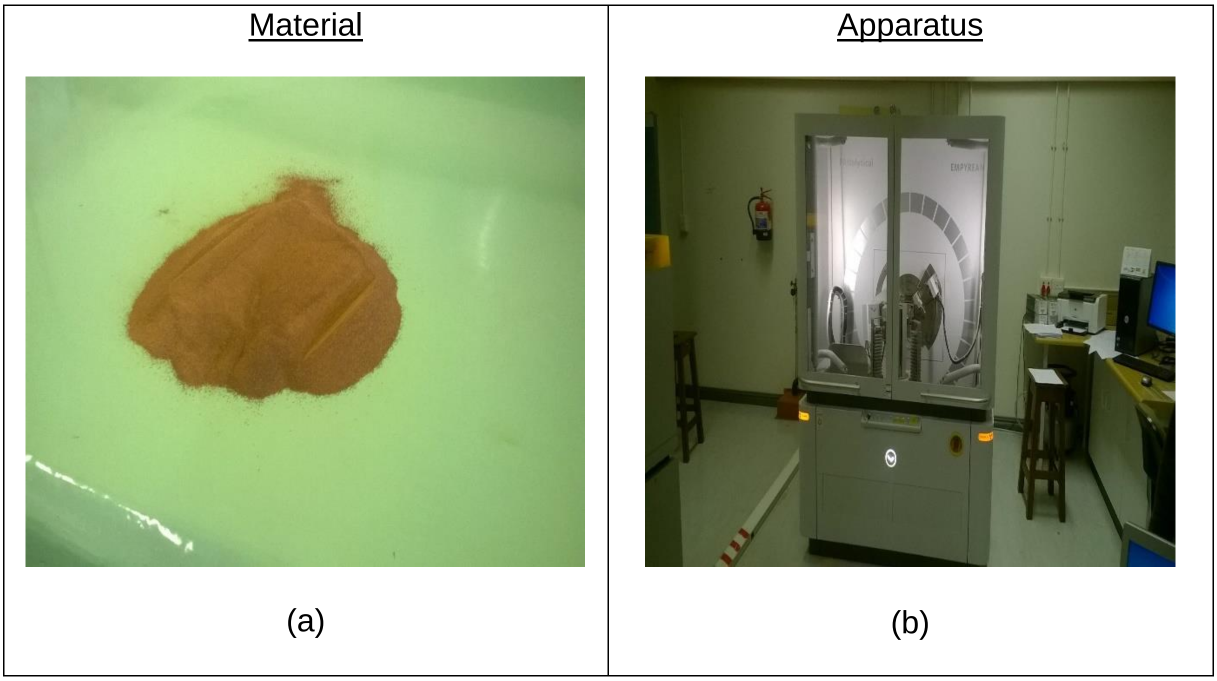


Figure 9: (a) Fine material, material less than 0.425 mm used for X-RD analysis. (b) Diffractometer machine used for minerals identification

3.7.2 Methodology

The test commenced with grinding the soil samples into finer soil samples and oven-drying the samples to a temperature of 110 ºC. The soil samples were then x rayed from 2° to 70° theta using Cu Kά radiation. The range of 2° to 70° 2-theta was chosen to provide sufficient X-RD peaks to identify most common soil minerals in the soil samples. Samples were placed in the sample holder and mounted with screws and tightened so as to preclude the sample holder alignment being lost. Data was collected using a predefined measurement procedure designed to ensure high peak ratios. X-rays of a fixed wave length were used to illuminate the sample. A goniometer was used to record the intensity of diffraction of minerals within each soil sample. This was then continuously recorded as the sample and the detector of the diffractometer rotated through their respective planes.

3.8 SEM and EDS/EDX scans

3.8.1 Materials and equipment

1 g of powdered fine material of each lime content for each soil sample, after 7, 14 and 28 days of curing for UCS was used. A diffractometer was used for this test.

Material	Apparatus
	
(a)	(b)

Figure 10: (a) Fine material less than 0.425 mm used for SEM analysis. (b) SEM machine

3.8.2 Methodology

The soil samples were placed on an electron gun generating a beam with sufficiently small diameter resulting in the magnification of the soil samples for identification of mineral elements.

CHAPTER 4

RESULTS AND DISCUSSION

The analysis of the test results shown in tables and figures relating to lime-soil stabilisation are presented in this chapter. The results and the values determined in the laboratory investigation of the soil samples are discussed and interpreted. This data was obtained through the defined experiments. For each of the soil properties, data is presented in the tables and figures followed by an analysis relating to that data.

4.1 Index properties of soil samples

Table 1: Index properties of the soil and soil pH

For admixing lime to reduce plasticity index of soil, the standard recommended target lime percentages are 1%, 2%, 3% & 4% for base materials. For this research 4% was used by weight method of the soil.

Properties	**Soil samples**					
	1	**2**	**3**	**4**	**5**	**6**
Liquid limit (%)	32	23.43	22	31	41	33
Plastic limit (%)	21.25	10.61	11.31	21.94	32.82	22.31
Plasticity index (%)-Raw	10.98	12.82	10.68	9.05	8.17	10.69
***Lime used (g)**	12	12	12	12	12	12
Plasticity index (%)-Lime treated	8.42	10.72	7.61	8.11	7.12	9.52
Linear shrinkage (mm)	4.210	4.24	3.89	5.57	3.37	1.76
Soil pH before treatment	3.94	4.54	4.50	8.95	8.05	8.34
Soil pH after treatment	4.02	4.92	5.55	9.20	8.27	8.68

The soil samples that were tested were classified and identified based also on the index properties. These are properties which help in the identification and classification of soil and are presented in Table 1 above. Table 1 shows Atterberg limits results for the six soil samples tested. The subsequent discussion is based on scrutiny of these results. From the analysis carried out, it was found that the treatment of the samples with lime content increased the pH of the samples. The changes were as a result of the changes in the chemical properties and the composition of the samples due to their chemical reactions with the lime additive. This is a substantial pH increase compared to the pH of natural soil (untreated soil samples). The values increased with increasing lime content for all the samples. On average across all the percentages of lime added, the pH value for acidic soil sample one changed from 3.94 to 4.02, the pH for soil sample two changed from 4.54 to 4.92, the pH for soil sample three changed from 4.50 to 5.22, the pH of soil sample four changed from 8.95 to 9.20, the pH of soil sample five changed from 8.05 to 8.27 and the pH for soil sample six from 8.34 to 8.68. The results showed that lime impacted on the soil samples. For acidic soil samples and upon the application of hydrated lime, soil pH increased with the rate of lime applied. Conversely, basic or alkaline soil is the consequence of the buffering of soil pH by base elements or by the presence of buffering compounds such as carbonates. Some of the soil features affected by soil pH included (but are not limited to):

- The availability of mineral elements in the soil.
- The physical properties: Low Ca concentration in acidic soil samples relating to an increased dispersion of colloids if Al is not present at high concentration.

The addition of lime to the six tested soil samples led to the reduction of the plasticity index as can be seen in Table 1. This reduction occurred due to the decrease in the thickness of the layer of the soil particles of the soil samples that were tested. The reduction resulted in a cation exchange chemical reaction causing an increase in the attraction capabilities of the soil, thus leading to flocculation. It therefore implies that the addition of lime increased the percentage of sand particles fraction, thus increasing the percentage of fines. Lime used for this experiment had an impact on this in that the hydrated lime used was a fine powdered material and was reactive in the presence of moisture. Hydrated lime helped in the filling of the air voids of the soil. Compaction also aided in the reduction in soil void ratio by expulsion of air from the voids.

For soil grading, figure 11 below shows the grading curves for soil samples 1 to 6. Samples 1 to 3 were acidic soil samples and 4 to 6 were alkaline samples. Based on the grading analysis of the six soil samples, almost all soil samples were well graded. This implies that the soil samples contained particles of a wide range of sizes and had good representation of all sizes. Good representation of the particle sizes makes provision for air voids to be particle filled during mixing and compaction. A certain percentage of air voids in the soil samples that were tested allowed for some additional compaction under lime application and to provide spaces into which small amounts of lime flowed during subsequent compaction.

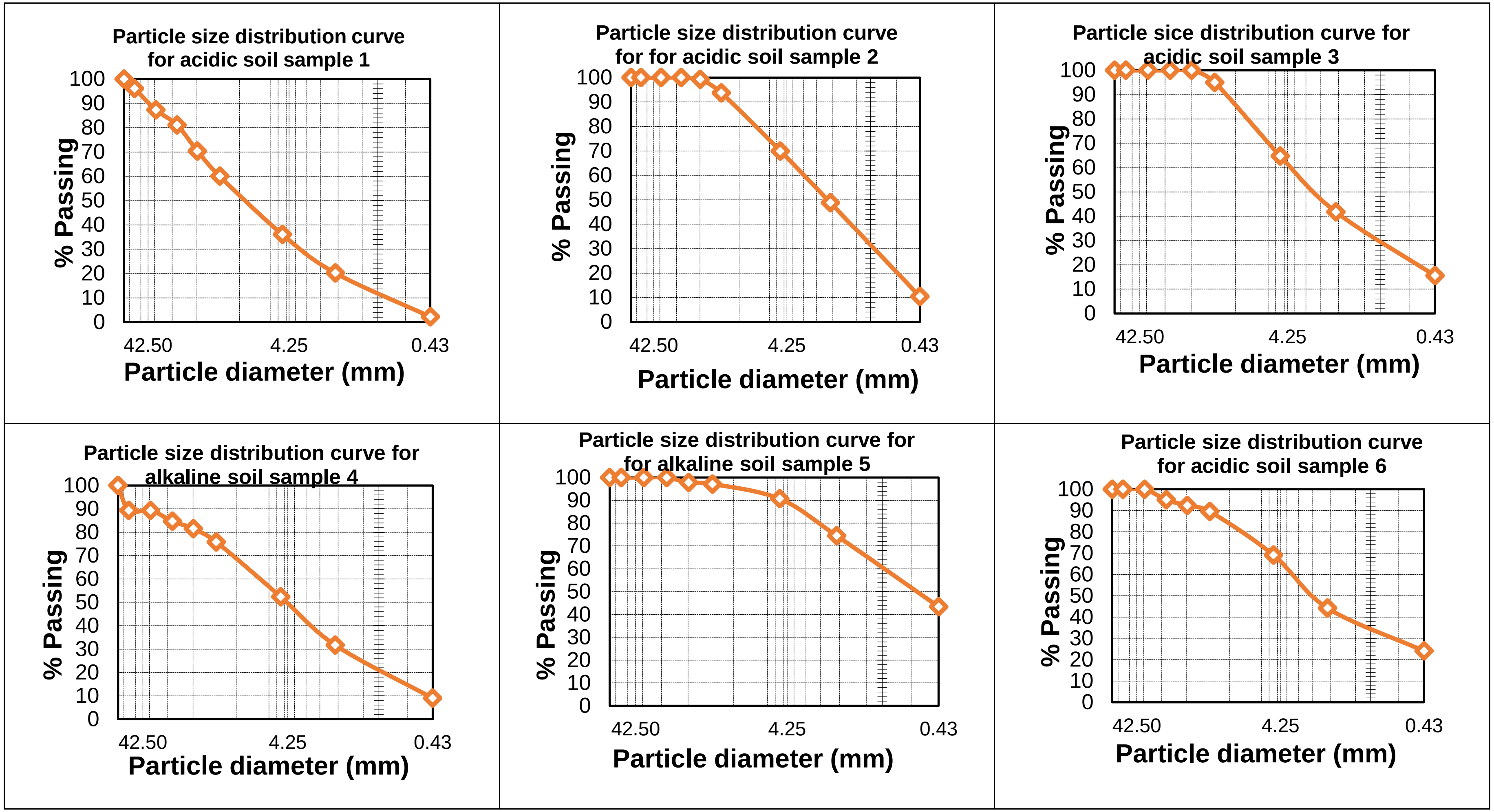


Figure 11: Particle size distribution curves for soil samples 1 to 6

4.2 Engineering properties of the soil samples

4.2.1 Maximum dry density and optimum moisture content

Many of the important engineering properties of soil can be enhanced by the addition of lime. The properties of such soil-lime mixtures vary and depend upon the type of soil as well as the pH (acidic and alkaline) of each soil sample. To develop an understanding of the possible mechanisms involved, a series of experiments through variation of parameters or properties were carried out. The following conclusions relating to MDD and OMC can be drawn from the results of the series of tests aimed at studying the influence of lime on the engineering properties of the six soil samples. The results of the compaction tests conducted on the soil samples showed that the addition of lime resulted in an improvement in the characteristics of all of the six soil samples. The six soil samples displayed maximum dry densities ranging from 1500 kg/m³ to 2000 kg/m³ and optimum moisture content ranging from 14 % to 29 %.

Almost all soil samples of different pH values reacted to the addition of lime as a soil stabilisation agent (as a predefined percentage by weight) and this is illustrated in Table 2. Soil sample results showed that the marginal addition of lime had the effect of decreasing the samples' density with constant or increasing moisture content. Ajayi, (2012) reported that the above situation (i.e. the increase in the moisture content vs the decrease in dry density in relation to the addition of lime) results from lower amount of compaction or less compactive efforts. At pH of 8.68 after the application of lime, alkaline soil sample six indicated the highest density of 2075 kg/m³ at moisture content of 22 % when treated with lime content of 4 %. The dry density of some soil samples showed a slight increase as the lime content increased.

Table 2: Maximum dry density* and optimum moisture content of lime treated six soil samples

Sample number	MDD OMC & 2 % lime	MDD OMC & 4 % lime	MDD OMC & 6 % lime	MDD OMC & 8 % lime	MDD OMC & 10 % lime
1	1702.5 kg/m³ 20 % 0.7 kg lime	1731.4 kg/m³ 20 % 1.4 kg lime	1740.6 kg/m³ 20 % 2.1 kg lime	1749.2 kg/m³ 20 % 2.8 kg lime	1672 kg/m³ 19 % 3.5 kg lime
2	1667.2 kg/m³ 22 % 0.7 kg lime	1643 kg/m³ 20 % 1.4 kg lime	1670.1 kg/m³ 20 % 1.4 kg lime	1677.35 kg/m³ 20 % 2.8 kg lime	1645.59 kg/m³ 20 % 3.5 kg lime
3	1834.4 kg/m³	1937.3 kg/m³	1811.3 kg/m³	1899.9 kg/m³	1792.7 kg/m³

	15 % 0.7 kg lime	14 % 1.4 kg lime	21 % 1.4 kg lime	14 % 2.8 kg lime	17 % 3.5 kg lime
4	1752.2 kg/m³ 17.33 % 0.7 kg lime	1731.4 kg/m³ 19.5 % 1.4 kg lime	1663.93 kg/m³ 18.23 % 1.4 kg lime	1674.9 kg/m³ 18.16 % 2.8 kg lime	1591.53 kg/m³ 18.19 % 3.5 kg lime
5	1867.6 kg/m³ 23.95 % 0.7 kg lime	1786.4 kg/m³ 17.58 % 1.4 kg lime	1657.1 kg/m³ 23.85 % 1.4 kg lime	1673.6 kg/m³ 23.9 % 2.8 kg lime	1705.59 kg/m³ 24.83 % 3.5 kg lime
6	1721 kg/m³ 22.41 % 0.7 kg lime	2075 kg/m³ 22.01 % 1.4 kg lime	1835.3 kg/m³ 22.19 % 1.4 kg lime	1778.1 kg/m³ 23.76 % 2.8 kg lime	1597.4 kg/m³ 29.17 % 3.5 kg lime

*The above densities are maximum densities achieved when a series of soil samples at each lime content were compacted at different water contents and the MDD vs OMC plot showed distinct peaks (i.e. ones shown above). - Per 35kg soil sample after riffling.

The addition of lime contributed to the increase in the optimum moisture content and the decrease in dry density for some soil samples. Generally, all soil samples exhibited a similar correlation between moisture content and dry density when subjected to a given compactive effort. For each soil sample, maximum dry density develops at the optimum moisture content for the compactive effort used. An analysis of the maximum dry density and the optimum moisture content of the six soil samples at different contents of lime performed to determine the relationship between the moisture content and the dry density is presented. The results of the compaction tests conducted on the soil samples showed that the addition of lime resulted in the improvement in the characteristics of the six soil samples. In the paragraphs below the underlined values are maximum densities of each of the soil samples of different pH ranges displaying optimum values and are significant in that as soil is compacted, the bulk density increases to optimum levels. As the soil density increases, so does its ability to reduce water seepage, and to reduce crop yield and vegetative cover, thus promoting an increase in soil strength.

To limit excessive discussion, the sub headings below are reflect only on the highest densities achieved for the soil sample at each lime content. Short analysis of the results per sample is done at each sub-section. Five portions of 7kg for each of the actual-densities were used for each lime content.

Acidic soil sample one

Acidic soil sample one at pH = 4.02 after lime treatment achieved the maximum density of 1749.2 kg/m³. This was from actual densities of 1609.1 kg/m³, 1699 kg/m³, 1749.2 kg/m^3, 1669.9 kg/m^3 and 1596.5 kg/m^3 at lime content of 8 %. The results, at pH= 4.02, the MDD=1749kg/m^3 was obtained at 20% of OMC at 8% lime content. This shows an improvement in strength factor by 2.74%, 1.02%, 0.49%, and 4.62% when comparing with other lime contents of 2%, 4%, 6% and 10% of the same samples of the same pH condition. Comparing the above results, it implies that acidic soil sample one, under the test conditions operate optimally with respect to soil strength parameters at pH=4.02 and 20% OMC.

Acidic soil sample two

Acidic soil sample two at pH = 4.92 after lime treatment achieved the maximum density of 1677.35 kg/m^3. This was from actual densities of 1532.99 kg/m^3, 1541 kg/m^3, 1677.35 kg/m^3, 1529 kg/m^3 and 1499 kg/m^3 at lime content of 8 % of lime. The results, at pH= 4.92, the MDD=1677.35kg/m^3 was obtained at 20% of OMC at 8% lime content. This shows an improvement in strength factor by 0.61%, 2.09%, 0.43%, and 1.93% when comparing with other lime contents of 2%, 4%, 6% and 10% of the same samples of the same pH condition. Comparing the above results, it implies that acidic soil sample two, under the test conditions operate optimally with respect to soil strength parameters at pH=4.92 and 20% OMC.

Acidic soil sample three

Acidic soil sample three at pH = 5.55 after lime treatment achieved the maximum density of 1937.3 kg/m^3. This was from actual densities of 1689.1 kg/m^3, 1805.4 kg/m^3, 1937.3 kg/m^3, 1846.3 kg/m^3 and 1691.9 kg/m^3 at lime content of 4 % of lime. The results, at pH= 5.55, the MDD=1937.3kg/m^3 was obtained at 14% of OMC at 4% lime content. This shows an improvement in strength factor by 5.61%, 6.97%, 1.97%, and 8.07% when comparing with other lime contents of 2%, 4%, 6% and 10% of the same samples of the same pH condition. Comparing the above results, it implies that acidic soil sample three, under the test conditions operate optimally with respect to soil strength parameters at pH=5.55 and 14% OMC.

Alkaline soil sample four

Alkaline soil sample four at pH = 9.20 after lime treatment achieved the maximum density of 1752.16 kg/m^3. This was from actual densities of 1523.8 kg/m^3, 1653.1 kg/m^3, 1752.16 kg/m^3, 1679.7 kg/m^3 and 1542.3 kg/m^3 at lime content of 2 % of lime. The results, at pH= 9.20, the MDD=1752.2kg/m^3 was obtained at 17.33% of

OMC at 2% lime content. This shows an improvement in strength factor by 1.20%, 5.30%, 4.62%, and 10.10% when comparing with other lime contents of 4%, 6%, 8% and 10% of the same samples of the same pH condition. Comparing the above results, it implies that alkaline soil sample four, under the test conditions operate optimally with respect to soil strength parameters at pH=9.20 and 17.33% OMC.

Alkaline soil sample five

Alkaline soil sample five at pH = 8.27 after lime treatment achieved the maximum density of 1867.58 kg/m³. This was from actual densities of 1523.8 kg/m³, 1801 kg/m³, 1867.58 kg/m³, 1733 kg/m³ and 1625 kg/m³ at lime content of 2 % of lime. The results, at pH= 8.27, the MDD=1867.6kg/m³ was obtained at 23.95% of OMC and 2% lime content. This shows an improvement in strength factor by 4.55%, 12.70%, 11.95%, and 9.50% when comparing with other lime contents of 2%, 4%, 6% and 10% of the same samples of the same pH condition. Comparing the above results, it implies that alkaline soil sample five, under the test conditions operate optimally with respect to soil strength parameters at pH=8.27 and 23.95% OMC.

Alkaline soil sample six

Alkaline soil sample six at pH = 8.68 after lime treatment achieved the maximum density of 2075.01 kg/m³. This was from actual densities of 1265 kg/m³, 1836 kg/m³, 2075.01 kg/m³, 1765 kg/m³ and 1354 kg/m³ at lime content of 4 % of lime.

Therefore by comparing all the six soil samples, it can be concluded by saying that lime content at range of 4 % to 8 % indicates the highest density increases of the stabilised soil samples. The densities of the soil samples showed a slight increase at the lime content of 10 %. However, for almost all samples, the results showed that further addition of lime decreases the density and increases moisture content.

Further to the above and based on the above results from the experiment, it can be seen that the MDD is achieved at 2075 kg/m³ at 22 % of OMC for alkaline soil sample six when treated with lime content of 4 %. The above implies that maximum cohesion and maximum friction are achieved at pH = 8.68. When the pH of the soil changes (i.e. increases) this promotes the disintegration of the clay particles in the soil allowing air spaces within the soil sample to be filled accordingly, thus aiding the compaction of the soil. This implies, when comparing all the acidic soil samples and alkaline soil samples, alkaline soil sample six, under the test conditions operate optimally with respect to soil strength parameters at pH=8.68 and 22.01% OMC.

However for the other soil samples, there was an observed significant daily decrease in MDD for each of the pH condition.

The above further indicated that the particles of the soil samples tested were being disintegrated. This reduction in the density of the soil had an impact on the strength of the soil. A typical example for the latter is alkaline soil sample four at pH = 9.20, with an MDD of 1591.53 kg/m^3 at 18 % of OMC.

4.2.2 California Bearing Ratio penetration

The CBR test was performed by measuring the pressure required to penetrate the surface of the compacted soil samples at different compactive efforts. These compactive efforts were 55 CBR mechanically compacted, 25 CBR mechanically compacted and 55 CBR manually compacted. The CBR test results of the soil samples are provided in Figures 12 to 23 and the subsequent discussion relates to the scrutiny of these results.

The improvement in the strength of CBR penetration of soil samples can be explained by the formation of agglomerates due to the application of lime. CBR penetration test results illustrated the importance of the size, shape, arrangement of soil aggregations, as well as the distribution and connectivity of pores. Micrographs of microstructural properties results discussed later in this chapter make reference to this. The CBR for treated soil samples compacted at 25 compactive efforts recorded lower CBR values compared to the soil samples compacted at 55 compactive efforts. Alkaline soil sample six of pH = 8.68 indicated constant increase in CBR for respective penetration depths of 2.54 mm, 5.08 mm and 7.62 mm. The constant increase in CBR for alkaline soil sample six compacted at 55 compactive efforts was a direct indication of the principal chemical reactions that took place during the lime-soil stabilisation process (i.e. cation and flocculation-agglomeration.

Refer to additional figures 43 to 72 on appendix C since the soil samples at all compactive efforts (i.e. 55 CBR mechanically compacted, 25 CBR mechanically compacted and 55 CBR manually compacted) were cured not only at 7 days but 14 and 28 days as well.

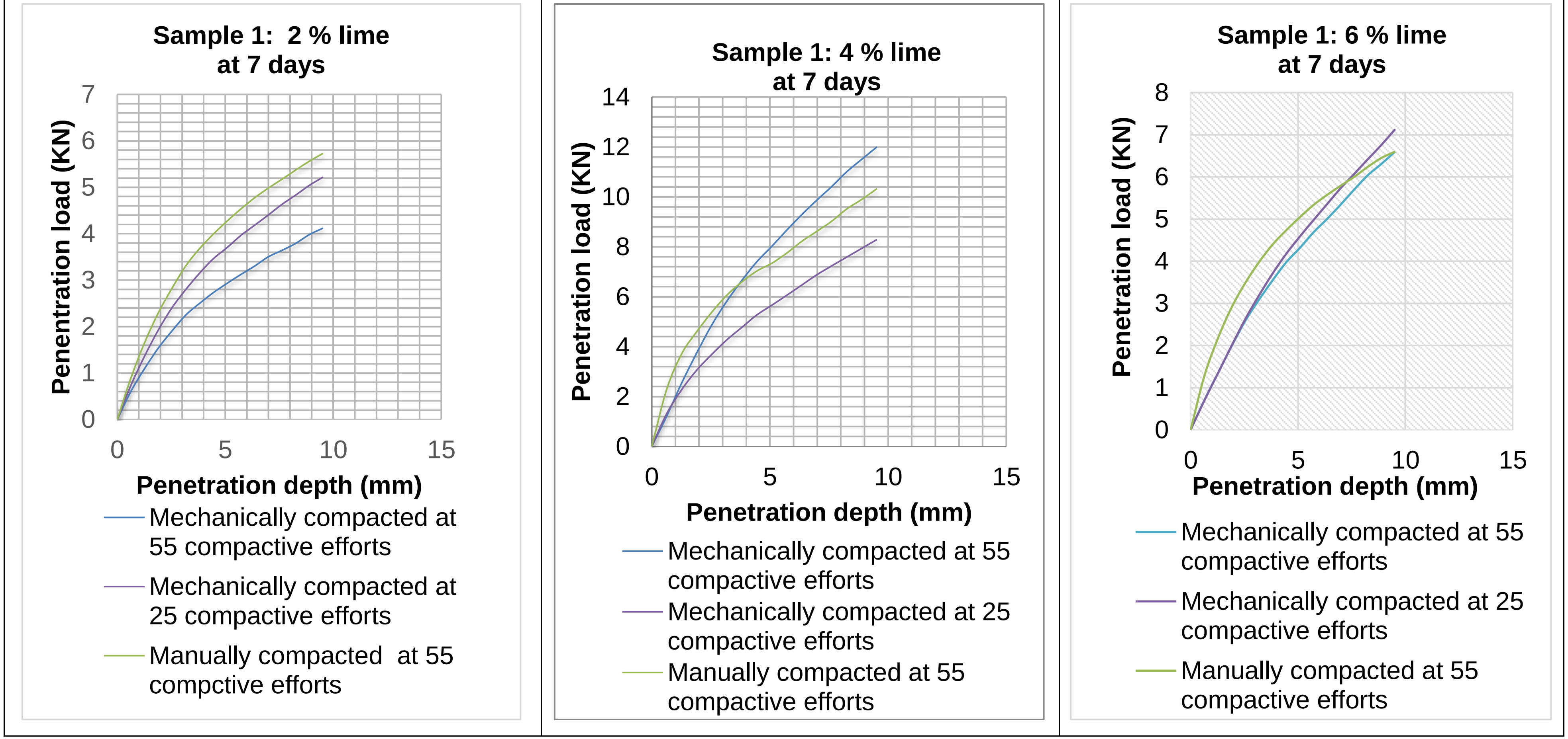


Figure 12: CBR penetration curves for sample 1 at lime contents of 2 %, 4 % & 6 % cured for 7 days

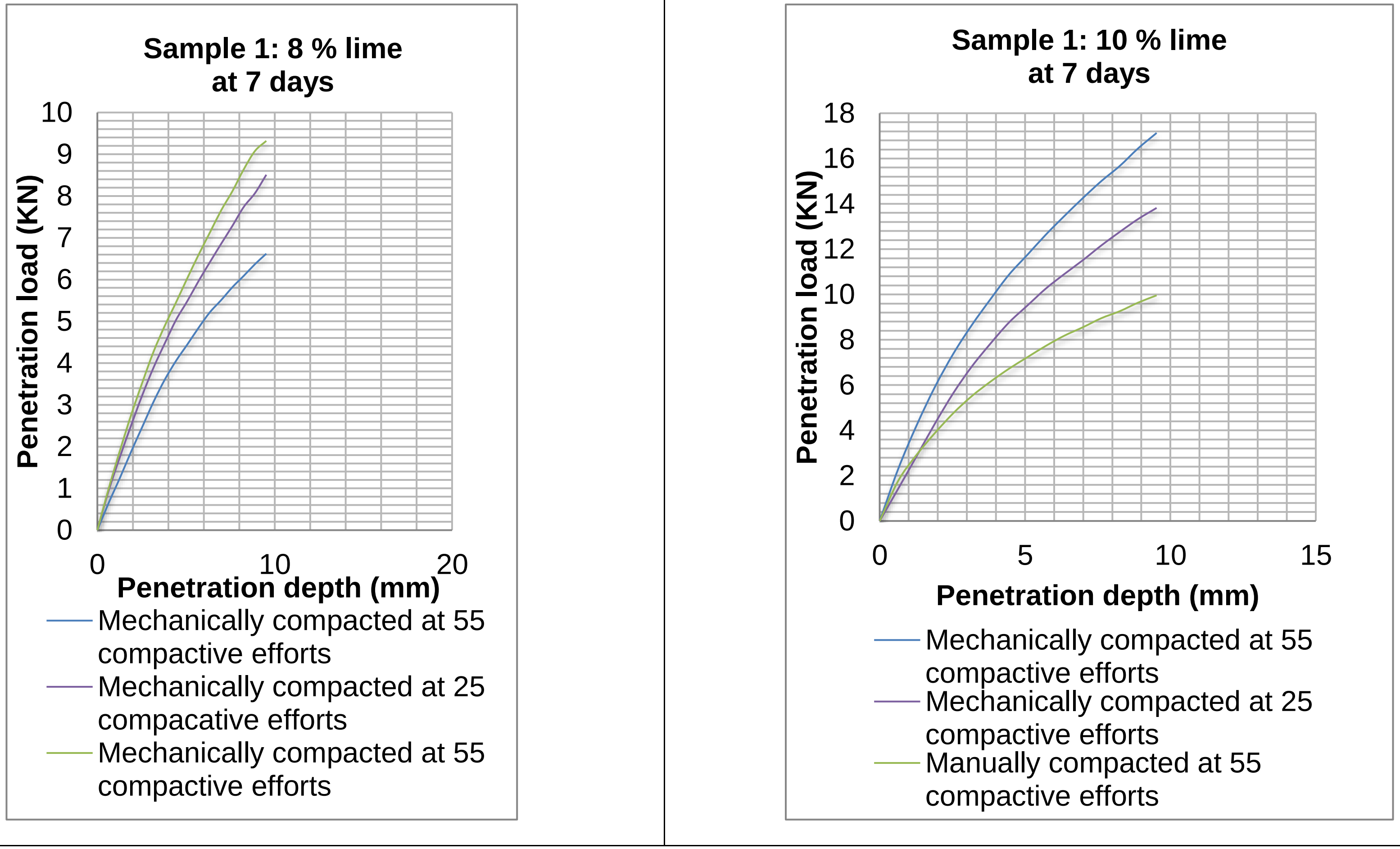


Figure 13: CBR penetration curves for sample 1 at lime contents of 8 % & 10 % cured for 7 days

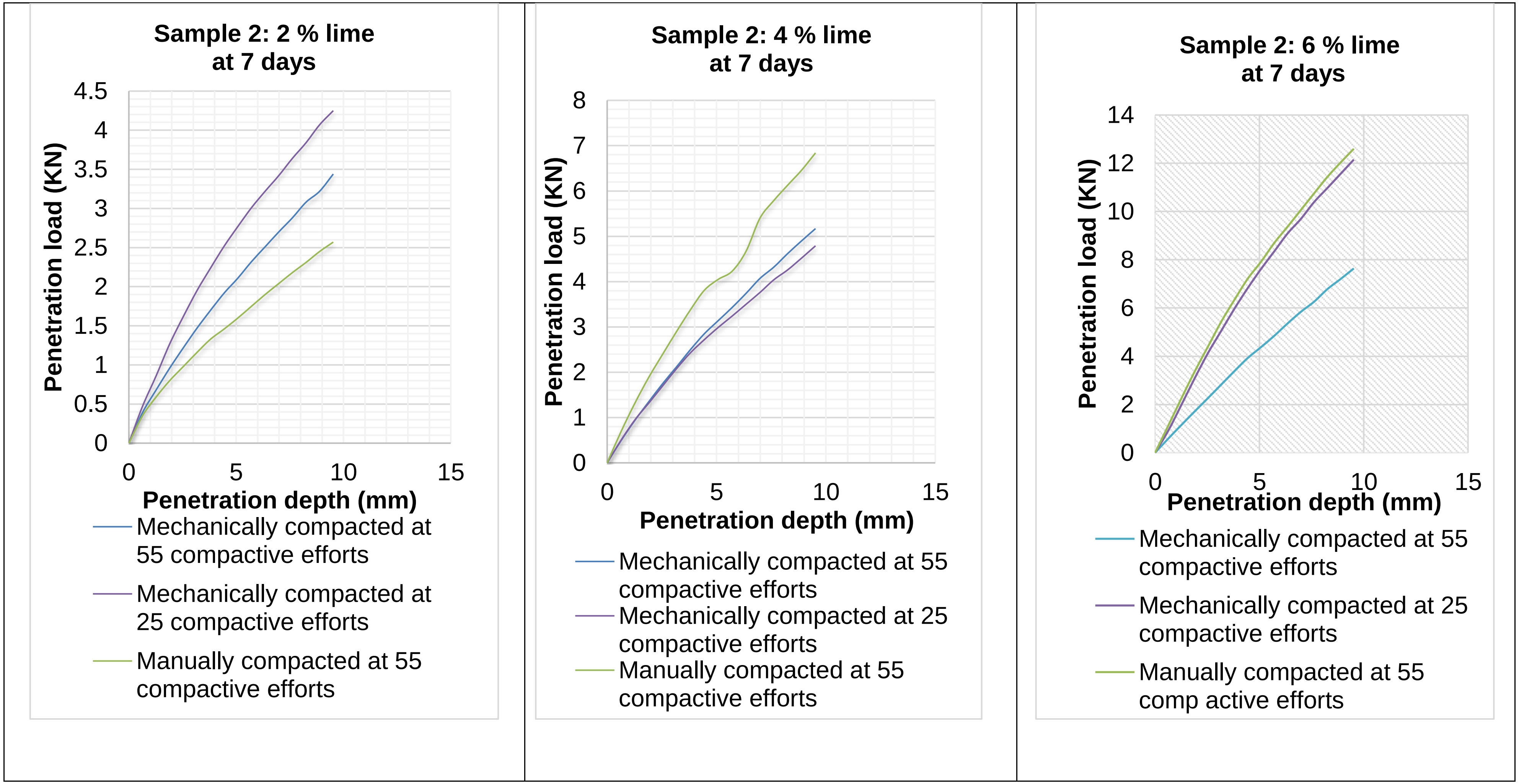


Figure 14: CBR penetration curves for sample 2 at lime contents of 2 %, 4 % & 6 % cured for 7 days

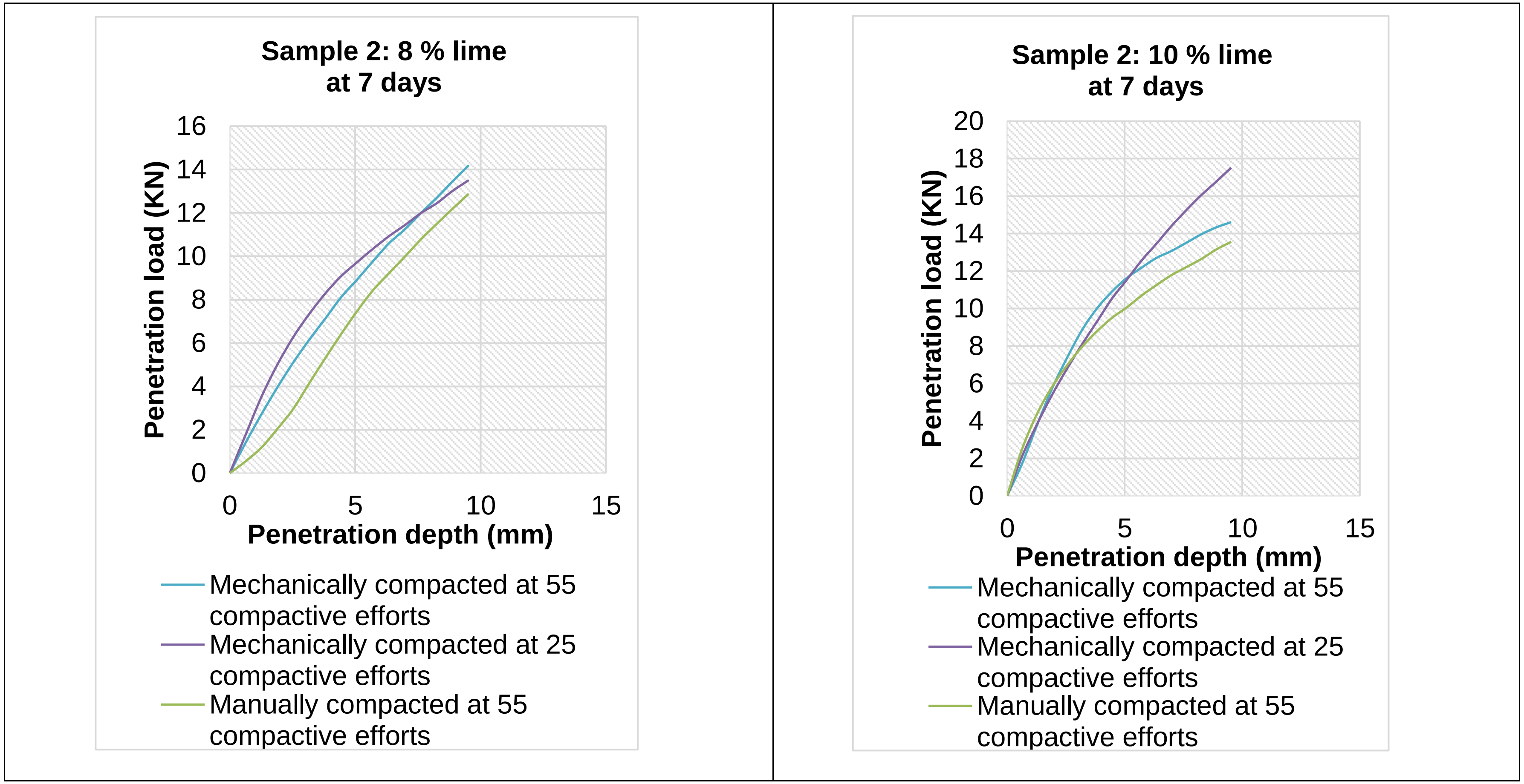


Figure 15: CBR penetration curves for sample 2 at lime contents of 8 % & 10 % cured for 7 days

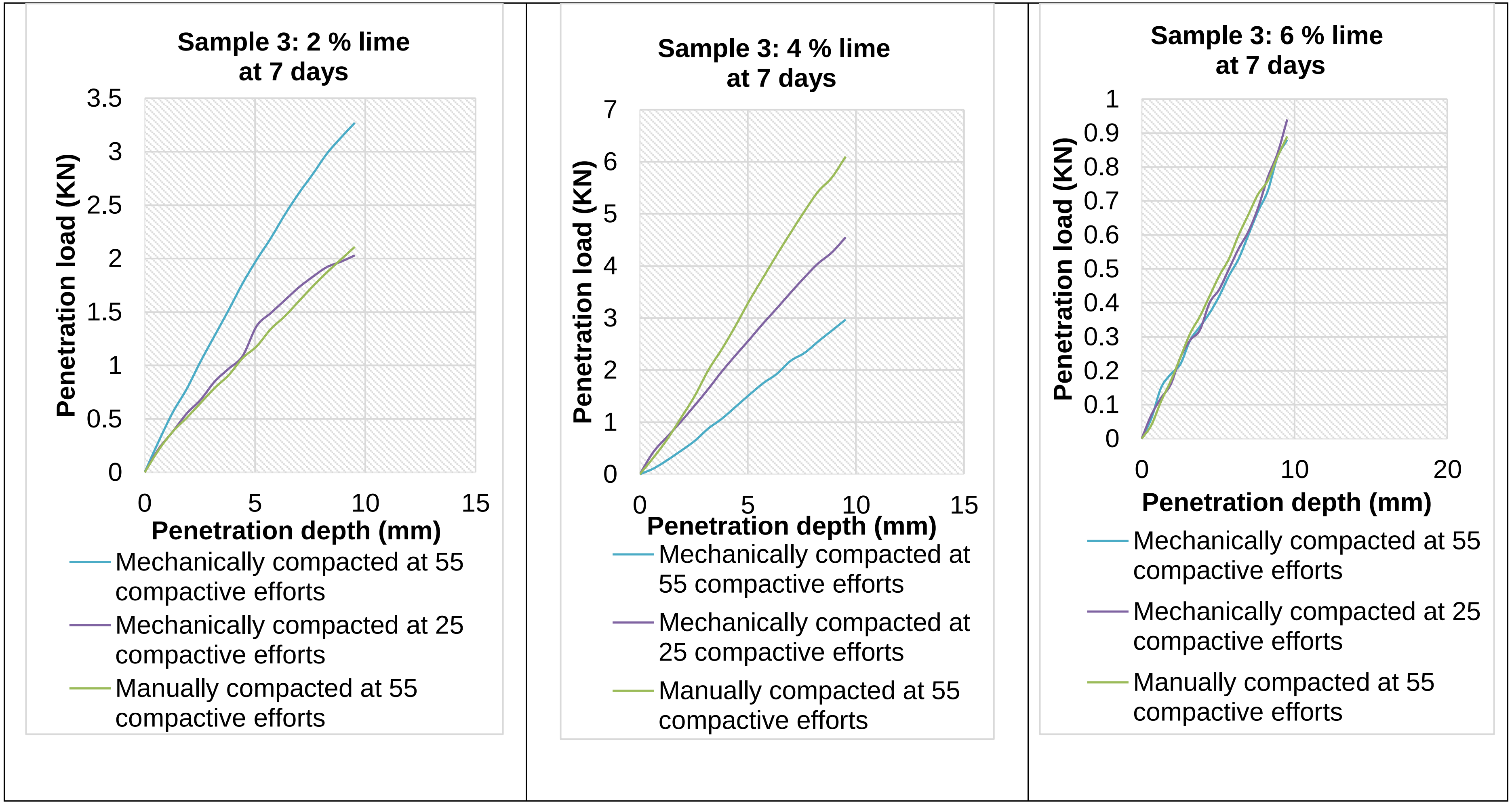


Figure 16: CBR penetration curves for sample 3 at lime contents of 2 %, 4 % & 6 % cured for 7 days

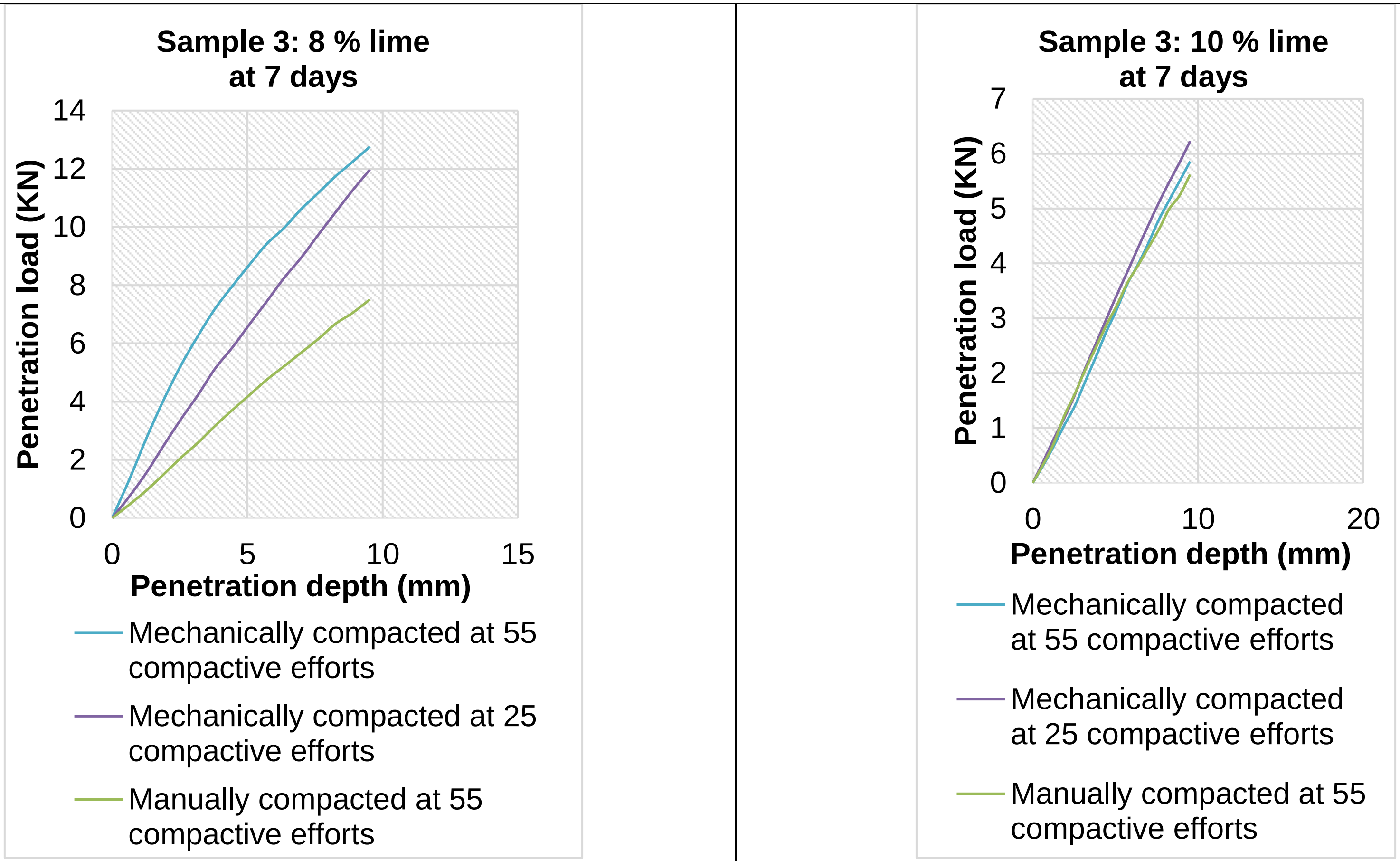


Figure 17: CBR penetration curves for sample 3 at lime contents of 8 % & 10 % cured for 7 days

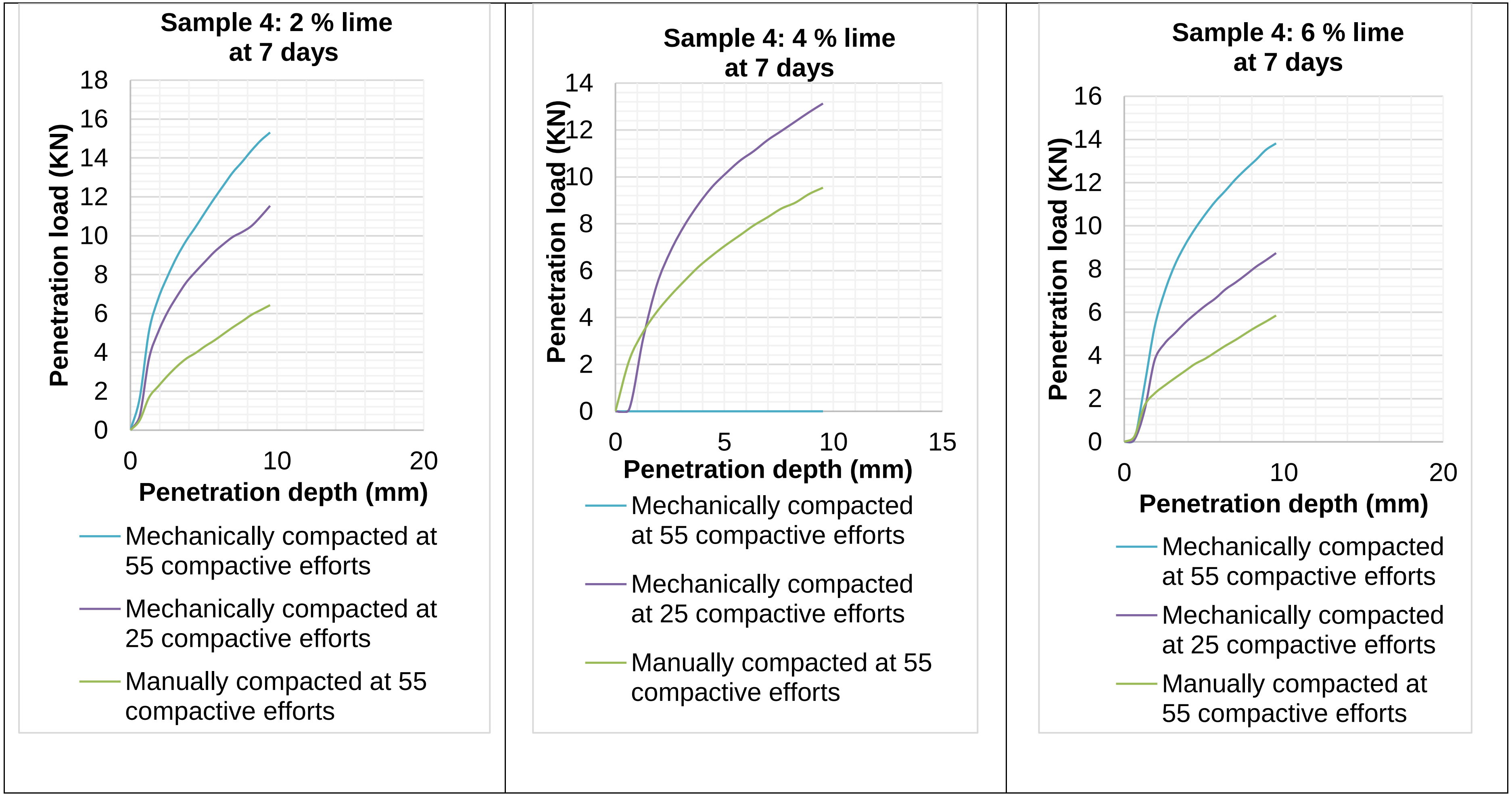


Figure 18: CBR penetration curves for sample 4 at lime contents of 2 %, 4 % & 6 % cured for 7 days

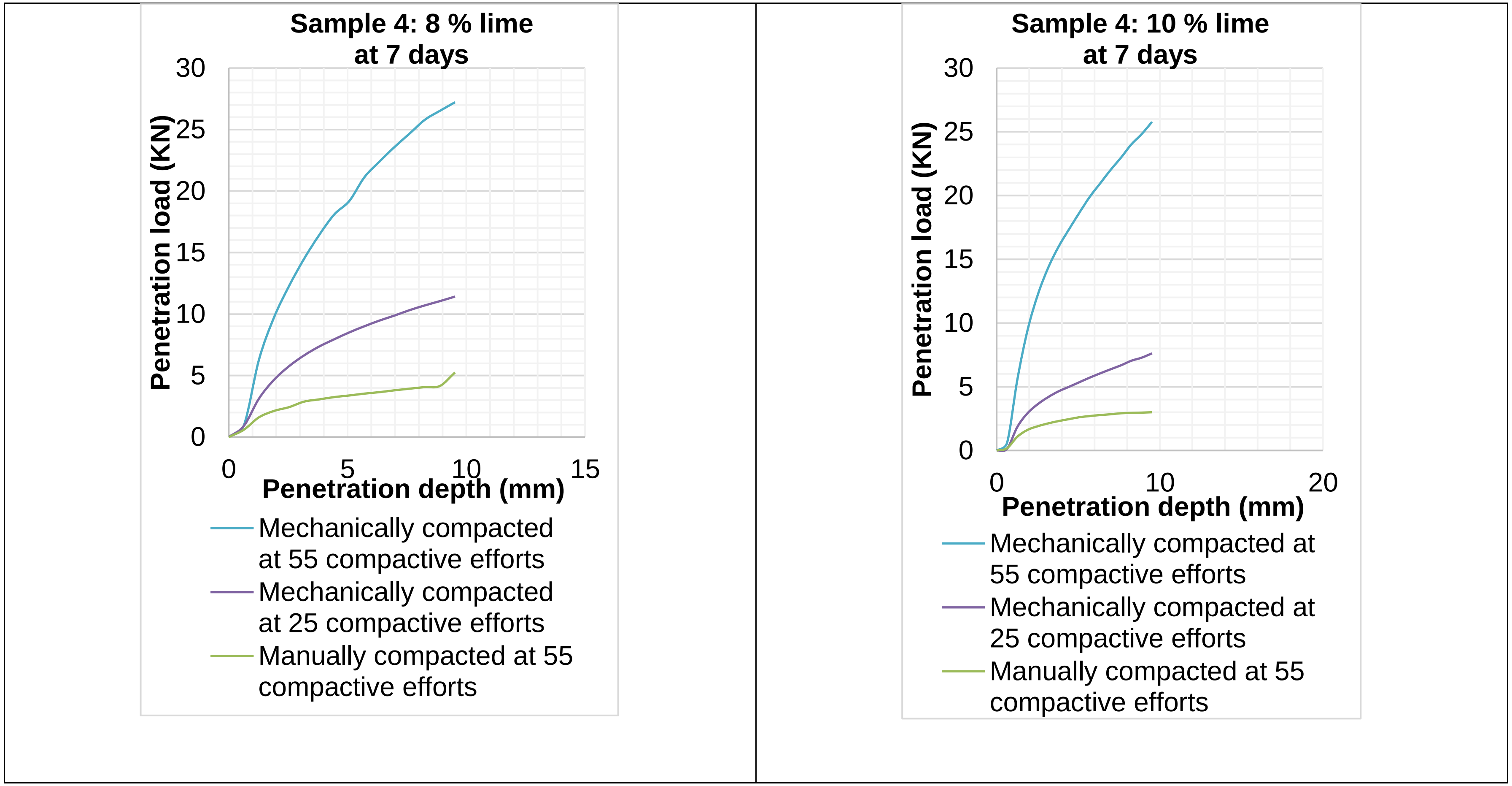


Figure 19: CBR penetration curves for sample 4 at lime contents of 8 % & 10 % cured for 7 days

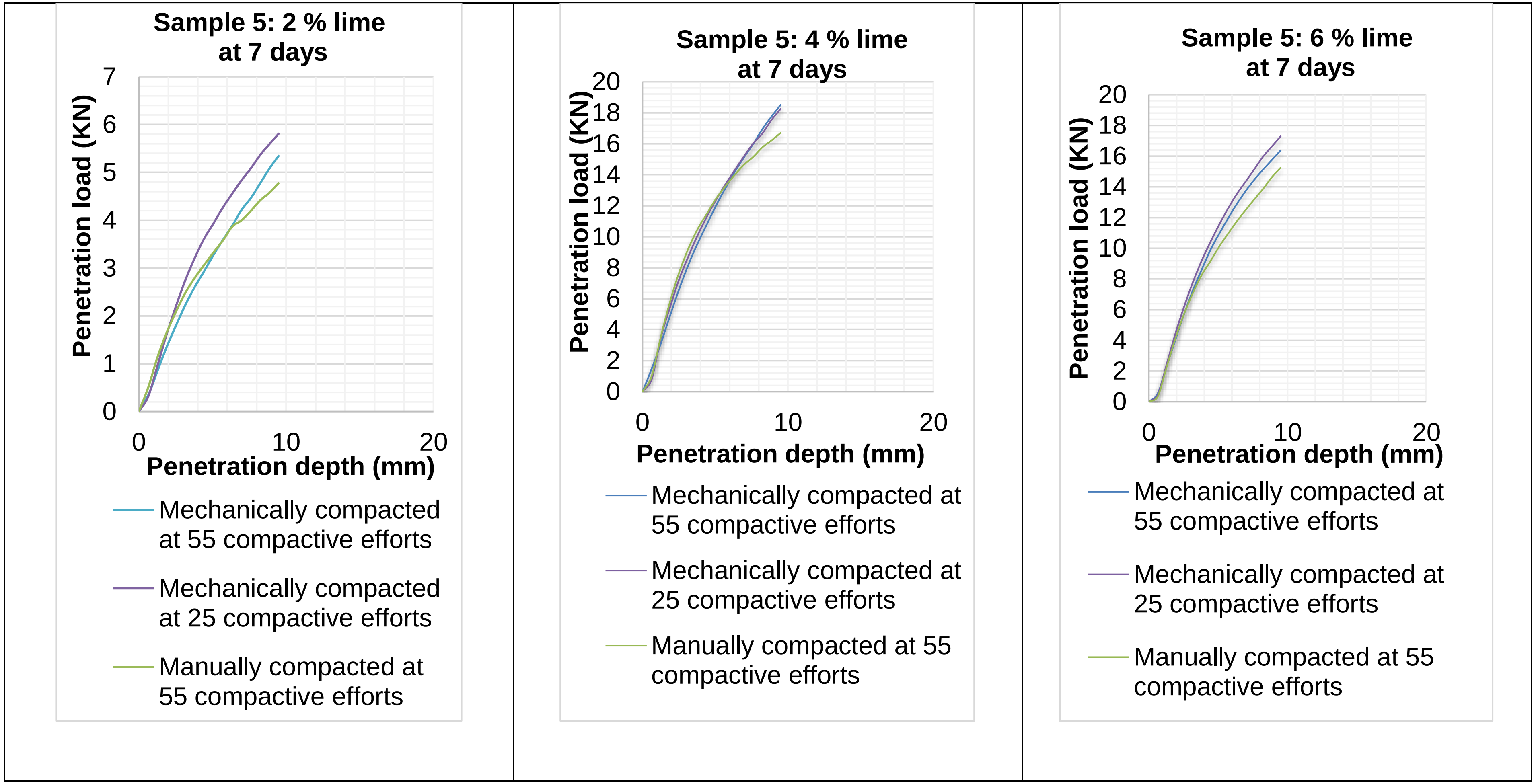


Figure 20: CBR penetration curves for sample 5 at lime contents of 2 %, 4 % & 6 % cured for 7 days

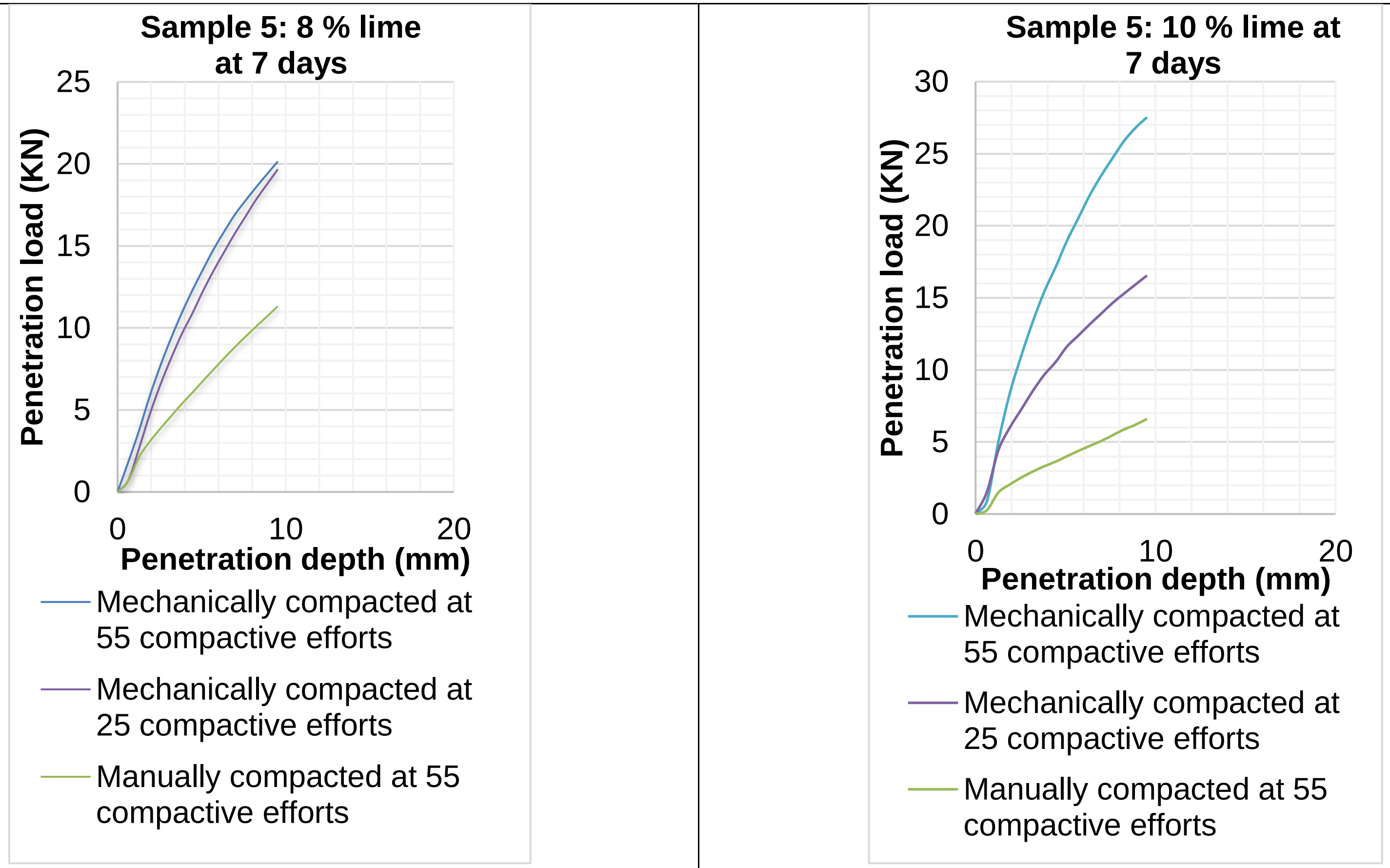


Figure 21: CBR penetration curves for sample 5 at lime contents of 8 % & 10 % cured for 7 days

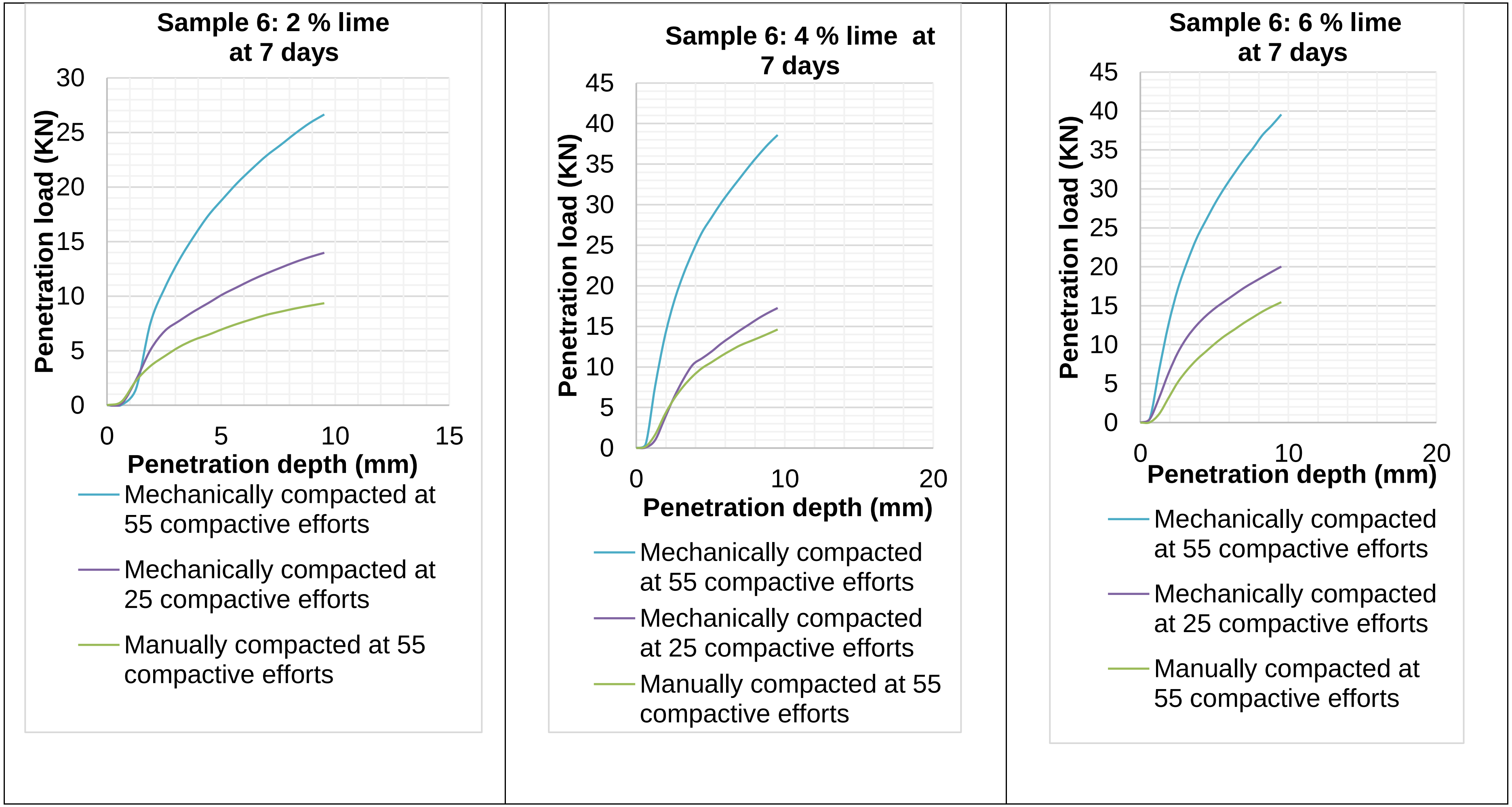


Figure 22: CBR penetration curves for sample 6 at lime contents of 2 %, 4 % & 6 % cured for 7 days

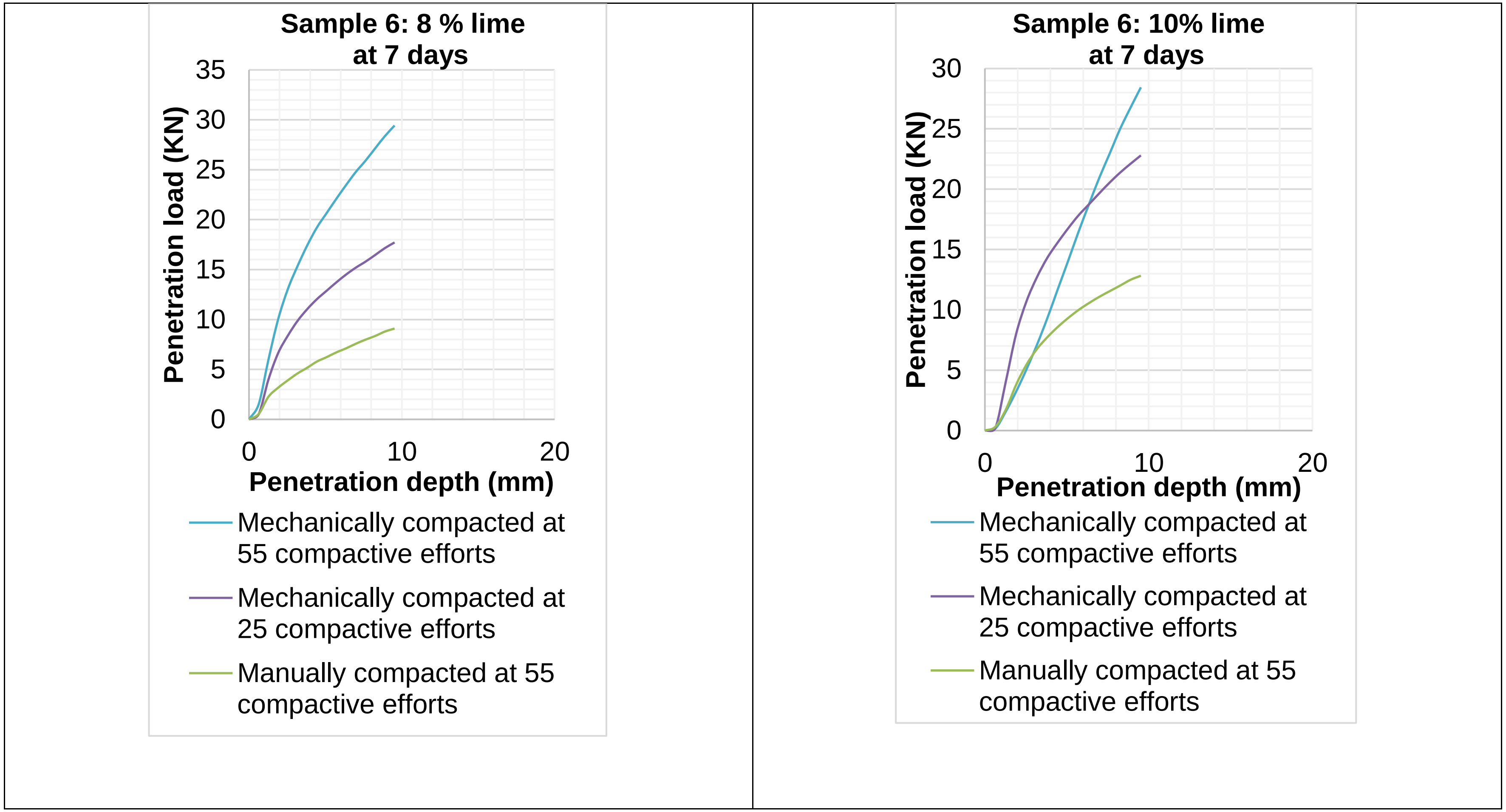


Figure 23: CBR penetration curves for sample 6 at lime contents of 8 % & 10 % cured for 7 days

4.2.2.1 Acidic soil samples-CBR results (samples 1, 2 & 3)

Acidic CBR soil samples were cured for 7, 14 and 28 days, but to limit excessive discussion, the interpretation of the results is based on curing the soil samples for 7 days. The CBR values discussed below relate to loads but are expressed as a percentage of California Standard Values (CSV). These were forces were required to penetrate the compacted surface of the soil samples at a rate of 1.27 mm per minute at CBR penetration depths of 2.54 mm, 5.08 mm and 7.62 mm. The CSV used for the above depths were 13,344 N, 20,016 N and 25,354 N for 2.54 mm, 5.08 mm and 7.62 mm respectively. The discussion below compares acidic soil samples (i.e. 1, 2 and 3) at depths specified. The comparison is in terms of the highest CBR forces recorded for each lime content, when mechanically compacted at 55 compactive efforts, mechanically compacted at 25 compactive efforts and manually compacted at 55 compactive efforts.

Comparison between acidic soil samples and alkaline soil samples is given at the end of the CBR sub-section.

At 2 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Acidic soil sample 1 of pH = 4.02 after lime treatment incorporating 2 % lime content recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing, and at CBR penetration depth of 2.54 mm, forces recorded to penetrate the compacted surface of the soil were 14.31 %, 18.06 % and 21.21 % respectively for compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually).

5.08 mm CBR depth of penetration

- Acidic soil sample 1 of pH = 4.02 after lime treatment at CBR penetration depth of 5.08 mm recorded 14.63 %, 18.48 % and 21.33 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

7.62 mm CBR depth of penetration

- Acidic soil sample 1 of pH = 4.02 after lime treatment at CBR penetration depth of 7.62 mm recorded 14.36 %, 18.26 % and 20.39 % for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

At 4 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Acidic soil sample 1 of pH = 4.02 after lime treatment at 4 % of lime content recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing and at CBR penetration depth of 2.54 mm, 36.5 %, 27.65 % and 40.32 % were the recorded forces required for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually).

5.08 mm CBR depth of penetration

- Acidic soil sample 1 of pH = 4.02 after lime treatment at CBR penetration depth of 5.08 mm recorded 40.07 %, 28.28 % and 36.67 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

7.62 mm CBR depth of penetration

- Acidic soil sample 1 of pH = 4.02 after lime treatment at CBR penetration depth of 7.62 mm recorded 41.1 %, 28.56 % and 35.61 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

At 6 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Acidic soil sample 2 of pH = 4.92 after lime treatment at 6 % lime content recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing and at CBR penetration depth of 2.54 mm, 17.01 %, 31.03 %, and 33.5 % were recorded the forces required to penetrate the compacted surface of the soil samples for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually).
- At the same lime content of 6 % for CBR penetration depth of 2.54 mm and at 55 mechanical compactive efforts, acidic soil sample 1 of pH = 4.02 after lime treatment recorded 19.33 % as the force required to penetrate the compacted surface of the soil. This was in comparison to other soil samples at the same depth and lime content.

5.08 mm CBR depth of penetration

- Acidic soil sample 2 of pH = 4.92 after lime treatment at a CBR penetration depth of 5.08 mm, recorded percentages were 21.88 %, 38.07 % and 39.57 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e.55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

7.62 mm CBR depth of penetration

- Acidic soil sample 2 of pH = 4.92 after lime treatment at a CBR penetration depth of 7.62 mm recorded 24.69 %, 40.97 % and 42.4 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

At 8 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Acidic soil samples 1, 2 and 3 of pH = 4.02, 4.92 and 5.55 respectively after lime treatment of 8 % recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing and at CBR penetration depth of 2.54 mm, sample three recorded 39.27 % at 55 mechanical compactive efforts.
- At the same lime content of 8 % and at CBR penetration depth of 2.54 mm, acidic soil sample 2 of pH = 4.92 after lime treatment recorded 47.14 % at 25 mechanical compactive efforts. This was in comparison to other soil samples at the same depth and lime content.
- Also at the same lime content and depth, acidic soil sample 2 of pH = 4.02 after lime treatment recorded 26.53 % at 55 manual compactive efforts.

5.08 mm CBR depth of penetration

- Acidic soil sample 2 of pH = 4.92 after lime treatment and at CBR penetration depth of 5.08 mm recorded 44.61 %, 48.61 % and 37.37 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

7.62 mm CBR depth of penetration

- Acidic soil sample 2 of pH = 4.92 after lime treatment at a CBR penetration depth of 7.62 mm recorded 47.29 %, 47.29 %, 42.52 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

At 10 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Acidic soil sample 2 of pH = 4.92 after lime treatment at 10 % of lime content recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing and at CBR penetration depth of 2.54 mm, 55.08 %, 50.73 % and 52.08 % were recorded as the percentages of force required to penetrate the compacted surface of the soil for respective compactive efforts for soil sample two (i.e. 55 mechanically, 25 mechanically and 55 manually).

5.08 mm CBR depth of penetration

- Acidic soil sample 2 of pH = 4.92 after lime treatment and at CBR depth of 5.08 mm, recorded 58.7 %, 57.55 % and 50.21 % as the required forces to penetrate the compacted surface of the soil samples for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.
- At the same depth and same lime content of 10 %, acidic soil sample 1 of pH = 4.02 after lime treatment recorded 58.70 % as the required force to penetrate the compacted surface at 55 mechanical compactive efforts. This was in comparison to other soil samples at the same depth and lime content.

7.62 mm CBR depth of penetration

- Acidic soil sample 2 of pH = 4.92 after lime treatment and at CBR depth of 7.62 mm, 59.16 %, and 60.14 % and, 48.16 % were recorded as the required forces for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

To conclude, acidic soil sample 3 of pH = 5.55 recorded lower CBR percentages for required forces to penetrate the compacted surface of the soil at almost every CBR depth of penetration and every compactive efforts. The rate of change in CBR relating to acidic soil sample 3 percentage change was impacted by the lower moisture contents compared to other soil samples (see Table 2). This was one contributory factor to lower values of CBR compared to that of other soil samples.

Acidic soil samples 1 of pH = 4.02 and acidic soil sample two of pH = 4.92 showed constant increase in CBR penetration at all depths (i.e. 2.54 mm, 5.08 mm and 7.62 mm). This was mostly at lime contents 2 %, 4 % and 10 %. The constant increase in

CBR for soil samples compacted at 55 compactive efforts was a direct indication of the principal chemical reactions that took place during the lime-soil stabilisation process.

4.2.2.2 Alkaline soil samples-CBR results (samples 4, 5 & 6)

The discussion below compares alkaline soil samples (i.e. 4, 5 and 6) at depths specified. The comparison is in terms of the highest CBR forces recorded for each lime content, when mechanically compacted at 55 compactive efforts, mechanically compacted at 25 compactive efforts and manually compacted at 55 compactive efforts.

At 2 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Alkaline soil sample 6 of pH = 8.68 after lime treatment, at 2 % lime content recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing and at CBR penetration depth of 2.54 mm, recorded percentages were 80.79 %, 86.26 % and 33.8 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually).

5.08 mm CBR depth of penetration

- Alkaline soil sample 6 of pH = 8.68 after lime treatment and at 5.08 mm CBR depth of penetration recorded 94.52 %, 80.34 % and 34.92 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

7.62 mm CBR depth of penetration

- Alkaline soil sample 6 of pH = 8.68 after lime treatment and at 7.62 mm CBR penetration depth recorded 94.15 %, 76.52 % and 33.84 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually).

This was in comparison to other soil samples at the same depth and lime content.

At 4 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Alkaline soil samples 5 and 6 of pH = 8.27 and 8.68 respectively after lime treatment, recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing and at CBR penetration depth of 2.54 mm, soil sample 5 recorded 54.71 % and 58 % as the forces required at 25 mechanical compactive efforts and 55 manual compactive efforts respectively.
- At the same lime content of 4 % and at the same CBR depth of penetration, alkaline soil sample 6 of pH = 8.68 after lime treatment, recorded 135.12 % as the forces required at 55 mechanical compactive efforts. This was in comparison to other soil samples at the same depth and lime content.

5.08 mm CBR depth of penetration

- Alkaline soil sample 5 of pH = 8.27 after lime treatment and at CBR penetration depth of 5.08 mm recorded 62.05 % and 62.4 % as the forces required at 25 mechanical compactive efforts and 55 manual compactive efforts respectively. This was in comparison to other soil samples at the same depth and lime content.
- At the same lime content and CBR penetration depth, alkaline soil sample 6 of pH = 8.68 after lime treatment, recorded 142.14 % as the force required at 55 mechanical compactive efforts. This was in comparison to other soil samples at the same depth and lime content.

7.62m CBR depth of penetration

- Alkaline soil sample 5 of pH = 8.27 after lime treatment and at CBR penetration depth of 7.62 mm, 63.22 % and 59.79 % as the forces required at 25 mechanical compactive efforts and 55 manual compactive efforts respectively. This was in comparison to other soil samples at the same depth and lime content.

- At the same lime content and CBR penetration depth, alkaline soil sample 6 of pH = 8.68 after lime treatment, recorded 137.18 % as the force required at 55 mechanical compactive efforts. This was in comparison to other soil samples at the same depth and lime content.

At 6 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Alkaline soil sample 5 of pH = 8.27 after lime treatment and at 6% lime concentration recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing and at CBR penetration depth of 2.54 mm, 128.9 %, 67.45 % and 42.79 % as the forces required to penetrate the compacted surface of the soil samples for the respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually).

5.08 mm CBR depth of penetration

- Alkaline soil sample 6 of pH = 8.68 after lime treatment, at CBR penetration depth of 5.08mm recorded 41.14 %, 73.59 % and 50.95 % as the forces required at respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

7.62 mm CBR depth of penetration

- Alkaline soil sample 6 of pH = 8.68 after lime treatment, at CBR depth of 7.62 mm, 38.99 %, 70.96 % and 53.32 % were the respective recorded forces required at respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

At 8 % of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Alkaline soil sample 5 of pH = 8.27 after lime treatment, incorporating 8 % lime concentration recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content. After 7 days of curing and at penetration depth of 2.54 mm, recorded 97.72 %, 62.78 % and 29.3 % as the forces required for compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually).

5.08 mm CBR depth of penetration

- Alkaline soil sample 5 of pH = 8.27 after lime treatment, at CBR penetration depth of 5.08 mm recorded 103.21 %, 64.35 % and 33.82 % as the forces required to penetrate the compacted surface of the soil for respective compactive efforts (i.e. 55 mechanically, 25 mechanically and 55 manually). This was in comparison to other soil samples at the same depth and lime content.

7.62mm CBR depth of penetration

- Alkaline soil sample 6 of pH = 8.68 after lime treatment, at CBR depth of 7.62 mm, 102.15 % and 66.3 % were recorded as the forces required at 55 mechanical compactive efforts and 25 mechanical compactive efforts respectively. This was in comparison to other soil samples at the same depth and lime content.
- At the same lime content and depth, alkaline soil sample 5 of pH = 8.27 after lime treatment, recorded 53.32 % as the force required at 55 manual compactive efforts. This was in comparison to other soil samples at the same depth and lime content.

At 10% of lime content after 7 days of curing

2.54 mm CBR depth of penetration

- Alkaline soil samples 4, 5 and 6 of pH = 5.55, 9.20 and 8.68 respectively after lime treatment at 10 % lime concentration recorded an increase in CBR penetration compared to other soil samples at the same depth and same lime content.
- After 7 days of curing and at CBR penetration depth of 2.54 mm, 92.02 % was the recorded force required for alkaline soil sample 5 of pH = 5.55 after lime treatment at 55 mechanical compactive efforts. This was in comparison to other soil samples at the same depth and lime content.
- At the same lime content and CBR penetration depth, 80.26 % and 40.92 % were the recorded forces required for alkaline soil sample 6 of pH = 8.68

after lime treatment, at 25 mechanical compactive efforts and 55 manual compactive efforts respectively. This was in comparison to other soil samples at the same depth and lime content.

5.08 mm CBR depth of penetration

- Alkaline soil sample 6 of pH = 8.68 after lime treatment, at depth of 5.08 mm recorded 83.68 % and 46.56 % as the forces required at 25 mechanical compactive effort and 55 manual compactive efforts respectively. This was in comparison to other soil samples at the same depth and lime content.
- At the same lime content and CBR penetration depth, alkaline soil sample 5 of pH = 8.27 after lime treatment, recorded 94.72 % as the force required at 55 mechanical compactive effort. This was in comparison to other soil samples at the same depth and lime content.

7.62 mm CBR depth of penetration

- Alkaline soil sample 6 of pH = 8.68 after lime treatment, at depth of 7.62 mm recorded 81.05 % and 45.5 % as the forces required at 25 mechanical compactive efforts and 55 manual compactive effort respectively. This was in comparison to other soil samples at the same depth and lime content.
- At the same lime content and CBR penetration depth, alkaline soil sample 5 of pH = 8.27 after lime treatment recorded 97.46 % as the force required at 55 mechanical compactive effort. This was in comparison to other soil samples at the same depth and lime content.

To conclude, alkaline soil sample 4 of pH = 9.20 recorded lower CBR percentages for required force to penetrate the compacted surface of the soil sample. Reference can be made to results in Table 2 which illustrate that alkaline soil sample 4 recorded the second least percentages of OMC after sample 3 of pH = 5.55.

In comparing all the soil samples, the six soil samples were, for CBR, compacted manually and mechanically at different compactive efforts, i.e. 55 and 25 respectively. Mechanically compacted soil samples, owing to the number of compactive efforts that were applied to the soil, produced marked change in their geotechnical properties. This implied that compaction process of mechanically densifying the soil samples assisted in pressing the soil particles together into a closer state. In the process, air was expelled from the soil mass.

When soil particles were forced together by compaction, both the number of voids contained in the soil mass and the size of the individual void spaces were reduced. The above-mentioned change in voids had an obvious effect on the movement of water through the soil, thus reducing the permeability and reducing the seepage of water. A short discussion relating to the later (i.e. permeability) is provided in the sub-section below.

Therefore, from an overall point of view, it would appear that alkaline soil samples, particularly at an optimum pH of 8 (i.e. pH = 8.68 for soil sample 6), performed well compared to acidic soil samples for CBR penetration values. Some of the soil features affected by the soil pH associated with the above performance related to the minerals in the soil such as calcium, iron and others.

4.2.3 Soil swelling properties

The swelling of the of the soil samples was tested and analysed. These were soil samples soaked in water. As the soil swelled, pressure exerted on the soaked soil samples was measured by means of providing ring and dial gauge. While the soaked soil samples swelled, both the volume and the pressure of the soil changed and was measured in percentages.

The subsequent discussions arise from scrutinization of the results relating to soil swelling of the soil samples. The applications of lime resulted in a remarkable change in the percentage swell of the soil samples.

4.2.3.1 Less swelling of the soil samples

It is evident that the addition of lime to the six soil samples at contents of 2 %, 4 %, 6 %, 8 % and 10 % enabled the swelling of the soil. Most noticeable were the swelling properties of acidic soil sample 2 of pH = 4.92 which had, on average, a swell of 0.01 % after 7, 14 and 28 days of soaking. Acidic soil sample 1 of pH = 4.02 and alkaline soil sample 5 of pH = 8.27 had an average swell of 0.02 % after 7, 14 and 28 days of water soaking at 8 % of lime content. These results were as a consequence of less intercalation of water molecules into the inter-plane space of soil minerals, thus causing a strong layer of impermeability of the soil samples. The reduction in pore spaces or the non-existence of the pores within the soil particles indicated a change in microstructure of the soil on the addition of lime, hence promoting the strength of the tested soil samples. Prolonged days of soaking played a crucial part in that some of the soil samples showed an increase in resistance to CBR penetration test.

4.2.3.2 More swelling of the soil samples

Alkaline soil sample 5 of pH = 8.27 at lime content of 2 %, on average swelled 0.71 % after 7, 14 and 28 days of soaking. Acidic soil sample 3 of pH = 5.55 at lime content of 4 % had an average swell of 1.59 % after 7, 14 and 28 days of water soaking. Sample 3 at lime content of 6 % had a swell of 2.33 % after 7, 14 and 28 days of soaking. Acidic soil sample 3 on average swelled 0.87 % after 7, 14 and 28 days of soaking. Alkaline soil sample 5 at lime of 8 % had an average swell of 0.81 % after 7, 14 and 28 days of soaking. The above implied the availability of pore spaces or the existence of the pores within the soil samples mentioned above, indicating the change in microstructure of the soil on addition of lime as a stabiliser. This promoted the seepage of water in the soil sample, thus resulting in the decrease in strength on the lime stabilised soil samples.

4.2.4 Unconfined compressive strength results

The UCS test was conducted to determine the undrained strength of the soil samples tested under unconfined conditions. The result of the UCS test conducted on the three acidic soil samples and three alkaline soil samples stabilised with 2 %, 4 %, 6 %, 8 % and 10 % lime contents respectively, are shown in Figure 24. The results are in order of the lime content used for the soil samples, and are in order of the curing days. The result indicated that the UCS of the soil samples can be significantly improved by lime stabilisation.

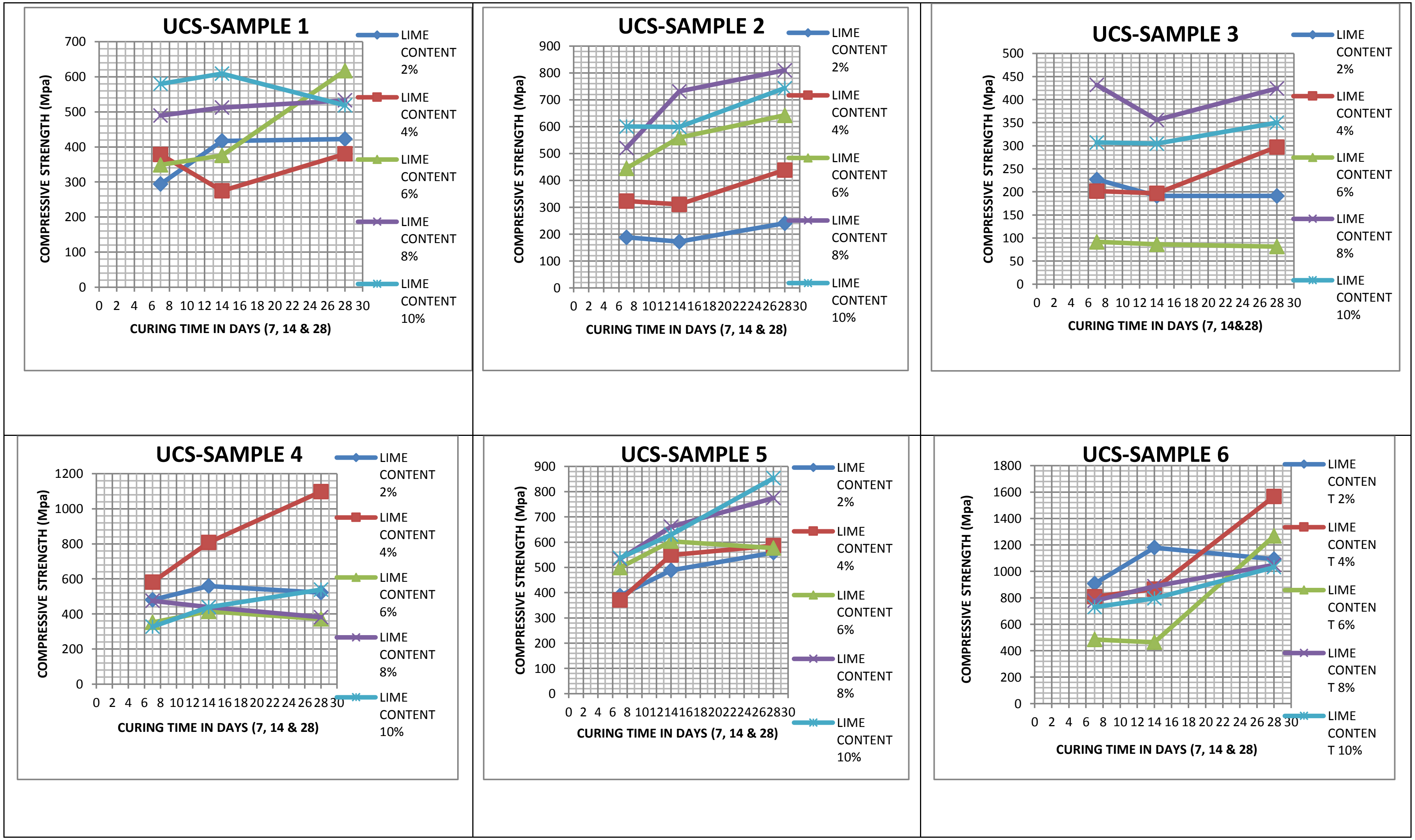


Figure 24: Unconfined Compressive Strength (UCS) for soil samples 1 to 6

4.2.4.1 UCS at 2 % of lime content for all soil samples

After 7 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 906.69 Mpa compared to 480.82 Mpa for sample 4, 387.95 Mpa for sample 5, 294.17 Mpa for sample 1, 277.09 Mpa for sample 3 and 188.26 Mpa for sample 2 after curing day 7.

After 14 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 1179.36 Mpa compared to 559 Mpa for sample 4, 448.45 Mpa for sample 5, 416.76 Mpa for sample 1, 191.48 Mpa for sample 3 and 172.35 Mpa for sample 2 after curing day 14.

After 28 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 1092.05 Mpa compared to 558.29 Mpa for sample 5, 521.59 Mpa for sample 4, 422.44 Mpa for sample 1, 240.72 Mpa for sample 2 and 191.29 Mpa for sample 3 after curing day 28.

4.2.4.2 UCS at 4 % of lime content for all soil samples

After 7 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 809.28 Mpa compared to 581.44 Mpa for sample 4, 377.98 Mpa for sample 1, 370.26 Mpa for sample 5, 323.49 Mpa for sample 2 and 201.7 Mpa for sample 3 after curing day 7.

After 14 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 865.53 Mpa compared to 807.77 Mpa for sample 4, 548.49 Mpa for sample 5, 310.80 Mpa for sample 2, 274.69 Mpa for sample 1 and 196.97 Mpa for sample 3 after curing day 14.

After 28 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 1566.86 Mpa compared to 1097.16 Mpa for sample 4, 586.36 Mpa for sample 5, 438.82 Mpa for sample 2, 380.06 Mpa for sample 1 and 297.35 Mpa for sample 3 after curing day 28.

4.2.4.3 UCS at 6 % of lime content for all soil samples

After 7 days of curing

- Alkaline soil sample 5 of pH = 8.27 recorded the highest UCS value 499.05 Mpa compared to 483.71 Mpa for sample 6, 445.07 Mpa for sample 2, 351.89 Mpa for sample 4, 348 Mpa for sample 1 and 316.76 Mpa for sample 3 after curing 7.

After 14 days of curing

- Alkaline soil sample 5 of pH = 8.27 recorded the highest UCS value of 603.41 Mpa compared to 463.6 Mpa for sample 6, 559.06 Mpa for sample 2, 414.96 Mpa for sample 4, 375.71 Mpa for sample 1 and 276.52 Mpa for sample 3 after curing day 14.

After 28 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 1267.23 Mpa compared to 642.61 Mpa for sample 2, 617.29 Mpa for sample 1, 577.08 Mpa for sample 5, 371.02 Mpa for sample 4 and 360.61 Mpa for sample 3 after curing day 28.

4.2.4.4 UCS at 8 % of lime content for all soil samples

After 7 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 776.7 Mpa compared to 533.33 Mpa for sample 5, 520.65 Mpa for sample 2, 489.41 Mpa for sample 1, 475 Mpa for sample 4 and 431.82 Mpa for sample 3 after curing day 7.

After 14 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest value UCS value of 886.55 Mpa compared to 731.44 Mpa for sample 2, 660.61 Mpa for sample 5, 512.11 Mpa for sample 1, 439.39 Mpa for sample 4 and 356.06 Mpa for sample three after curing day 14.

After 28 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 1049.24 Mpa compared to 810.04 Mpa for sample 2, 774.62 Mpa for 5, 532.54 Mpa for sample 1, 423.86 Mpa for sample 3 and 382.01 Mpa for sample 4 after curing day twenty eight (28).

4.2.4.5 UCS at 10 % of lime content for all soil samples

After 7 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 729.17 Mpa compared to 601.14 Mpa for sample 2, 580.01 Mpa for sample 1, 537.12 Mpa for sample 5, 327.46 Mpa for sample 4 and 307.39 Mpa for sample 3 after curing day 7.

After 14 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 796.59 Mpa compared to 629.74 Mpa for 5, 608.83 Mpa for sample 1, 599.14Mpa for sample 2, 439.2 Mpa for sample 4 and 304.74 Mpa for sample 3 after curing day 14.

After 28 days of curing

- Alkaline soil sample 6 of pH = 6.68 recorded the highest UCS value of 1031.06 Mpa compared to 853.41 Mpa for sample 5, 743.56 Mpa for sample 2, 538.83 Mpa for sample 4, 518.54 Mpa for sample 1 and 350 Mpa for sample 3 after curing day 28.

Constant increase in strength was indicated by the lime stabilised material for alkaline soil sample 6 of pH = 8.68 at each level of lime content with the highest strength recorded at lime content of 4 % (1566.86 MPa) after curing for 28 days. Acidic soil sample 1 and 2 of pH = 4.02 and 4.92 respectively indicated slow growth in strength compared to sample 2 when treated with lime content of 6 %. Possible contributory factors leading to the above were minor issues relating to the testing methodology and perhaps problems relating to the loss of cementitious content in stabilised soil as a result of mixing the samples with lime and moist soil in the open air. The latter possibly promoted the formation of calcium carbonate as a result of carbonation (Cizer *et al*., 2006).

In order to investigate the effect of pH on shear strength of treated soil for UCS, geotechnical properties of the soil samples of different pH values (pH = 4.02, 4.92, 5.55, 9.20, 8.27 and 8.68 for sample 1 to 6 respectively) were determined using the UCS machine. Based on the above results of the UCS strength tests, it was found that the geotechnical properties increased considerably if the soil had a high pH (e.g. pH = 8.68 for alkaline soil sample soil 6 and pH = 8.27 for alkaline soil sample 5). At an alkaline pH, the increase of ionic elements/minerals favoured face-to-face aggregation of the soil samples. The UCS geotechnical properties decreased considerably when the pH values decreased to less than pH = 8. This was particularly the case for acidic soil sample 1 of pH = 4.02, soil sample 2 of pH = 4.92 and soil sample 3 of pH = 5.55.

4.2.5 Microstructural properties

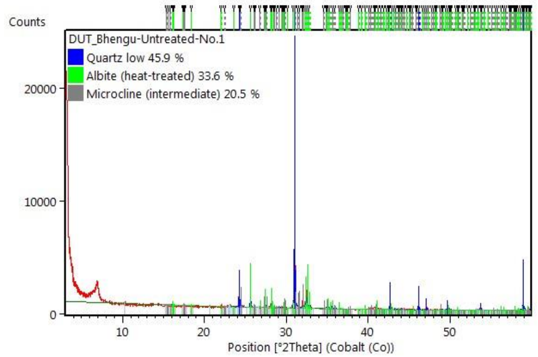
4.2.5.1 X-ray diffraction

The soil pH had no significant or direct impact on X-RD; however, for the sake of studying the chemical elements found of the soil samples, the subsequent discussion has relevance.

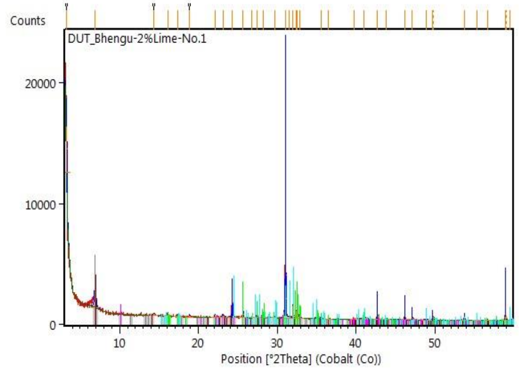
Figures 25 to 30 show the X-RD graphs for both sets of soil samples treated with different lime variations. The X-RD technique provided detailed information about the atomic structure of the crystalline nature of the six soil samples that were lime treated.

The Y-axis on Figures 25 to 30 show the counts. These are the number of x-rays received and processed by the detector. The X-axis on Figures 25 to 30 shows the energy level of those counts. From the X-RD results, the soils tested consisted of the minerals quartz, albite, microcline, montmorillonite, biotite, rutile and chrysotile. These were identified from the peaks.

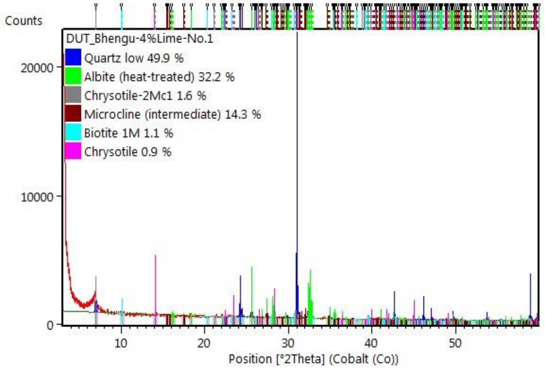
Untreated soil sample 1



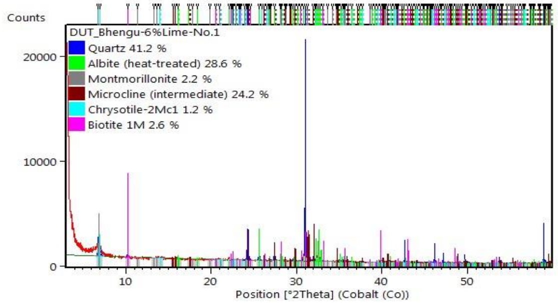
Sample 1: 2 % lime



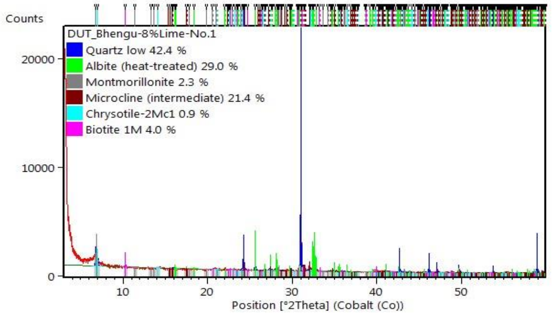
Sample 1: 4% lime



Sample 1: 6 % lime



Sample 1: 8 % lime



Sample 1: 10 % lime

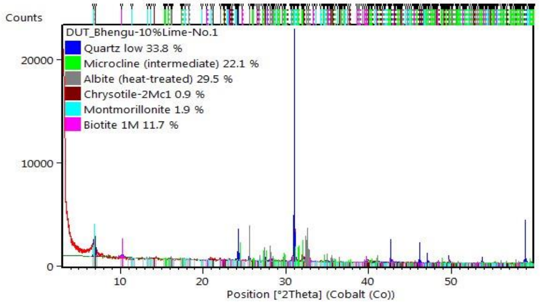
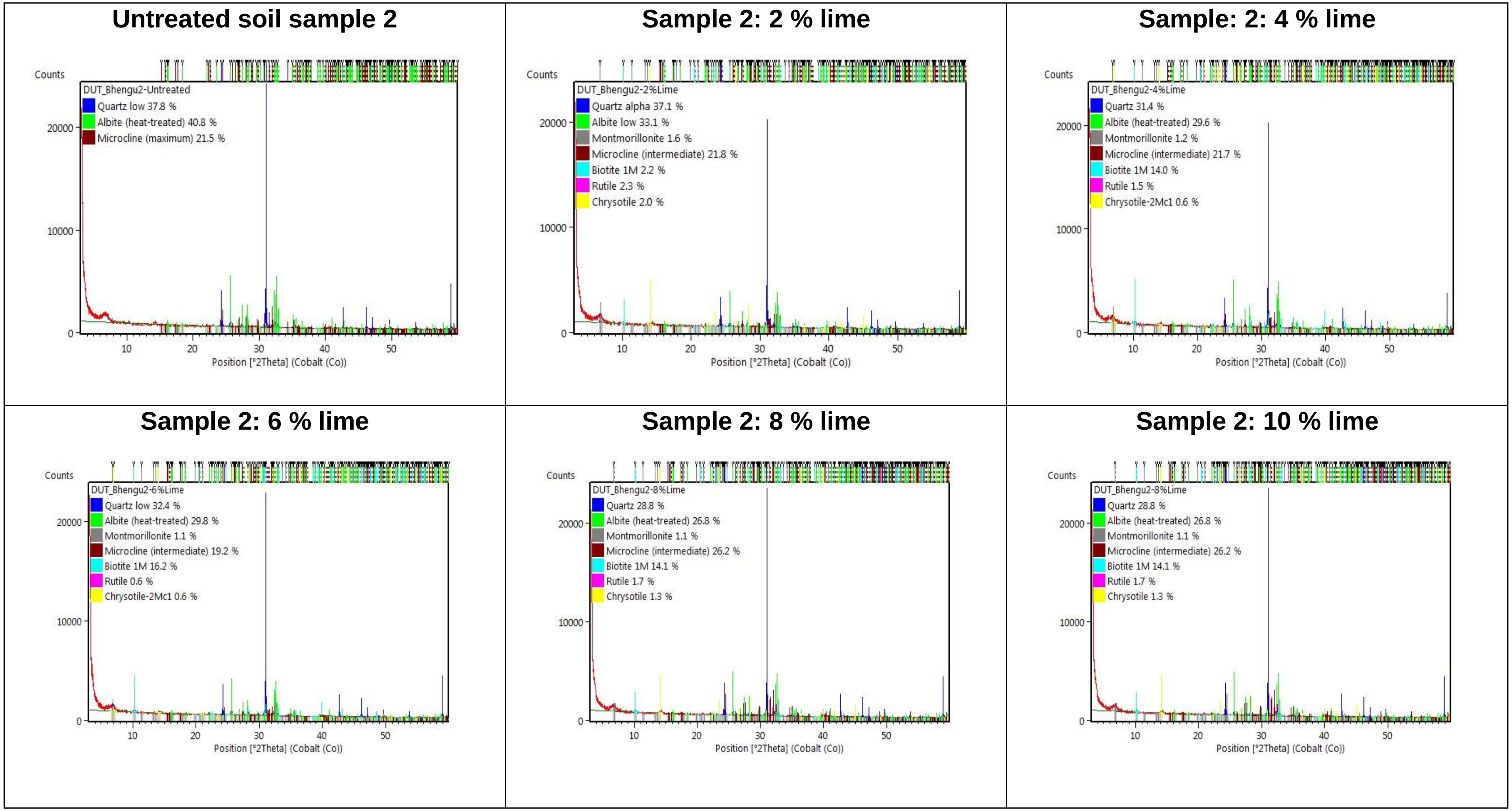


Figure 25: Sample 1 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively



Untreated soil sample 2

Sample 2: 2 % lime

Sample: 2: 4 % lime

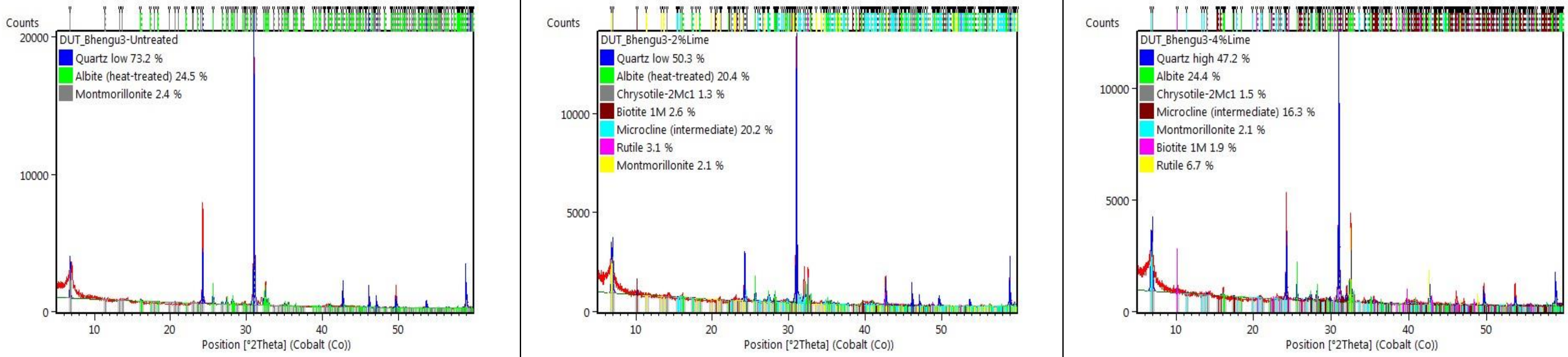
Sample 2: 6 % lime

Sample 2: 8 % lime

Sample 2: 10 % lime

Figure 26: Sample 2 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively

Untreated soil sample 3 | **Sample 3: 2 % lime** | **Sample 3: 4 % lime**



Sample 3: 6 % lime | **Sample 3: 8 % lime** | **Sample 3: 10 % lime**

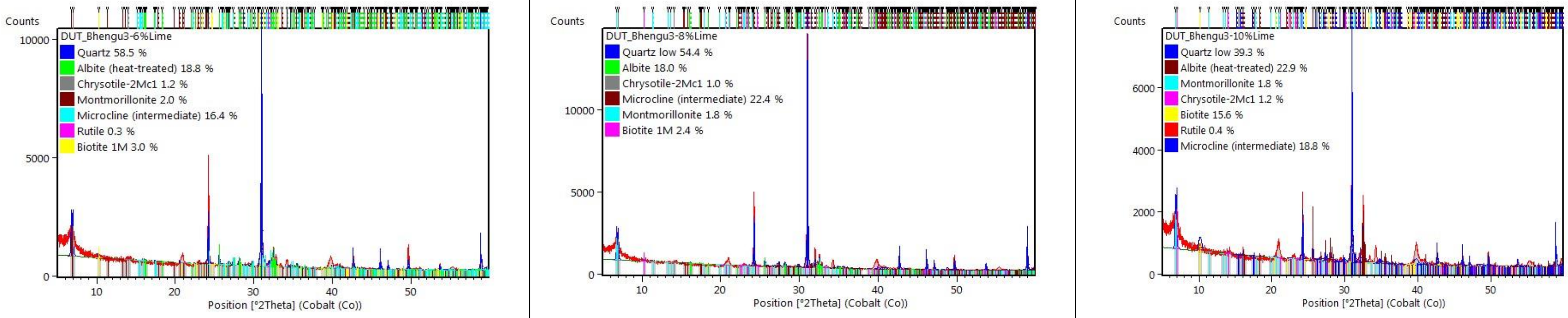
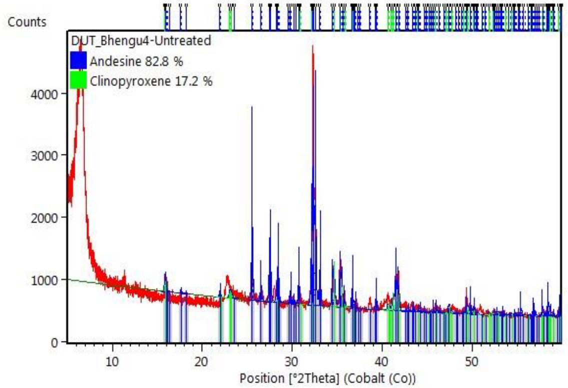
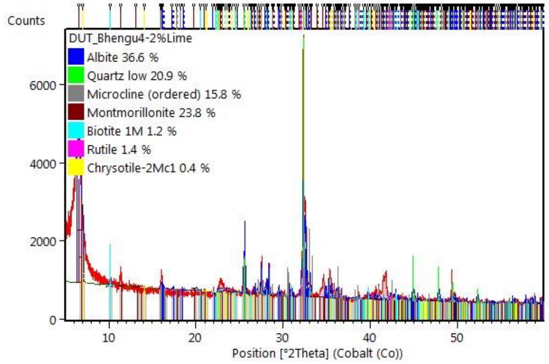


Figure 27: Sample 3 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively

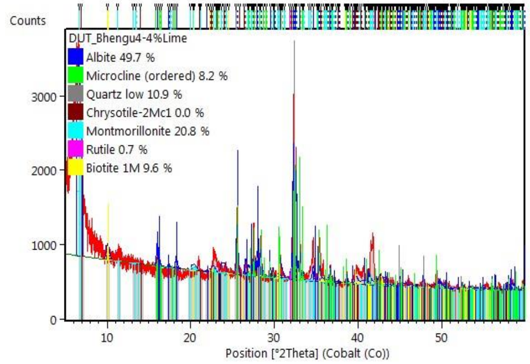
Untreated soil sample 4



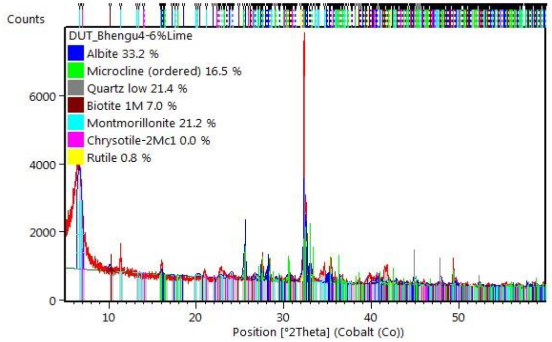
Sample 4: 2 % lime



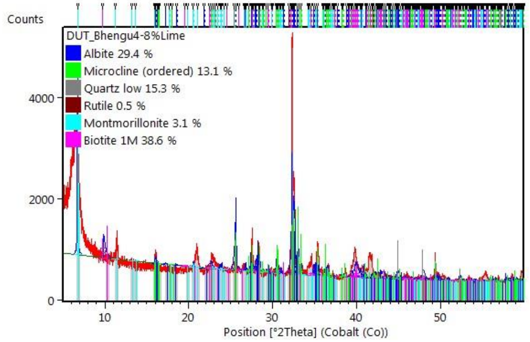
Sample 4: 4 % lime



Sample 4: 6 % lime



Sample 4: 8 % lime



Sample 4: 10 % lime

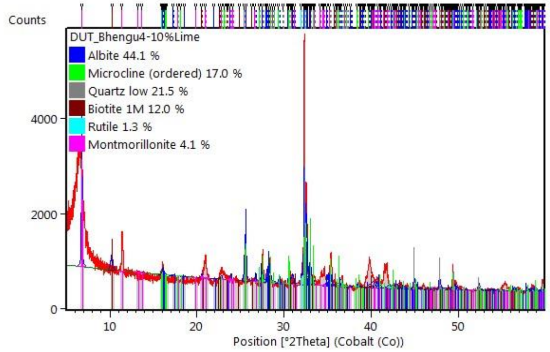
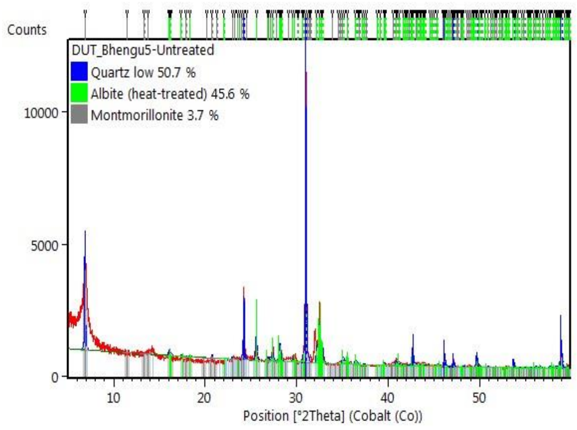
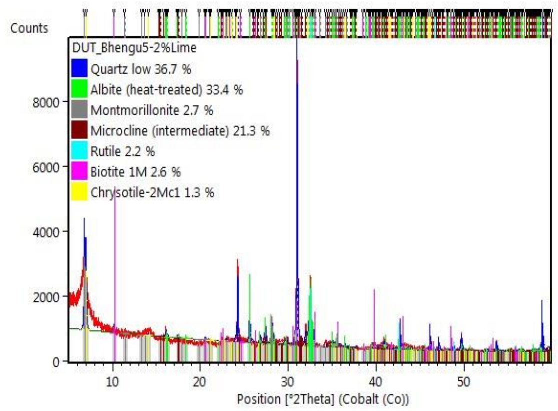


Figure 28: Sample 4 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively

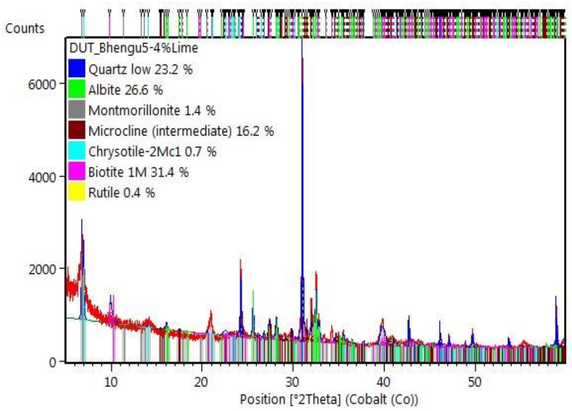
Untreated soil sample 5



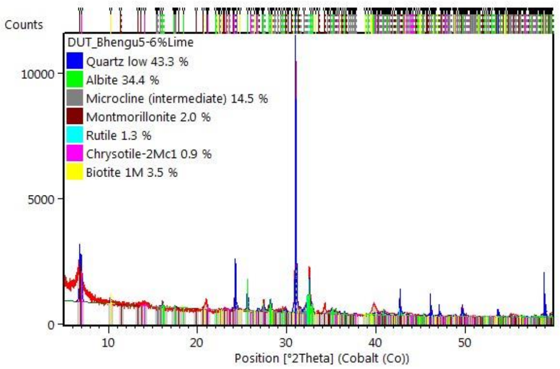
Sample 5: 2 % lime



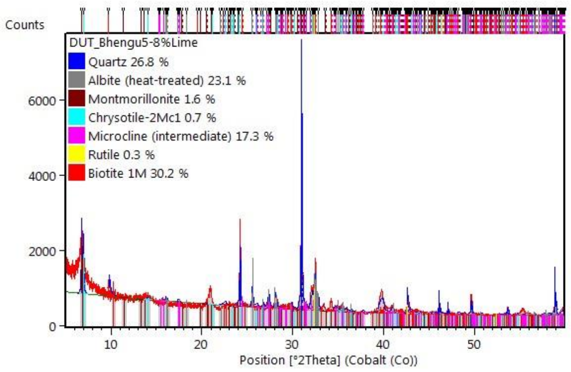
Sample 5: 4 % lime



Sample 5: 6 % lime



Sample 5: 8 % lime



Sample 5:10 % lime

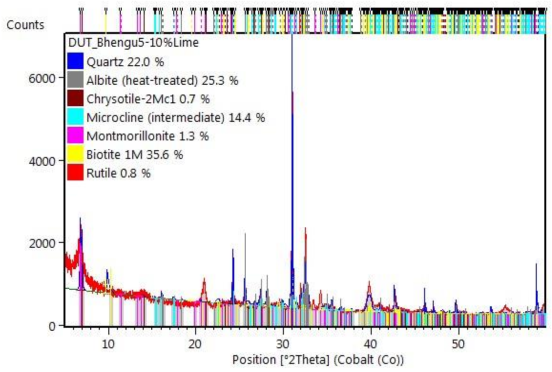


Figure 29: Sample 5 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively

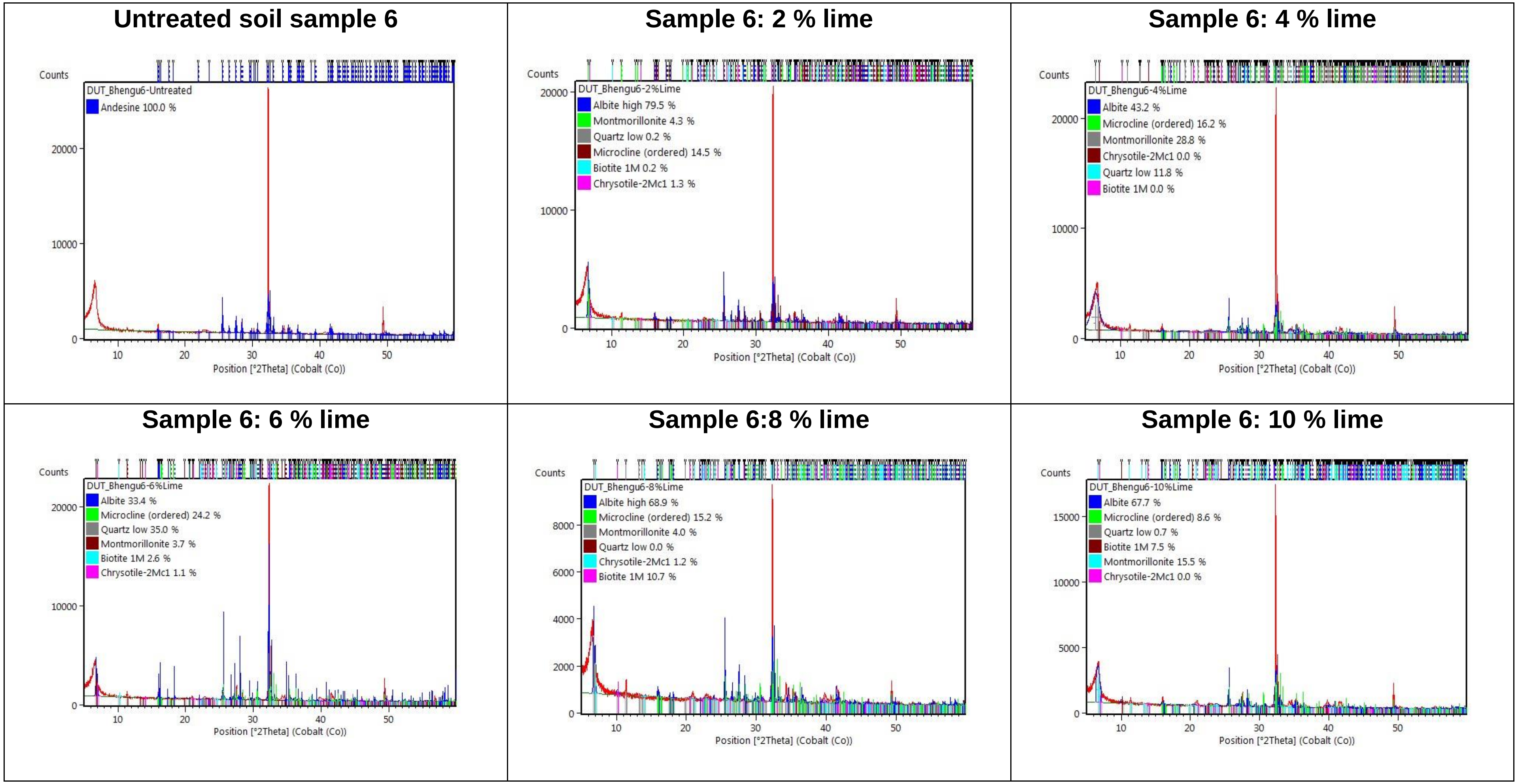


Figure 30: Sample 6 X-RD graphs: Untreated sample, treated samples at 2 %, 4 %, 6 %, 8 %, and 10 % lime respectively

The X-RD testing showed different kinds of mineral groups that were discovered in the soil samples. The following subsection discusses the mineral groups discovered during testing.

4.2.5.2 Scanning electron microscope (SEM) & EDS/EDX

The soil pH had no significant impact on SEM/EDS/EDX studies; however, studying the microstructural behaviour of the soil samples benefits the subsequent discussion.

The SEM studies indicated that the microstructures of the tested soil samples for the six soil samples of different pH ranges changed due to the application of lime. The SEM micrographs of lime stabilised soil samples which showed rod-like crystals (ettringite). Pozzolanic reaction through the long-term curing contributed to the increase in strength gain. The chemical reaction referred to here promotes pozzolanic reactions and produces new minerals such as calcium aluminate hydrates (Al-Mukhtar, Lasledj and Alcover, 2010). The reactions between lime, water, soil silica and alumina that constitute various cementing-type materials are referred to as pozzolanic reactions (National Lime Association, 2004).

SEM and EDS/EDX analysis was carried out on the tiny soil samples after the unconfined compression tests. Lime treatment changed the soil fabric significantly (depending on curing time and water content), the optimal time being seven days of curing. Figures 31 to 42 show the SEM and EDS/EDX micrographs of treated soil samples. The SEM and EDS/EDX images display compositional contrast that result from different atomic number elements and their distribution. As can be seen from these figures, soil particles of different pH ranges treated with different percentages of lime were observed and displayed flaky texture.

Flaky texture confirmed the formation of needle-like crystalline formations in the soil sample such as ettringite. Further to the above mentioned, the figures show a reduction in pore spaces or the non-existence of the pores within the soil particles indicating the change in microstructure of the soil on addition of lime as a stabiliser, hence promoting the strength of the tested soil samples. During lime soil reaction, hydroxide (OH^-) and bicarbonates ($HC03^-$) were released, hence reducing the soil acidity.

The EDS/EDX show the elements found in the soil samples. Chemical elements, ordered by their atomic number, electron configurations, and recurring chemical properties were identified in the soil samples tested. These (elements) ranged from magnesium (Mg), potassium (K), calcium (Ca), titanium (Ti), iron (Fe), aluminium (Al), silicon (Si) oxygen (O) to carbon.

With limestone being the source of Ca and Mg and in the presence of water, some of the elements listed above formed part of the chemical composition making up the hydrated lime used for this research. Among these are calcium, magnesium, iron, and silicone as can be seen on the EDS/EDX micrographs.

Micrographs or images of all the soil samples at other different areas, besides area one (i.e. area two and three) are shown in figures 73-102 on appendix D.

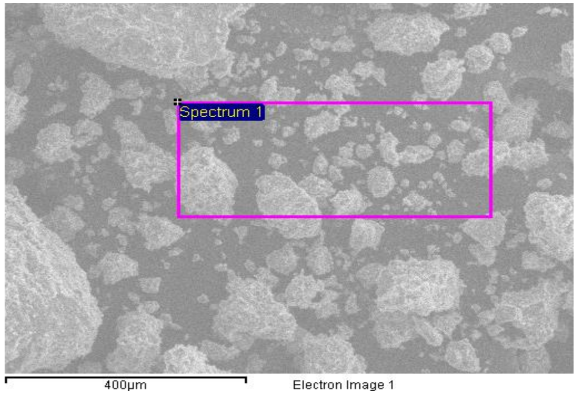
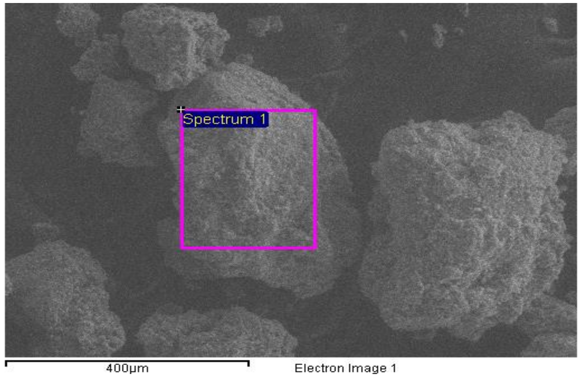
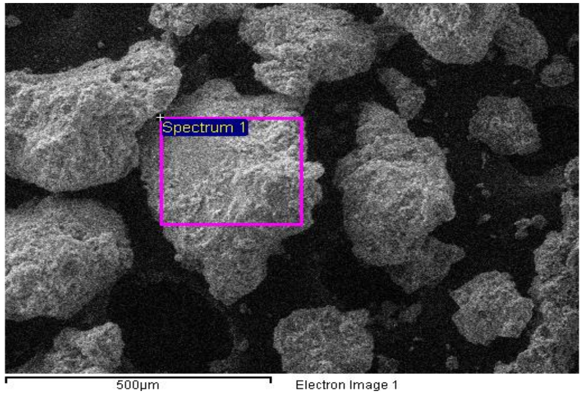
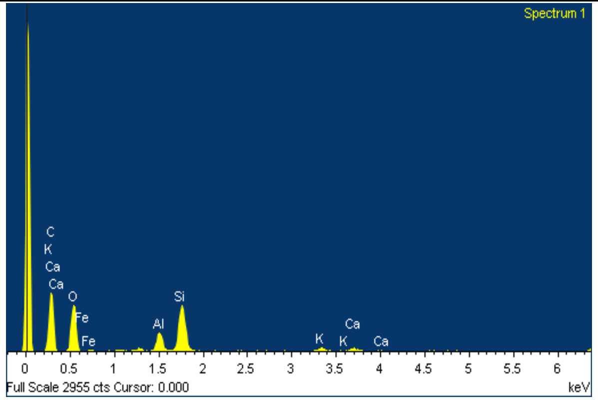
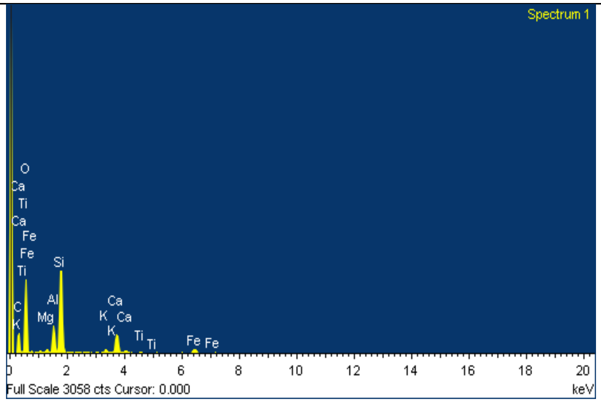
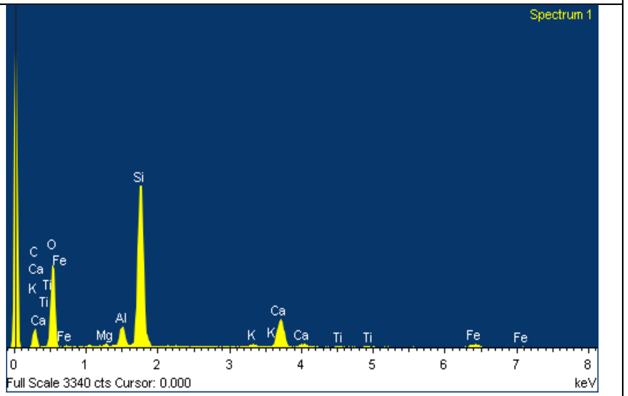
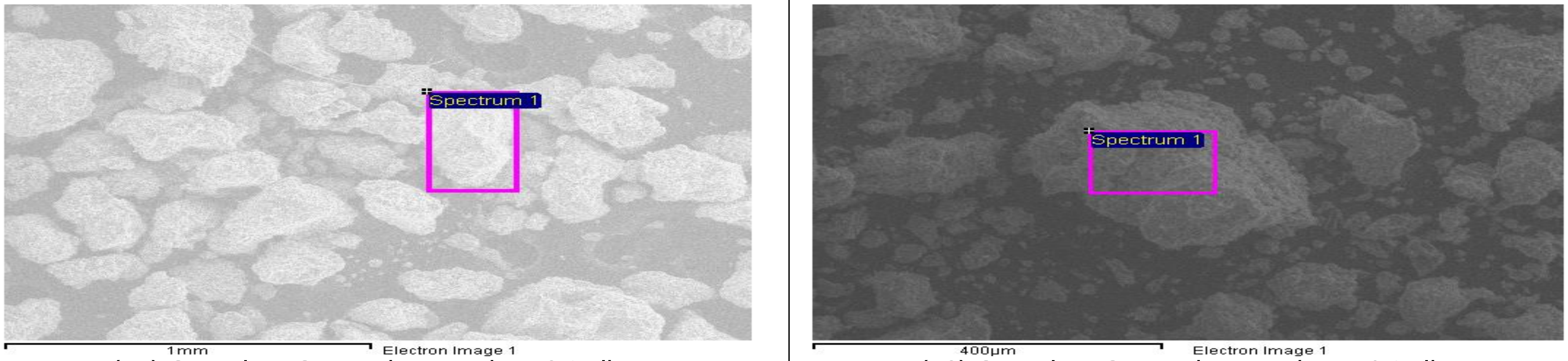
Sample 1: 2 % lime at 7days - Area 1	Sample 1: 4 % lime at 7 days - Area 1	Sample 1: 6 % lime at 7 days - Area 1
 (a1) Sample 1 SEM micrograph at 2 % lime	 (a2) Sample 1 SEM micrograph at 4 % lime	 (a3) Sample 1 SEM micrograph at 6 % lime
 (b1) Sample 1 EDS/EDX	 (b2) Sample 1 EDS/EDX	 (b3) Sample 1 EDS/EDX

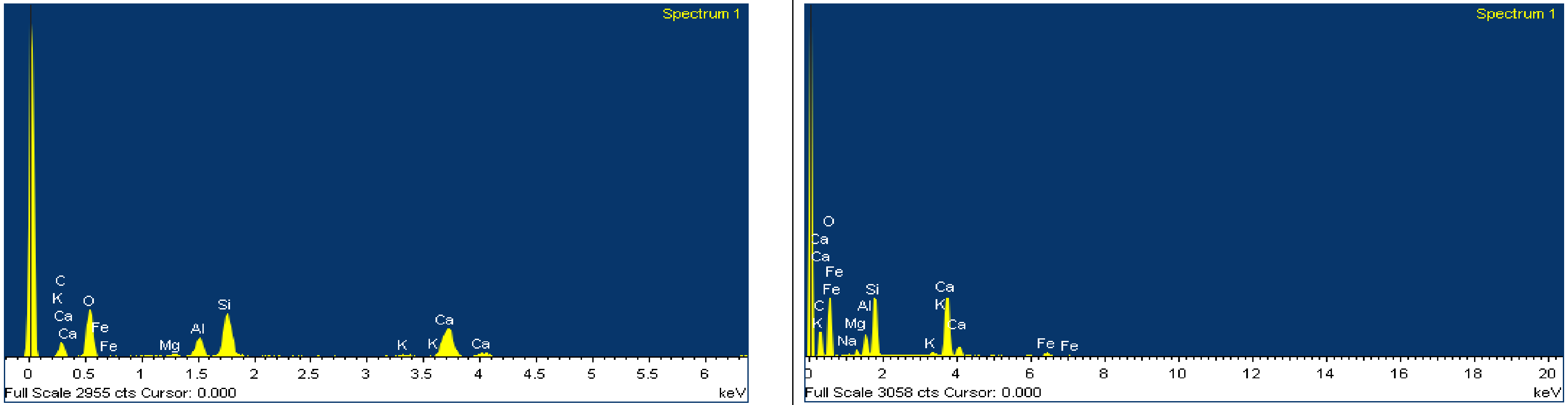
Figure 31: (a1), (a2) and (a3): Sample 1 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 1 EDS/EDX area 1 images respectively

Sample 1: 8 % lime at 7 days - Area 1 | **Sample 1: 10 % lime at 7 days - Area 1**



(a1) Sample 1 SEM micrograph at 8 % lime

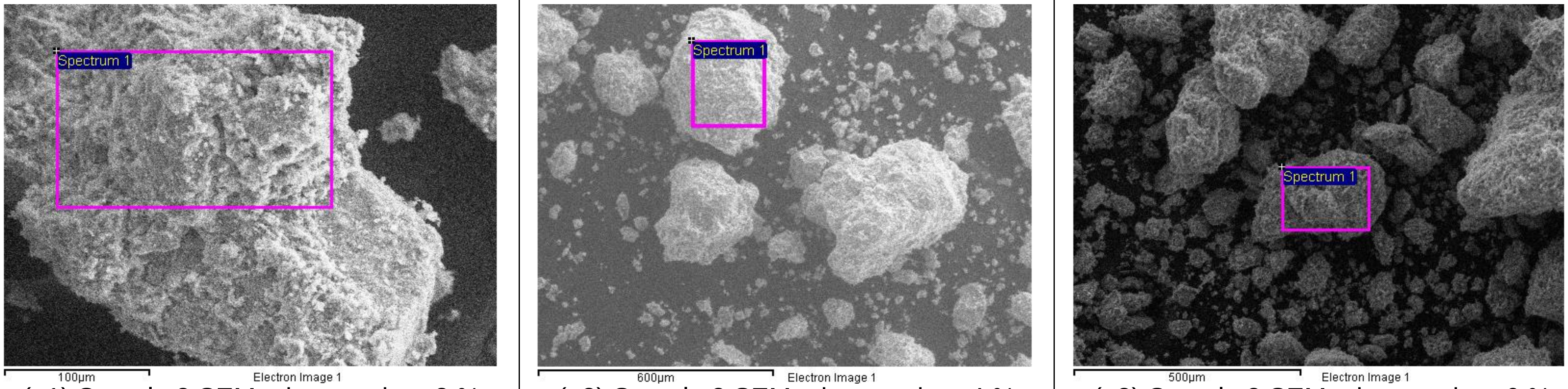
(a2) Sample 1 SEM micrograph at 10 % lime



(b1) Sample 1 EDS/EDX

(b2) Sample 1 EDS/EDX

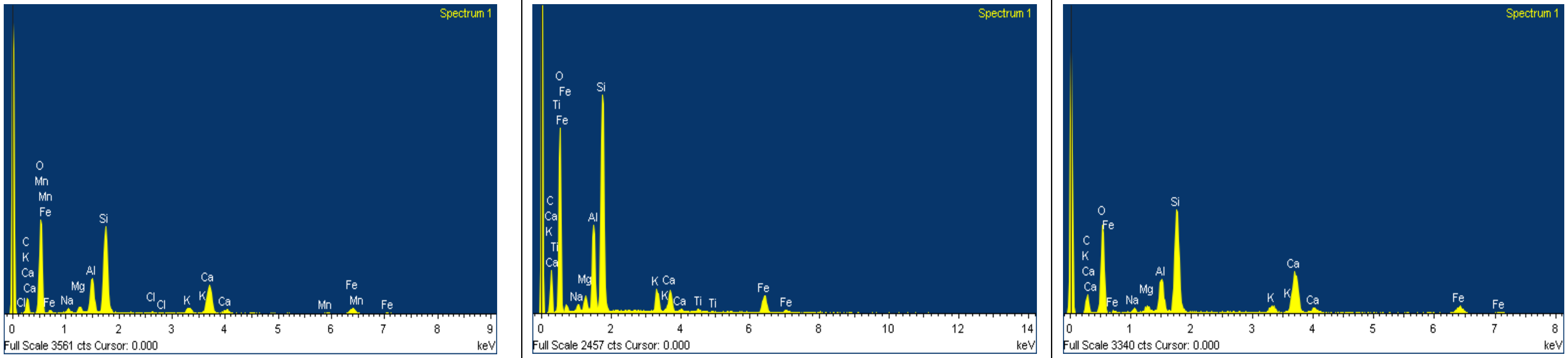
Figure 32: (a1) and (a2): Sample 1 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 1 EDS/EDX area 1 images respectively



(a1) Sample 2 SEM micrograph at 2 % lime

(a2) Sample 2 SEM micrograph at 4 % lime

(a3) Sample 2 SEM micrograph at 6 % lime

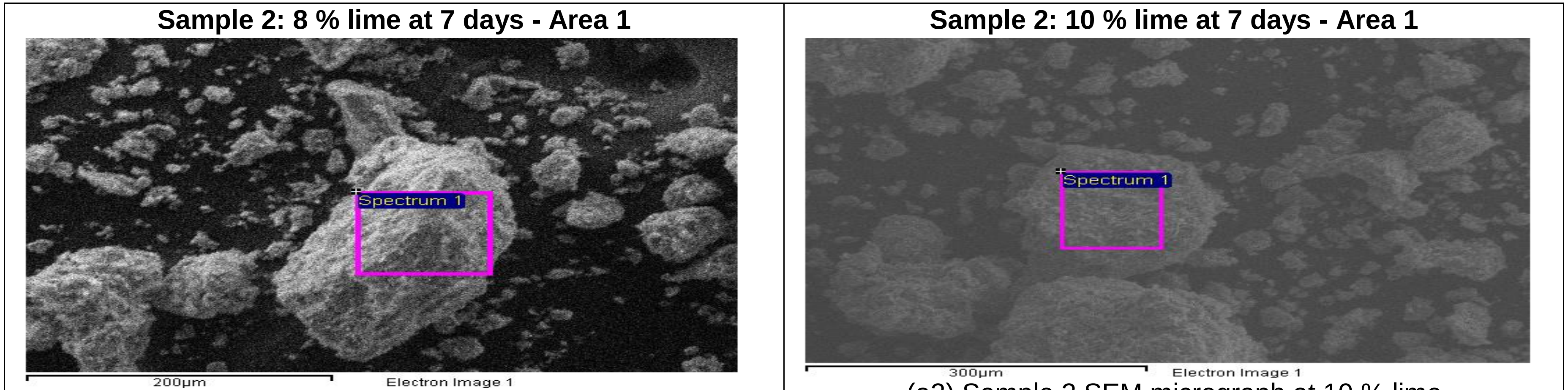


(b1) Sample 2 EDS/EDX

(b2) Sample 2 EDS/EDX

(b3) Sample 2 EDS/EDX

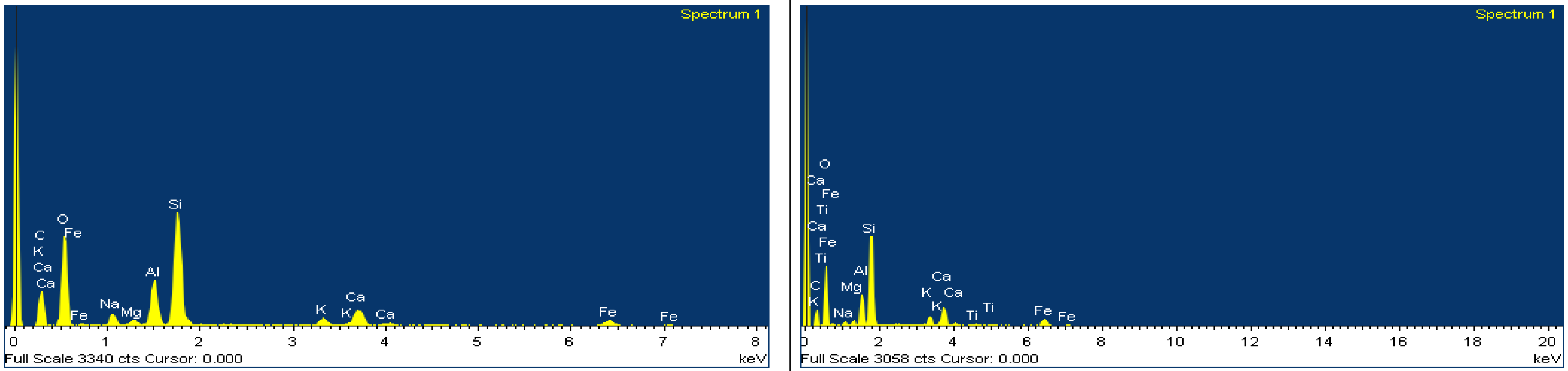
Figure 33: (a1), (a2) and (a3): Sample 2 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 2 EDS/EDX area 1 images respectively


Sample 2: 8 % lime at 7 days - Area 1

Sample 2: 10 % lime at 7 days - Area 1

(a1) Sample 2 SEM micrograph at 8 % lime

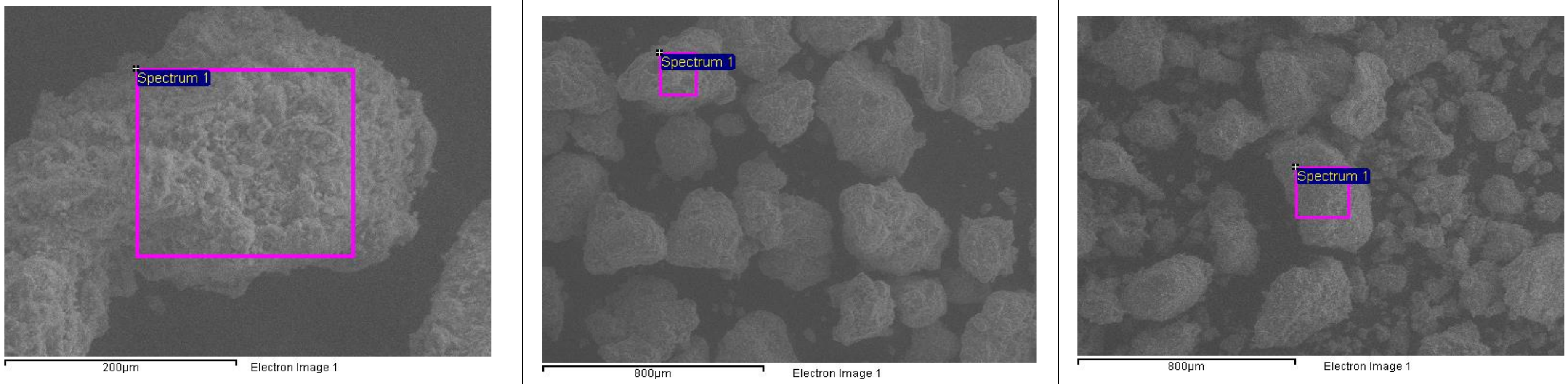
(a2) Sample 2 SEM micrograph at 10 % lime



(b1) Sample 2 EDS/EDX

(b2) Sample 2 EDS/EDX

Figure 34: (a1) and (a2): Sample 2 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 2 EDS/EDX area 1 images respectively



Sample 3: 2 % lime at 7 days - Area 1

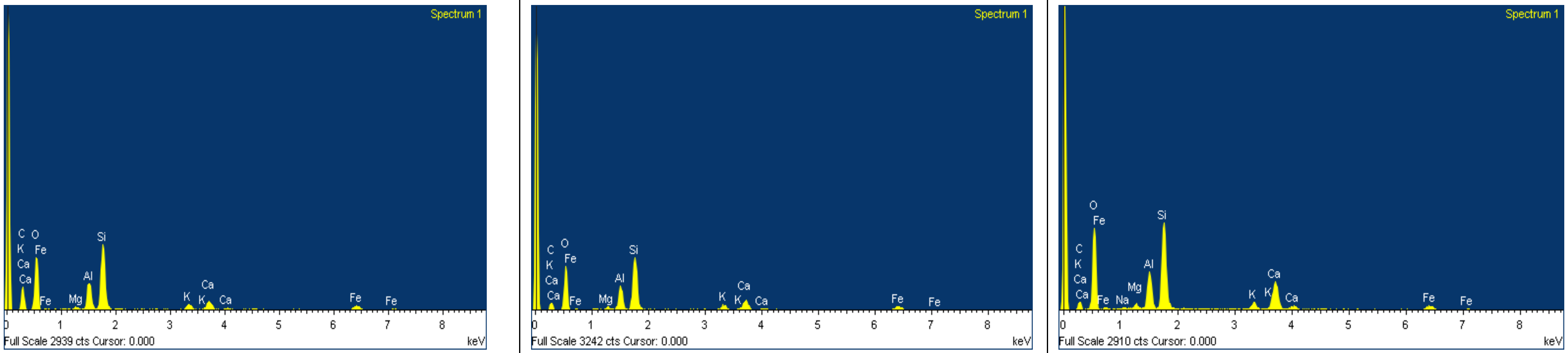
Sample 3: 4 % lime at 7 days - Area 1

Sample 3: 6 % lime at 7 days - Area 1

(a1) Sample 3 SEM micrograph at 2 % lime

(a2) Sample 3 SEM micrograph at 4 % lime

(a3) Sample 3 SEM micrograph at 6 % lime

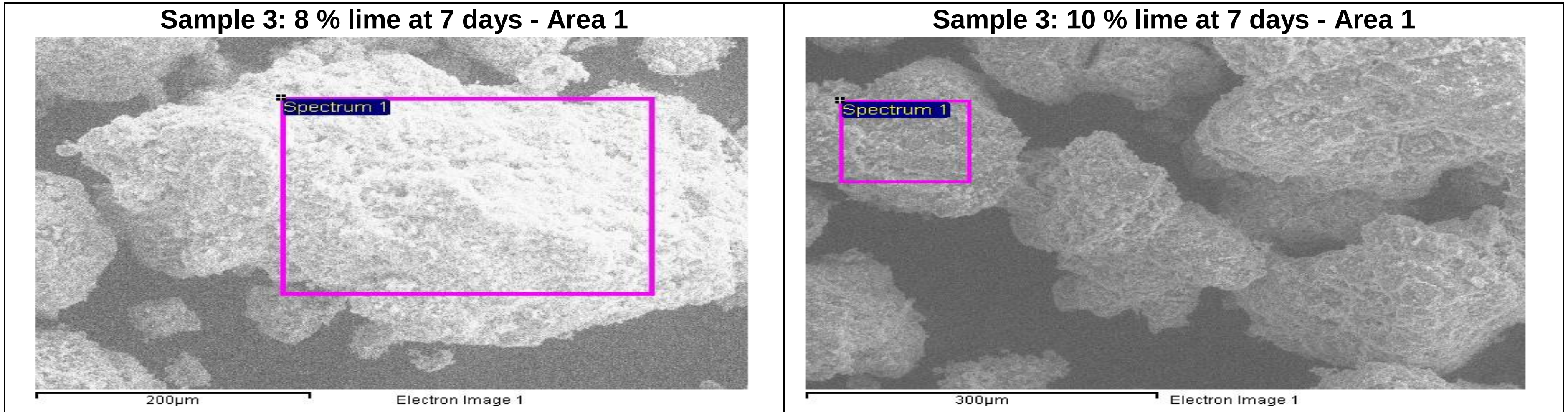


(b1) Sample 3 EDS/EDX

(b2) Sample 3 EDS/EDX

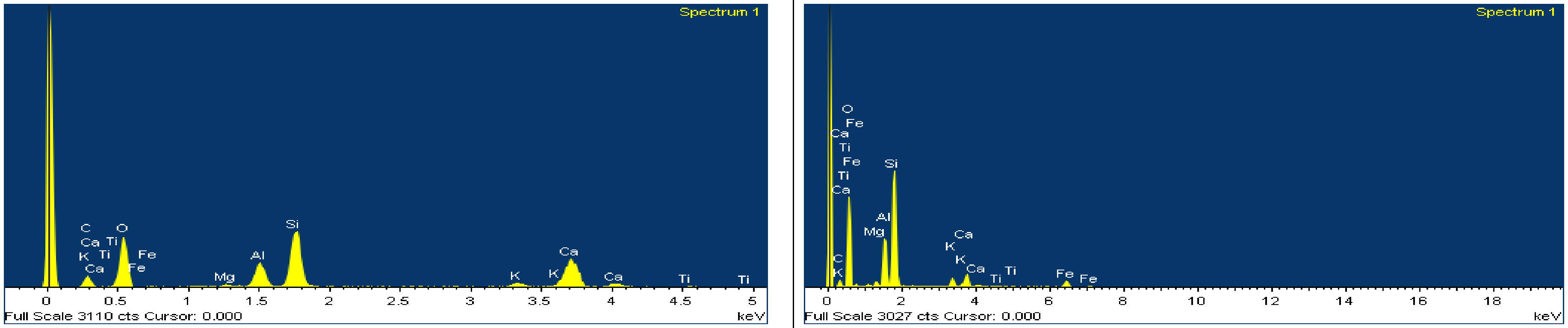
(b3) Sample 3 EDS/EDX

Figure 35: (a1), (a2) and (a3): Sample 3 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 3 EDS/EDX area 1 images respectively



(a1) Sample 3 SEM micrograph at 8 % lime

(a2) Sample 3 SEM micrograph at 10 % lime



(b1) Sample 3 EDS/EDX

(b2) Sample 3 EDS/EDX

Figure 36: (a1) and (a2): Sample 3 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 3 EDS/EDX area 1 images respectively

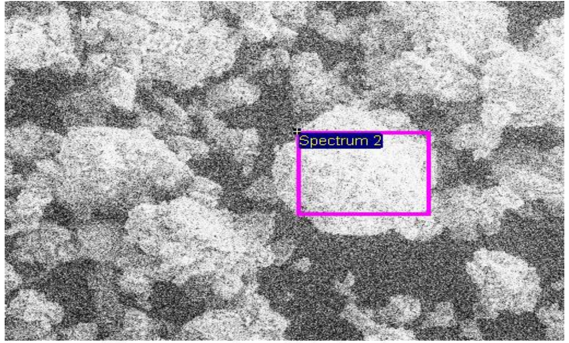
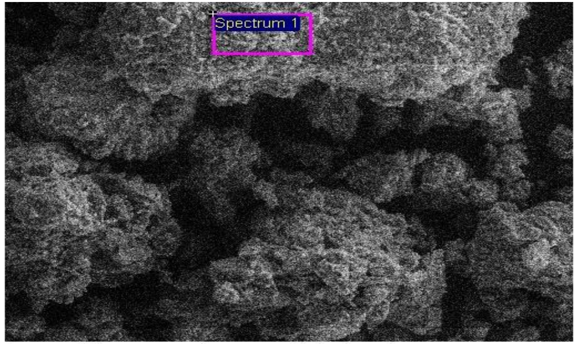
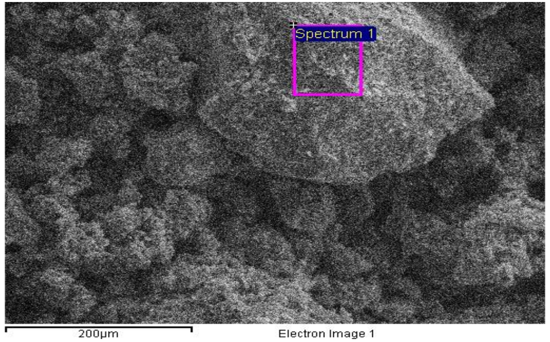
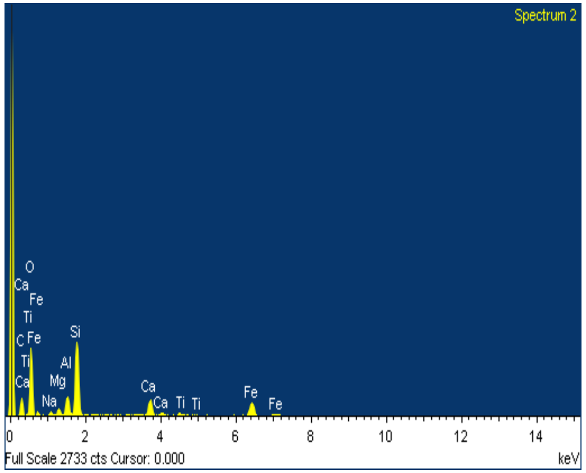
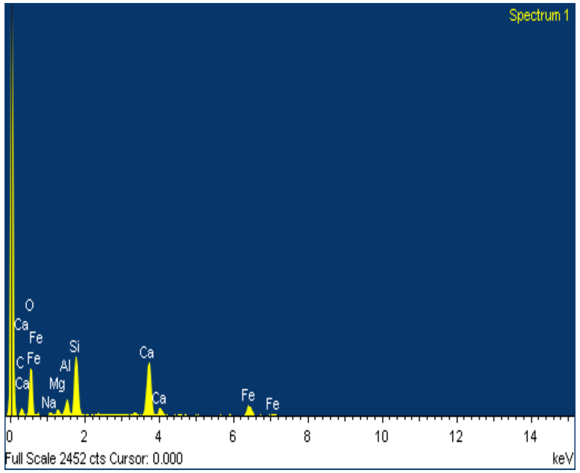
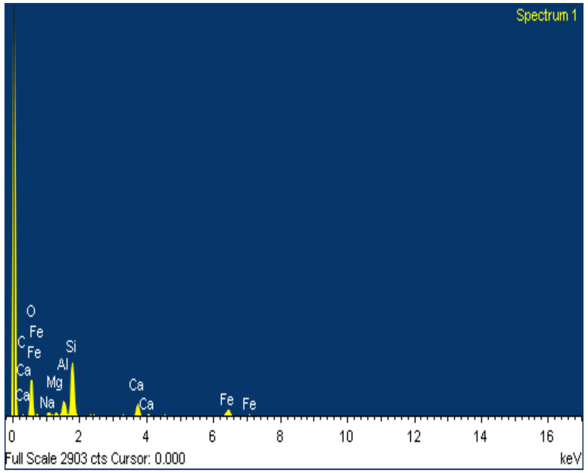
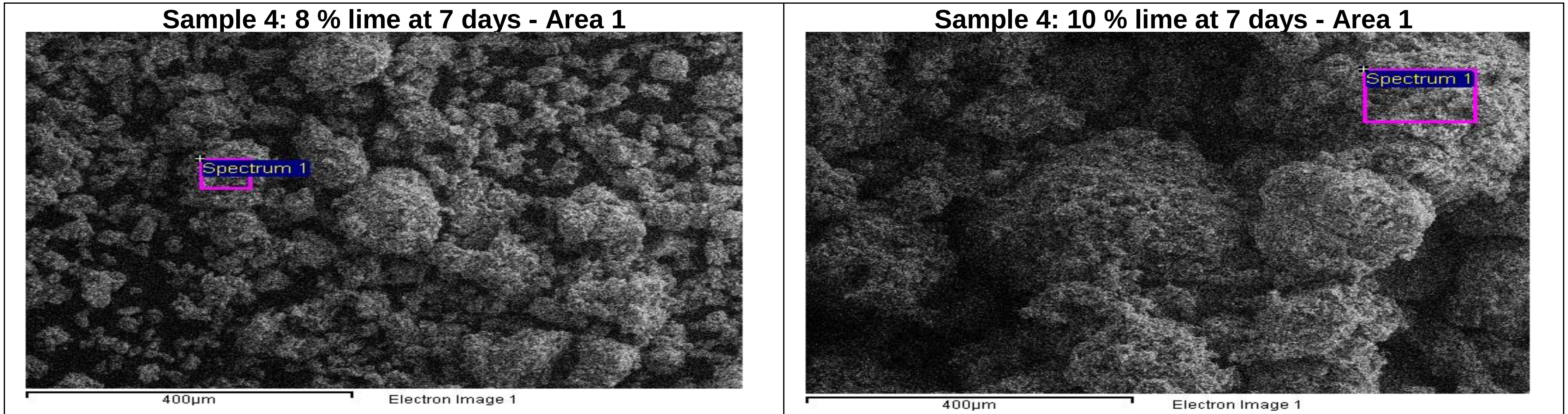
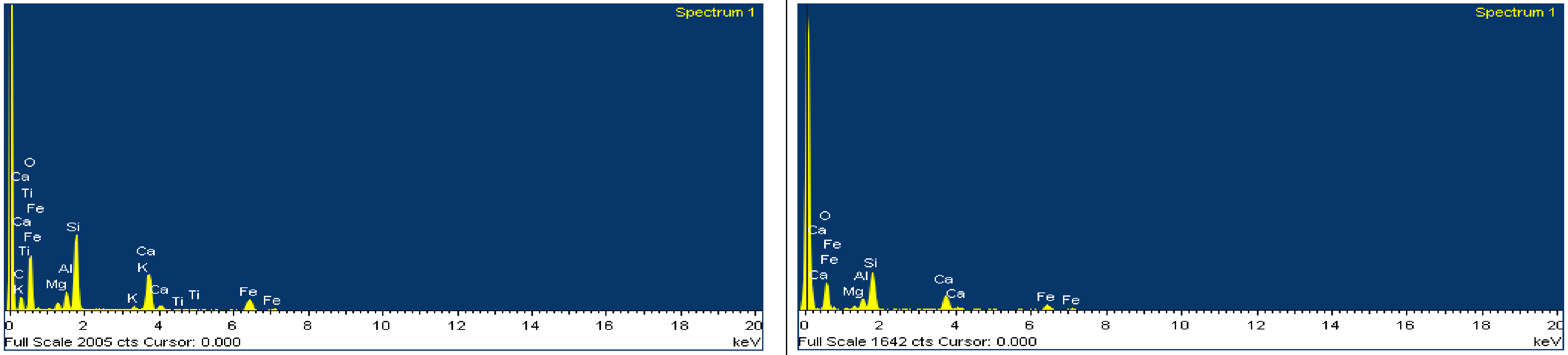
Sample 4: 2 % lime at 7 days - Area 1	**Sample 4: 4 % lime at 7 days - Area 1**	**Sample 4: 6 % lime at 7 days - Area 1**
 (a1) Sample 4 SEM micrograph at 2 % lime	 (a2) Sample 4 SEM micrograph at 4 % lime	 (a3) Sample 4 SEM micrograph at 6 % lime
 (b1) Sample 4 EDS/EDX	 (b2) Sample 4 EDS/EDX	 (b3) Sample 4 EDS/EDX

Figure 37: (a1), (a2) and (a3): Sample 4 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 4 EDS/EDX area 1 images respectively



(a1) Sample 4 SEM micrograph at 8 % lime

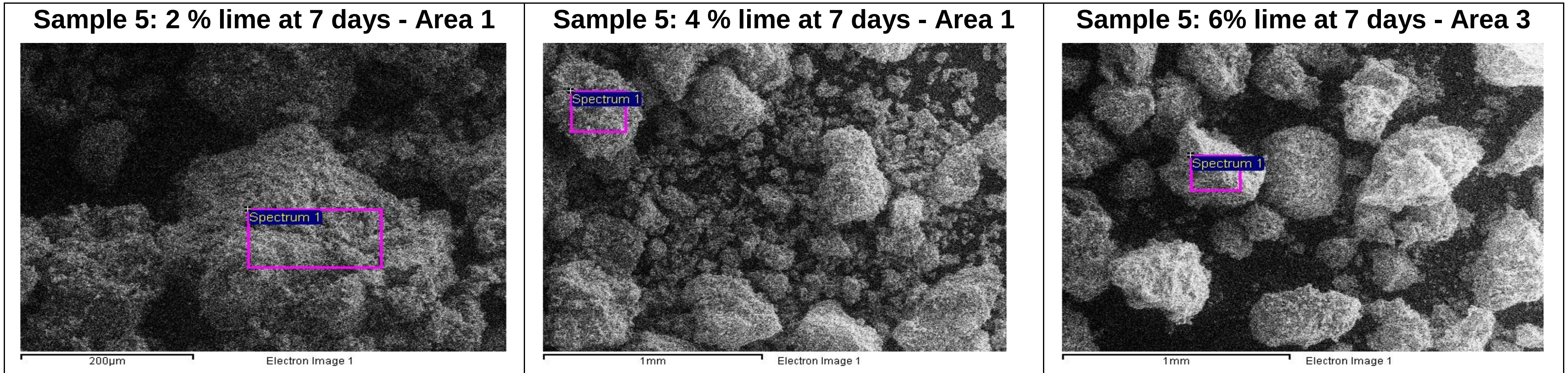
(a2) Sample 4 SEM micrograph at 10 % lime



(b1) Sample 4 EDS/EDX

(b2) Sample 4 EDS/EDX

Figure 38: (a1) and (a2): Sample 4 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 4 EDS/EDX area 1 images respectively



Sample 5: 2 % lime at 7 days - Area 1

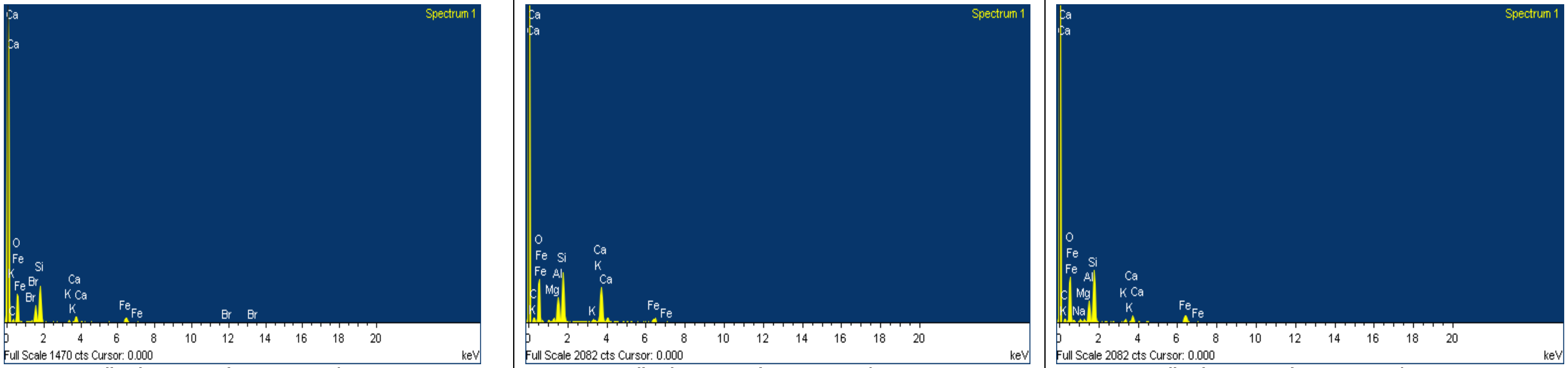
Sample 5: 4 % lime at 7 days - Area 1

Sample 5: 6% lime at 7 days - Area 3

(a1) Sample 5 SEM micrograph at 2 % lime

(a2) Sample 5 SEM micrograph at 4 % lime

(a3) Sample 5 SEM micrograph at 6 % lime

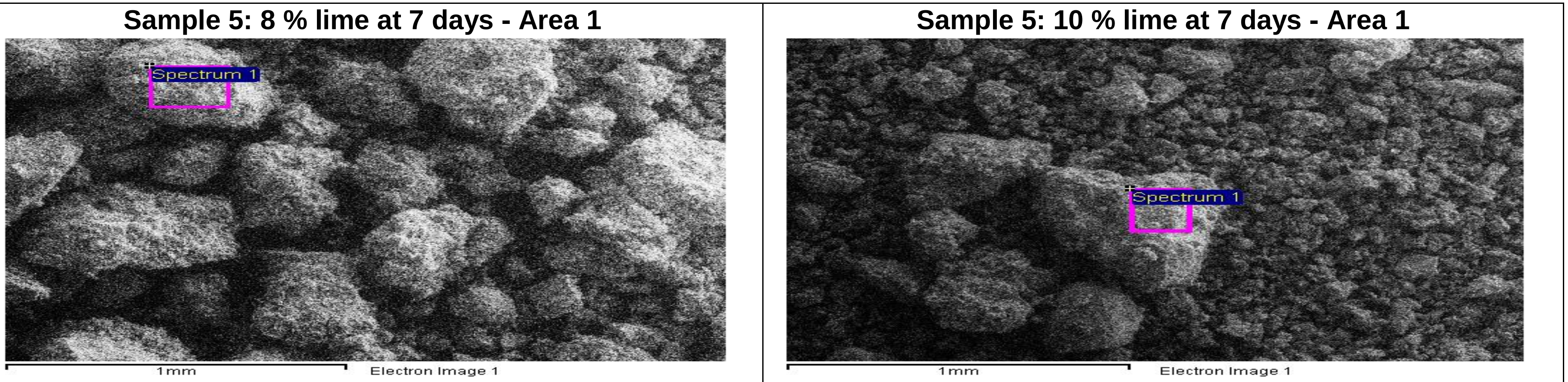


(b1) Sample 5 EDS/EDX

(b2) Sample 5 EDS/EDX

(b3) Sample 5 EDS/EDX

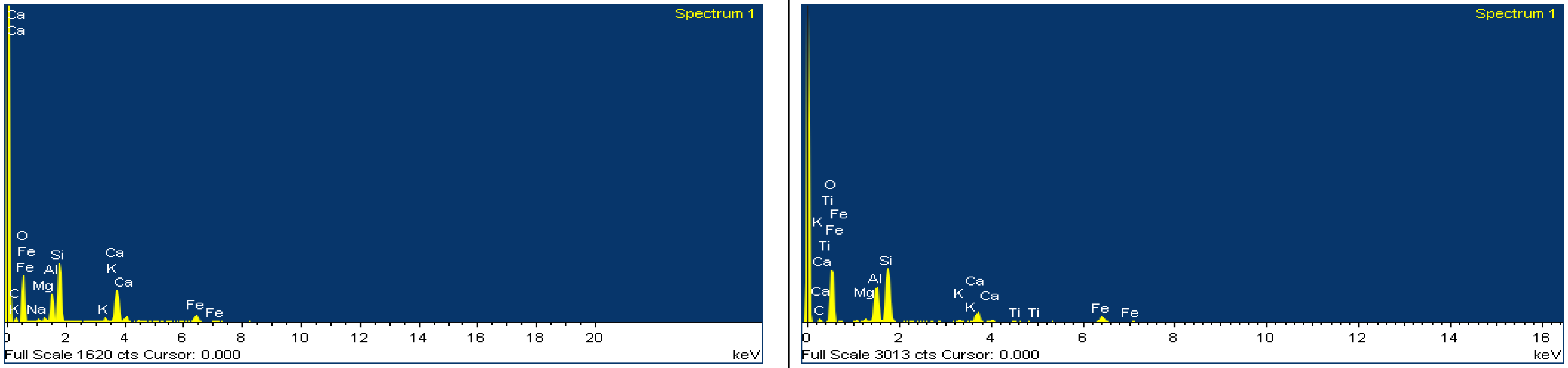
Figure 39: (a1), (a2) and (a3): Sample 5 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 5 EDS/EDX area 1 images respectively


Sample 5: 8 % lime at 7 days - Area 1

Sample 5: 10 % lime at 7 days - Area 1

(a1) Sample 5 SEM micrograph at 8 % lime

(a2) Sample 5 SEM micrograph at 10 % lime

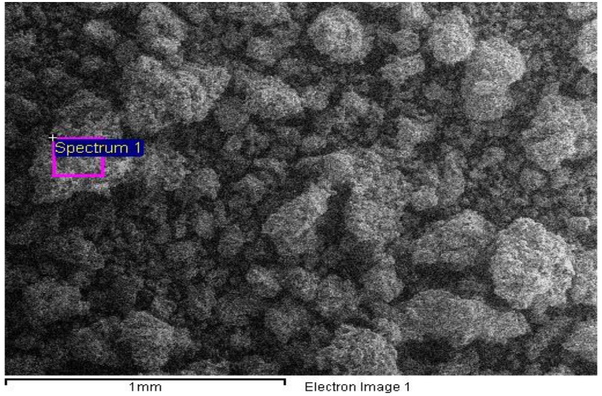


(b1) Sample 5 EDS/EDX

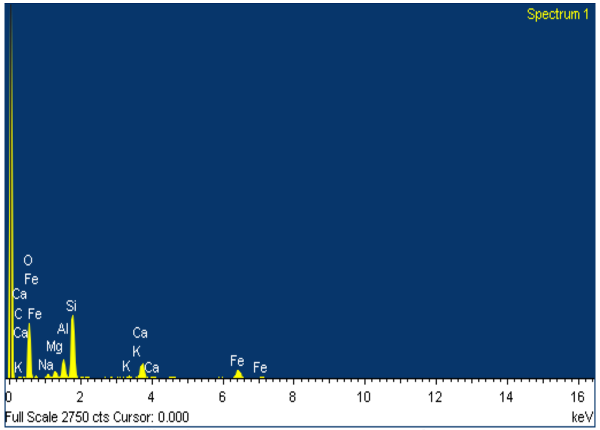
(b2) Sample 5 EDS/EDX

Figure 40: (a1) and (a2): Sample 5 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 5 EDS/EDX area 1 images respectively

Sample 6: 2 % lime at 7 days - Area 1

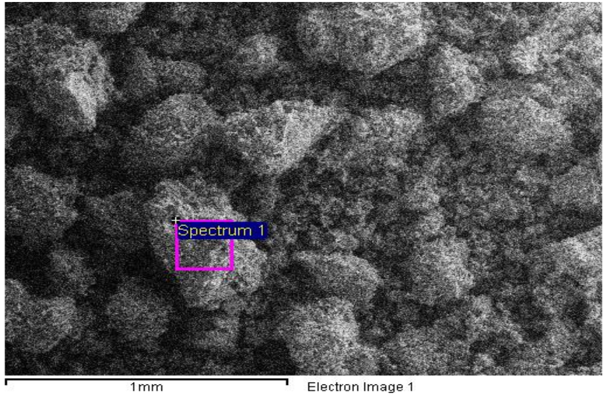


(a1) Sample 6 SEM micrograph at 2 % lime

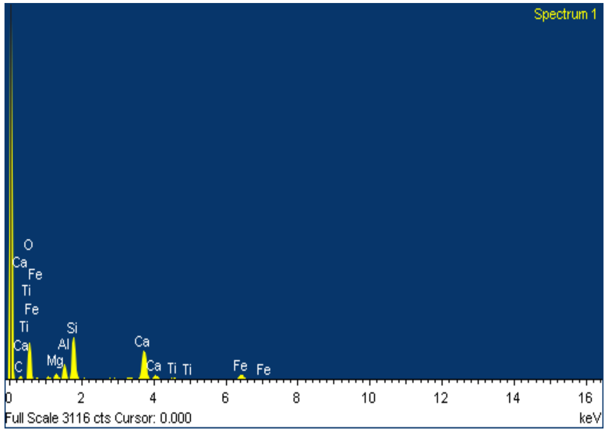


(b1) Sample 6 EDS/EDX

Sample 6: 4 % lime at 7 days - Area 1

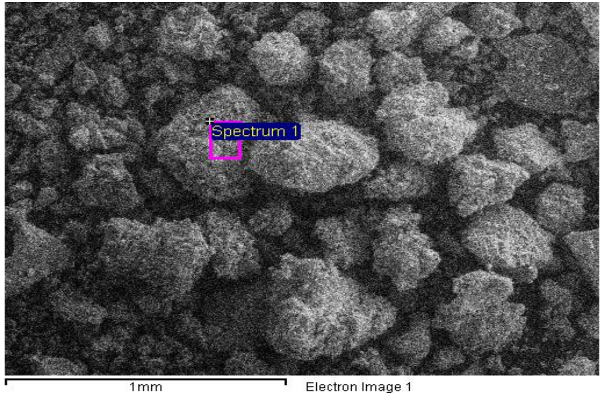


(a2) Sample 6 SEM micrograph at 4 % lime

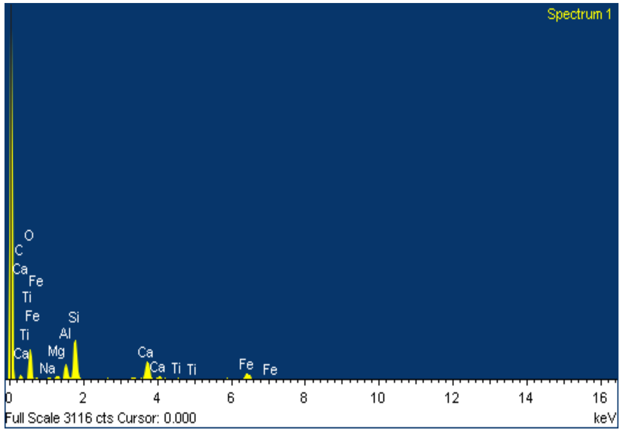


(b2) Sample 6 EDS/EDX

Sample 6: 6 % lime at 7 days - Area 1

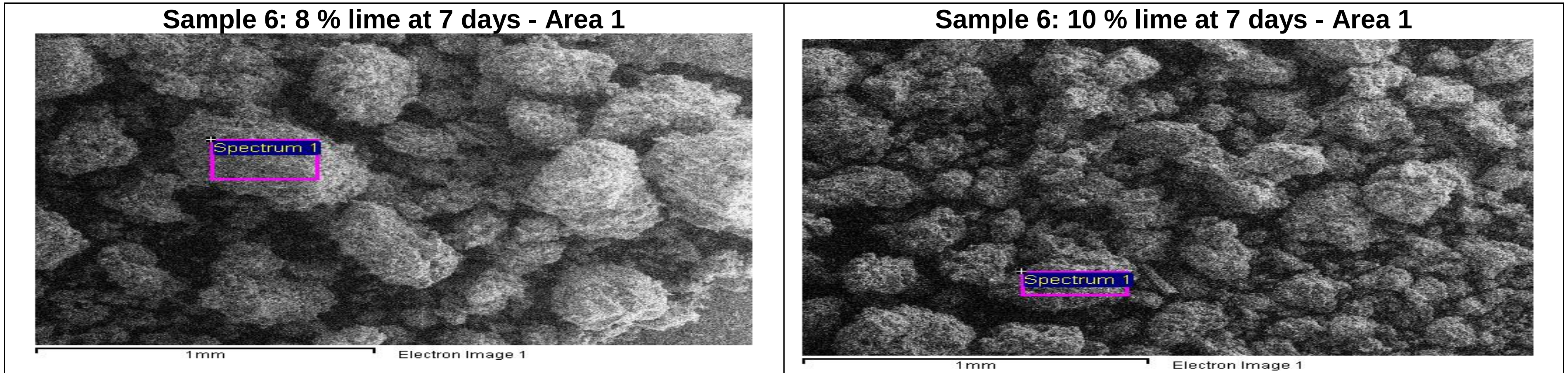


(a3) Sample 6 SEM micrograph at 6 % lime



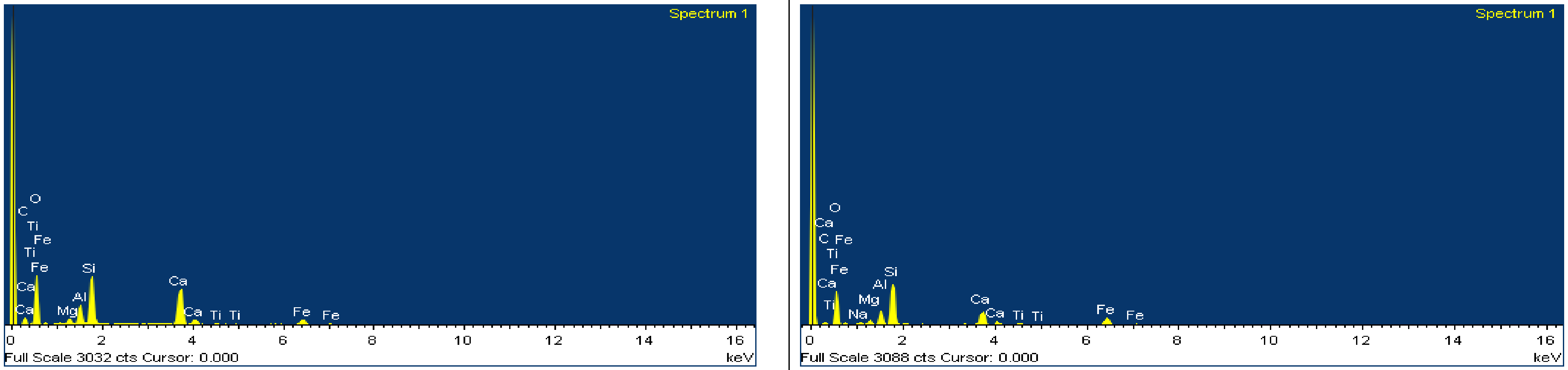
(b3) Sample 6 EDS/EDX

Figure 41: (a1), (a2) and (a3): Sample 6 SEM area 1 micrographs at 2 %, 4 % & 6 % lime respectively. (b1), (b2) and (b3): Sample 6 EDS/EDX area 1 images respectively



(a1) Sample 6 SEM micrograph at 8 % lime

(a2) Sample 6 SEM micrograph at 10 % lime



(b1) Sample 6 EDS/EDX

(b2) Sample 6 EDS/EDX

Figure 42: (a1) and (a2): Sample 6 SEM area 1 micrographs at 8 % & 10 % lime respectively. (b1) and (b2): Sample 6 EDS/EDX area 1 images respectively

4.2.6 Loss of cementitious elements– Carbonation

Studies have shown that the performance of stabilised soil samples can be affected by certain undesirable chemical reactions occurring in lime-treated soil. Carbonation is one of these, and this research was no exception. Carbonation refers to the reaction that occurs between free lime and atmospheric carbon dioxide. Also called lime carbonation, the reaction forms calcium carbonate instead of the cementitious CAHs and CSHs. This part of the chapter examines the effect of carbonation in the soil samples treated with lime, as evidenced by the results from UCS, CBR, X-RD, SEM, and EDS/EDX. Soil pH as a contributory factor is also looked at in this subsection.

4.2.6.1 The effect of carbonation on UCS

The UCS test was conducted to determine the strength of the soil samples tested under unconfined conditions according to the TMH1 and other complimentary soil science standards on materials testing by SANRAL.

Constant increase in strength was indicated by the lime stabilised material for alkaline sample 6 of pH = 8.68 at each level of lime content with the highest strength recorded as 1566.86 Mpa at lime content of 4 %. However, some soil samples indicated a slow growth. It can be noted from Figure 24 that the UCS of the soil decreases sharply for some soil samples, particularly at lime content of 2 % and 4 % for soil sample 1 of pH = 4.02 to soil sample 3 of pH = 5.55 respectively. One contributory factor directly impacting on this was carbonation which might have promoted the loss of cementitious content in the stabilised soil samples.

The above implies that carbon dioxide diffused through pores, both of the curing membrane and that of the soil sample, thus allowing calcium hydroxide and carbon dioxide dissolution in water, as well as the reaction of Ca+2 with CO_3-2 ions to form the $CaCO_3$ crystals forming carbonation reactions.

4.2.6.2 The effect of carbonation on CBR

The CBR test was conducted by measuring the load required to penetrate the surface of the compacted soil samples, at different compactive efforts. Some of the lime treated soil samples recorded inconsistent results. The inconsistency in CBR penetration values of tested soil samples was a direct indication of the principal chemical reactions taking place during lime-soil stabilization, with lime-carbonation being one of the reactions. There was weak bonding due to the loss of the cementitious element of the soil samples, calcium carbonate being a soluble salt eventually pulverizing due to being exposed. This might have found its way through the curing membrane and eventually the membrane of the soil sample thus promoting carbonation.

4.2.6.3 The effect of carbonation on, SEM and EDS/EDX

For SEM and EDS/EDX analysis, treating soil samples with lime changed the soil fabric significantly depending on the curing time and water content. The above confirmed chemical reaction took place when soil was mixed with lime. As it was seen from micrographs in Figures 31 to 42, soil particles treated with different contents of lime were observed and displayed flaky texture. Flaky texture confirmed the formation of needle-like crystalline formations in the soil sample such as ettringite. The EDS/EDX micro images, when magnified showed the existence of the pores within the soil particles as well. This indicated the change in microstructure due to a loss of cementitious element in soil -carbonation.

4.2.7 The effect of lime stabilisation on the pH of soil

The pH of soil depends upon the combination of the individual elements of the soil-forming factors including parent material, time, topography, organisms and climate.

For this research, six selected soil samples of different pH values were used and the effects of the added lime on the pH values were determined in the laboratory. The percentage of lime used on the samples varied from 2 %, 4 %, 6 %, 8 % to 10 % by weight of the soil samples that were tested.

From the analysis carried out, it was found that the treatment of the soil samples with lime content changed the pH of the soil samples. The values increased with increasing lime content for all the samples; on average across all the percentages of lime added, the pH value for sample 1 changed from 3.94 to 4.02, sample 2 changed from 4.54 to 4.92, sample 3 changed from 4.50 to 5.22, sample 4 changed from 8.95 to 9.20, sample 5 changed from 8.05 to 8.27 and sample 6 from 8.34 to 8.68. The changes were as a result of the changes in the chemical properties of the soil as a result of the added lime.

The results show that lime impacted on the soil samples. The application of hydrated lime increased the soil pH in relation to the rate of lime applied. Conversely, basic or alkaline soil is the consequence of the buffering of soil pH by base elements or by the presence of buffering compounds such as carbonates. Some of the soil features affected by soil pH include (but are not limited to):

- The availability of mineral elements in the soil.
- The physical properties: Low Ca concentration in acidic soil samples relating to an increased dispersion of colloids if Al is not present at high concentration.

The effect of soil pH plays a crucial part in lime soil stabilisation as it depends upon the combination of the individual elements of soil forming factors. During the use of lime for lime-soil stabilisation, soil pH increases but possibly not in organic soil, which is naturally acidic, unless large and, possibly uneconomic, amounts of lime are added.

When adequate quantities of lime and water are added, the pH of soil quickly increases, which promotes the breakdown of clay particles in the soil structure.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

The data derived in this study has been set out in figures and tabular format, based upon the principles laid down in Chapter 3, and has been summarised and analysed in Chapter 4.

Many of the important engineering properties of soil can be enhanced by the addition of lime. The results of this investigation have shown that beneficial effects are obtained by the addition of lime to soil samples. The concluding and recommending remarks on the research results, both experimental and derived from the literature review, appear in this chapter. Conclusions will be drawn and recommendations made in this chapter.

5.1 Conclusions

5.1.1 Atterberg limits

The soil samples that were tested were classified and identified based on their index properties, namely, the Atterberg limits. These are properties that help in the identification and classification of soil samples. The application of lime did have an impact on the soil. The addition of lime to the acidic and alkaline (i.e pH<7 and pH>7) soil samples led to a reduction in soil plasticity. The reduction in plasticity occurred due to the decrease in the thickness of the soil particles. Also resulting from this was a cation exchange chemical reaction which caused an increase in the attraction of soil particles, thus leading to flocculation.

The above implies that the addition of lime increased the proportion of sand particles fraction, thus increasing the proportion of fine particles. The hydrated lime used in this experiment was a fine powdered material which is reactive in the presence of moisture. Hydrated lime helped fill the air voids within the soil samples. It acts complimentary to compaction, aiding in the reduction in soil void ratio by expulsion of air from the voids. The fine powdered material in a form of lime also aided in the reduction of the void ratio by expulsion of water from the voids. These two processes act similarly in that they result in a decrease in the void ratio.

On soil sieve analysis, soil gradation and classification according to the Atterberg limits showed that almost all soil samples were well graded. This implies that the soil samples contained particles of a wide range of sizes and had a good representation of all sizes. Well graded soil samples meant limited availability of air voids. A certain percentage of air voids in the soil samples (acidic and alkaline) that were tested allowed for some additional compaction under lime application. They provided spaces into which small amounts of lime flowed during this subsequent compaction.

5.1.2 Maximum dry density and optimum moisture content

The results of the compaction tests conducted on the soil samples showed that the addition of lime resulted in the improvement in the characteristics of the six soil samples. The six soil samples displayed respective maximum dry densities ranging from 1500 kg/m^3 to 2000 kg/m^3 and optimum moisture contents ranging from 14 % to 29 %. Lime content at range of 4 % to 8 % indicateed the highest density increases of the stabilised soil samples. The densities of the soil samples showed a slight increase at the lime content of 10 %. However, for almost all samples, the results showed that further addition of lime decreases the density and increases moisture content.

Based on the results, it was discovered that the MDD is achieved at 2075 kg/m^3 at 22 % of OMC for alkaline soil sample when treated with lime content of 4 %. The above implies that maximum cohesion and maximum friction are achieved at pH = 8.68. For other soil samples, the MDD decreased with an increase in the number of days for each of the pH condition. This indicated that the particles of the soil samples tested were being disintegrated. This reduction in the density of the soil had an impact on the strength of the soil. Typical example for the latter is alkaline soil sample four at pH = 9.20, with an MDD of 1591.53 kg/m^3 at 18 % of OMC.

5.1.3 California bearing ratio

The CBR for treated soil samples compacted at 25 compactive efforts recorded lower CBR values compared to the soil samples compacted at 55 compactive efforts. Overall comparison between acidic soil samples and alkaline soil samples show that alkaline soil samples recorded higher percentages of CBR when lime-treated.

Acidic soil samples CBR

Acidic soil sample 3 of pH = 5.55 recorded lower CBR percentages for required force to penetrate the compacted surface of the soil at almost every CBR depth of penetration and every compactive efforts. The rate of change in CBR relating to sample 3 percentage was as a result of change in moisture content. This was one contributory factor to lower values of CBR compared to that of other soil samples.

Acidic soil samples 1 (pH = 4.02) and 2 (pH = 4.92) showed constant increases in CBR penetration at all depth of (i.e. 2.54 mm, 5.08 mm and 7.62 mm). This was mostly at lime contents 2 %, 4 % and 10 %. The constant increase in CBR for soil samples compacted at 55 compactive efforts was a direct indication of the principal chemical reactions that took place during lime-soil stabilisation process.

Alkaline soil samples CBR

Alkaline soil sample 4 at pH value of 9.20 recorded lower CBR percentages for required forces to penetrate the compacted surface of the soil sample. Reference can be made to results in Table 2 which illustrates that alkaline soil sample 4 recorded the second least percentages of OMC after sample 3 of pH value of 5.55.

The six soil samples were, for CBR, compacted manually and mechanically at different compactive efforts i.e. 55 and 25 respectively. Mechanically compacted soil samples, owing to the number of compactive efforts that were applied to the soil, produced marked change in their geotechnical properties. This implied that the compaction process of mechanically densifying a soil, assisted in pressing the soil particles together into a closer state. In the process, air was expelled from the soil mass.

With compaction, both the number of voids contained in the soil mass and the size of the individual void spaces werereduced. The above-mentioned change in voids had an obvious effect on the movement of water through the soil, reducing the permeability and reducing the seepage of water.

Therefore, it would appear that alkaline soil samples particularly at an optimum pH of 8 (i.e. pH = 8.68 for soil sample six) perform well compare to acidic soil samples for CBR penetration.

5.1.4 Soil swelling properties

Less swelling of the soil samples

It is evident that the addition of lime to the six soil samples at contents of 2 %, 4 %, 6 %, 8 % and 10 % enabled the swelling of the soil. Particularly noticeable were the swelling properties of acidic soil sample 2 of pH = 4.92 which had, on average, a swell of 0.01 % after 7, 14 and 28 days of soaking. Acidic soil sample 1 of pH = 4.02 and alkaline soil sample 5 of pH = 8.27 had an average swell of 0.02 % after 7, 14 and 28 days of water soaking at 8 % of lime content. These results were as a consequence of less intercalation of water molecules entering into the inter-plane space of soil minerals, thus causing a strong layer of impermeability in the soil samples. The reduction in pore spaces or the non-existence of the pores within the soil particles indicated a change in microstructure of the soil on the addition of lime, hence promoting the strength of the tested soil samples. Prolonged days of soaking played a crucial part in that some of the soil samples showed an increase in resistance to CBR penetration test.

More swelling of the soil samples

Alkaline soil sample 5 of pH = 8.27 at lime content of 2 %, on average, swelled to 0.71 % after 7, 14 and 28 days of soaking. Acidic soil sample 3 of pH = 5.55 at lime content of 4 % had an average swell of 1.59 % after 7, 14 and 28 days of water soaking. Sample 3 at lime content of 6 % had a swell of 2.33 % after 7, 14 and 28 days of soaking. Acidic soil sample three on average swelled to 0.87 % after 7, 14 and 28 days of soaking. Alkaline soil sample 5 at lime of 8 % had an average swell of 0.81 % after 7, 14 and 28 days of soaking. The above implied that the availability of pore spaces or the existence of the pores within the soil samples mentioned above, indicated the change in microstructure of the soil on addition of lime as a stabiliser. This promoted the seepage of water in the soil sample, thus resulting in the decrease in strength on these lime stabilised soil samples.

5.1.5 Unconfined compressive strength

In order to investigate the effect of pH on shear strength of treated soil, UCS properties of the soil samples of different pH values (pH = 4.02, 4.92, 5.55, 9.20, 8.27 and 8.68 for sample 1 to 6 respectively) were determined using the UCS machine. Based on the results of the UCS strength tests, it was found that the properties increased considerably if the soil had a high pH (pH = 8.68 for alkaline soil sample soil 6 and pH = 8.27 for alkaline soil sample 5). At an alkaline pH, the increasing of ionic strength favoured face-to-face aggregation of the soil samples. The UCS properties decreased considerably when the pH values decreased to less than pH = 8. This was particularly the case for acidic soil samples 1 of pH = 4.02, soil sample 2 of pH = 4.92 and soil sample 3 of pH = 5.55.

5.1.6 Microstructural properties

The soil pH (acidic and alkaline) had no significant impact on the microstructural studies (X-RD, SEM and EDS/EDX), but the microstructural studies had relevance in terms of the chemical reactions during lime-soil stabilisation.

As part of the microstructural properties analysis, certain elements were found in the soil through X-RD, SEM and EDS/EDX. The soil pH had no impact on the microstructural behaviour of the six soil samples, however, through microscopic examination, certain elements were found in the test soils. The elements found were magnesium (Mg), potassium (K), calcium (Ca), titanium (Ti), iron (Fe), aluminium (Al), silicon (Si) oxygen (O) and carbon (C). Some of the soil elements found and evaluated were significantly influenced by the usage of lime.

5.1.7 Carbonation

Acidic soil sample 1 of pH = 4.02 and acidic soil sample 2 of pH = 4.92 indicated slow growth in terms the UCS strength compared with other soil samples of different pH ranges. One contributory factor that led directly to the latter, was carbonation. There was a loss of cementitious content in stabilised soil samples that was found in some of the samples, both acidic and alkaline soil samples. Carbonation led to the formation of calcium carbonate due to the soil samples' exposure to open air at times.

5.1.8 Soil pH

In this research, six selected soil samples of different pH ranges were used and the effects of the lime stabiliser studied. From the analysis, it was found that the treatment of the soil samples with lime content changed the pH of the samples. Soil pH increased with the rate of lime applied, with particularly noticeable manifestations of the increase being with soil sample 3. On average across all the percentages of lime added sample 1 changed from 3.94 to 4.02, sample 2 changed from 4.54 to 4.92 , sample 3 changed from 4.50 to 5.22, sample 4 changed from 8.95 to 9.20, sample 5 changed from 8.05 to 8.27 and sample 6 from 8.34 to 8.68. The changes were as a result of the changes in the chemical properties and the composition of the soil samples due to their chemical reactions with the lime additive.

5.2 Future recommendations

The experimental results in this dissertation have demonstrated that the usage of lime does impact on both acidic and alkaline soil positively. However, to produce further quantitative and qualitative data in relation to the research and to develop an improvement strategy to current practices, the following recommendations are offered for consideration and implementation.

5.2.1 Atterberg limits

- Soil type should be carefully considered when opting to use lime for soil stabilisation. Reactive soil upon lime application such as acidic soil (i.e. soil with pH < 7) generated long-term strength gain through a pozzolanic reaction. This occurred due to the decrease in the thickness of the soil particles, implying that the addition of lime increased the proportion of sand particles, thus increasing the proportion of fine particles. Therefore considerations in this regard should be made for future use when analysing the the soil type.
- Almost all soil samples tested were well graded in terms of their gradation, and the type of lime used was a powered hydrated lime. Hydrated fine powdered lime helped in the filling of the smaller air voids of the soil samples that might have still be available. Complimentary to the above was compaction which aided in further reduction in the soil to void ratio. As a starting point for future extension of the research, particularly that relating to the Atterberg limits, it would be interesting to know the behaviour of the soil samples with different grading (i.e. poorly graded). The six soil samples used for the research related to groups or soil samples each having similar characteristics and potentially similar behaviour, particularly in terms of grading.
- Hydrated lime was used for this research. This is fine powdered material and is reactive in the presence of moisture. There are however other forms of lime,

such as quicklime. The main differences between hydrated lime and quicklime are their reactivity and their chemical composition. Hydrated lime and quicklime are both calcium compounds. It would be interesting to see the reaction of other limes in terms of the Atterberg properties, since quicklime and hydrated lime differ in terms of their chemical composition, pH and other.

5.2.2 Maximum dry density and optimum moisture content

- For lower compactive efforts, optimum usage of lime should be considered. This is attributed to the fact that further addition of lime decreases the density with constant or increasing moisture content. An increase in the moisture content as opposed to a decrease in dry density relative to the addition of lime results means that a lower amount of compaction is required, which translates to fewer compactive efforts, thus increased savings on compaction machinery and equipment.
- For lime-soil stabilisation, the target density of a soil should be achieved over a wider range of moisture contents. The required density should be easily achieved through a broad range of water contents, thereby conserving time, effort and energy. This should be done so as to reduce the thickness of the layer of the soil as a result of increased cation concentration through the addition of lime.
- Acidic soil samples (i.e. pH < 7) are particularly found in wet areas. This soil is expected to possess higher *in situ* moisture compared to alkaline soil, therefore, lime should be used to aid soil modification – reducing soil plasticity, aiding compaction, increasing early strength and generally enabling soil drying.

5.2.3 California bearing ratio

- Moisture content and compactive effort, which can be controlled, are important factors influencing soil compaction. To further understand the compaction behaviour of soil towards CBR, further representative soil samples, perhaps of different textural characteristics should be subjected to further Proctor compaction efforts such as 30, 50, and 100 blows, but of the same pH ranges for the soil samples.

- Historical evidence shows that a well-graded soil is preferred for construction of pavement layers and building platforms. This is because it is perceived to be easily compacted into a dense mass. It remains to be discovered as to why on average the lime treated soil samples at 25 compactive efforts recorded lower CBR compared to the soil samples at 55 compactive efforts. This is because hydrated lime used for this experiment was a fine powdered material and helped in the filling of the air voids of the soil samples. Therefore, the role of compaction in reducing the soil void ratio by expulsion of air from the voids should have been less. Along the above lines relating to 55 compactive efforts and 25 compactive efforts, the experiment should be extended further.

5.2.4 Swelling of the soil

- The acidic and alksline soil samples used for the experiment were engineering soil samples with no, or very little, organic content. However, factors such as organic content, in addition to soil mineralogical composition are important in modifying the tendency of a soil to exhibit swelling characteristics and should be studied as well.

5.2.5 Unconfined compressive strength

- A more effective approach should be followed in reviewing of designs and construction procedures relating to lime-soil stabilisation of different pH ranges and relating to the minimisation of carbonation to suit intended results. The loss of cementitious elements in lime stabilised soil samples continues to be an issue. This study was no exception to this in terms of the UCS results. This was despite the general precautionary measures taken, such as ensuring that soil samples were as moist as possible preventing contamination by carbon dioxide, and keeping the samples constantly covered with airtight plastic sheeting to prevent drying.
- Further to the above, factors such as humidity, room temperature, and the curing effect time need to be fully studied as well.

5.2.6 Soil pH

- The properties and characteristics of lime treated soil samples significantly depend on the types of soil, amount of additive, types of additive and curing conditions including time, temperature and moisture. The results showed that stabilising soil with lime improves soil's pH. Treatment of the soil samples with lime content changed their pH levels. The values increased with increasing lime content for all the samples. It has been reported that alkaline soil is not a significant risk, but it can be if used for road infrastructure. Alkaline soils can cause problems in supporting re-vegetation of road corridors, and in some cases, the prevalence of some declared pests who prefer alkaline soil conditions. Unlike alkaline soil, acid soil presents a significant risk to roads, particularly road infrastructure, if not treated. A typical example concerns steel structures subject to corrosion acceleration. The above implies that during design and construction, the soil pH should be carefully taken into consideration as it can have a significant impact. The risks associated with acidity need to be identified and managed as part of project design, assessment, maintenance and management.

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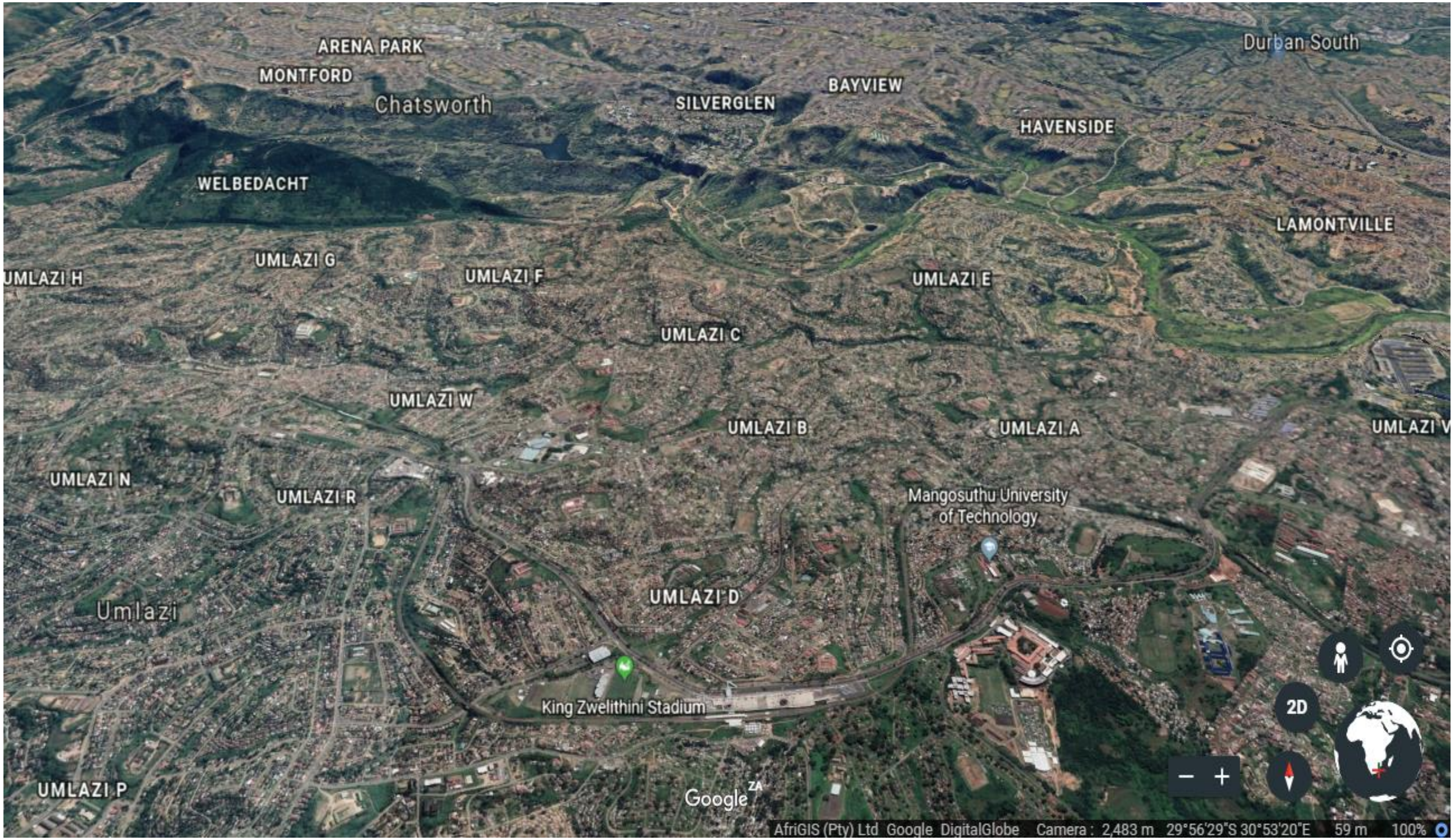
APPENDICES

Appendix A: Locality plans: Soil sampling

(a) Nkwalini-Eshowe

(b) Scottburgh-South of Durban

(c) Umlazi B section-Durban



(d) Mkuze-North of KZN

Appendix B: List of publications and conference proceedings

1. **BHENGU, P** and ALLOPI, D. 2016. Review on the lime-soil stabilization as one of the successful technologies used in the improvement of road-soil-pavement layers strength. *Proceedings of the 35th Southern African Transport Conference (SATC 2016):77-87.*

2. **BHENGU, P** and ALLOPI, D. 2016. Microstructural properties of lime stabilized naturally occurring acidic soil. *International Journal of Advanced Research in Engineering & Management (IJAREM),* 1(1), 9-16.

3. **BHENGU, P** and ALLOPI, D. 2017. Influence of lime on lime soil stabilization on natural occurring acidic soil engineering properties. *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS),* 30(1): 57-68.

4. **BHENGU, P** and ALLOPI, D. 2017. Effects of lime stabilization on the pH scales of soils in parts of KwaZulu Natal, South Africa. *European Journal of Advances in Engineering and Technology* (*ejaet),* 4(9): 644-648.

5. **BHENGU, P** and ALLOPI, D. 2017. An experimental correlation study on soil properties of lime stabilised soil samples. *Proceedings of the 9th South African Young Geotechnical Engineers Conference, 13, 14 & 15 September 2017 – Salt Rock Hotel, Dolphin Coast, Durban, KwaZulu-Natal*: 407-416.

6. **BHENGU, P** and ALLOPI, D. 2017. Loss of cementitious elements on lime stabilised soil samples*. Proceedings of 84th IASTEM international conference, Chicago, USA, 24th October 2017: 12-21.*

Appendix C: CBR penetration graphs

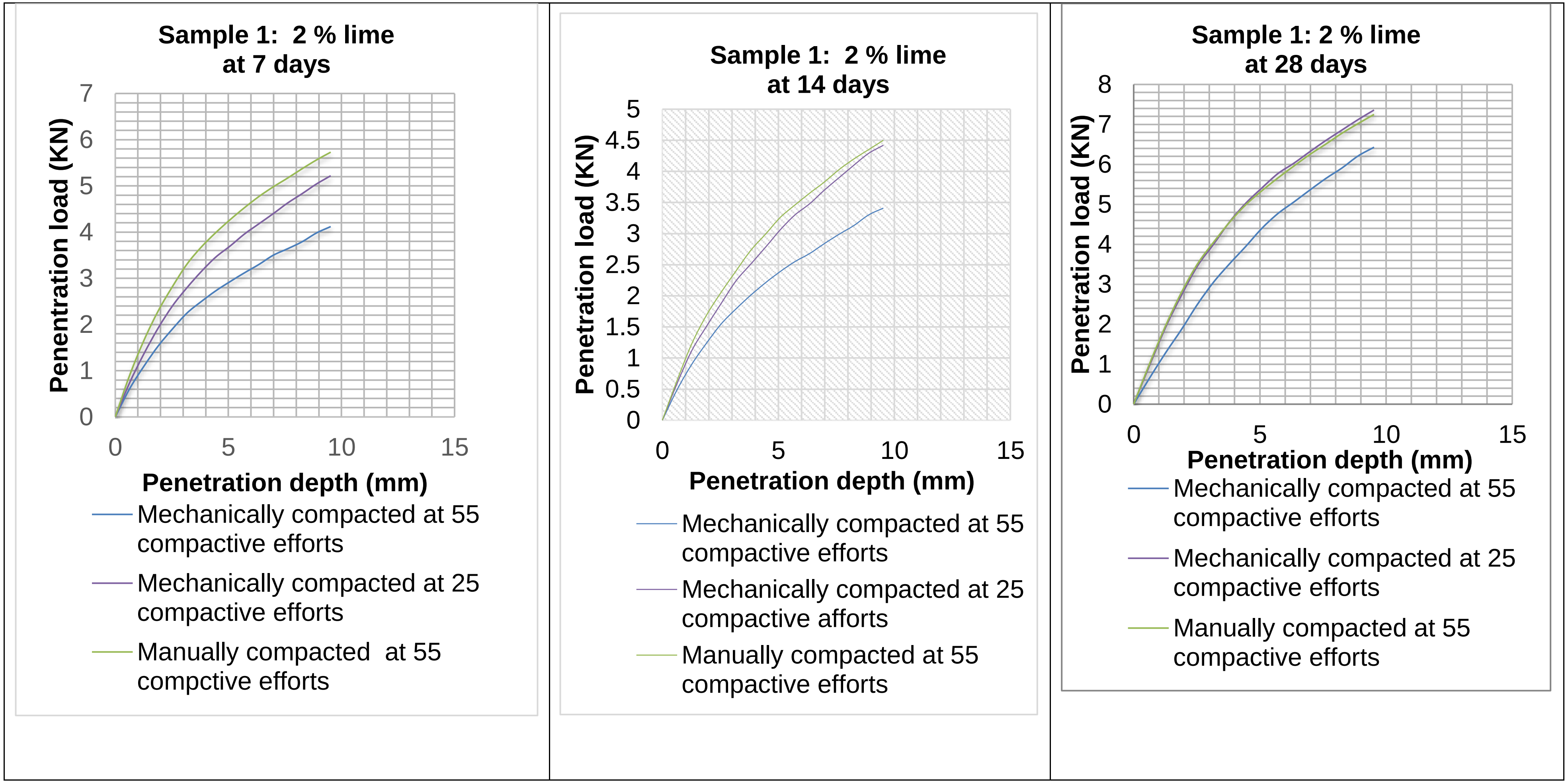


Figure 43: CBR penetration curve for sample 1 at lime content of 2 %, cured for 7, 14 and 28 days respectively

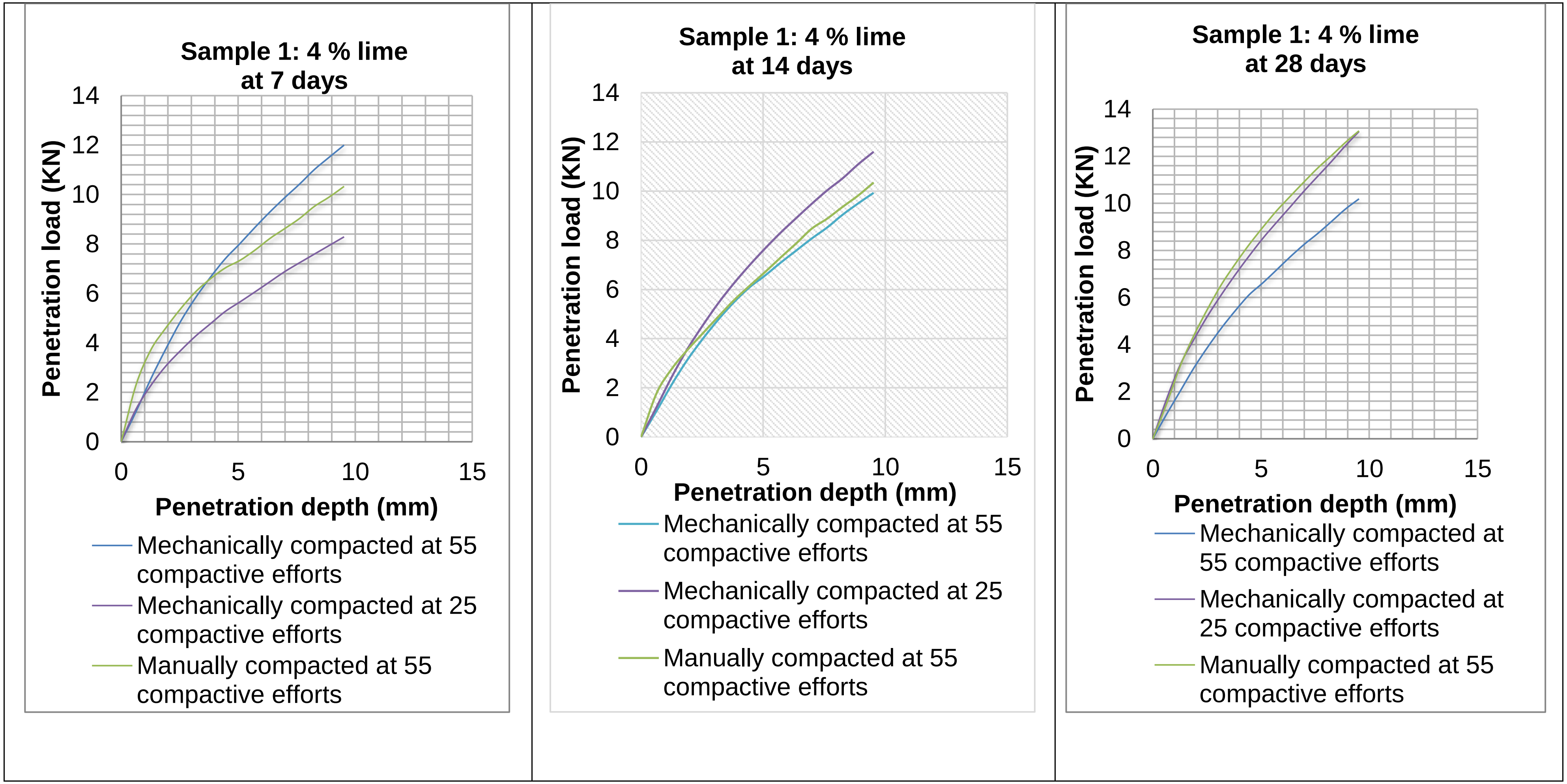


Figure 44**:** CBR penetration curve for sample 1 at lime content of 4 %, cured for 7, 14 and 28 days respectively

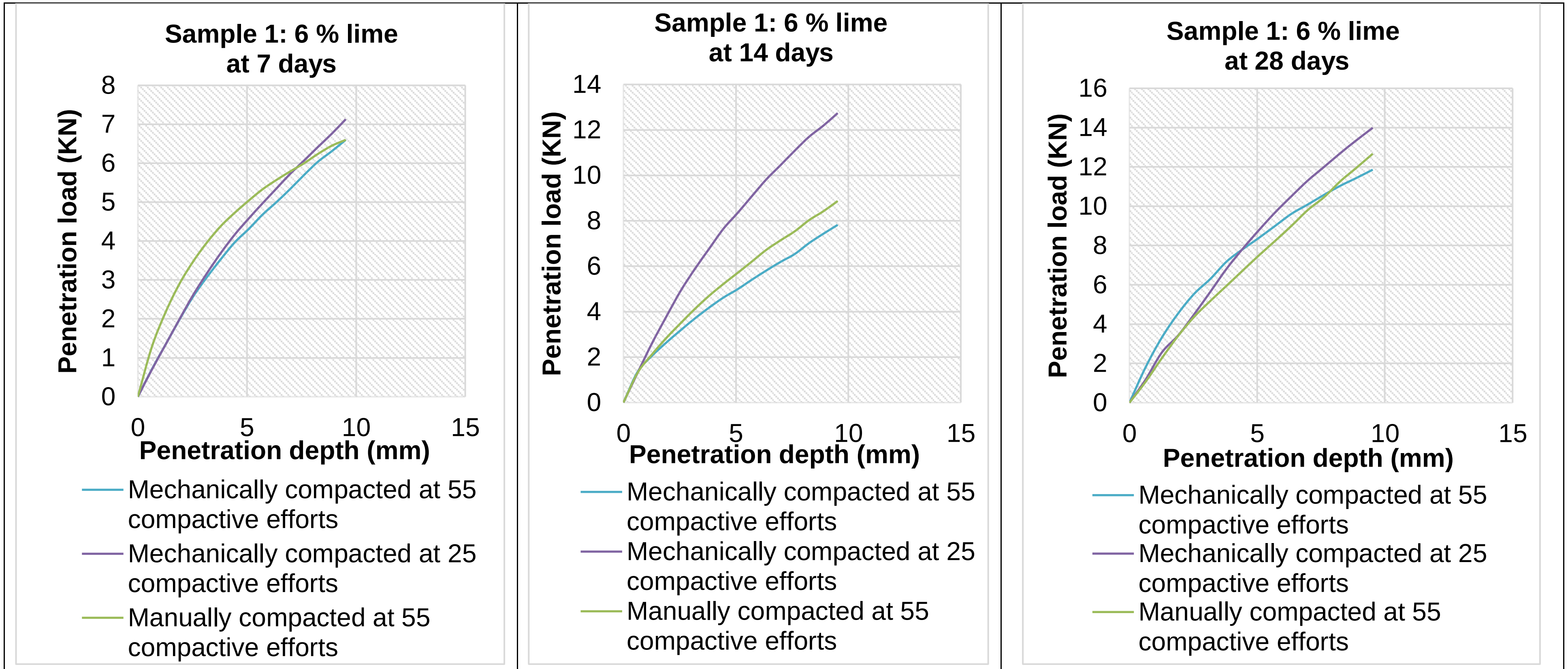


Figure 45: CBR penetration curve for sample 1 at lime content of 6 %, cured for 7, 14 and 28 days respectively

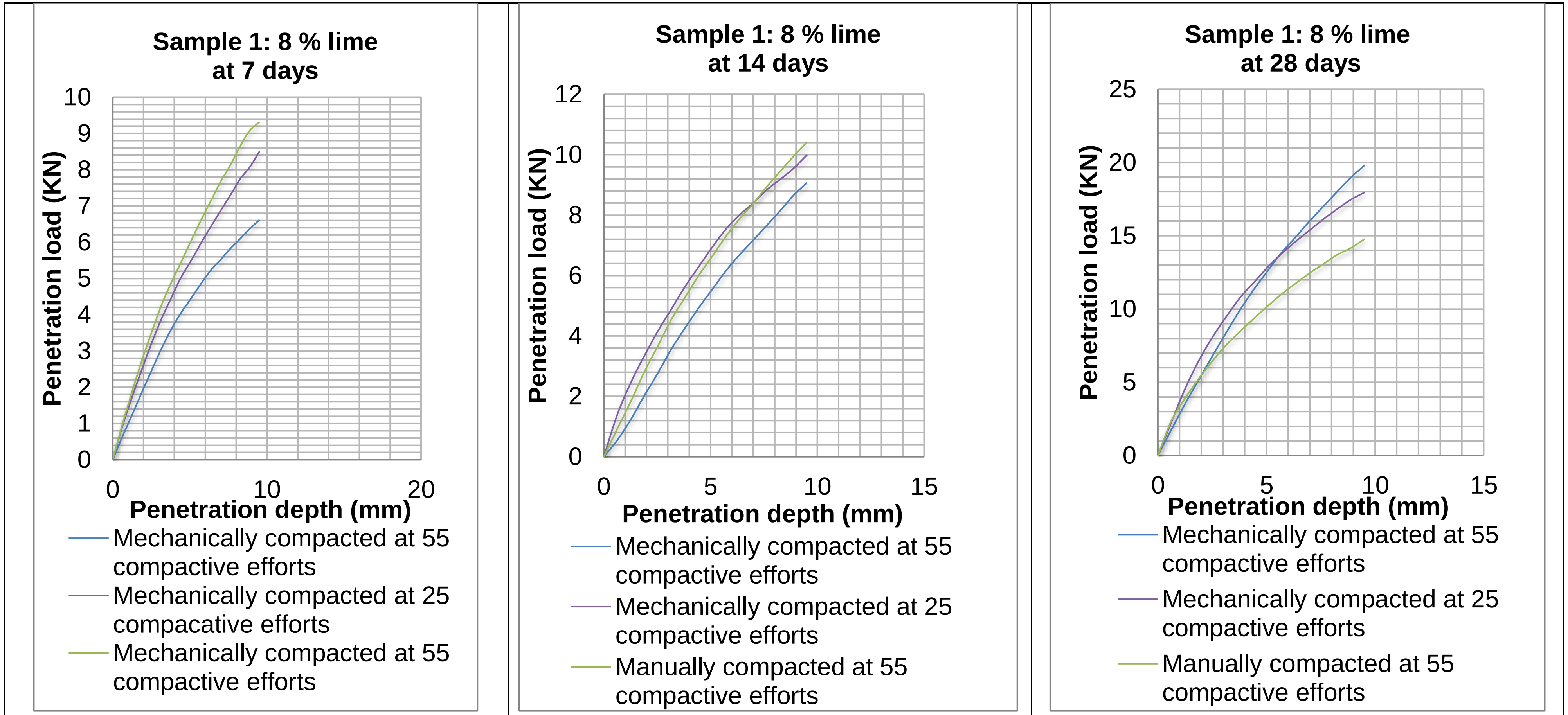


Figure 46**:** CBR penetration curve for sample 1 at lime content of 8 %, cured for 7, 14 and 28 days respectively

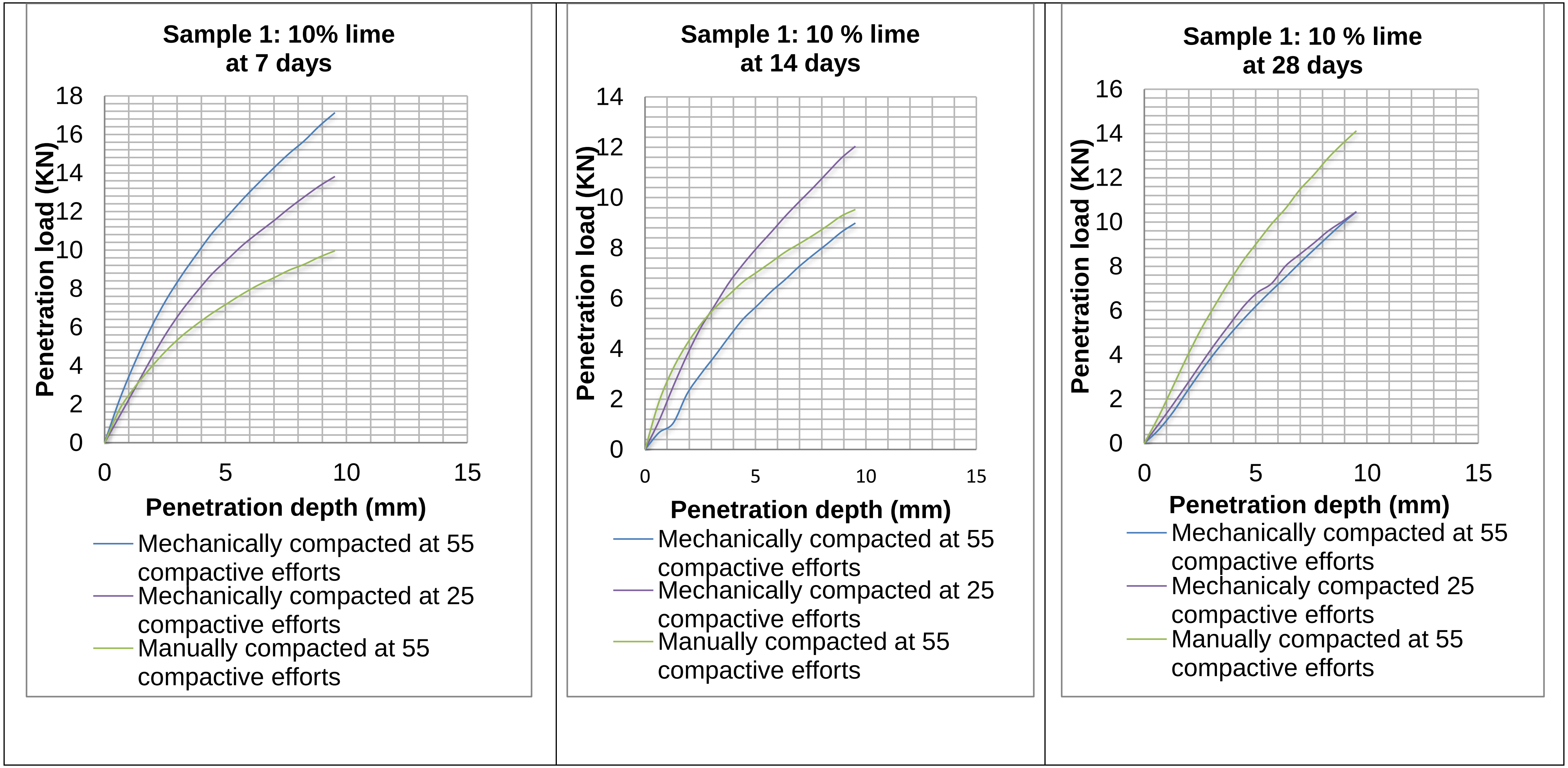


Figure 47: CBR penetration curve for sample 1 at lime content of 10 %, cured for 7, 14 and 28 days respectively

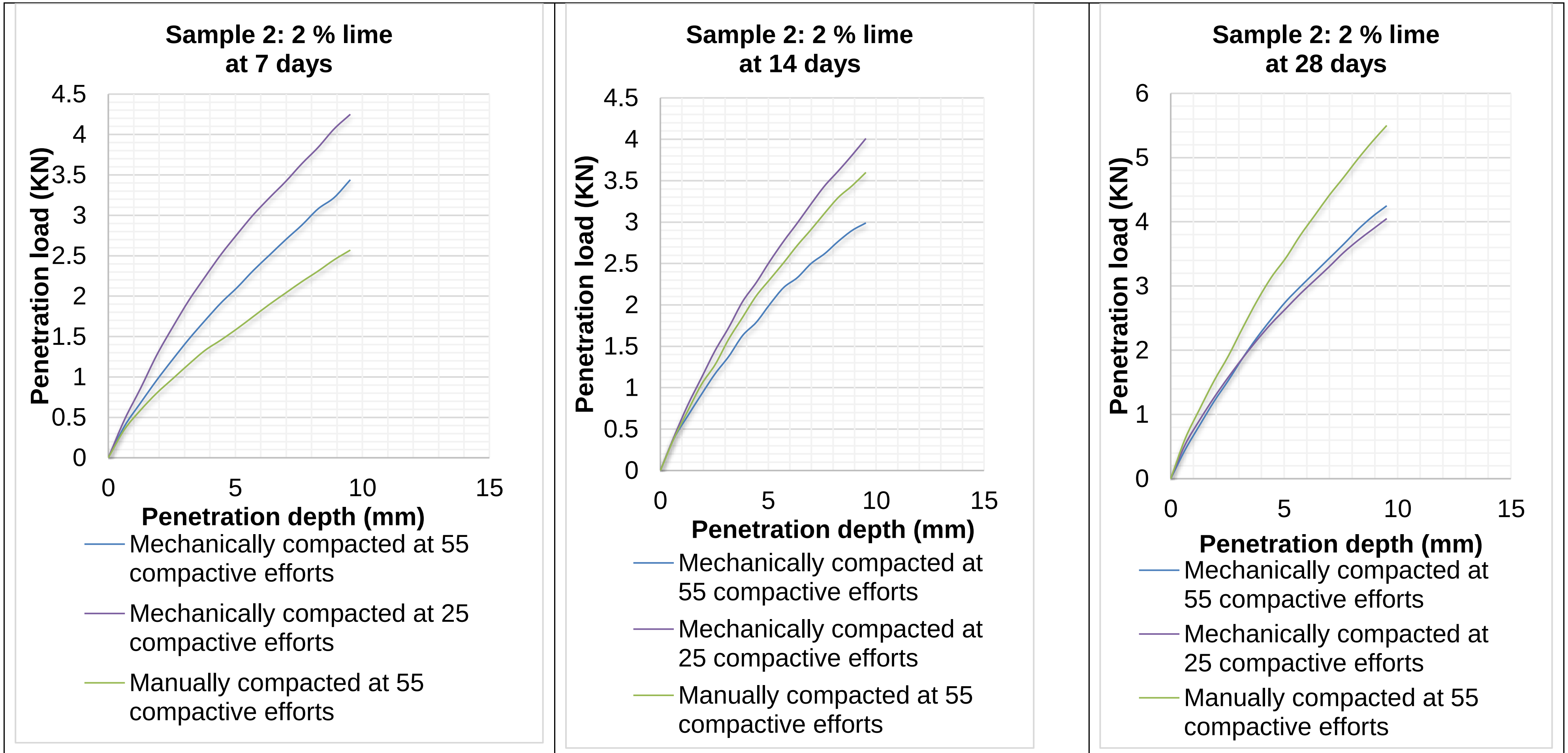


Figure 48: CBR penetration curve for sample 2 at lime content of 2 %, cured for 7, 14 and 28 days respectively

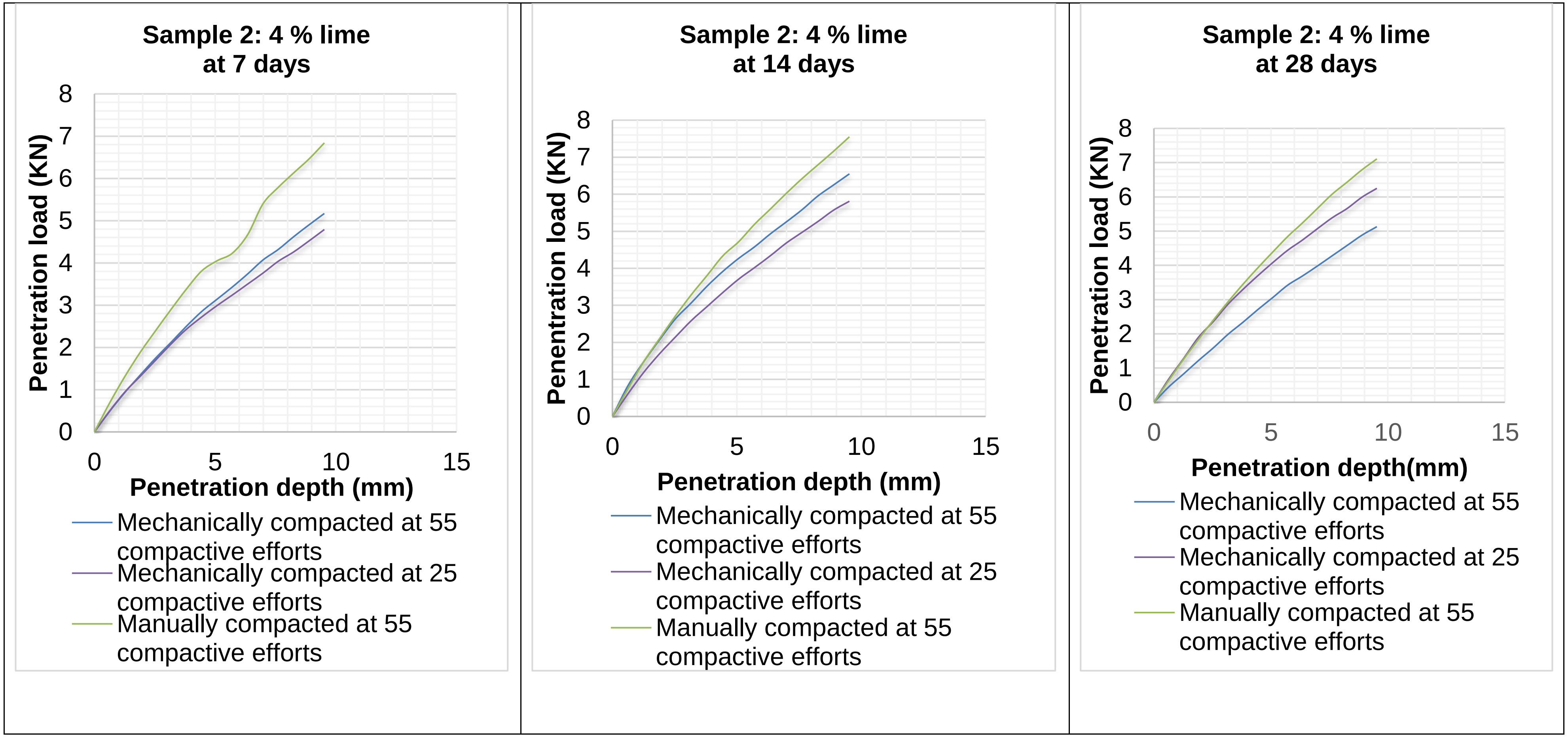
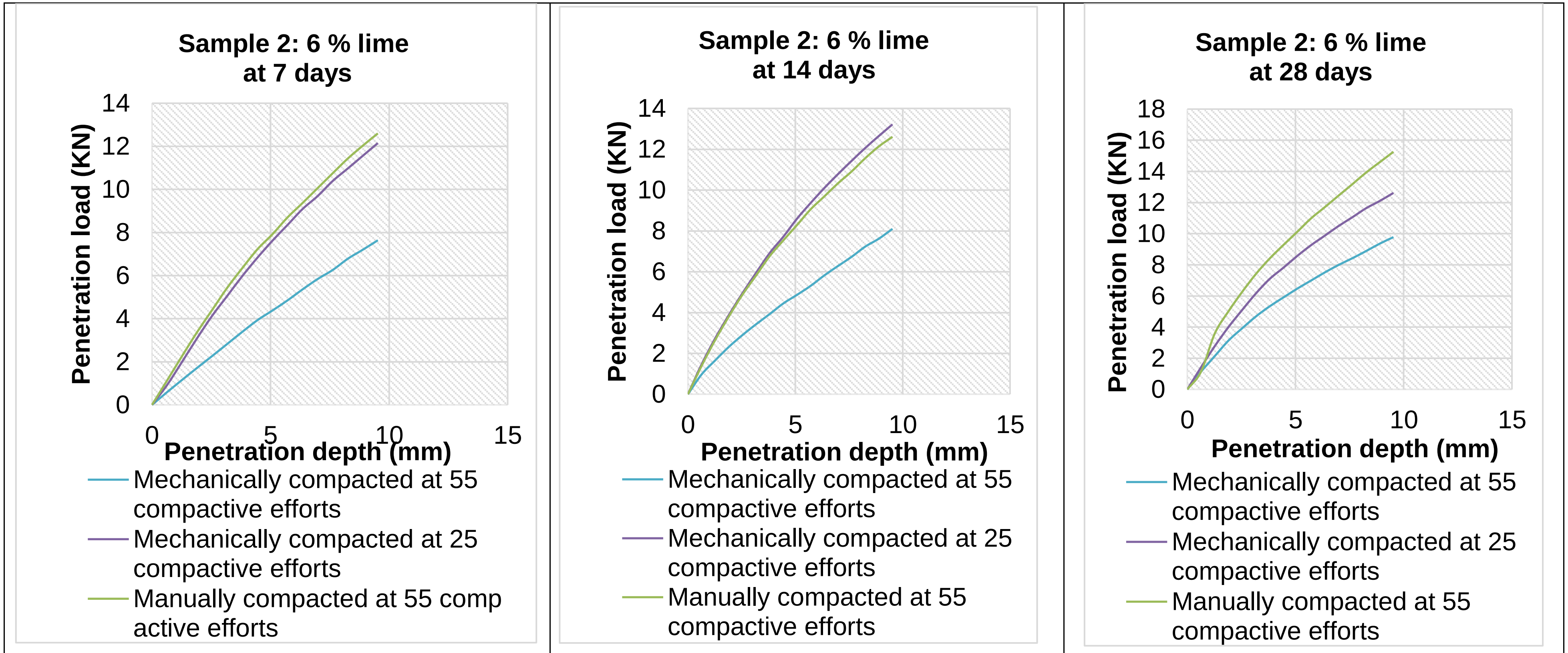


Figure 49: CBR penetration curve for sample 2 at lime content of 4 %, cured for 7, 14 and 28 days respectively


Sample 2: 6 % lime at 7 days

Sample 2: 6 % lime at 14 days

Sample 2: 6 % lime at 28 days

Figure 50: CBR penetration curve for sample 2 at lime content of 6 %, cured for 7, 14 and 28 days respectively

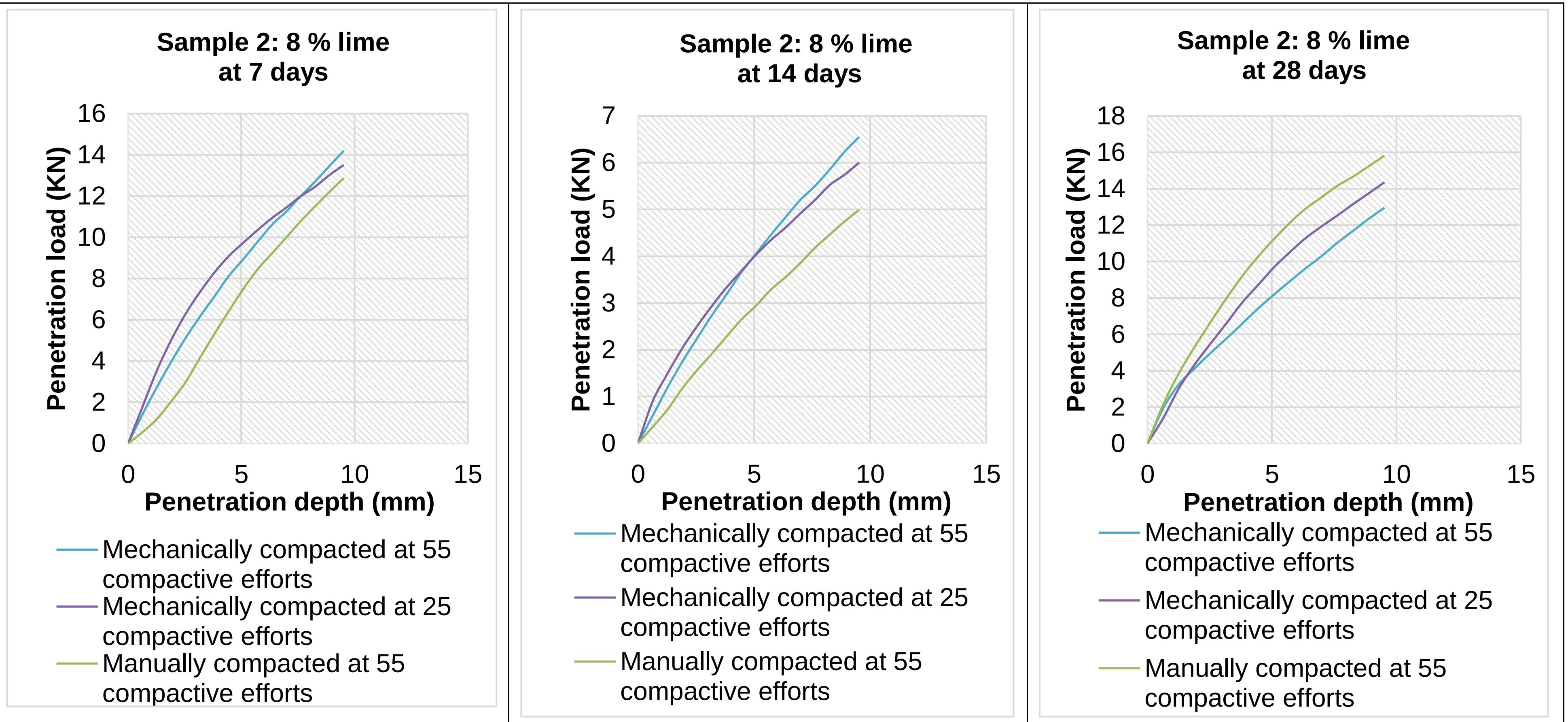


Figure 51: CBR penetration curve for sample 2 at lime content of 8 %, cured for 7, 14 and 28 days respectively

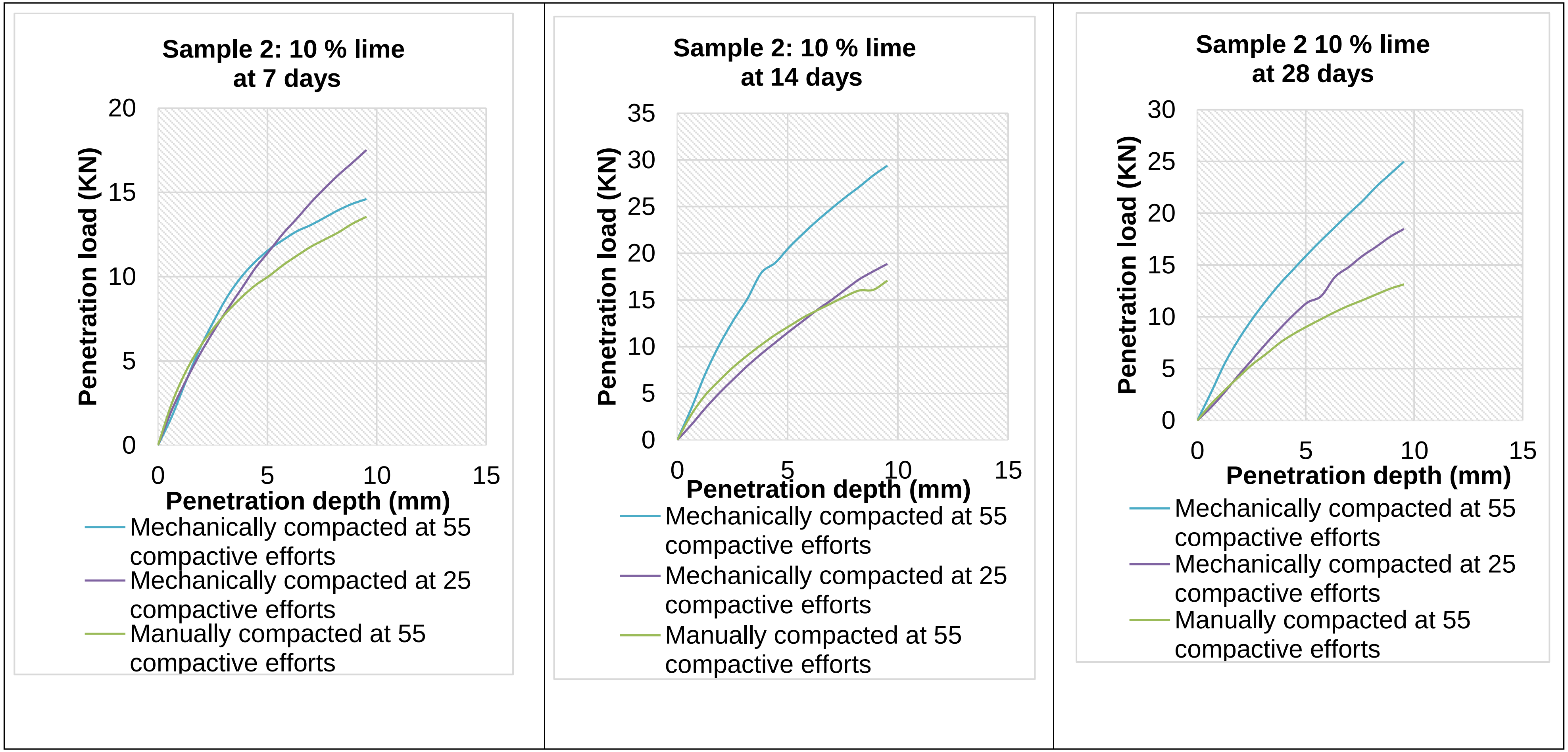


Figure 52: CBR penetration curve for sample 2 at lime content of 10 %, cured for 7, 14 and 28 days respectively

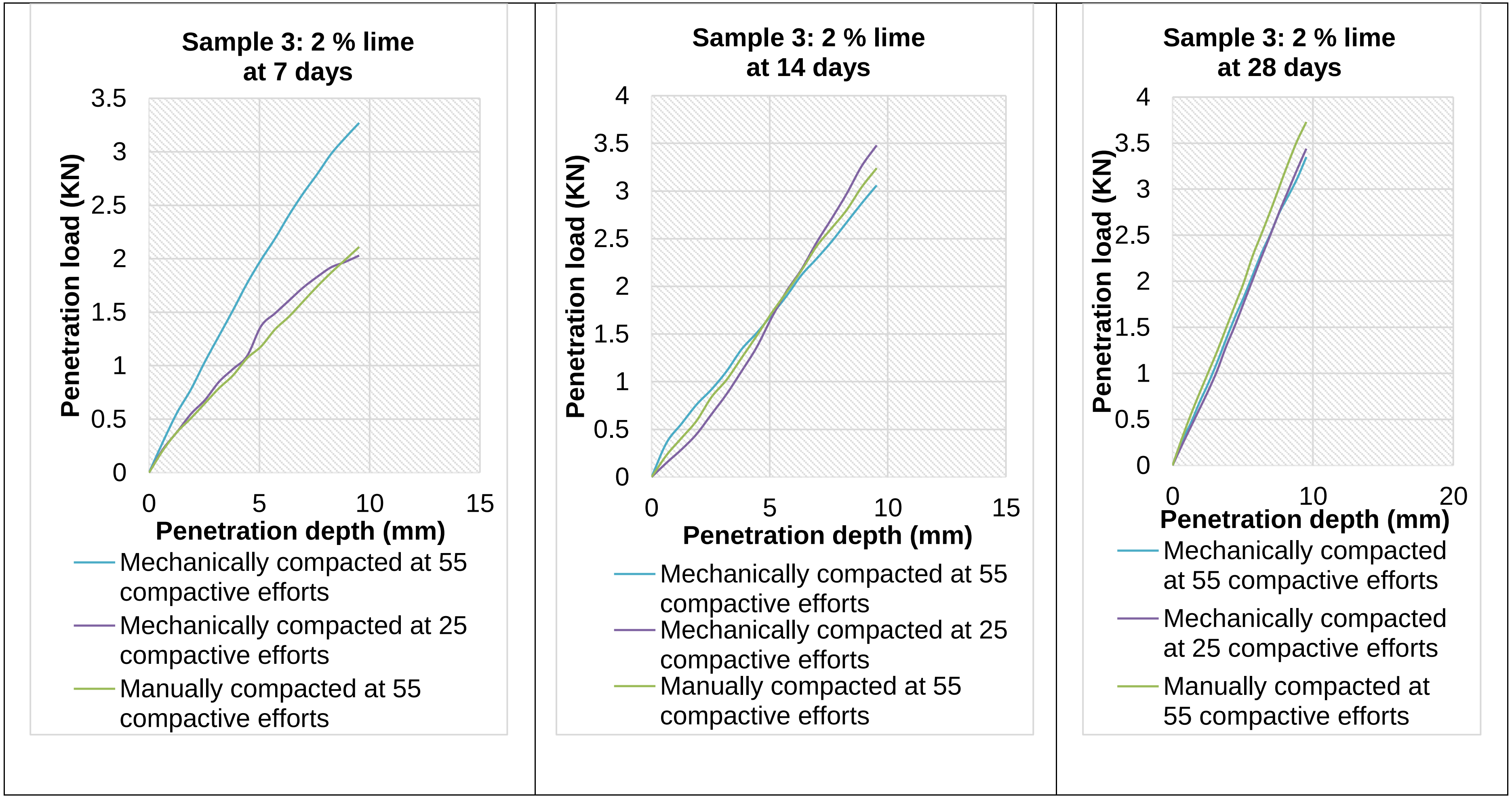


Figure 53: CBR penetration curve for sample 3 at lime content of 2 %, cured for 7, 14 and 28 days respectively

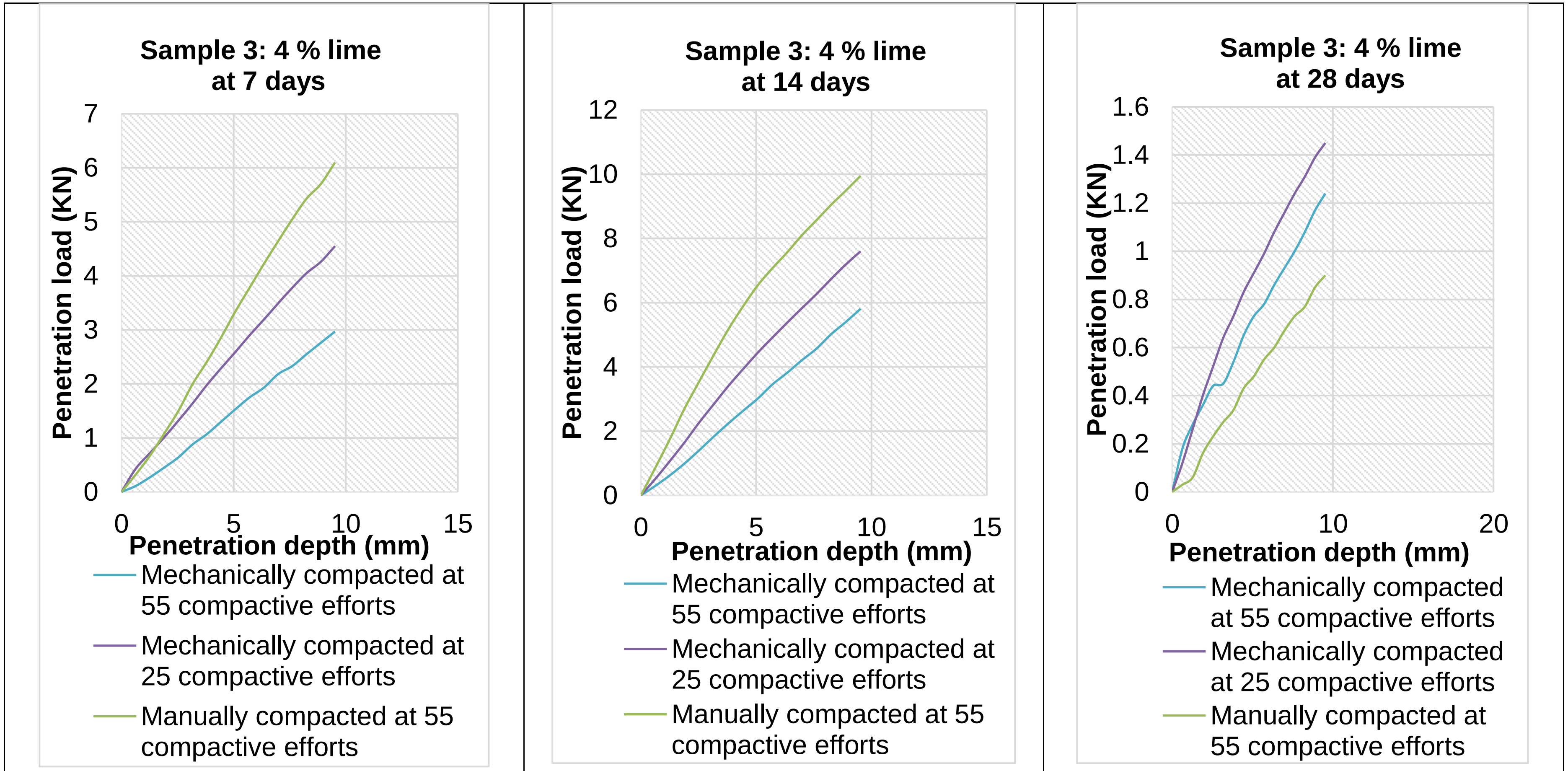


Figure 54: CBR penetration curve for sample 3 at lime content of 4 %, cured for 7, 14 and 28 days respectively

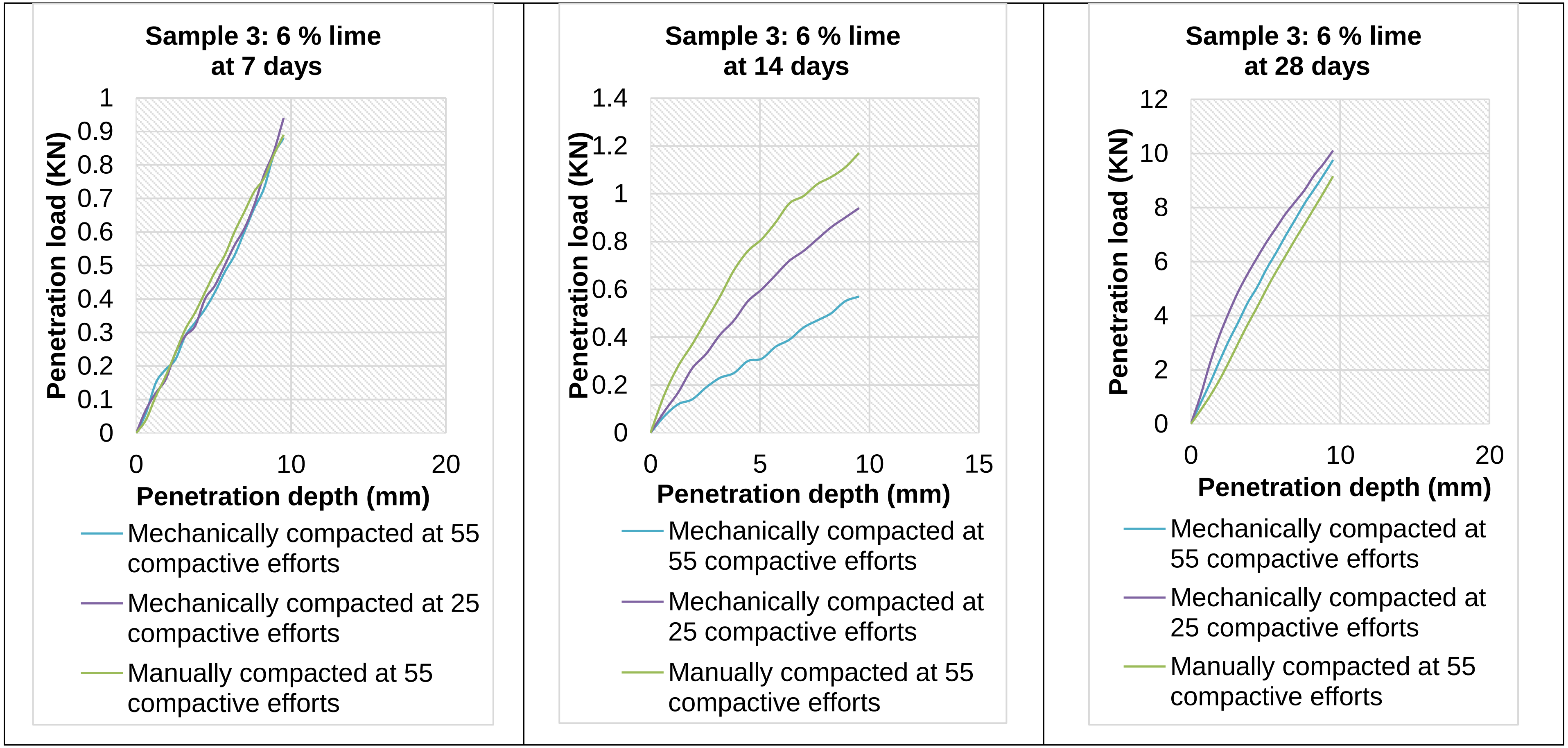


Figure 55: CBR penetration curve for sample 3 at lime content of 6, cured for 7, 14 and 28 days respectively

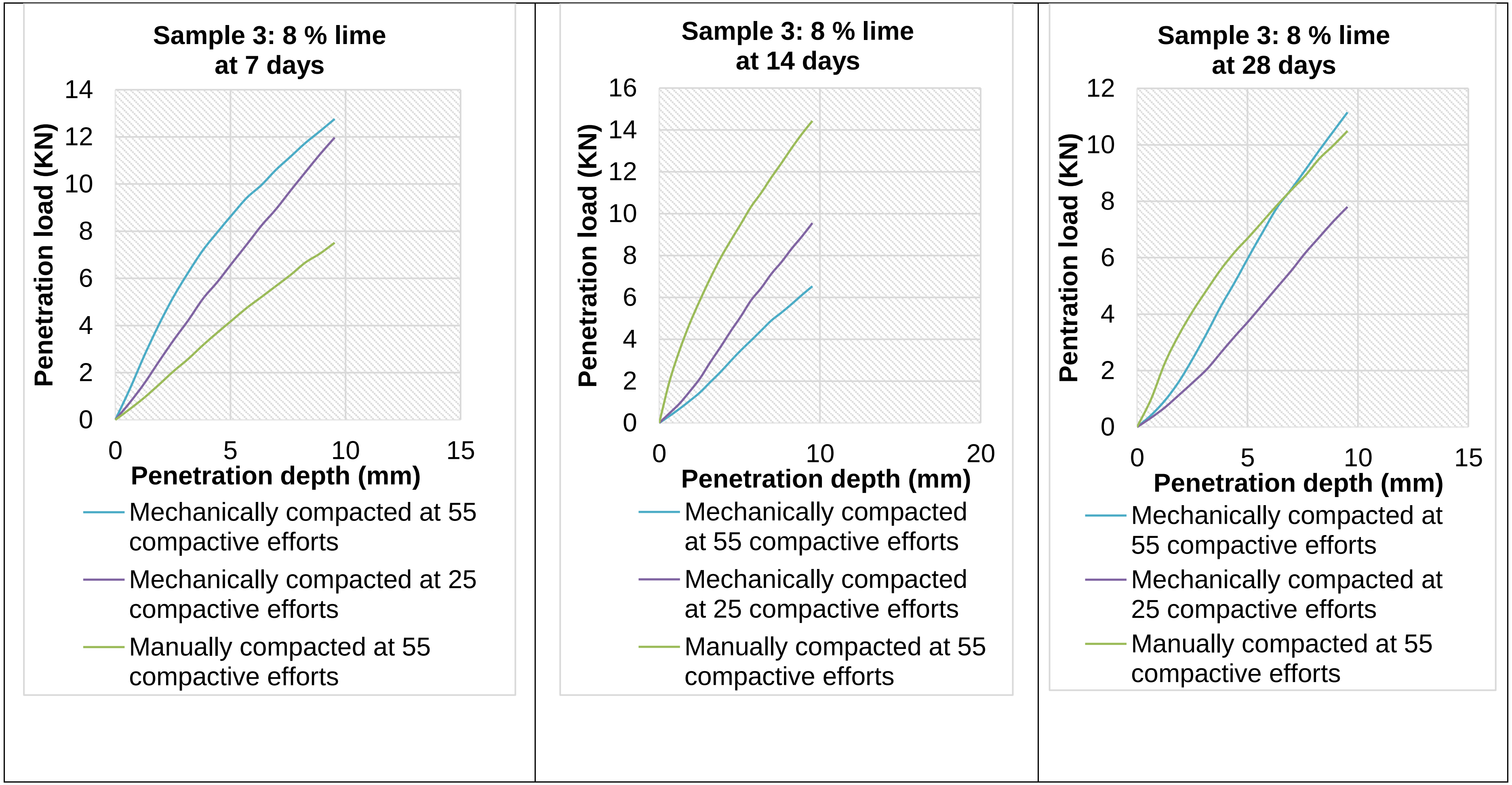


Figure 56: CBR penetration curve for sample 3 at lime content of 8 %, cured for 7, 14 and 28 days respectively

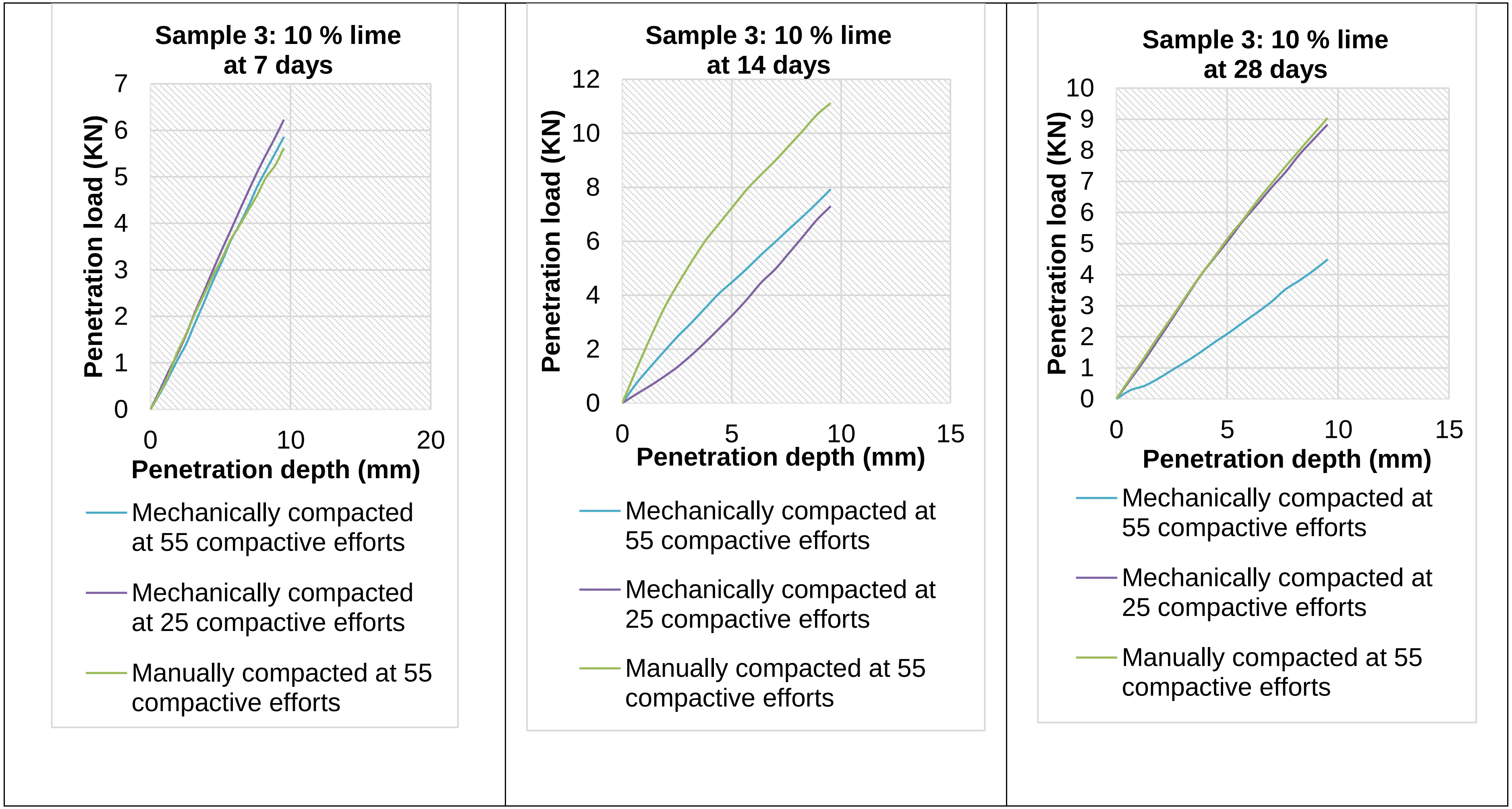


Figure 57: CBR penetration curve for sample 3 at lime content of 10 %, cured for 7, 14 and 28 days respectively

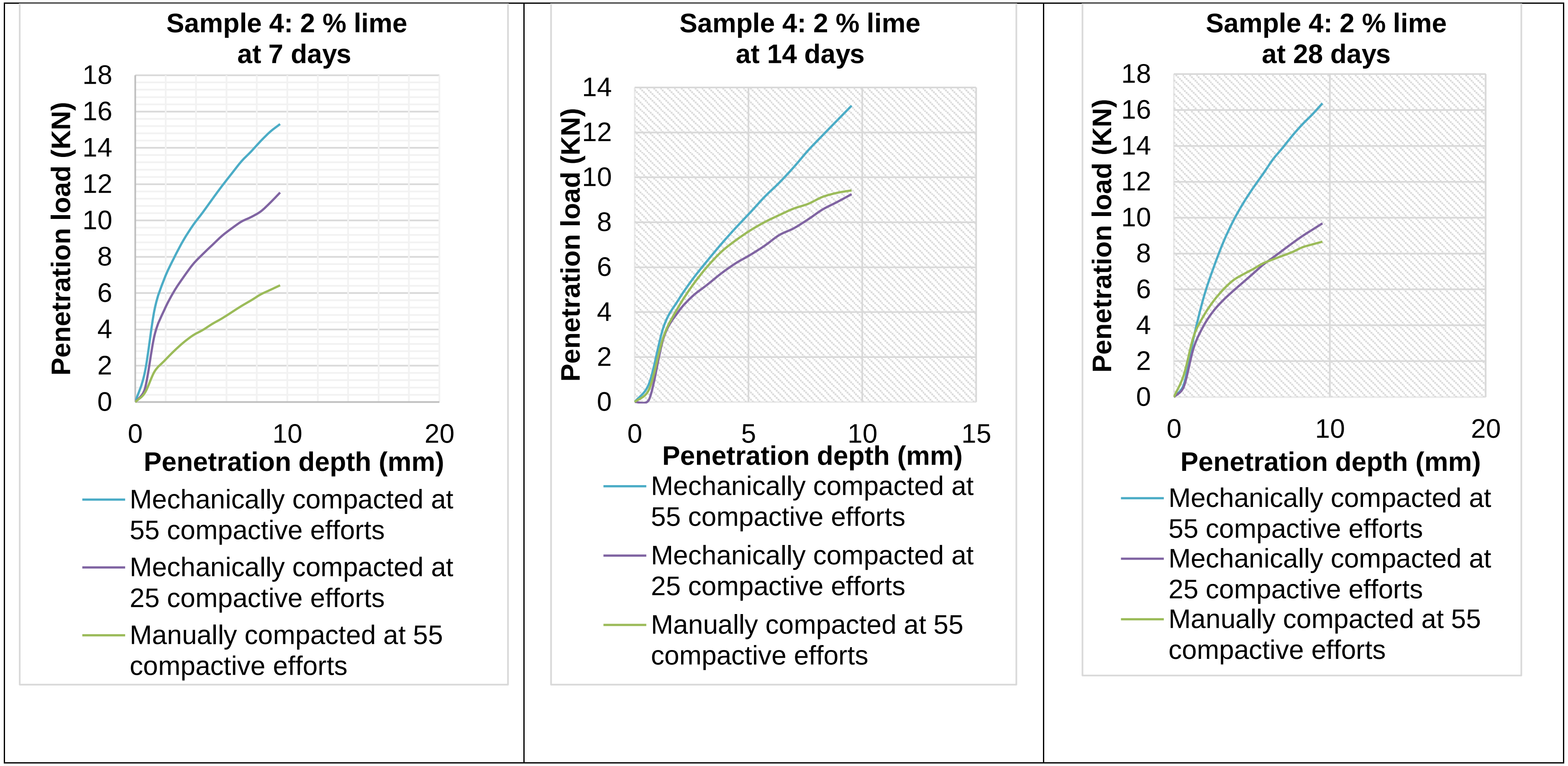


Figure 58: CBR penetration curve for sample 4 at lime content of 2 %, cured for 7, 14 and 28 days respectively

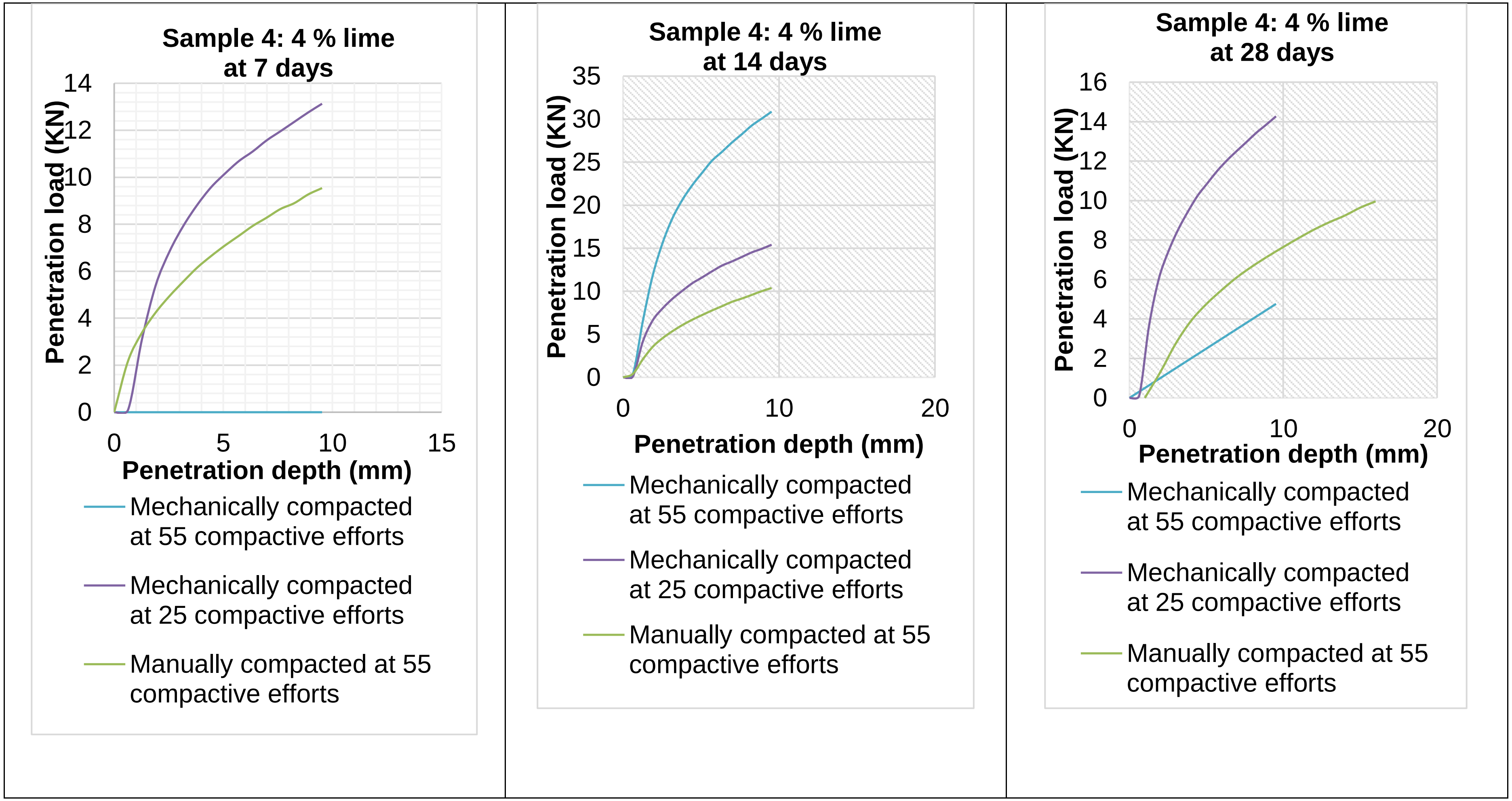


Figure 59: CBR penetration curve for sample 4 at lime content of 4 %, cured for 7, 14 and 28 days respectively

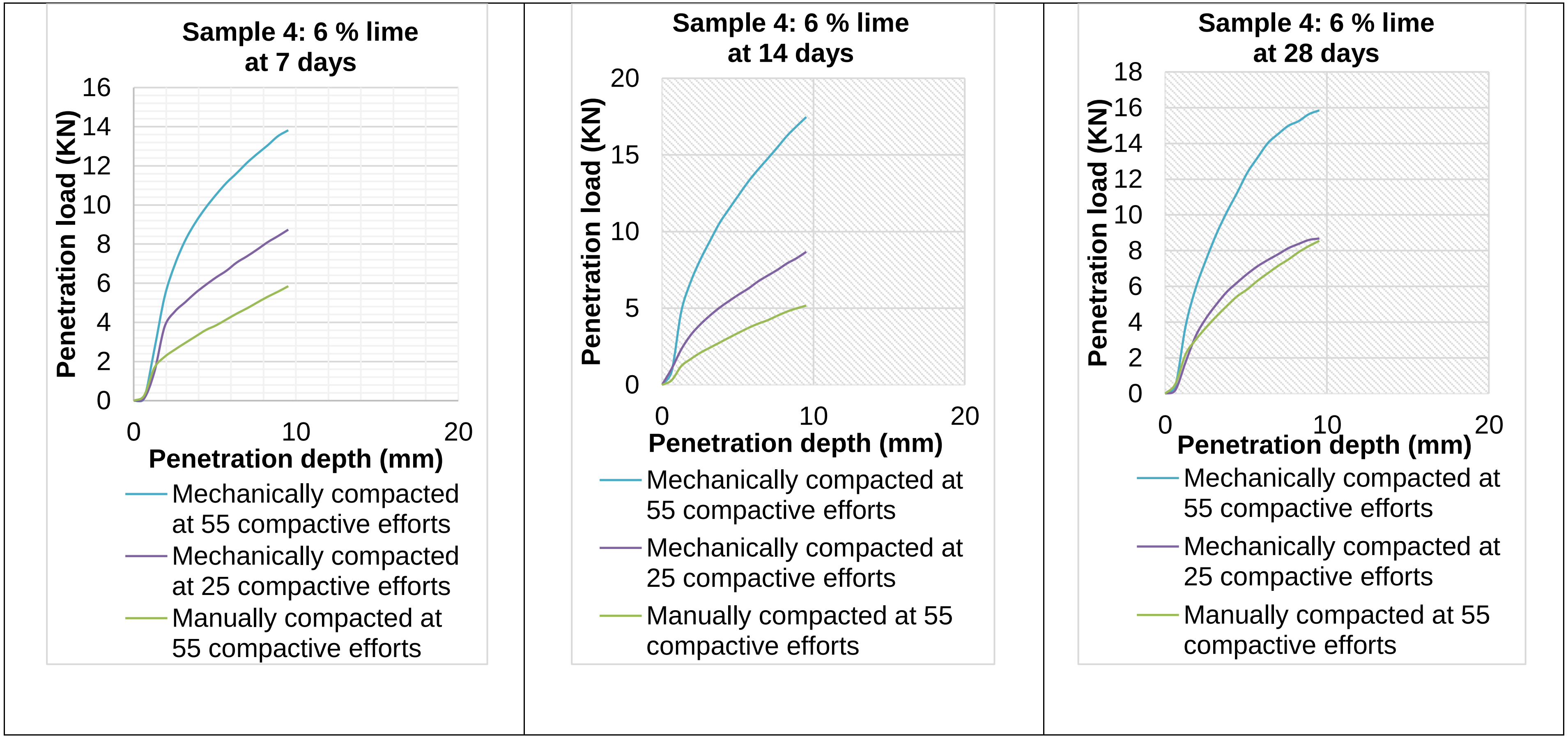


Figure 60: CBR penetration curve for sample 4 at lime content of 6 %, cured for 7, 14 and 28 days respectively

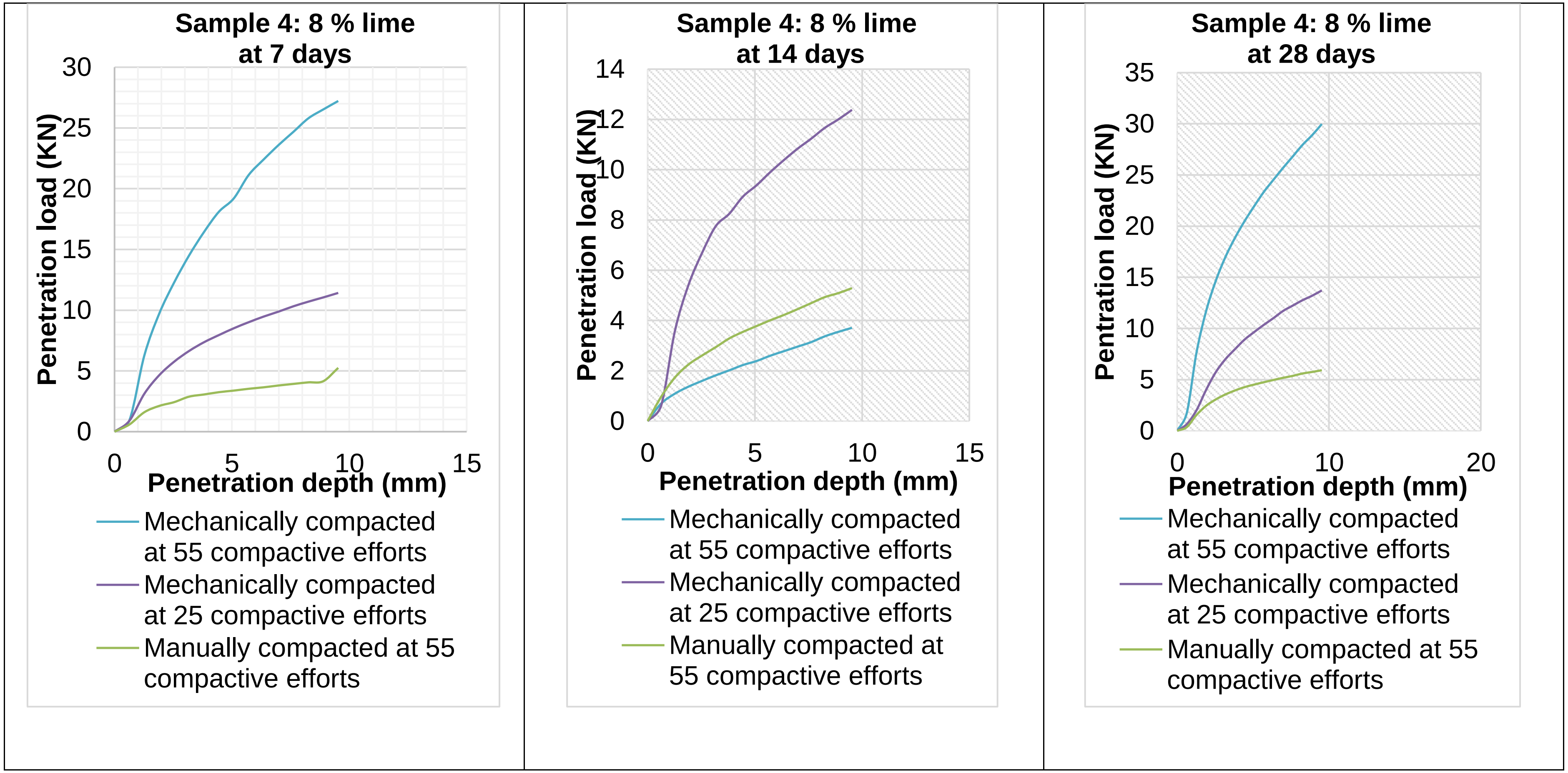


Figure 61**:** CBR penetration curve for sample 4 at lime content of 8 %, cured for 7, 14 and 28 days respectively

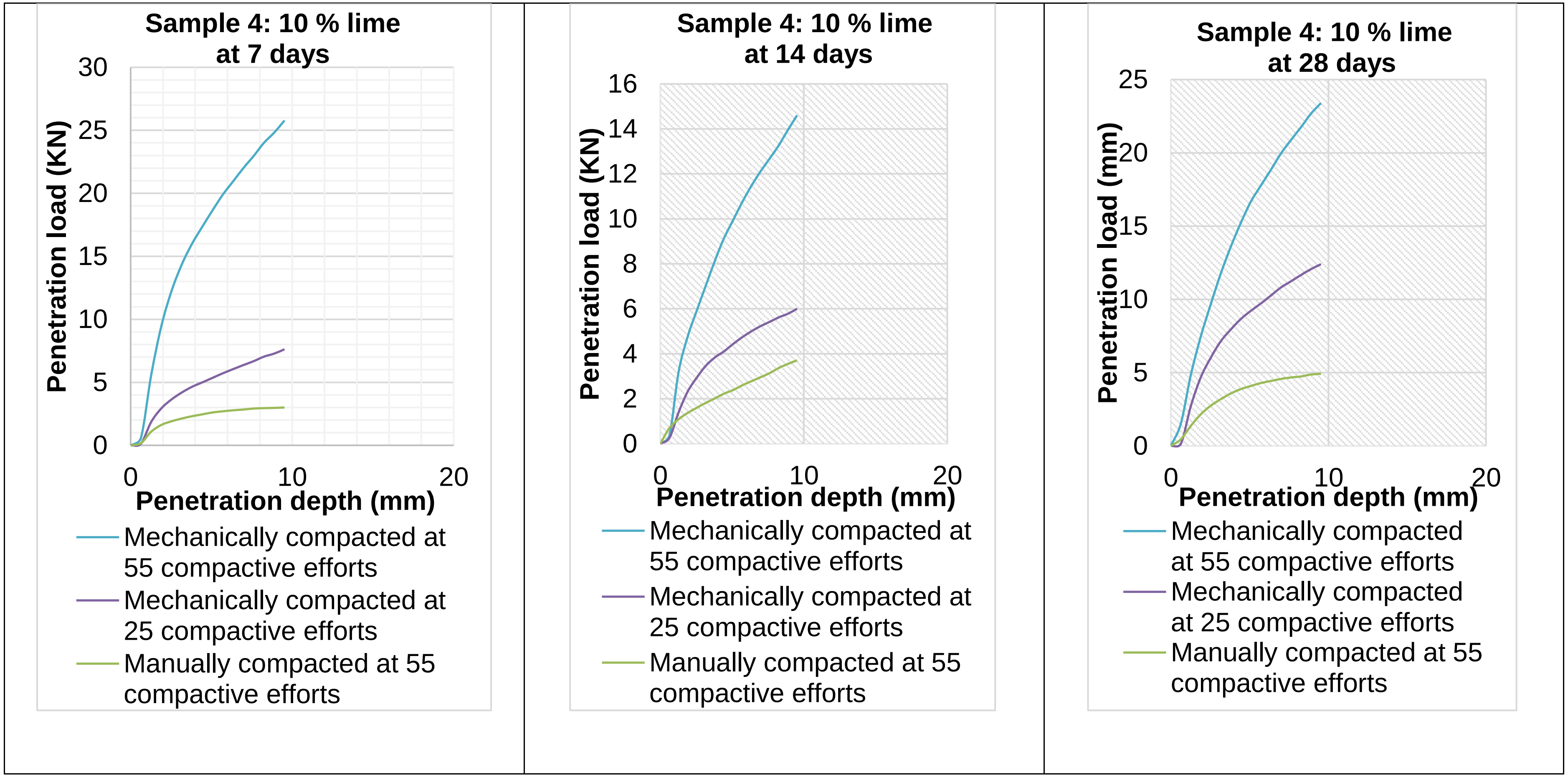


Figure 62: CBR penetration curve for sample 4 at lime content of 10 %, cured for 7, 14 and 28 days respectively.

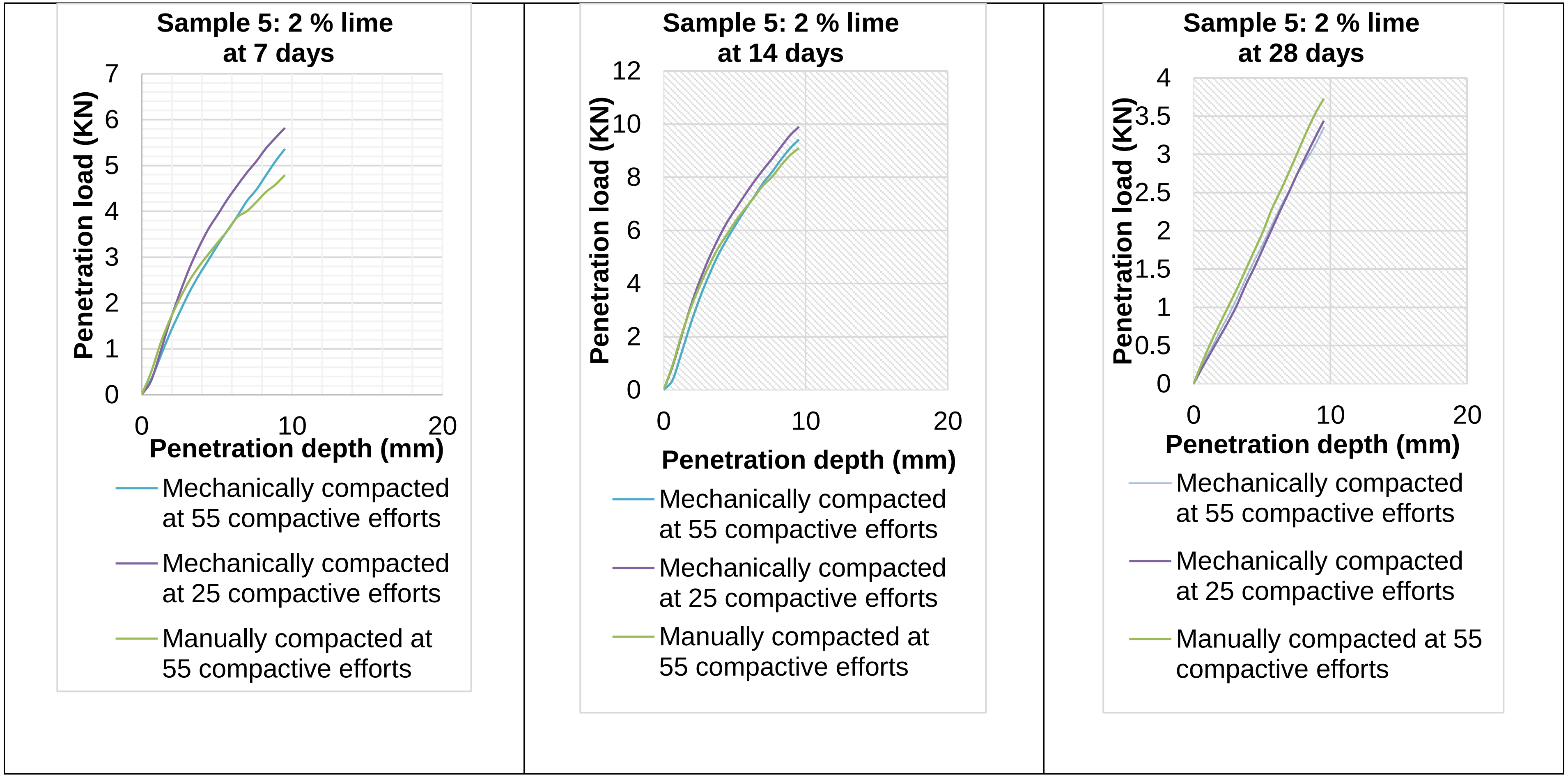


Figure 63**:** CBR penetration curve for sample 5 at lime content of 2 %, cured for 7, 14 and 28 days respectively

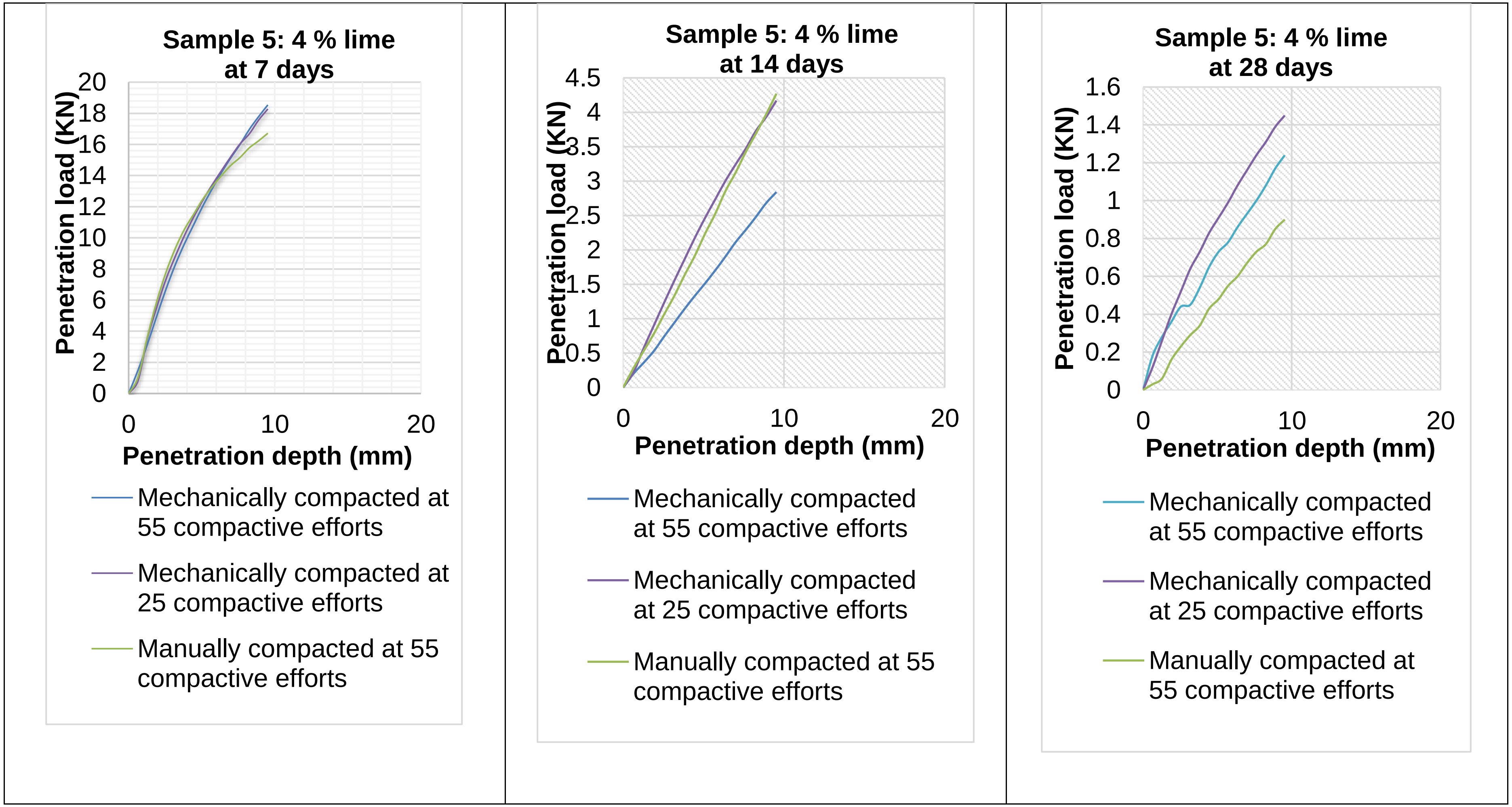


Figure 64: CBR penetration curve for sample 5 at lime content of 4 %, cured for 7, 14 and 28 days respectively

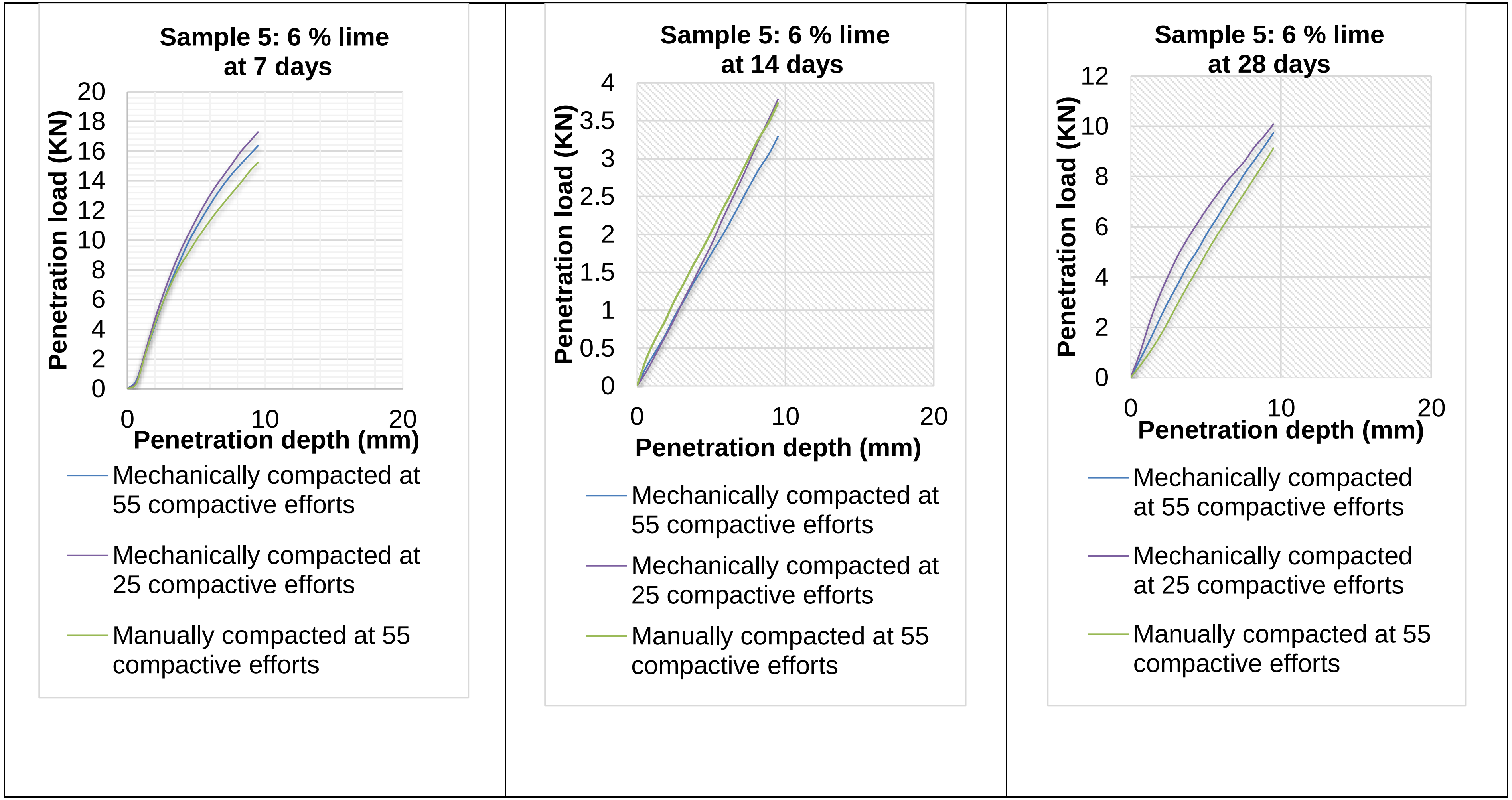


Figure 65: CBR penetration curve for sample 5 at lime content of 6 %, cured for 7, 14 and 28 days respectively

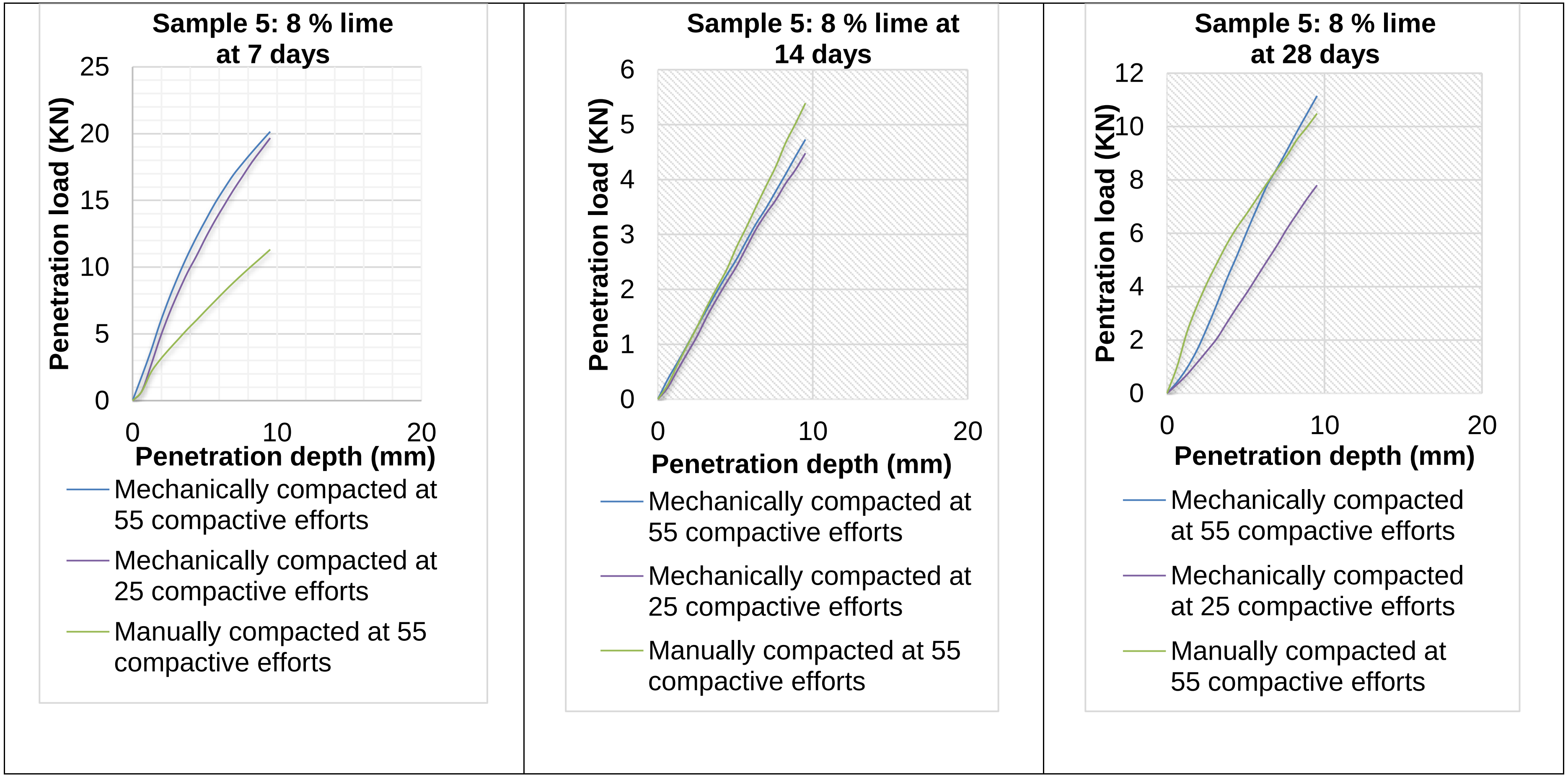


Figure 66: CBR penetration curve for sample 5 at lime content of 8 %, cured for 7, 14 and 28 days respectively

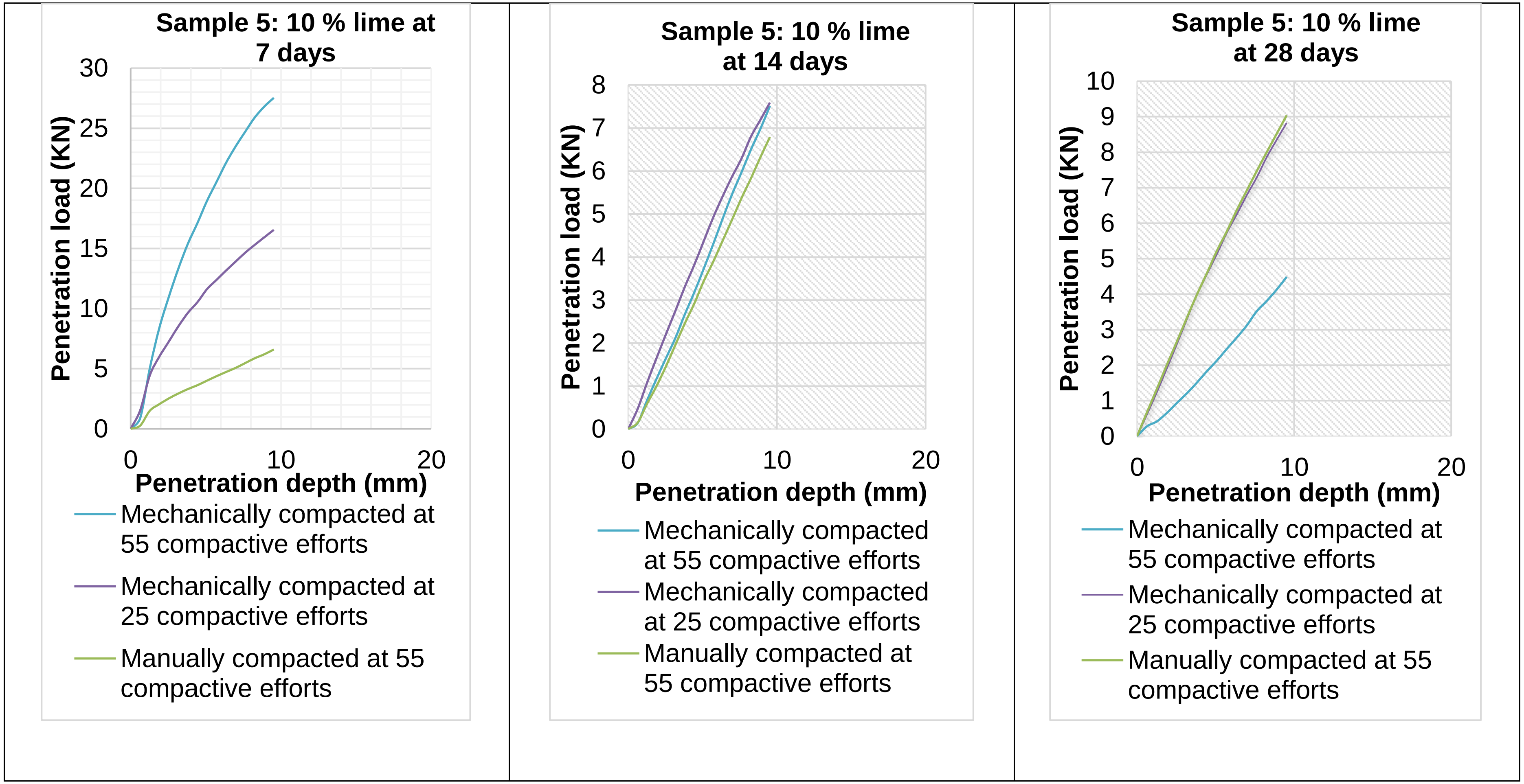


Figure 67: CBR penetration curve for sample 5 at lime content of 10 %, cured for 7, 14 and 28 days respectively

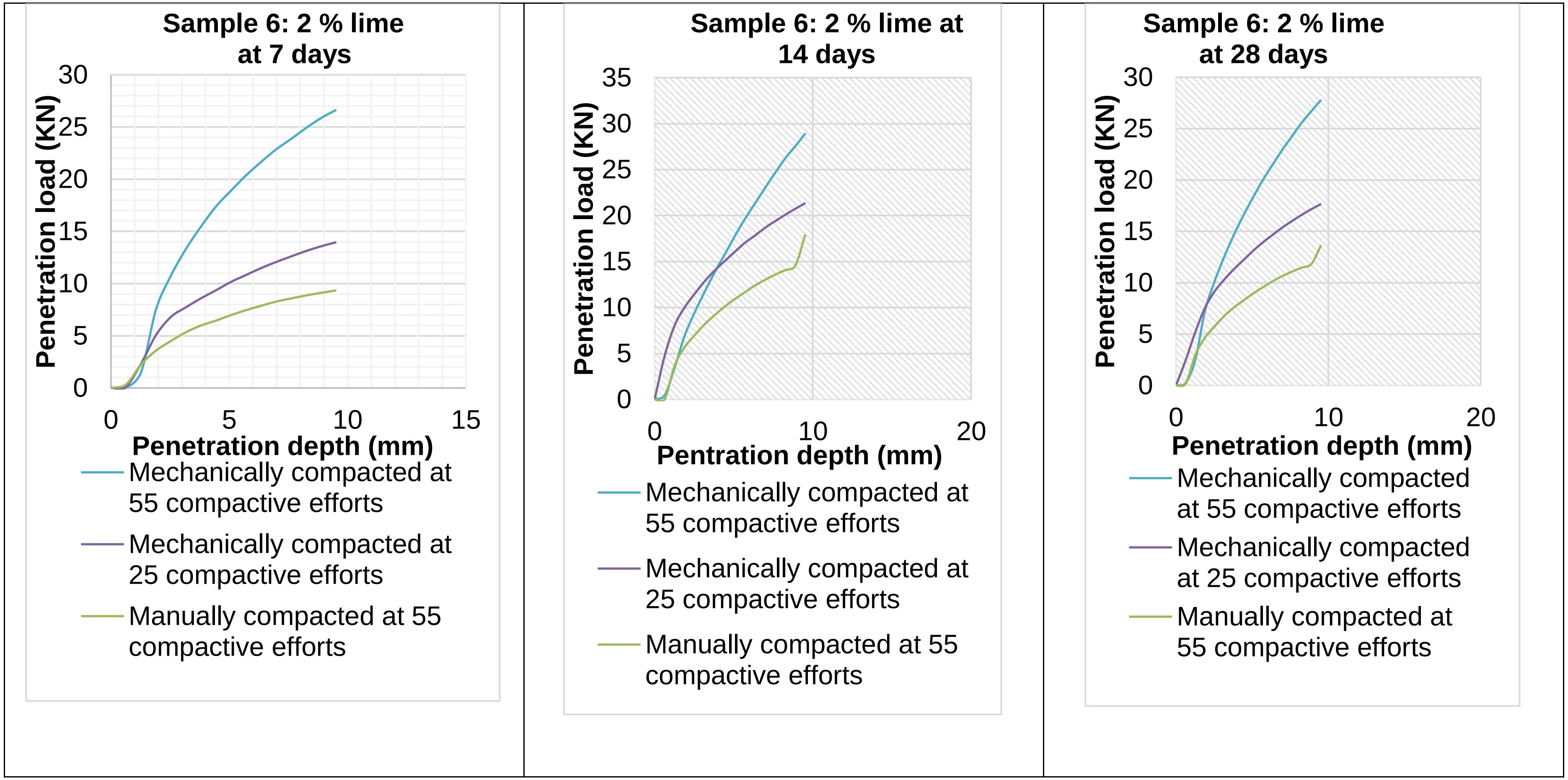
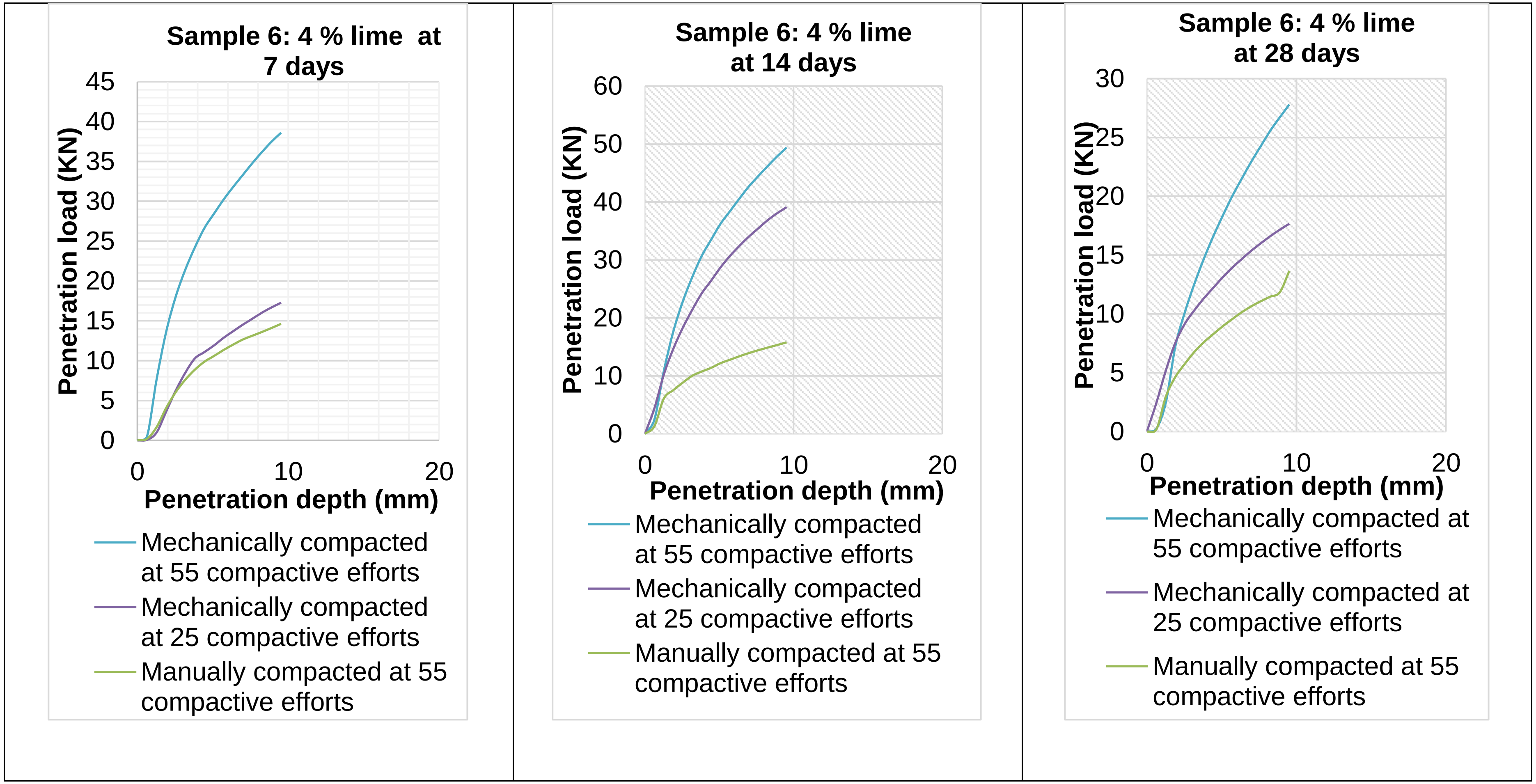


Figure 68: CBR penetration curve for sample 6 at lime content of 2 %, cured for 7, 14 and 28 days respectively



Sample 6: 4 % lime at 7 days

Sample 6: 4 % lime at 14 days

Sample 6: 4 % lime at 28 days

Figure 69: CBR penetration curve for sample 6 at lime content of 4 %, cured for 7, 14 and 28 days respectively

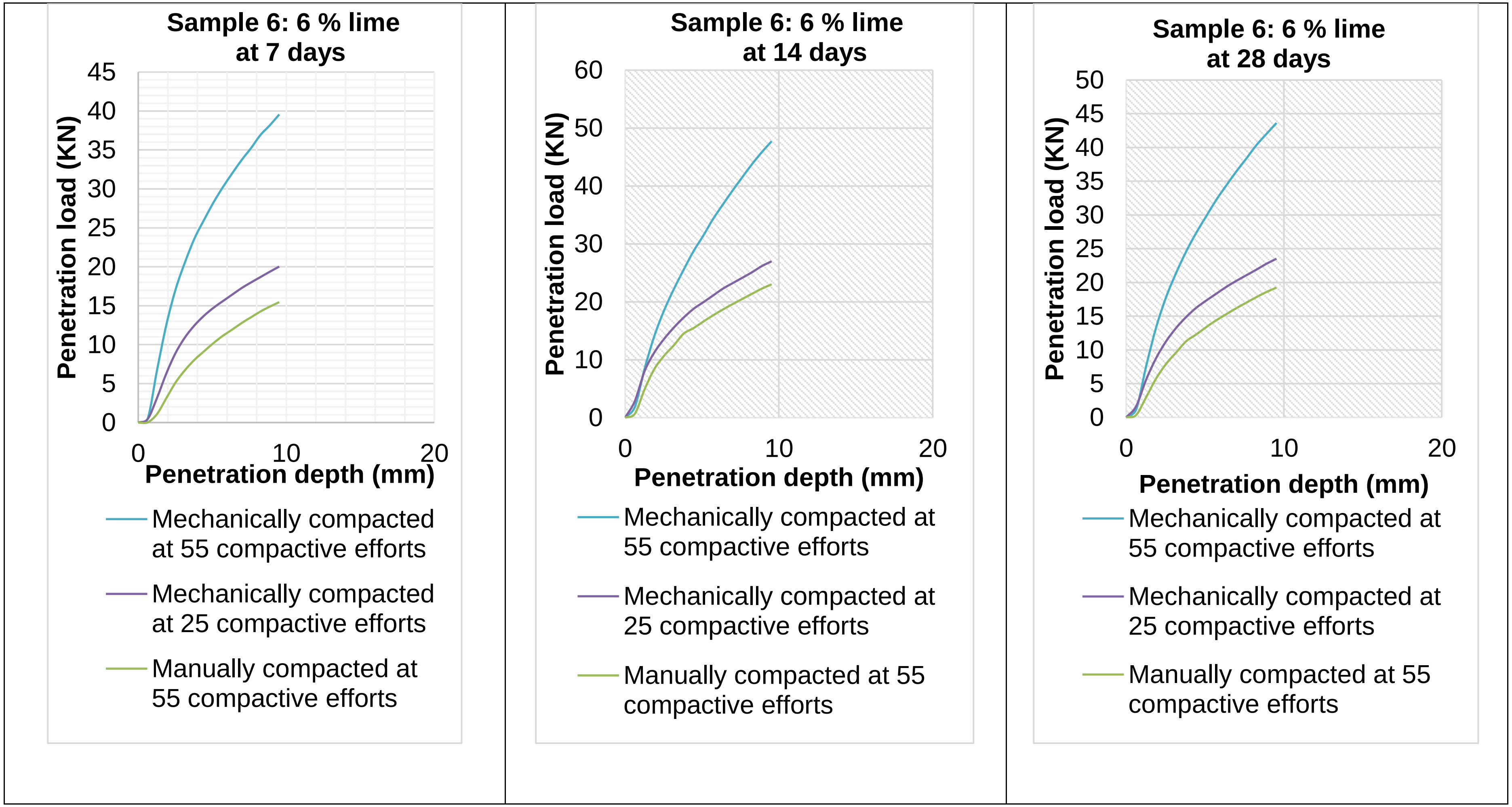


Figure 70: CBR penetration curve for sample 6 at lime content of 6 %, cured for 7, 14 and 28 days respectively

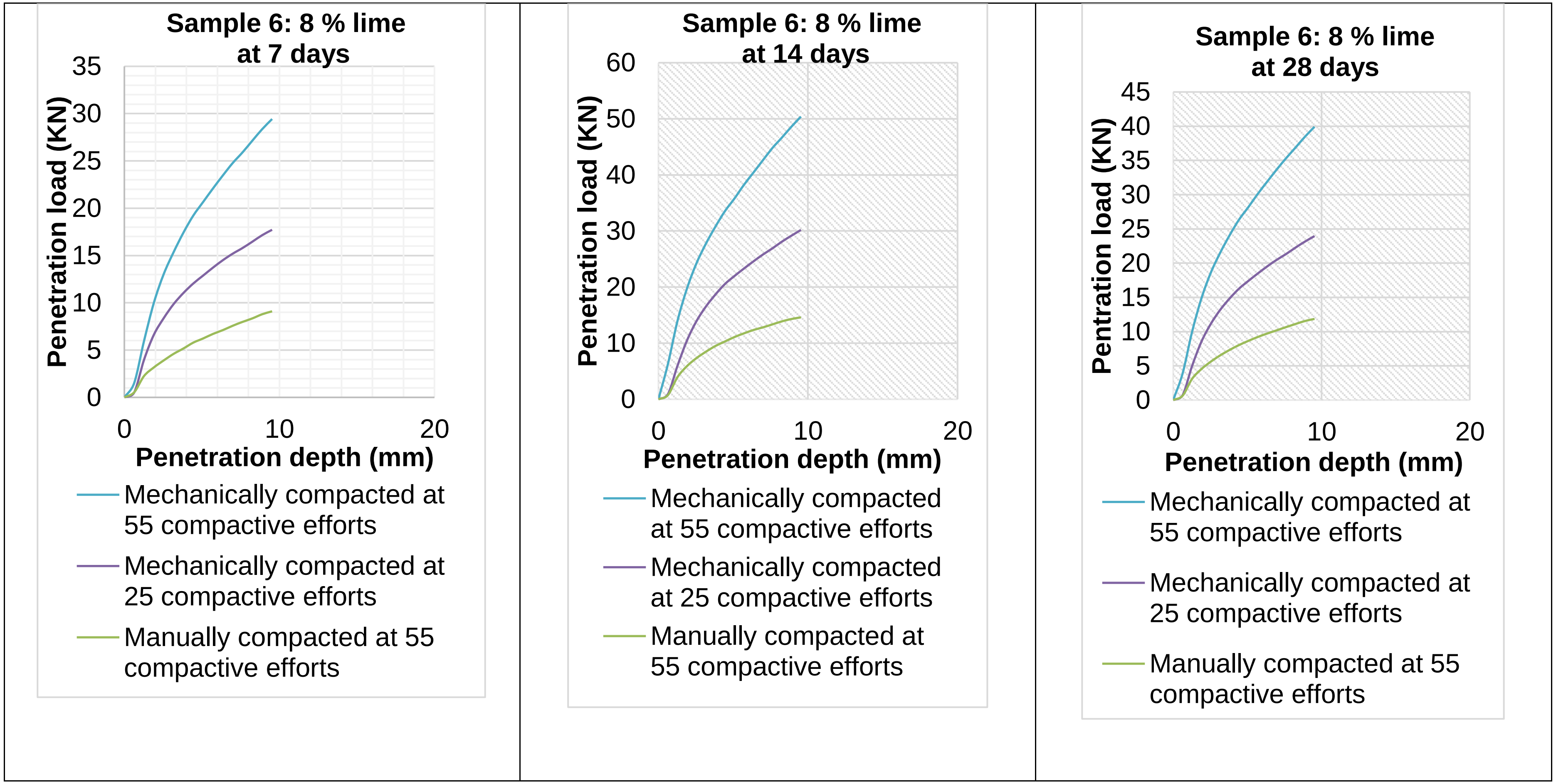


Figure 71: CBR penetration curve for sample 6 at lime content of 8 %, cured for 7, 14 and 28 days respectively

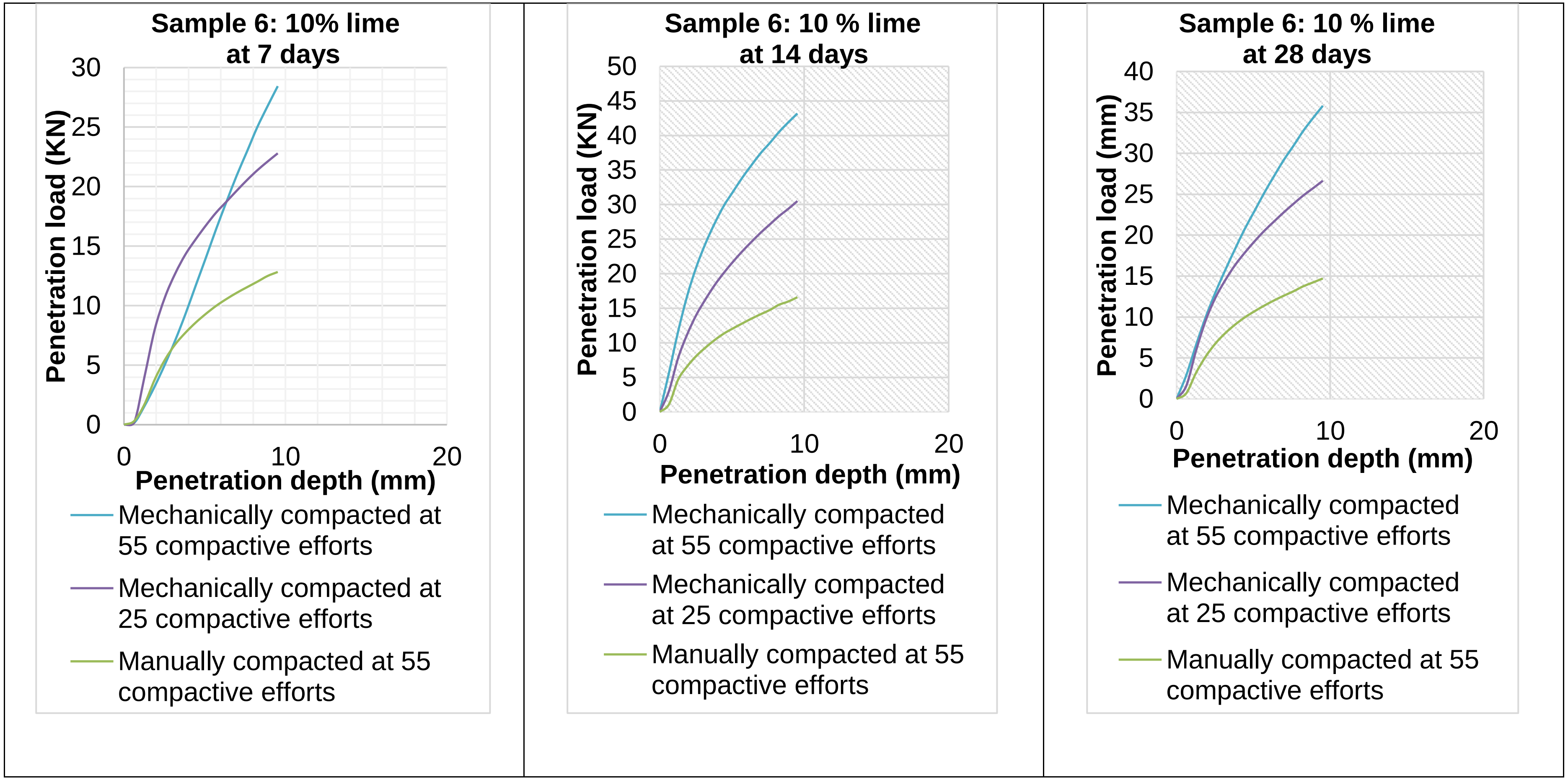


Figure 72: CBR penetration curve for sample 6 at lime content of 10 %, cured for 7, 14 and 28 days respectively

Appendix D: SEM, EDS/EDX micrographs

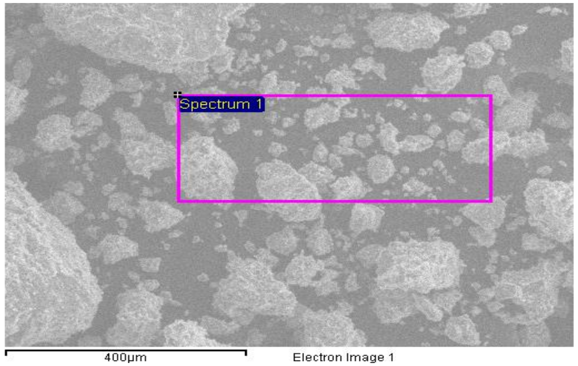
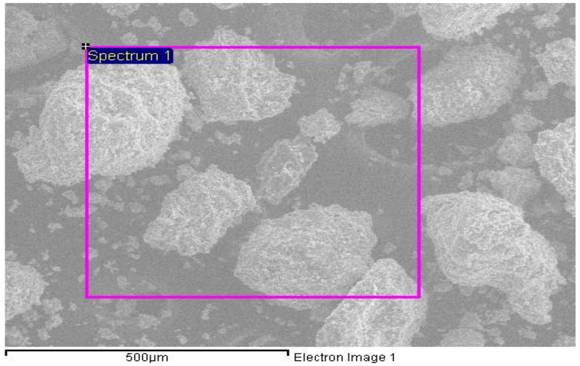
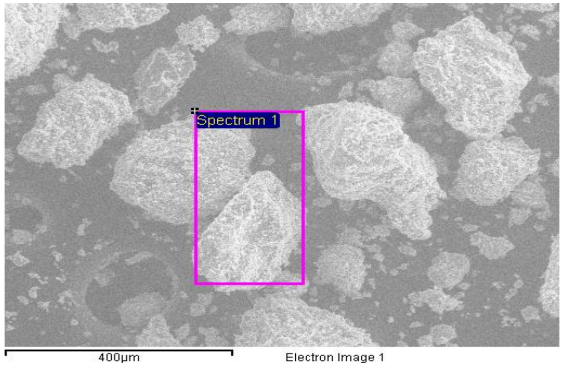
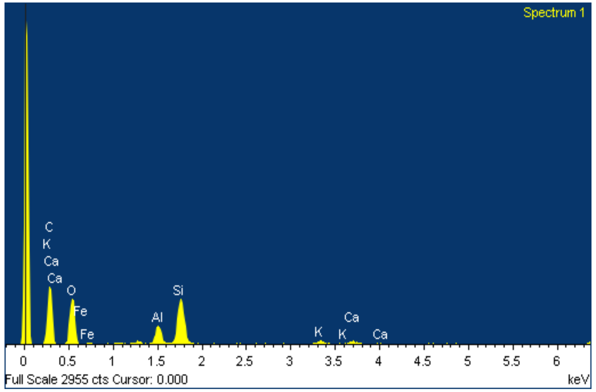
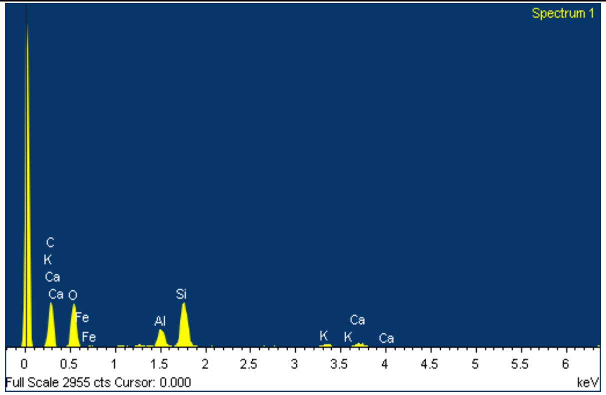
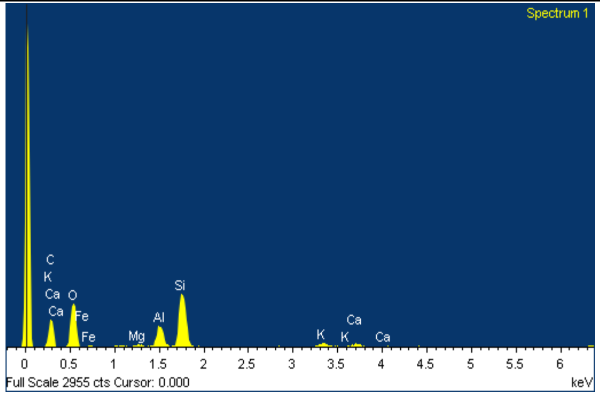
Sample 1: 2 % lime at 7days - Area 1	**Sample 1: 2 % lime at 7 days - Area 2**	**Sample 1: 2 % lime at 7 days - Area 3**
 (a1) Sample 1 SEM micrograph at 2 % lime	 (a2) Sample 1 SEM micrograph at 2 % lime	 (a3) Sample 1 SEM micrograph at 2 % lime
 (b1) Sample 1 EDS/EDX	 (b2) Sample 1 EDS/EDX	 (b3) Sample 1 EDS/EDX

Figure 73: (a1), (a2) and (a3): sample 1 SEM micrographs at 2 % lime, areas 1, 2 and 3 respectively. (b1), (b2 and (b3) sample 1 EDS/EDX images, areas 1, 2 and 3 respectively

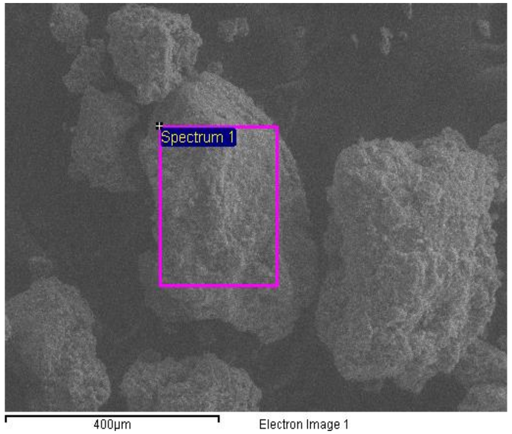
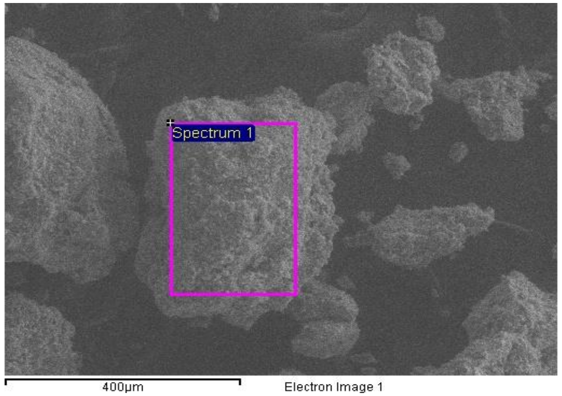
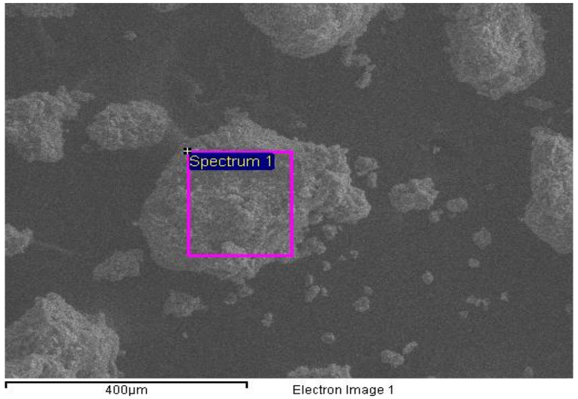
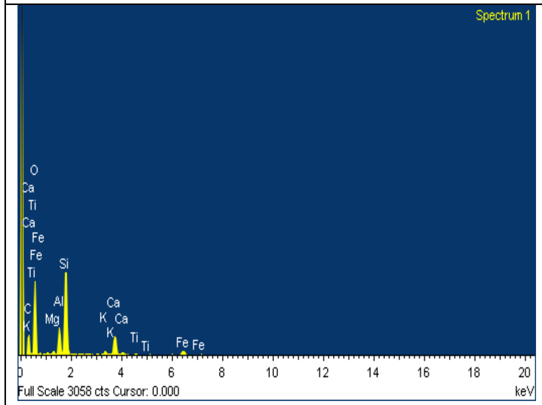
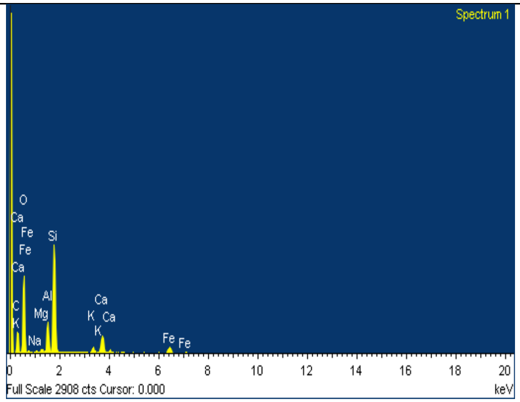
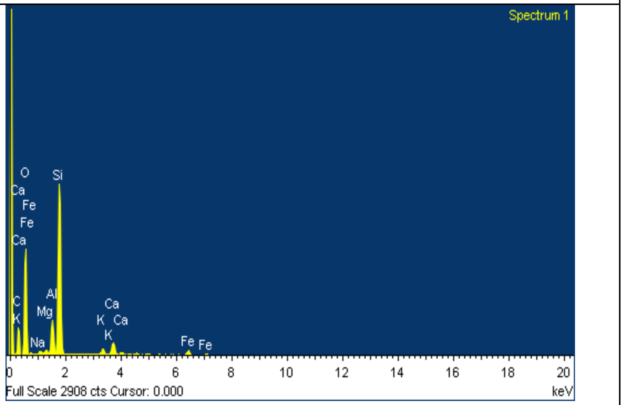
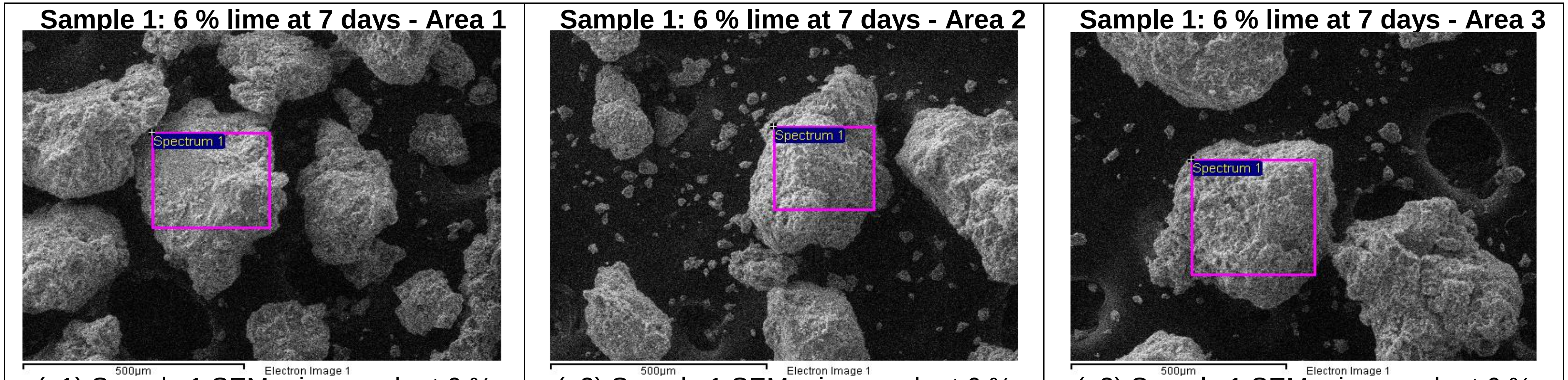
Sample 1: 4 % lime at 7 days - Area 1	**Sample 1: 4 % lime at 7 days - Area 2**	**Sample 1: 4 % lime at 7 days - Area 3**
		
(a1) Sample 1 SEM micrograph at 4 % lime	(a2) Sample 1 SEM micrograph at 4 % lime	(a3) Sample 1 SEM micrograph at 4 % lime
		
(b1) Sample 1 EDS/EDX	(b2) Sample 1 EDS/EDX	(b3) Sample 1 EDS/EDX

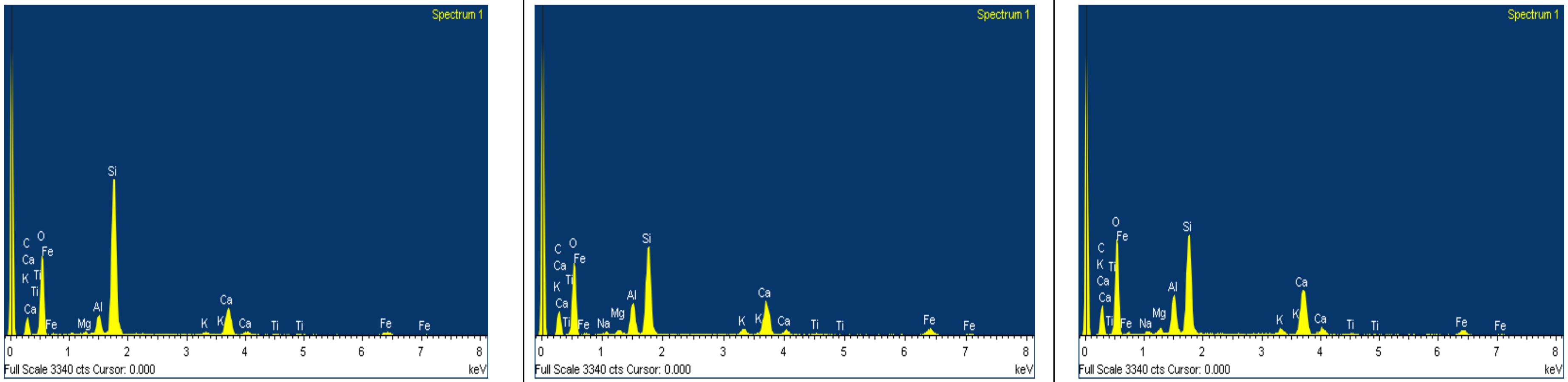
Figure 74: (a1), (a2) and (a3): sample 1 SEM micrographs at 4 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively



(a1) Sample 1 SEM micrograph at 6 % lime

(a2) Sample 1 SEM micrograph at 6 % lime

(a3) Sample 1 SEM micrograph at 6 % lime



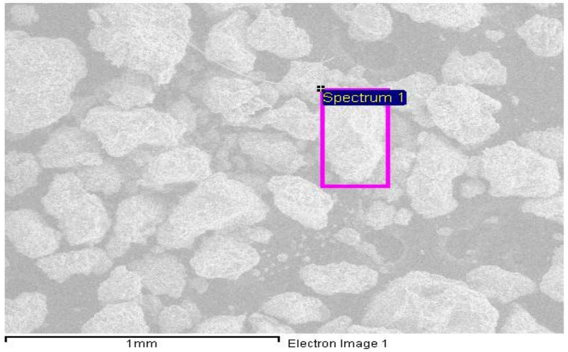
(b1) Sample 1 EDS/EDX

(b2) Sample 1 EDS/EDX

(b3) Sample 1 EDS/EDX

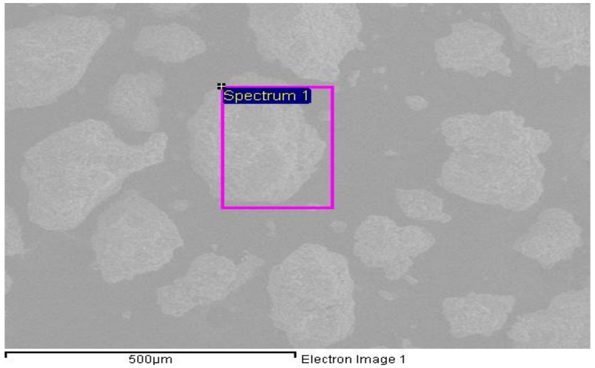
Figure 75: (a1), (a2) and (a3): sample 1 SEM micrographs at 6 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 1: 8 % lime at 7 days - Area 1



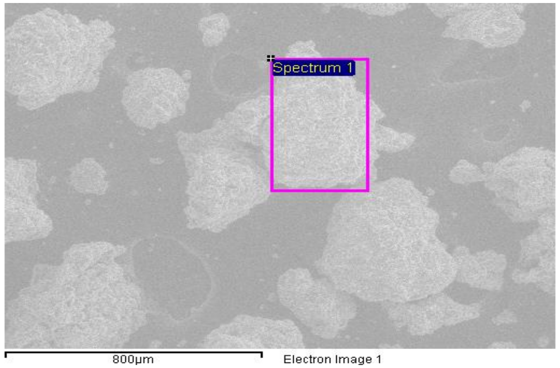
(a1) Sample 1 SEM micrograph at 8 % lime

Sample 1: 8 % lime at 7 days - Area 2

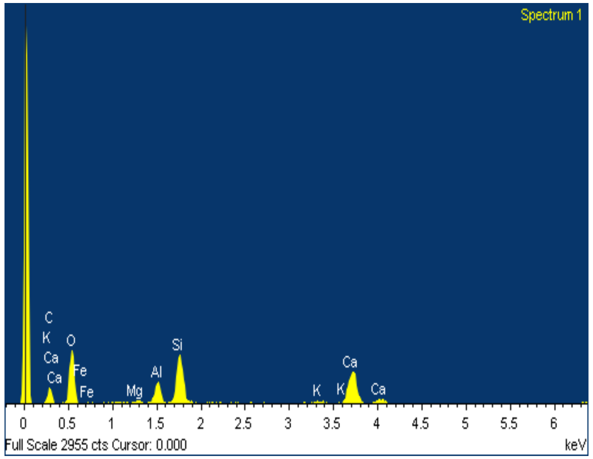


(a2) Sample 1 SEM micrograph at 8 % lime

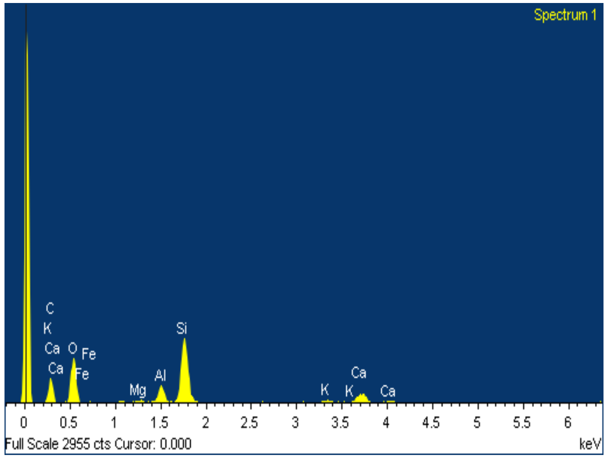
Sample 1: 8 % lime at 7 days - Area 3



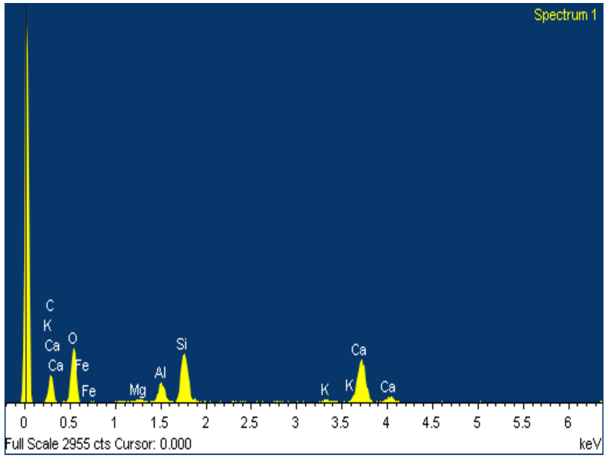
(a3) Sample 1 SEM micrograph at 8 % lime



(b1) Sample 1 EDS/EDX



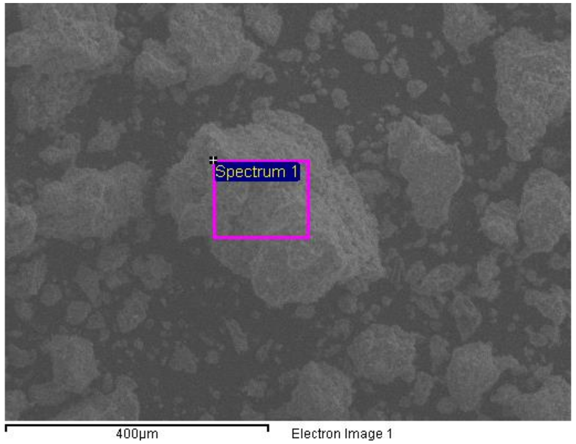
(b2) Sample 1 EDS/EDX



(b3) Sample 1 EDS/EDX

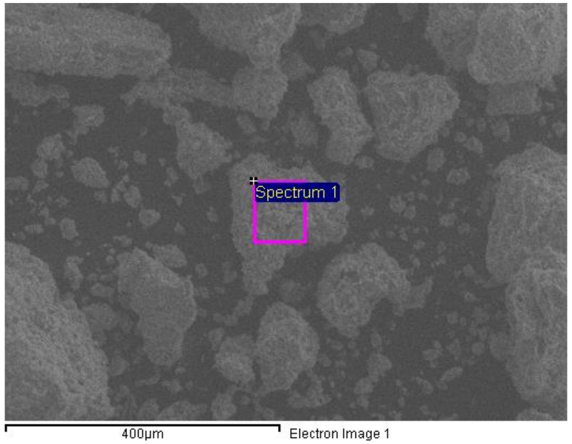
Figure 76: (a1), (a2) and (a3): sample 1 SEM micrographs at 8 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 1: 10 % lime at 7 days - Area 1



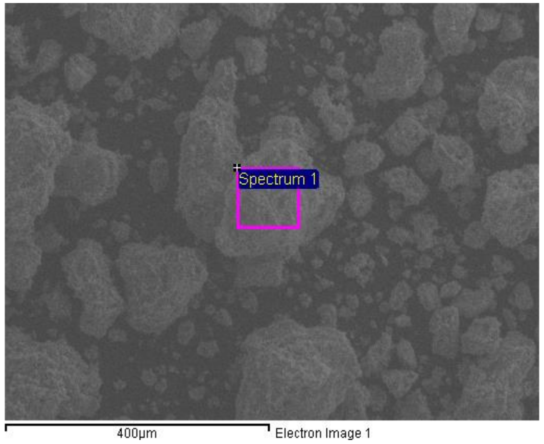
(a1) Sample 1 SEM micrograph at 10 % lime

Sample 1: 10 % lime at 7 days - Area 2

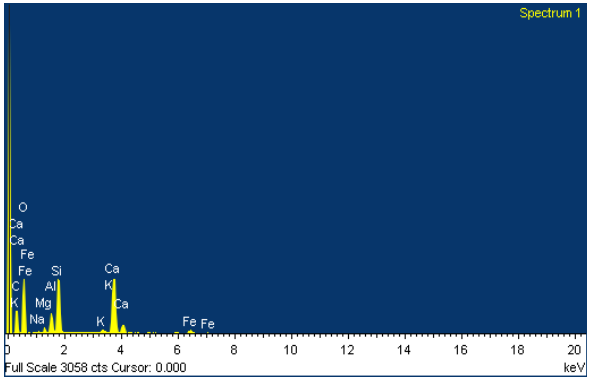


(a2) Sample 1 SEM micrograph at 10 % lime

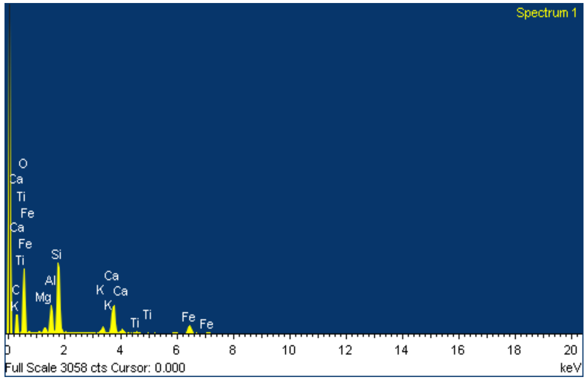
Sample 1: 10 % lime at 7 days - Area 3



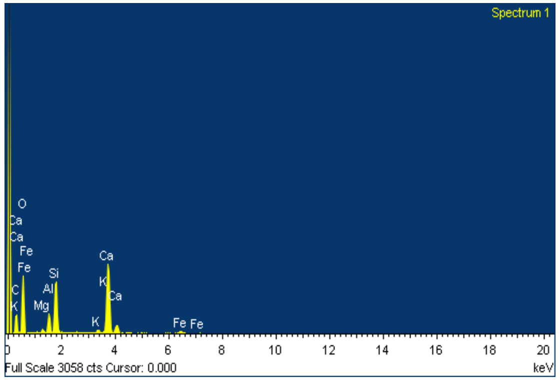
(a3) Sample 1 SEM micrograph at 10 % lime



(b1) Sample 1 EDS/EDX

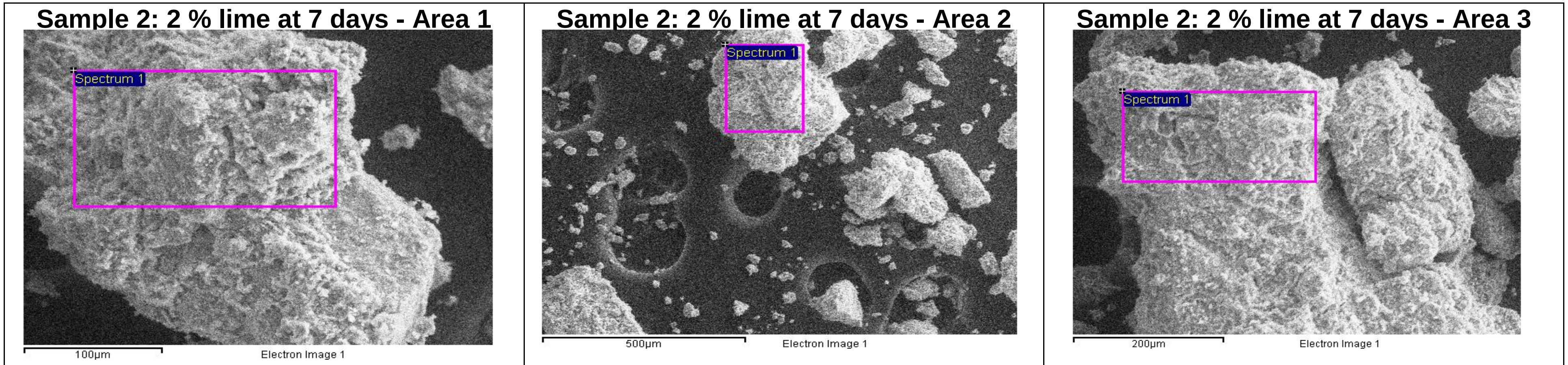


(b2) Sample 1 EDS/EDX

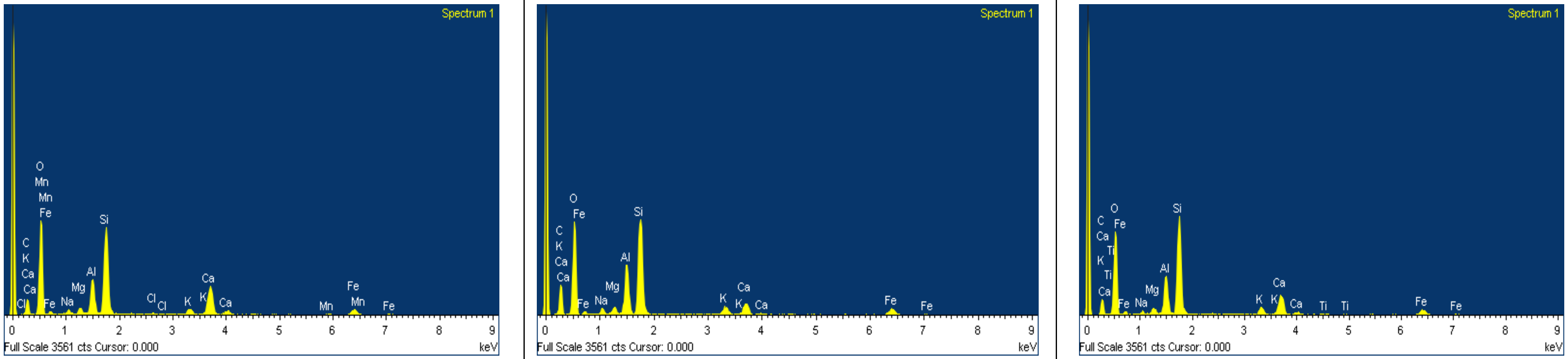


(b3) Sample 1 EDS/EDX

Figure 77: (a1), (a2) and (a3): sample 1 SEM micrographs at 10 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

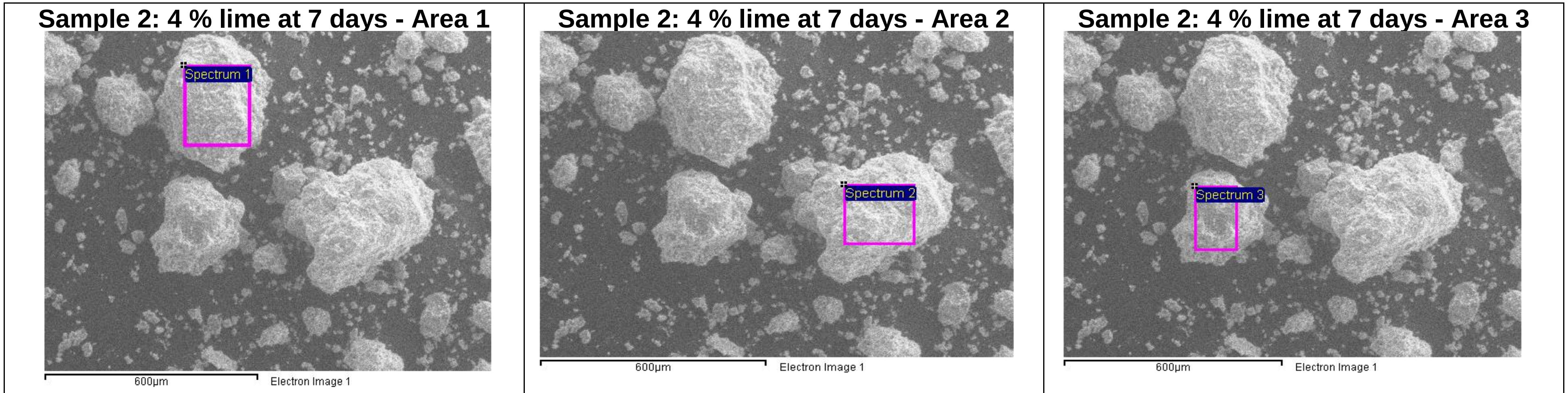


(a1) Sample 2 SEM micrograph at 2 % lime (a2) Sample 2 SEM micrograph at 2 % lime (a3) Sample 2 SEM micrograph at 2 % lime



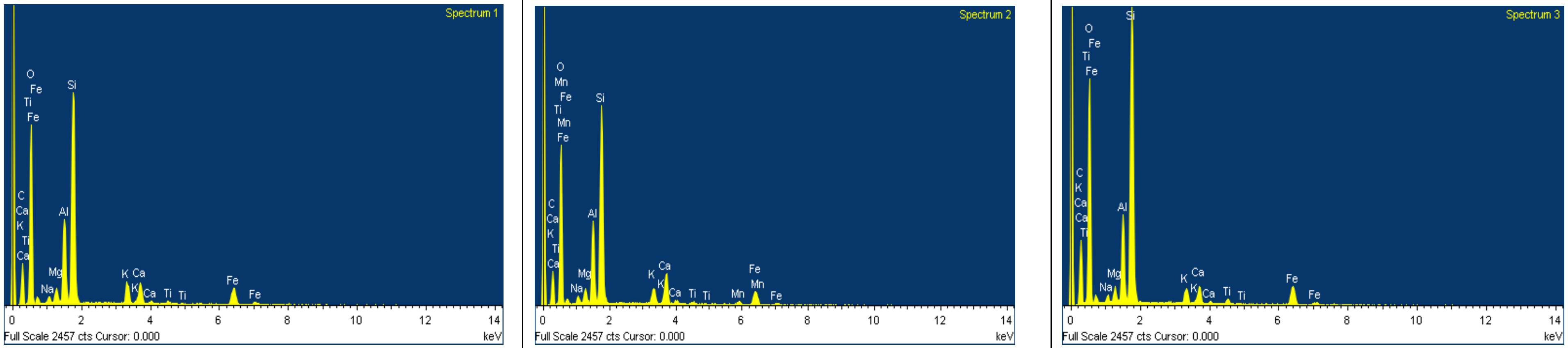
(b1) Sample 2 EDS/EDX (b2) Sample 2 EDS/EDX (b3) Sample 2 EDS/EDX

Figure 78: (a1), (a2) and (a3): sample 2 SEM micrographs at 2 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively



Sample 2: 4 % lime at 7 days - Area 1 **Sample 2: 4 % lime at 7 days - Area 2** **Sample 2: 4 % lime at 7 days - Area 3**

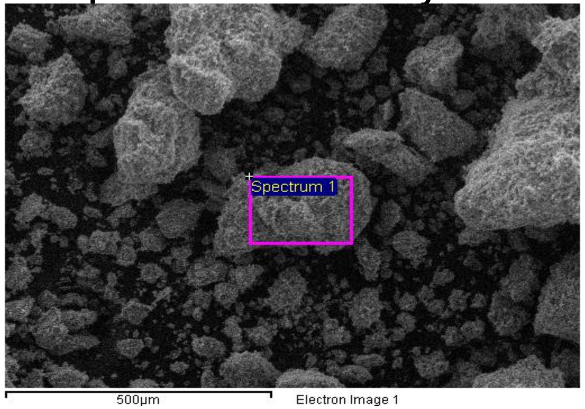
(a1) Sample 2 SEM micrograph at 4 % lime (a2) Sample 2 SEM micrograph at 4 % lime (a3) Sample 2 SEM micrograph at 4 % lime



(b1) Sample 2 EDS/EDX (b2) Sample 2 EDS/EDX (b3) Sample 2 EDS/EDX

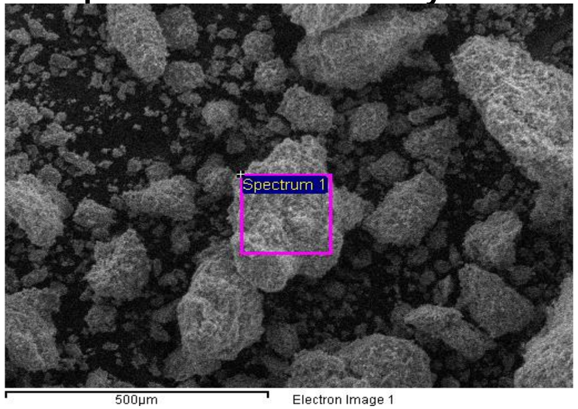
Figure 79: (a1), (a2) and (a3): sample 2 SEM micrographs at 4 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 2: 6 % lime at 7 days - Area 1



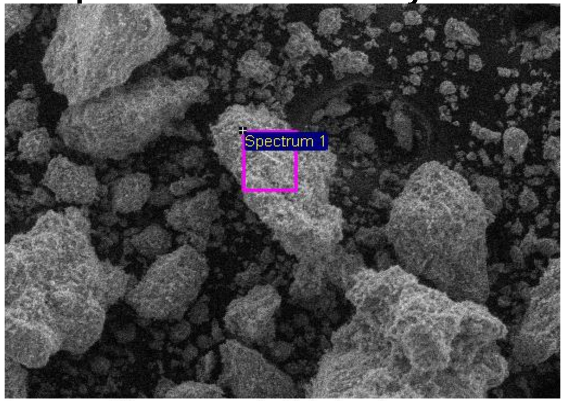
(a1) Sample 2 SEM micrograph at 6 % lime

Sample 2: - 6% lime at 7 days - Area 2

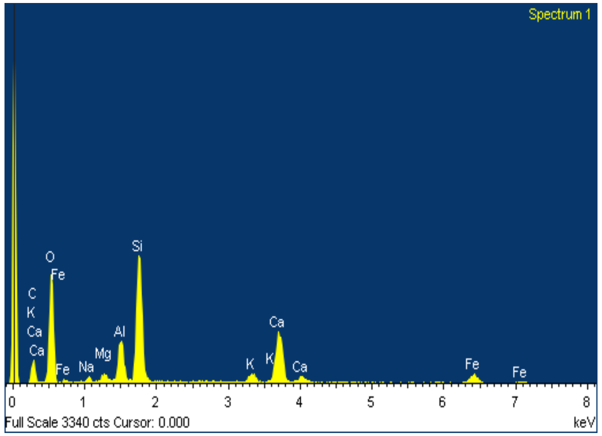


(a2) Sample 2 SEM micrograph at 6 % lime

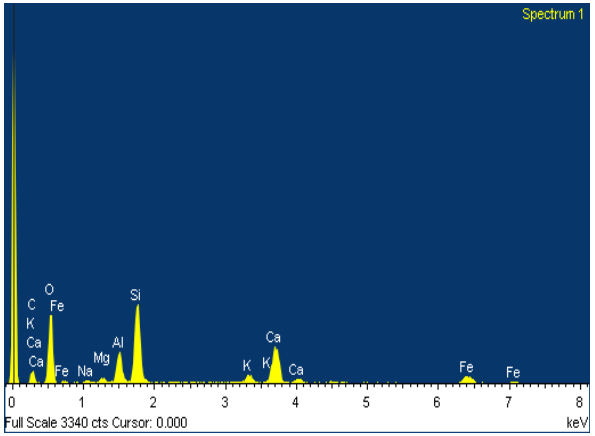
Sample 2: 6 % lime at 7 days - Area 3



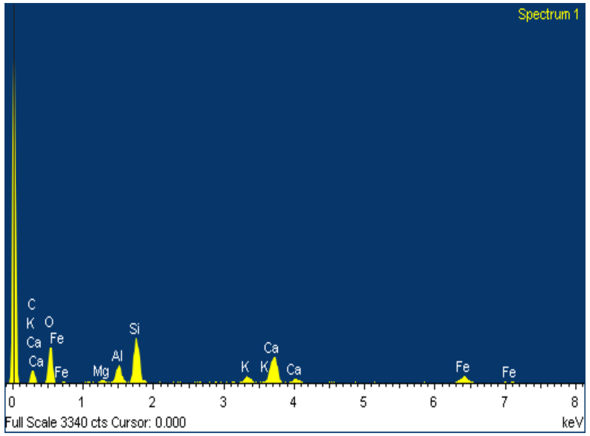
(a3) Sample 2 SEM micrograph at 6 % lime



(b1) Sample 2 EDS/EDX



(b2) Sample 2 EDS/EDX



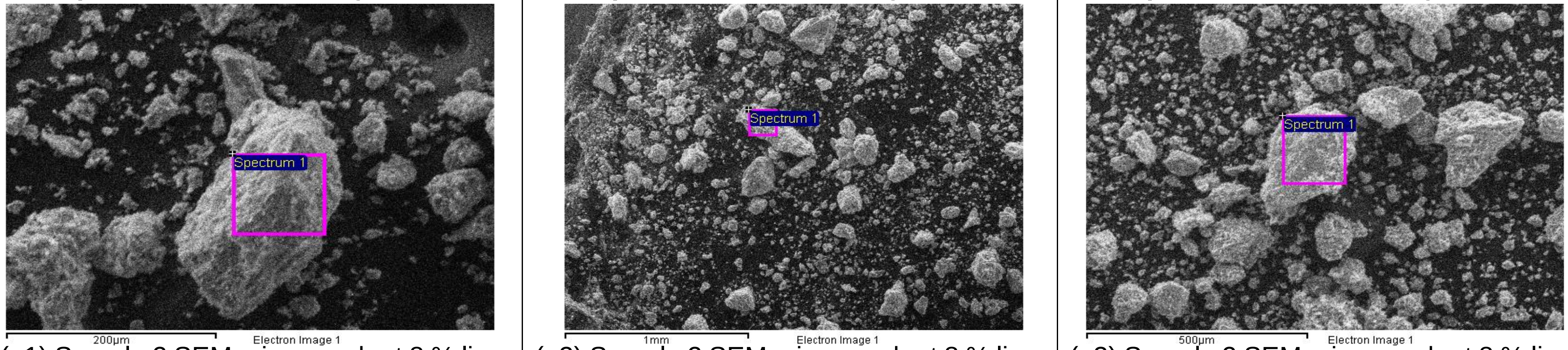
(b3) Sample 2 EDS/EDX

Figure 80: (a1), (a2) and (a3): sample 2 SEM micrographs at 6 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 2: 8 % lime at 7 days - Area 1

Sample 2: 8 % lime at 7 days - Area 2

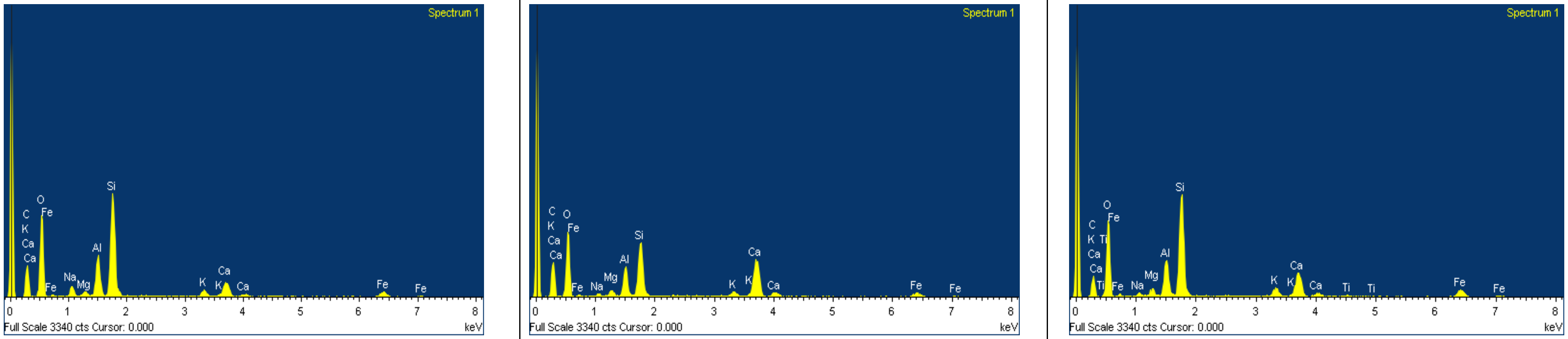
Sample 2: 8 % lime at 7 days - Area 3



(a1) Sample 2 SEM micrograph at 8 % lime

(a2) Sample 2 SEM micrograph at 8 % lime

(a3) Sample 2 SEM micrograph at 8 % lime



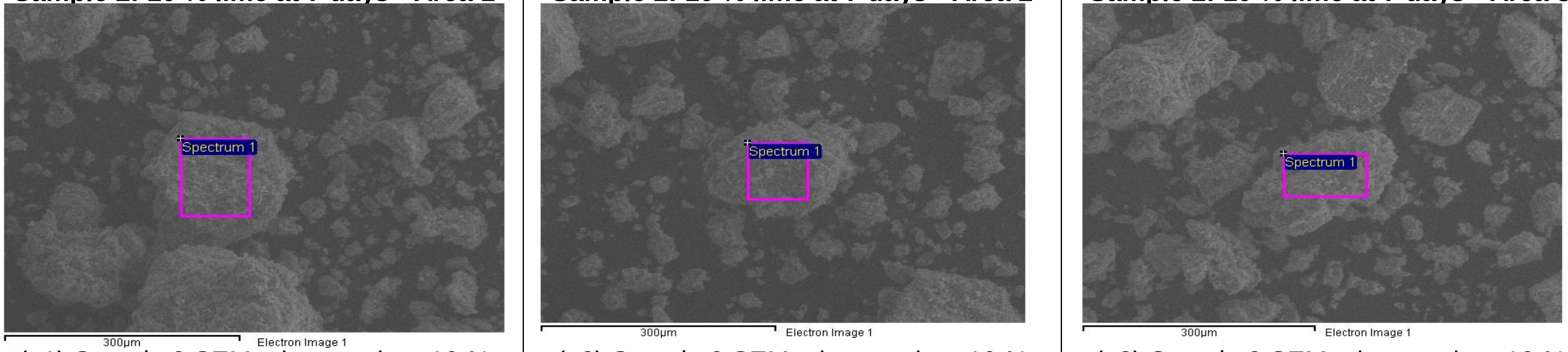
(b1) Sample 2 EDS/EDX

(b2) Sample 2 EDS/EDX

(b3) Sample 2 EDS/EDX

Figure 81: (a1), (a2) and (a3): sample 2 SEM micrographs at 8 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

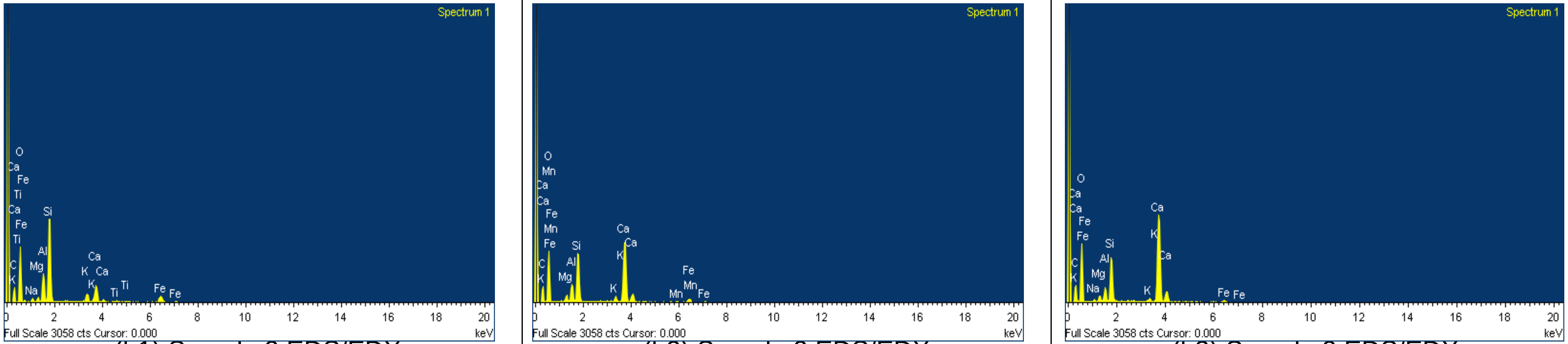
Sample 2: 10 % lime at 7 days - Area 1 | **Sample 2: 10 % lime at 7 days - Area 2** | **Sample 2: 10 % lime at 7 days - Area 3**



(a1) Sample 2 SEM micrograph at 10 % lime

(a2) Sample 2 SEM micrograph at 10 % lime

(a3) Sample 2 SEM micrograph at 10 % lime



(b1) Sample 2 EDS/EDX

(b2) Sample 2 EDS/EDX

(b3) Sample 2 EDS/EDX

Figure 82: (a1), (a2) and (a3): sample 2 SEM micrographs at 10 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

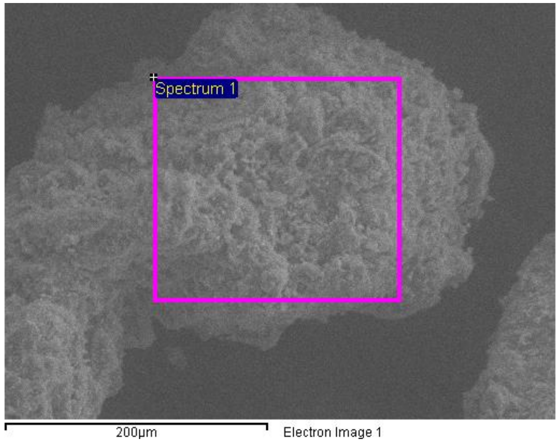
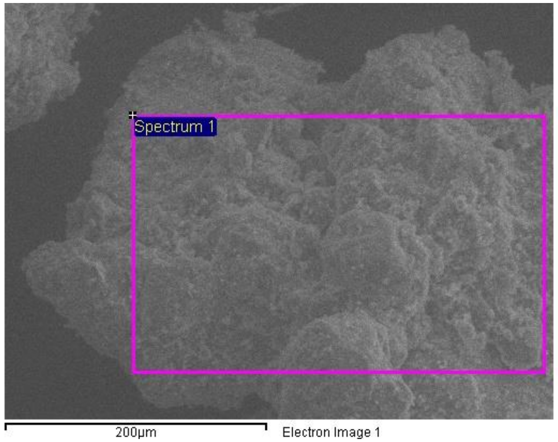
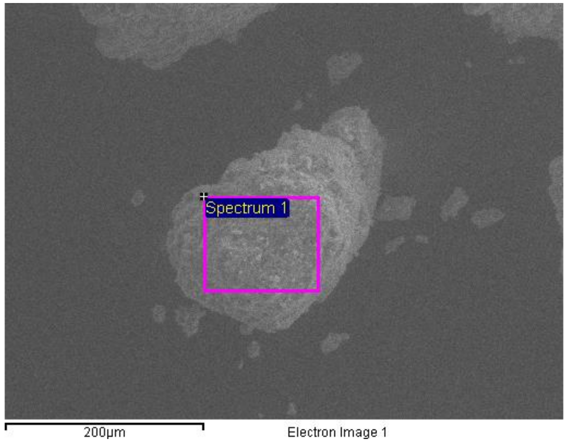
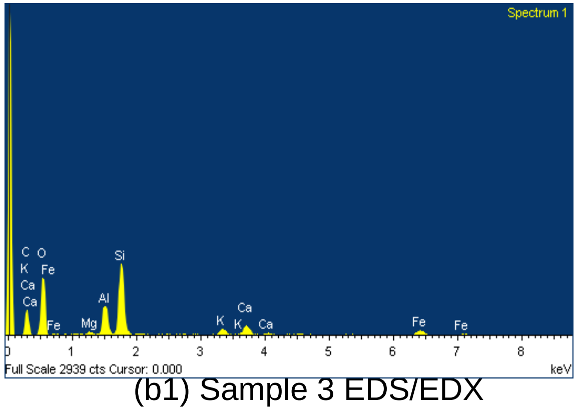
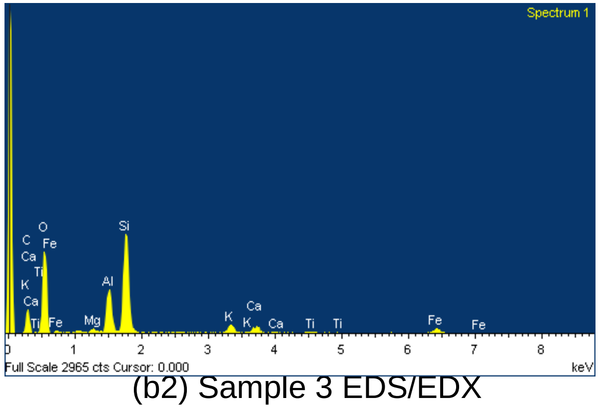
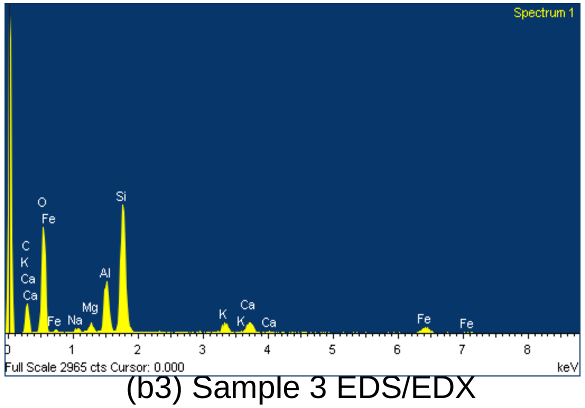
Sample 3: 2 % lime at 7 days - Area 1	**Sample 3: 2 % lime at 7 days - Area 2**	**Sample 3: 2 % lime at 7 days - Area 3**
 (a1) Sample 3 SEM micrograph at 2 % lime	 (a2) Sample 3 SEM micrograph at 2 % lime	 (a3) Sample 3 SEM micrograph at 2 % lime
 (b1) Sample 3 EDS/EDX	 (b2) Sample 3 EDS/EDX	 (b3) Sample 3 EDS/EDX

Figure 83: (a1), (a2) and (a3): sample 3 SEM micrographs at 2 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

<table>
<tr><th>Sample 3: 4 % lime at 7 days - Area 1</th><th>Sample 3: 4 % lime at 7 days - Area 2</th><th>Sample 3: 4 % lime at 7 days - Area 3</th></tr>
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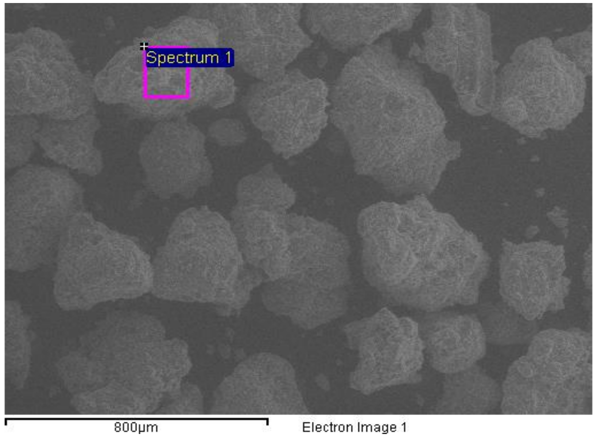
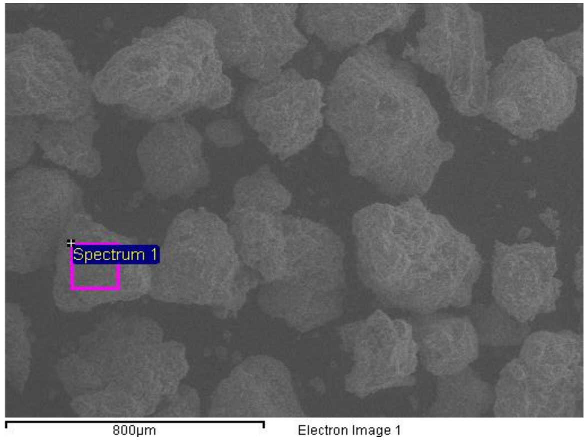
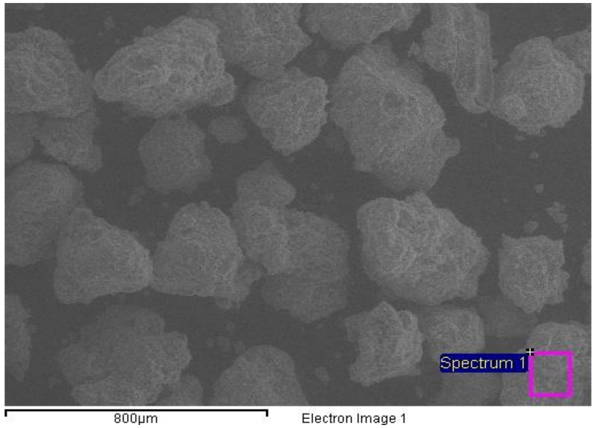
<td>

(a1) Sample 3 SEM micrograph at 4 % lime</td>
<td>

(a2) Sample 3 SEM micrograph at 4 % lime</td>
<td>

(a3) Sample 3 SEM micrograph at 4 % lime</td>
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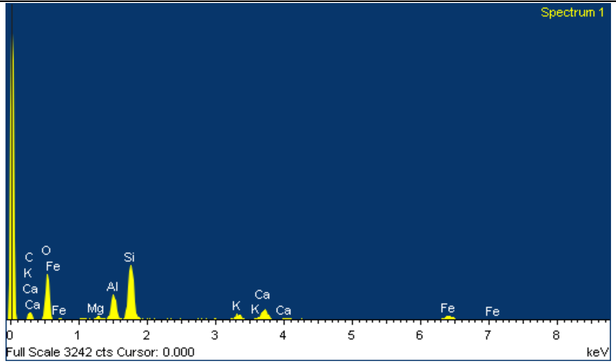
<td>

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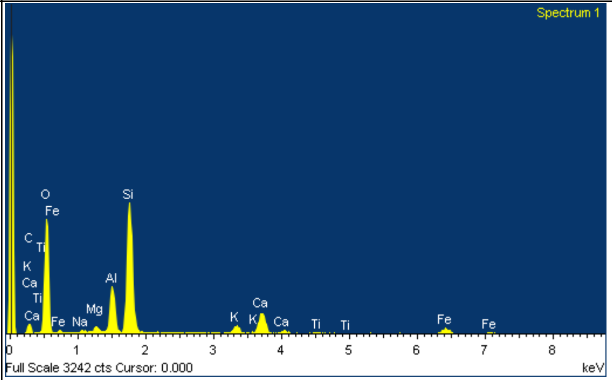
<td>

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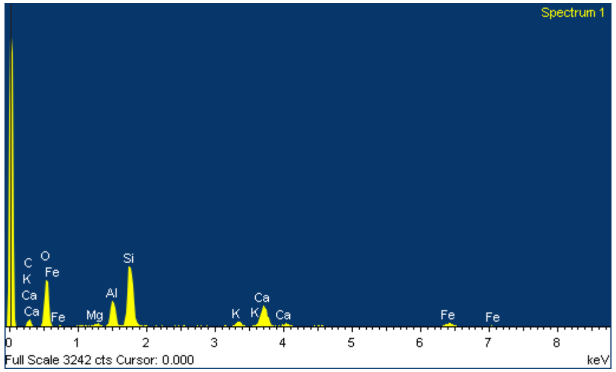
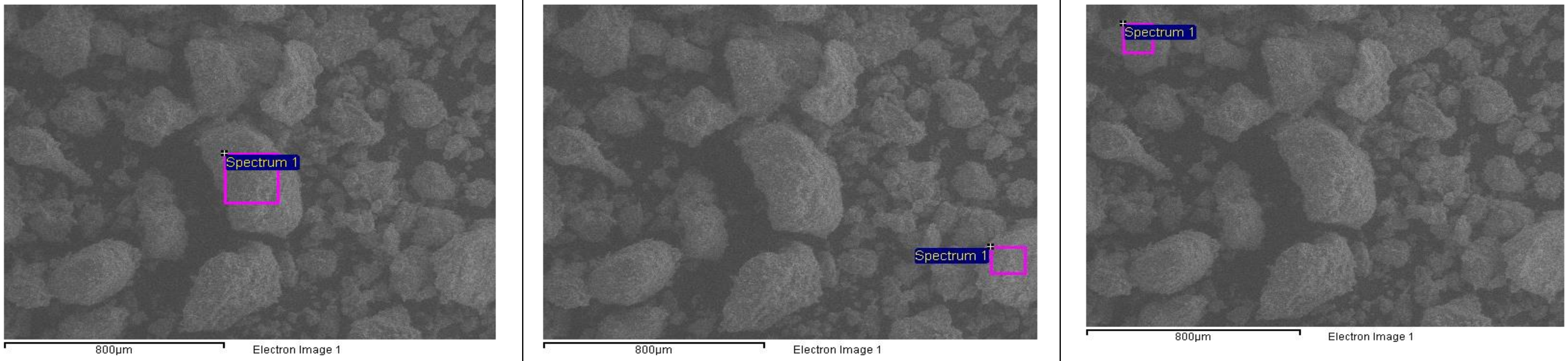
<td>

(b3) Sample 3 EDS/EDX</td>
</tr>
</table>

Figure 84: (a1), (a2) and (a3): sample 3 SEM micrographs at 4 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

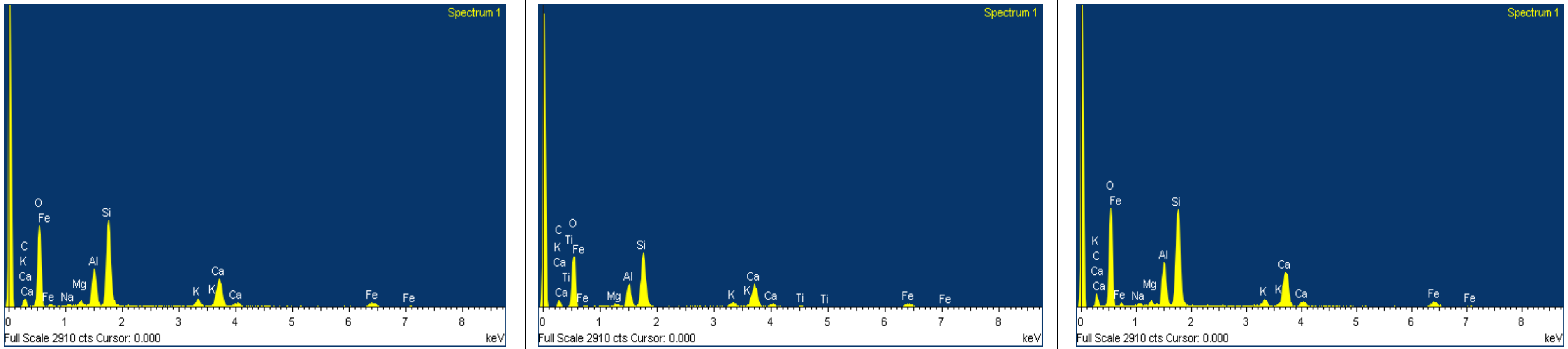
Sample 3: 6 % lime at 7 days - Area 1 | **Sample 3: 6 % lime at 7 days - Area 2** | **Sample 3: 6 % lime at 7 days - Area 3**



(a1) Sample 3 SEM micrograph at 6 % lime

(a2) Sample 3 SEM micrograph at 6 % lime

(a3) Sample 3 SEM micrograph at 6 % lime



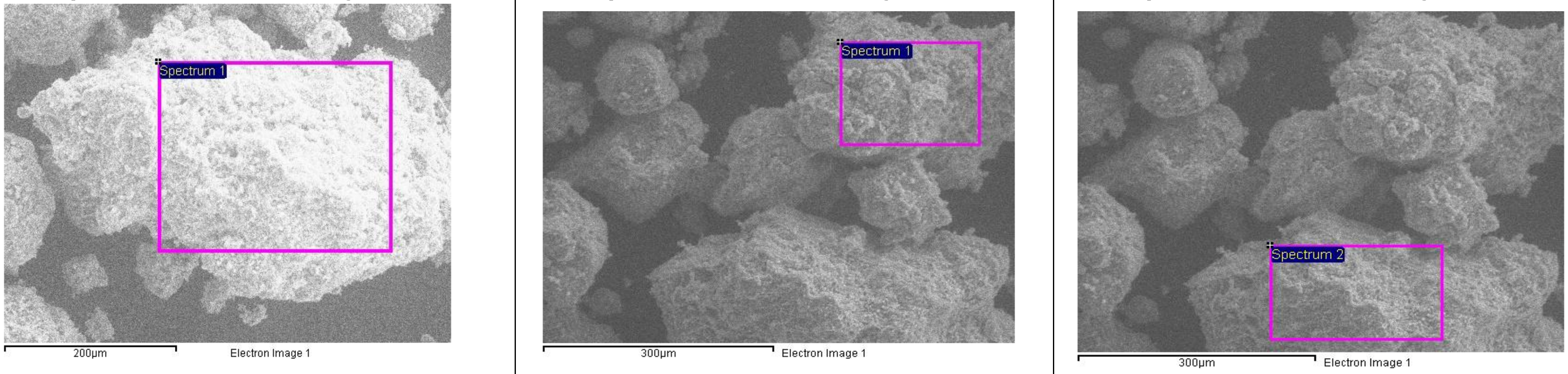
(b1) Sample 3 EDS/EDX

(b2) Sample 3 EDS/EDX

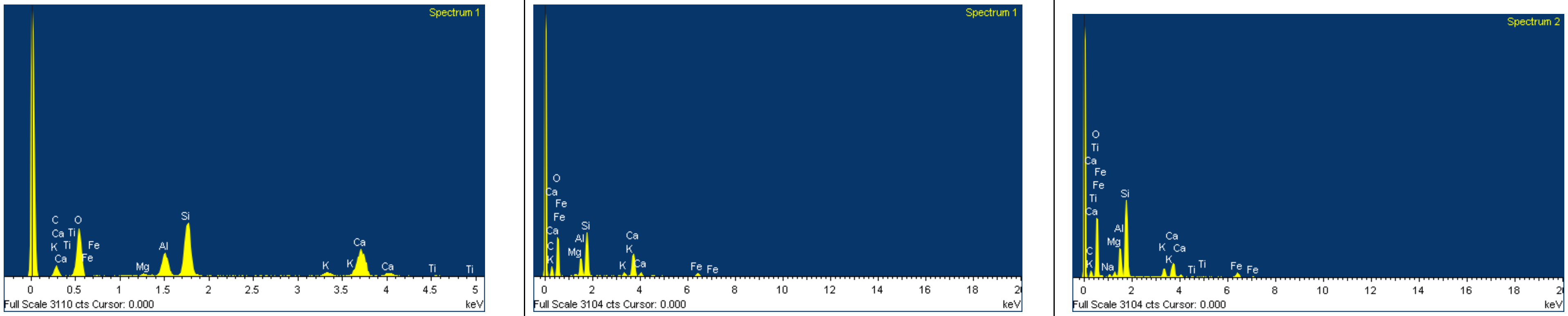
(b3) Sample 3 EDS/EDX

Figure 85: (a1), (a2) and (a3): sample 3 SEM micrographs at 6 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 3: 8 % lime at 7 days - Area 1 **Sample 3: 8 % lime at 7 days - Area 2** **Sample 3: 8 % lime at 7 days - Area 3**



(a1) Sample 3 SEM micrograph at 8 % lime (a2) Sample 3 SEM micrograph at 8 % lime (a3) Sample 3 SEM micrograph at 8 % lime



(b1) Sample 3 EDS/EDX (b2) Sample 3 EDS/EDX (b3) Sample 3 EDS/EDX

Figure 86: (a1), (a2) and (a3): sample 3 SEM micrographs at 8 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

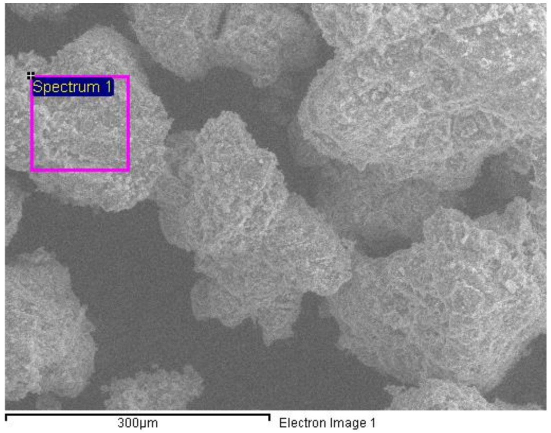
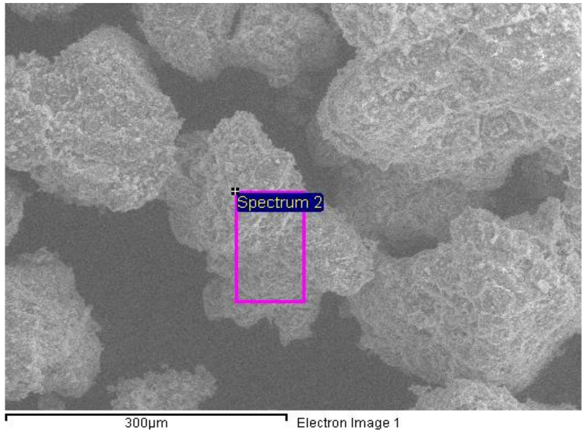
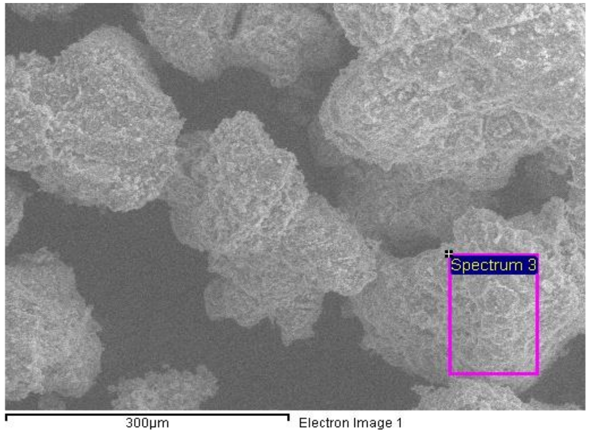
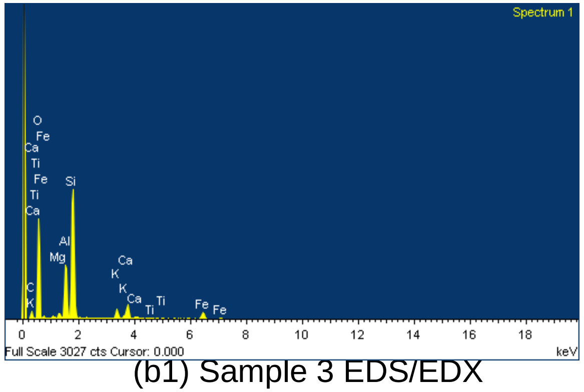
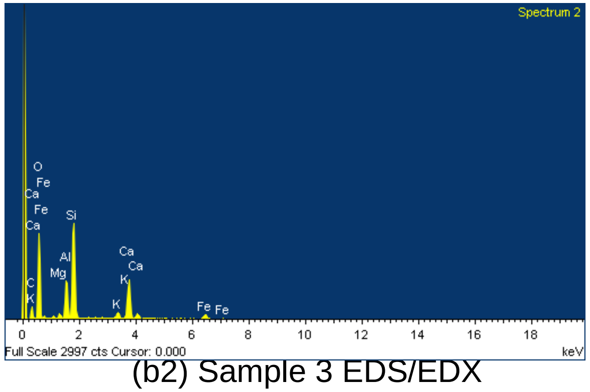
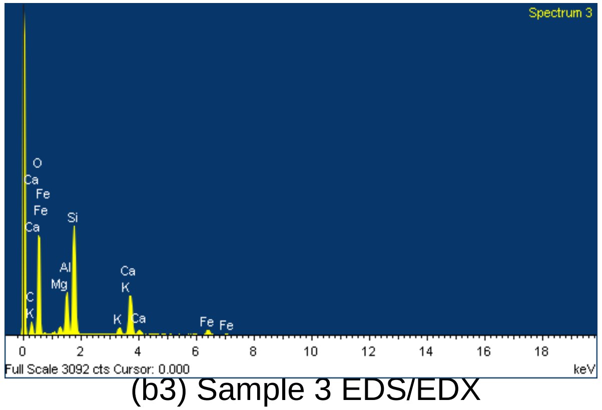
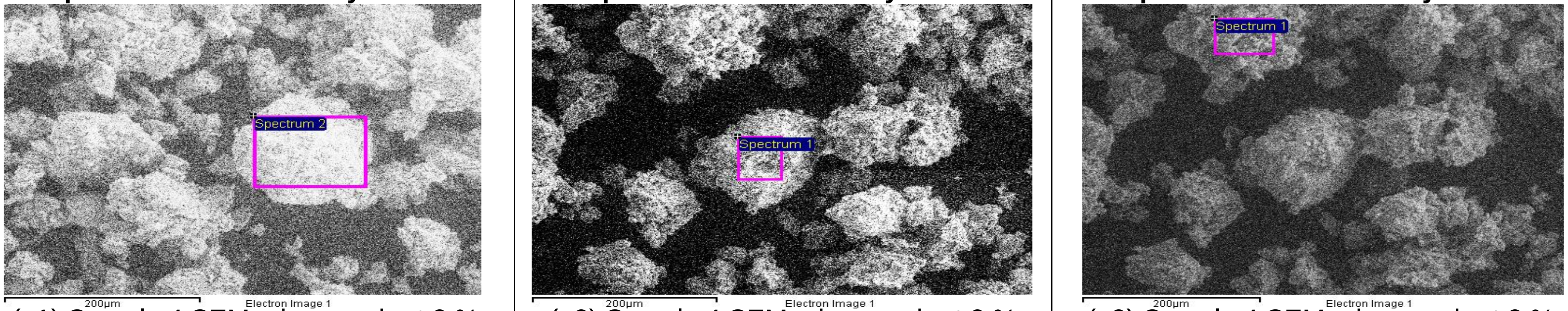
Sample 3: 10% lime at 7 days - Area 1	**Sample 3: 10% lime at 7 days - Area 2**	**Sample 3: 10 % lime at 7 days - Area 3**
 (a1) Sample 3 SEM micrograph at 10 % lime	 (a2) Sample 3 SEM micrograph at 10 % lime	 (a3) Sample 3 SEM micrograph at 10 % lime
 (b1) Sample 3 EDS/EDX	 (b2) Sample 3 EDS/EDX	 (b3) Sample 3 EDS/EDX

Figure 87: (a1), (a2) and (a3): sample 3 SEM micrographs at 10 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

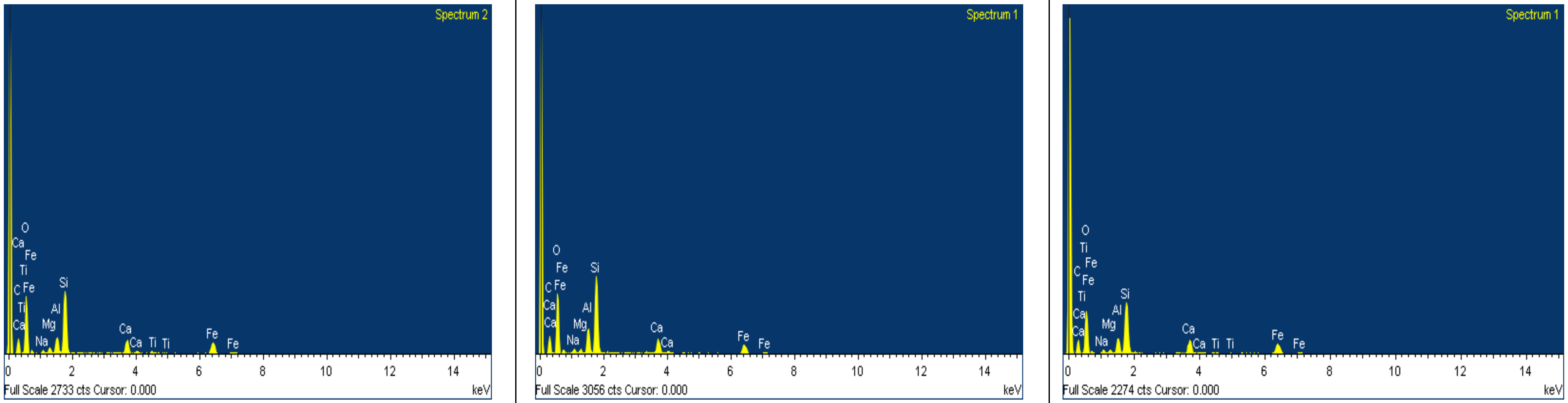


Sample 4: 2 % lime at 7 days - Area 1 | **Sample 4: 2 % lime at 7 days - Area 2** | **Sample 4: 2 % lime at 7 days - Area 3**

(a1) Sample 4 SEM micrograph at 2 % lime

(a2) Sample 4 SEM micrograph at 2 % lime

(a3) Sample 4 SEM micrograph at 2 % lime



(b1) Sample 4 EDS/EDX

(b2) Sample 4 EDS/EDX

(b3) Sample 4 EDS/EDX

Figure 88: (a1), (a2) and (a3): sample 4 SEM micrographs at 2 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

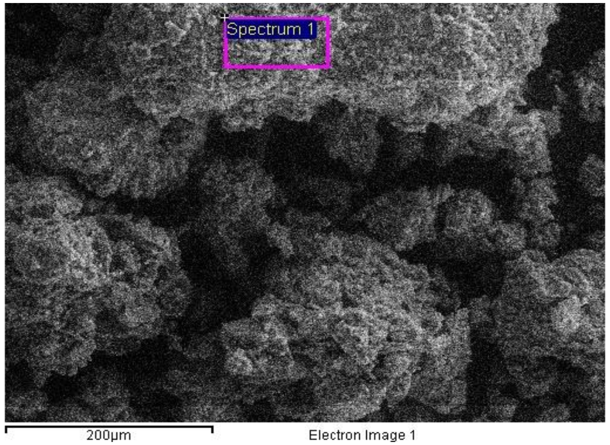
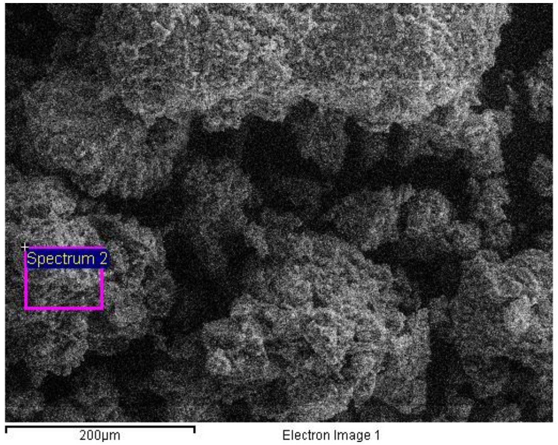
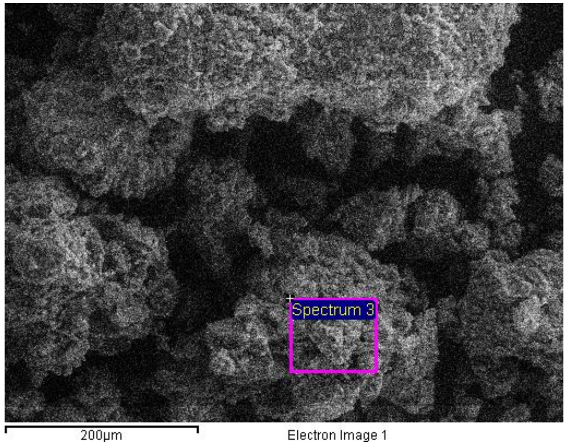
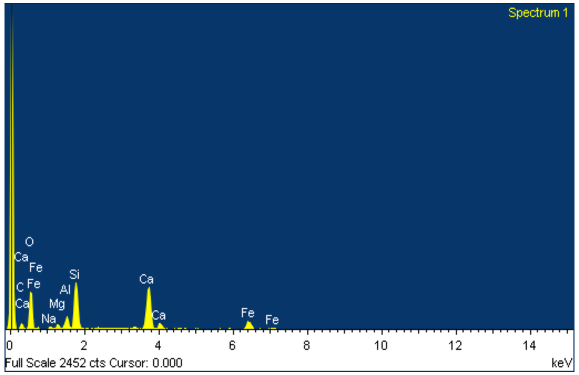
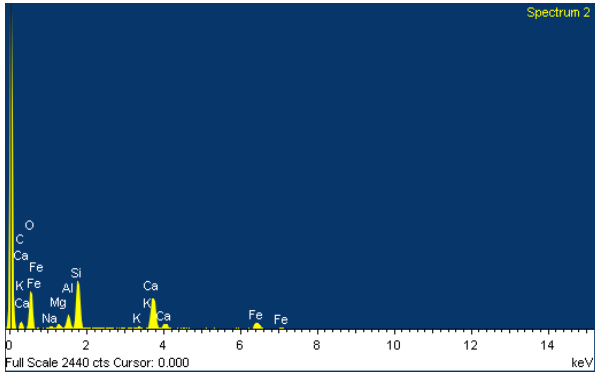
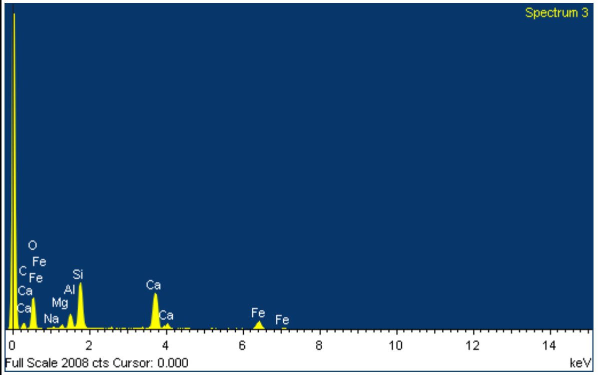
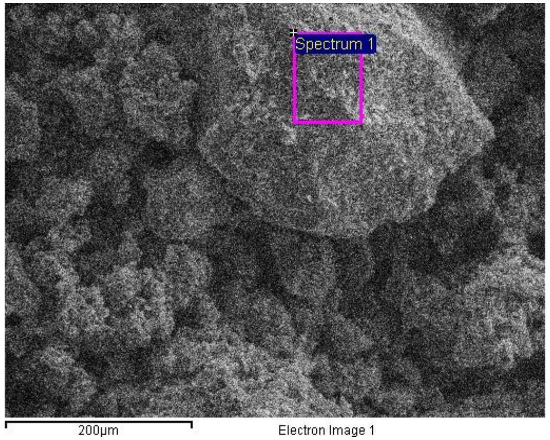
Sample 4: 4 % lime at 7 days - Area 1	**Sample 4: 4 % lime at 7 days - Area 2**	**Sample 4: 4 % lime at 7 days - Area 3**
 (a1) Sample 4 SEM micrograph at 4 % lime	 (a2) Sample 4 SEM micrograph at 4 % lime	 (a3) Sample 4 SEM micrograph at 4 % lime
 (b1) Sample 4 EDS/EDX	 (b2) Sample 4 EDS/EDX	 (b3) Sample 4 EDS/EDX

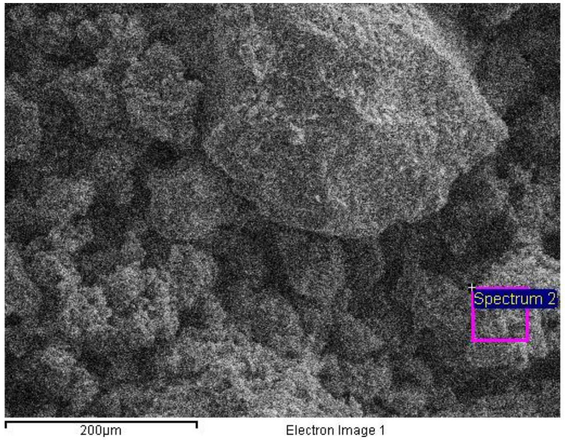
Figure 89: (a1), (a2) and (a3): sample 4 SEM micrographs at 4 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 4: 6 % lime at 7 days - Area 1



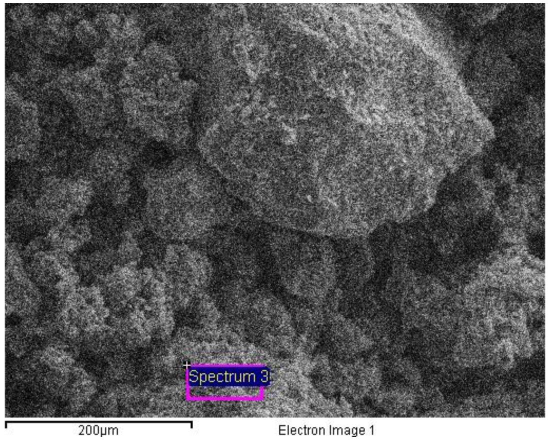
(a1) Sample 4 SEM micrograph at 6 % lime

Sample 4: 6 % lime at 7 days - Area 2

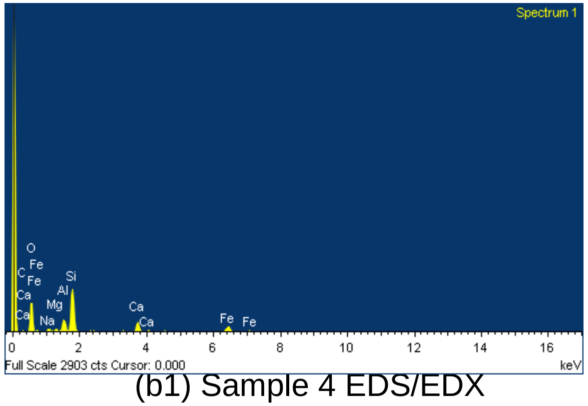


(a2) Sample 4 SEM micrograph at 6 % lime

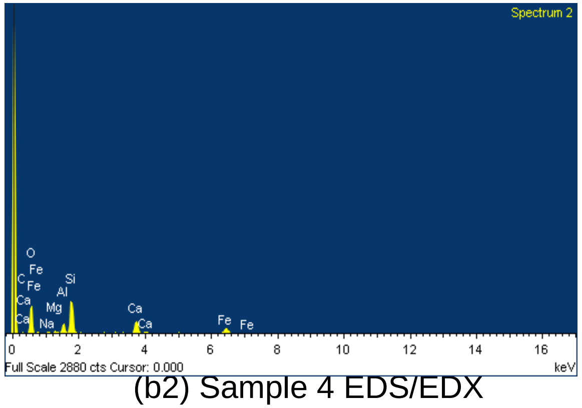
Sample 4: 6 % lime at 7 days - Area 3



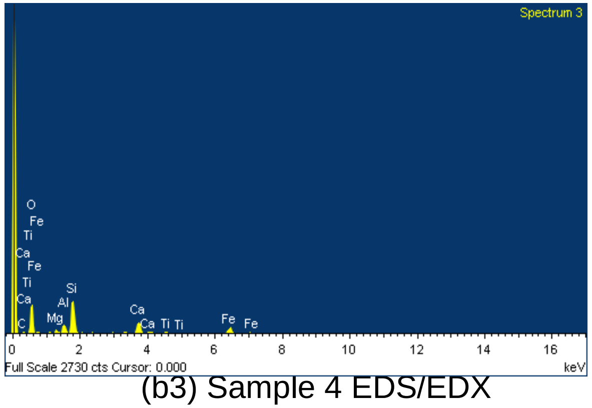
(a3) Sample 4 SEM micrograph at 6 % lime



(b1) Sample 4 EDS/EDX



(b2) Sample 4 EDS/EDX



(b3) Sample 4 EDS/EDX

Figure 90: (a1), (a2) and (a3): sample 4 SEM micrographs at 6 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

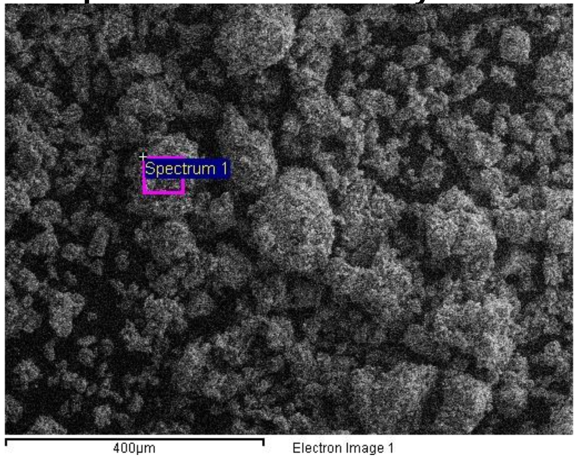
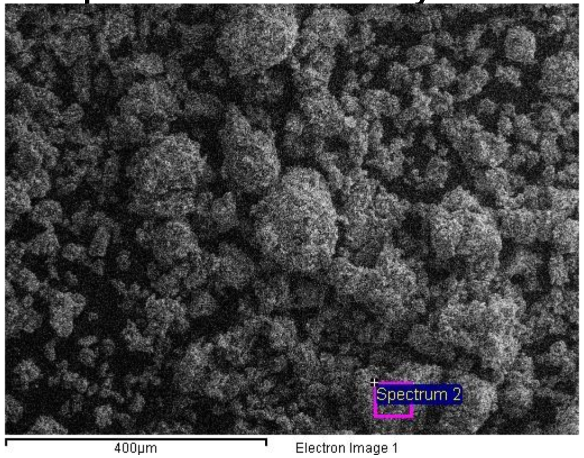
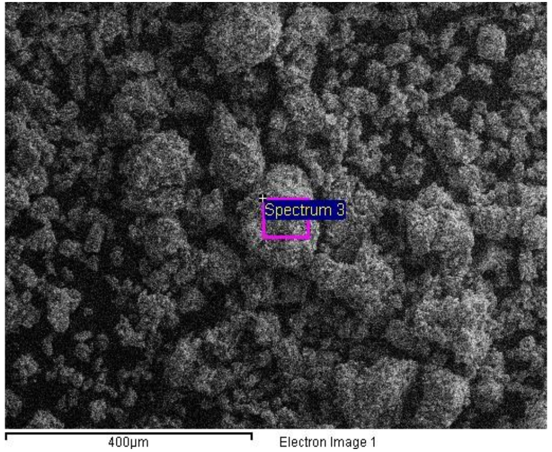
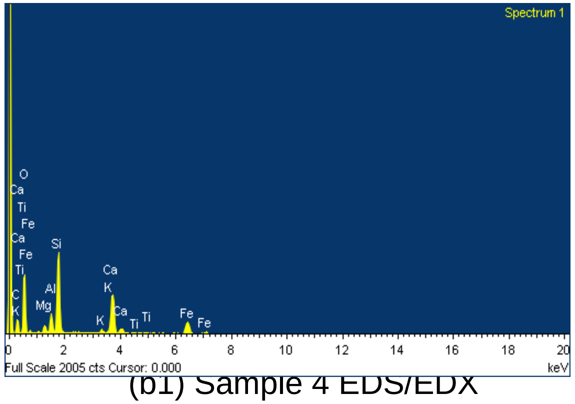
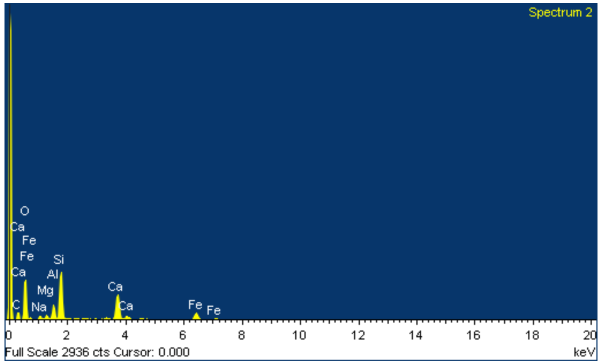
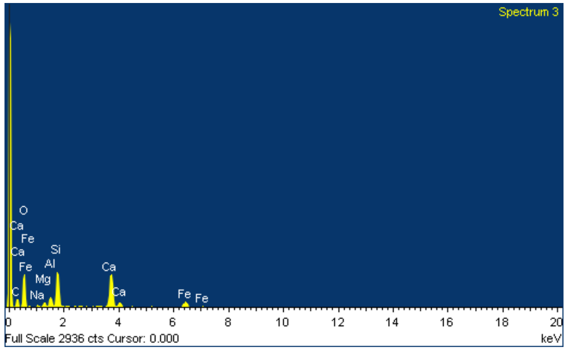
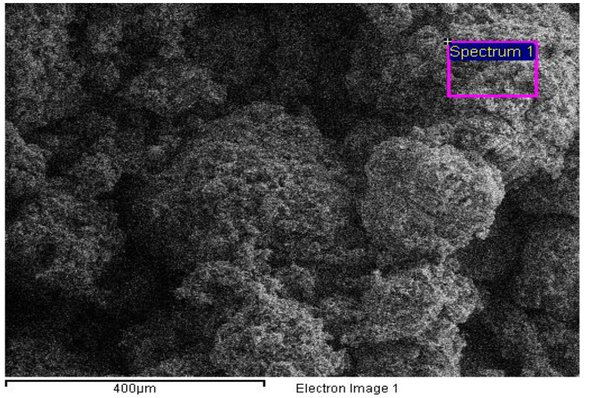
Sample 4: 8 % lime at 7 days - Area 1	**Sample 4: 8 % lime at 7 days - Area 2**	**Sample 4: 8 % lime at 7 days - Area 3**
 (a1) Sample 4 SEM micrograph at 8 % lime	 (a2) Sample 4 SEM micrograph at 8 % lime	 (a3) Sample 4 SEM micrograph at 8 % lime
 (b1) Sample 4 EDS/EDX	 (b2) Sample 4 EDS/EDX	 (b3) Sample 4 EDS/EDX

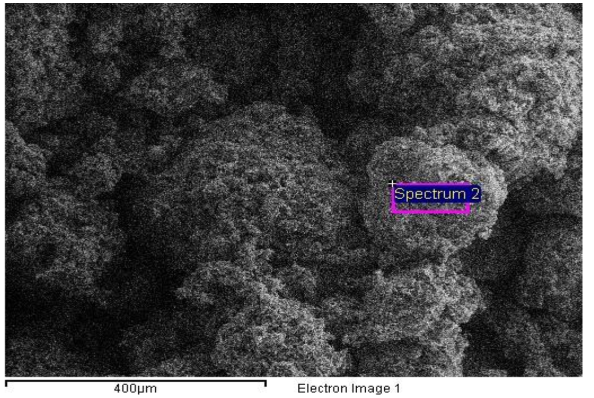
Figure 91: (a1), (a2) and (a3): sample 4 SEM micrographs at 8 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 4: 10 % lime at 7 days - Area 1



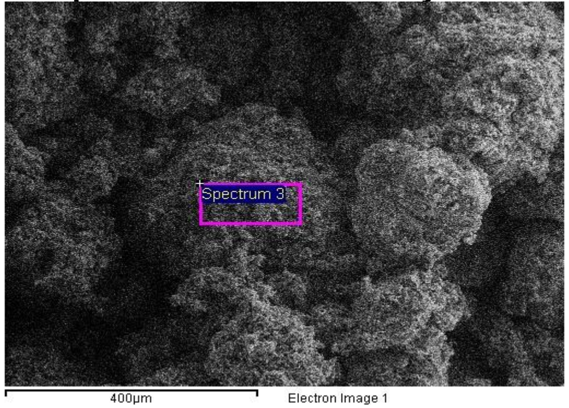
(a1) Sample 4 SEM micrograph at 10 % lime

Sample 4: 10 % lime at 7 days - Area 2

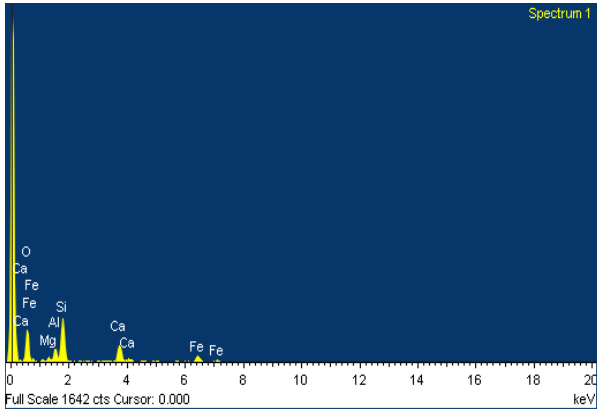


(a2) Sample 4 SEM micrograph at 10 % lime

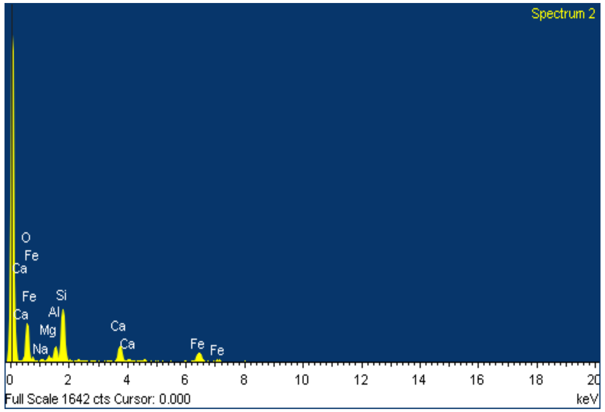
Sample 4: 10 % lime at 7 days - Area 3



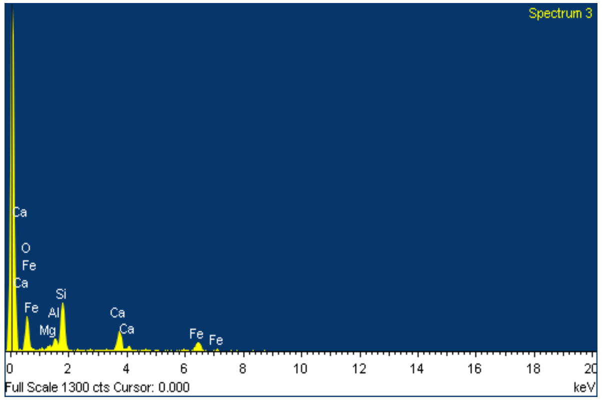
(a3) Sample 4 SEM micrograph at 10 % lime



(b1) Sample 4 EDS/EDX

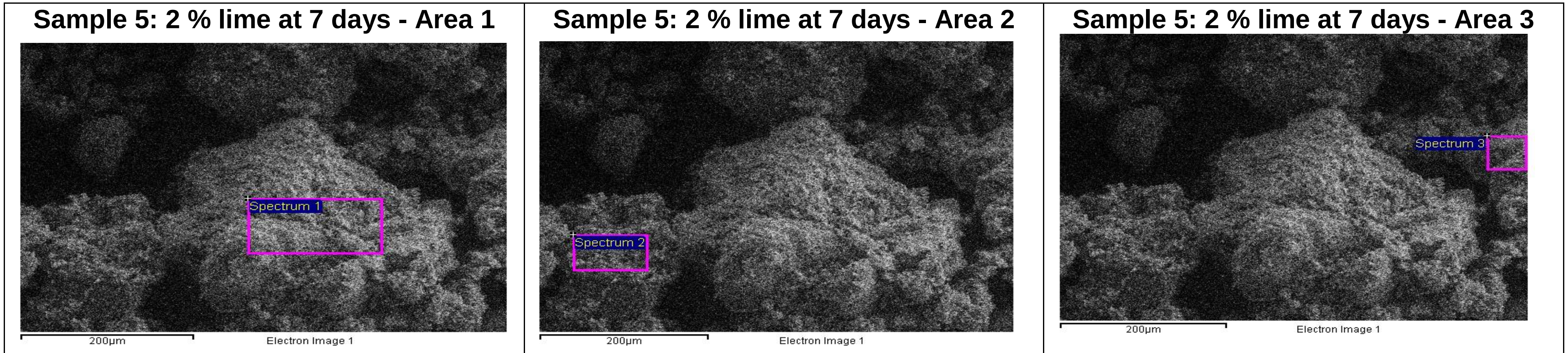


(b2) Sample 4 EDS/EDX



(b3) Sample 4 EDS/EDX

Figure 92: (a1), (a2) and (a3): sample 4 SEM micrographs at 10 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively


Sample 5: 2 % lime at 7 days - Area 1

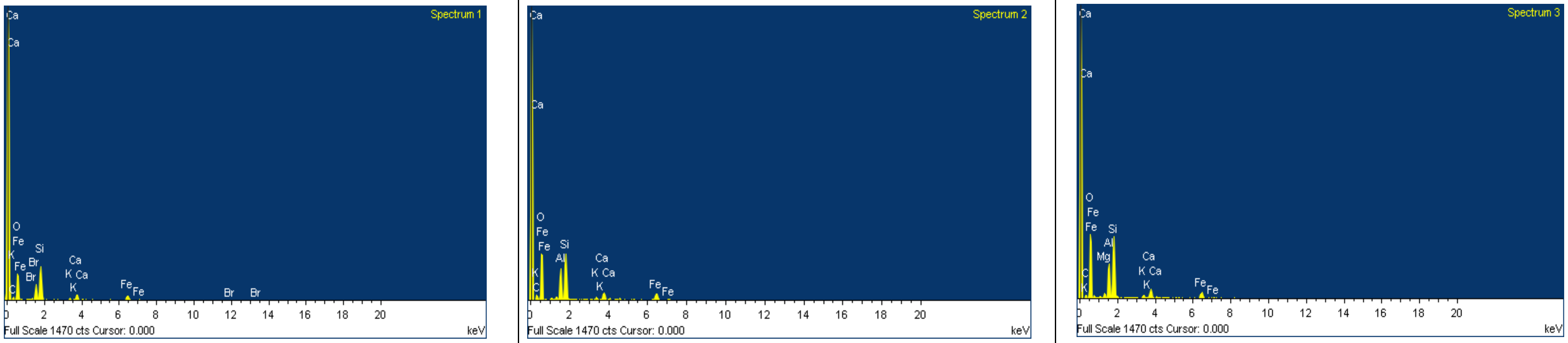
Sample 5: 2 % lime at 7 days - Area 2

Sample 5: 2 % lime at 7 days - Area 3

(a1) Sample 5 SEM micrograph at 2 % lime

(a2) Sample 5 SEM micrograph at 2 % lime

(a3) Sample 5 SEM micrograph at 2 % lime

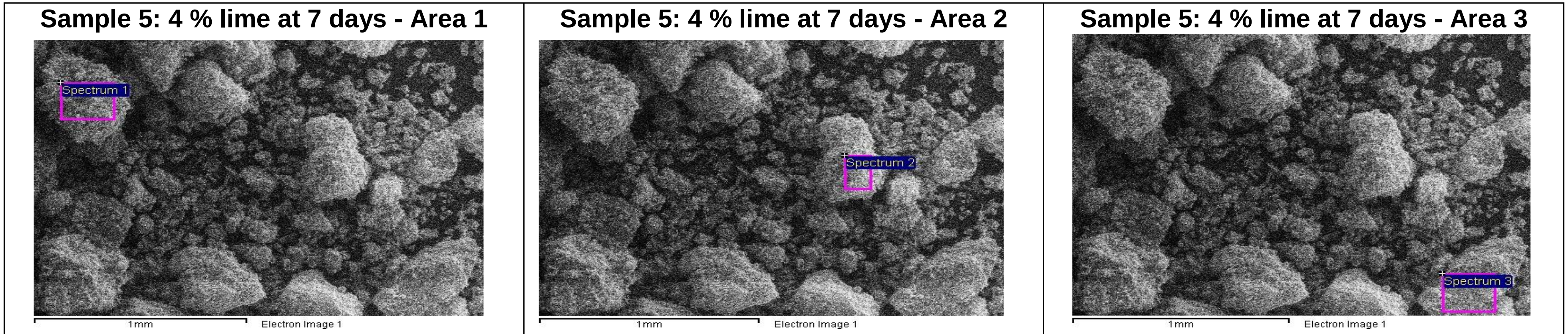


(b1) Sample 5 EDS/EDX

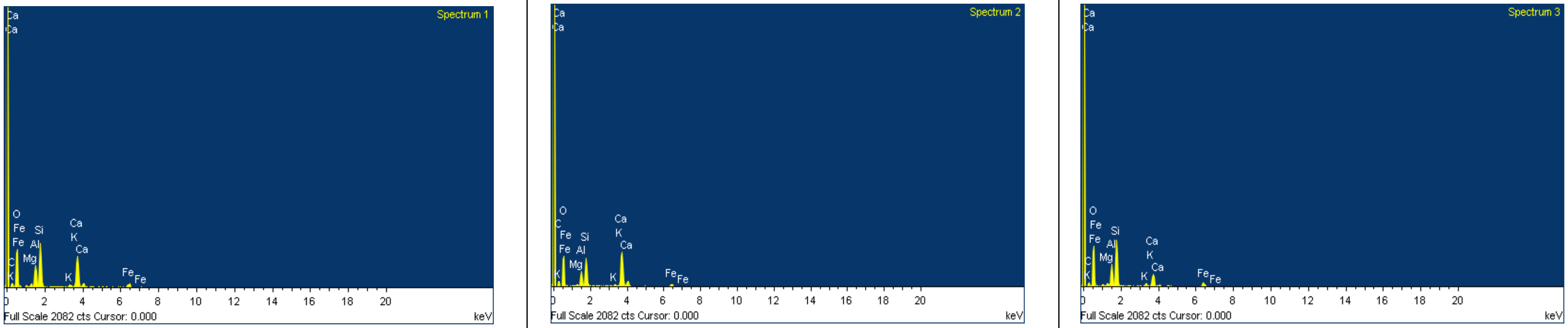
(b2) Sample 5 EDS/EDX

(b3) Sample 5 EDS/EDX

Figure 93: (a1), (a2) and (a3): sample 5 SEM micrographs at 2 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively



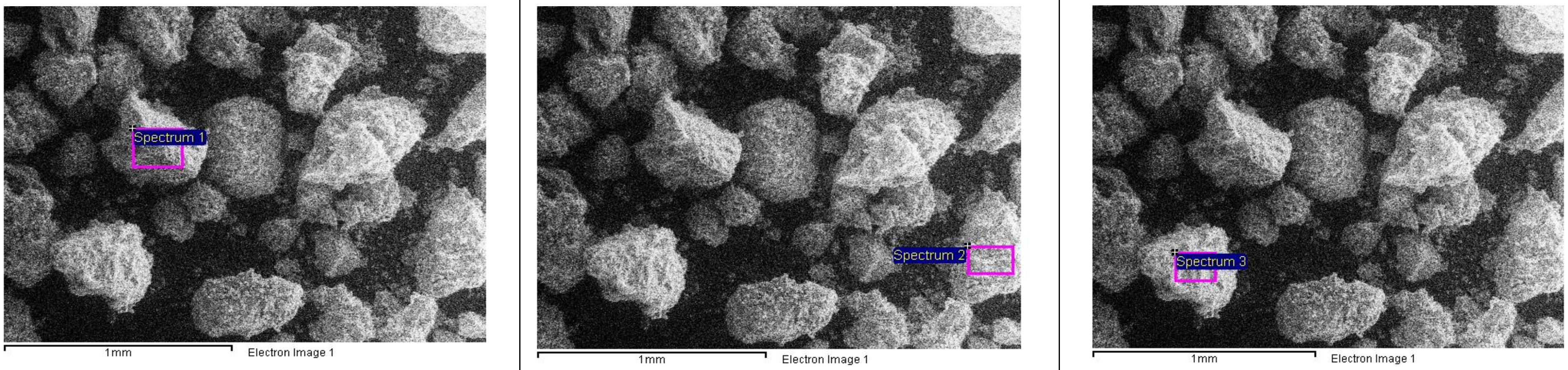
(a1) Sample 5 SEM micrograph at 4 % lime (a2) Sample 5 SEM micrograph at 4 % lime (a3) Sample 5 SEM micrograph at 4 % lime



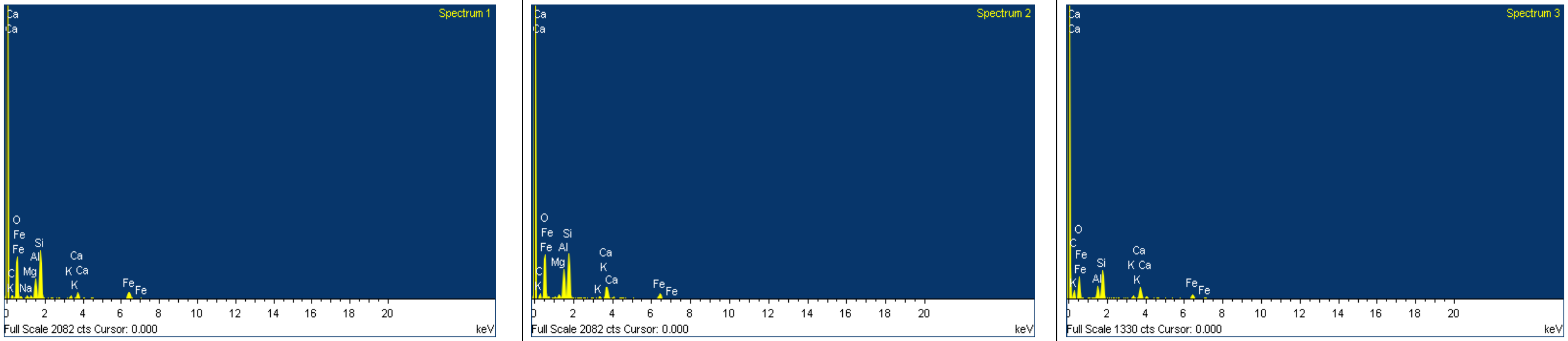
(b1) Sample 5 EDS/EDX (b2) Sample 5 EDS/EDX (b3) Sample 5 EDS/EDX

Figure 94: (a1), (a2) and (a3): sample 5 SEM micrographs at 4 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 5: 6 % lime at 7 days - Area 1 | **Sample 5: 6 % lime at 7 days - Area 2** | **Sample 5: 6 % lime at 7 days - Area 3**



(a1) Sample 5 SEM micrograph at 6% lime | (a2) Sample 5 SEM micrograph at 6% lime | (a3) Sample 5 SEM micrograph at 6% lime



(b1) Sample 5 EDS/EDX | (b2) Sample 5 EDS/EDX | (b3) Sample 5 EDS/EDX

Figure 95: (a1), (a2) and (a3): sample 5 SEM micrographs at 6 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

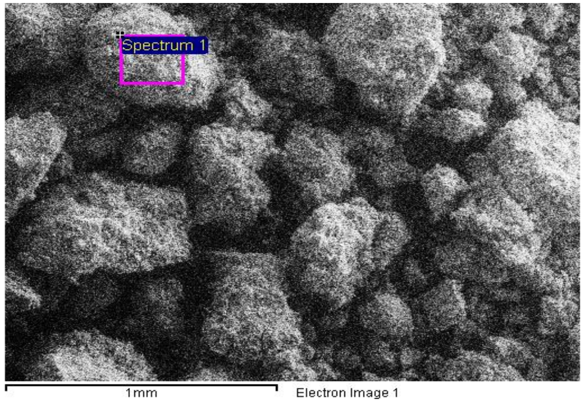
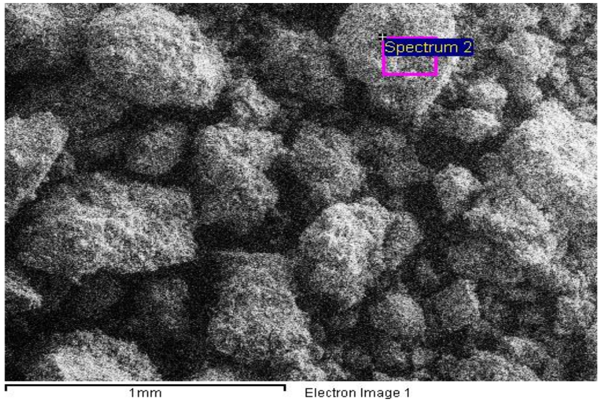
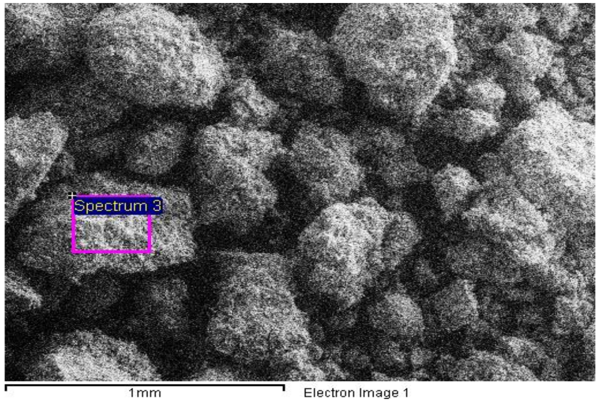
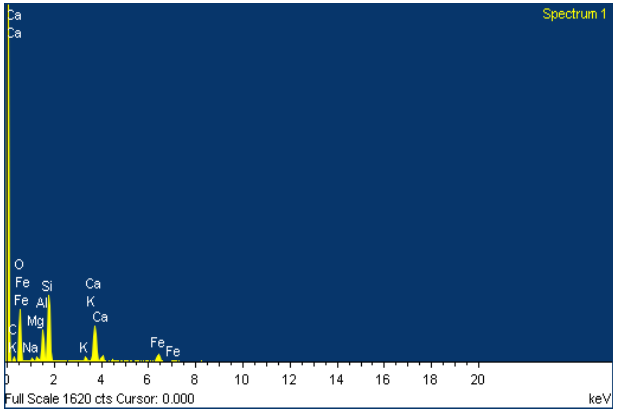
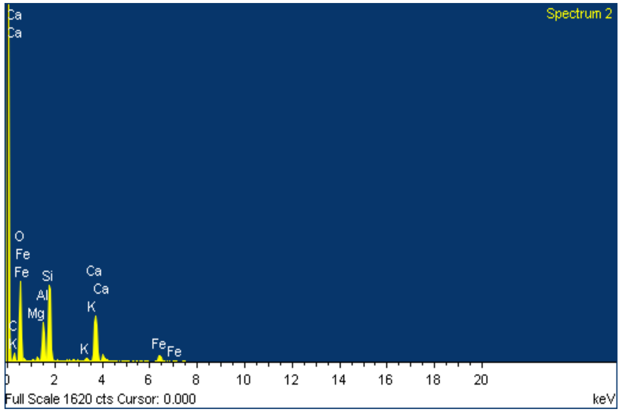
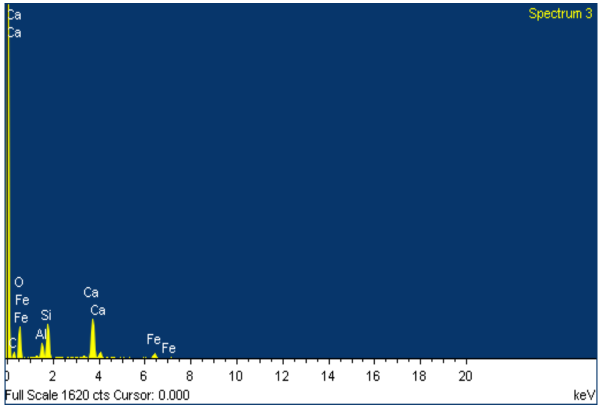
Sample 5: 8 % lime at 7 days - Area 1  (a1) Sample 5 SEM micrograph at 8 % lime	**Sample 5: 8 % lime at 7 days - Area 2**  (a2) Sample 5 SEM micrograph at 8 % lime	**Sample 5: 8 % lime at 7 days - Area 3**  (a3) Sample 5 SEM micrograph at 8 % lime
 (b1) Sample 5 EDS/EDX	 (b2) Sample 5 EDS/EDX	 (b3) Sample 5 EDS/EDX

Figure 96: (a1), (a2) and (a3): sample 5 SEM micrographs at 8 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

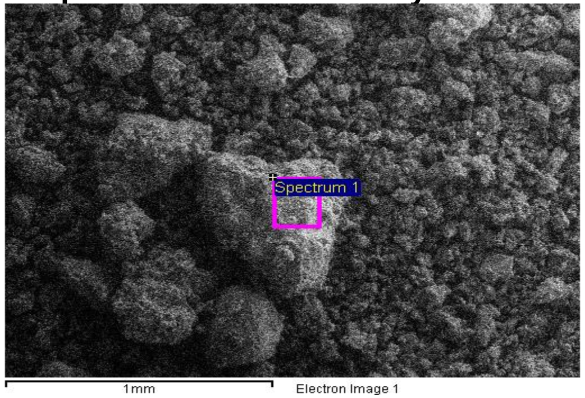
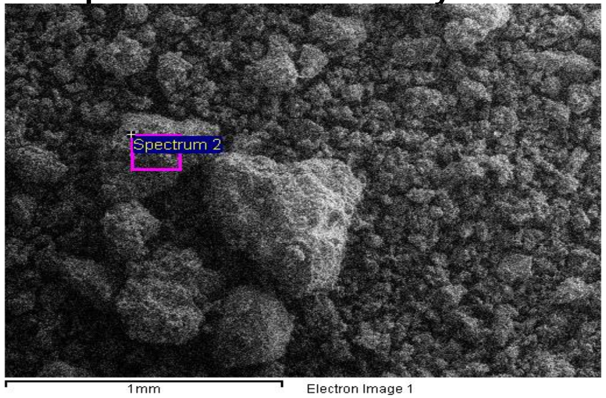
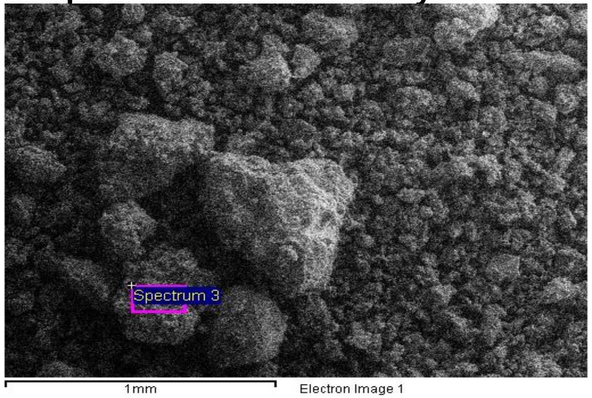
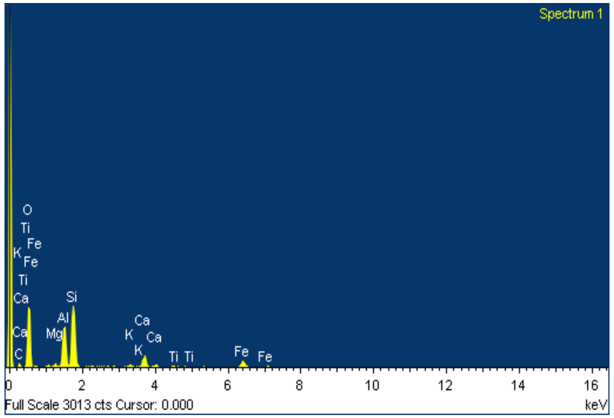
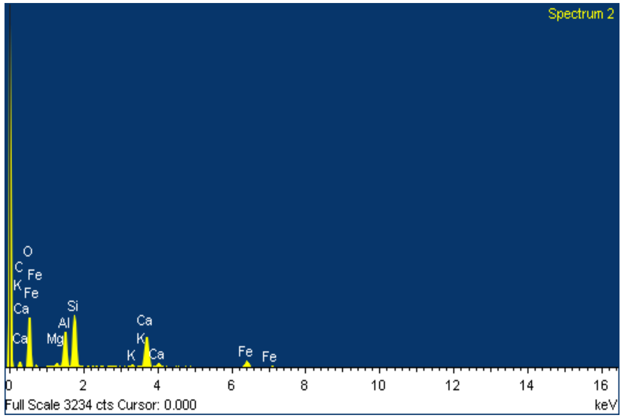
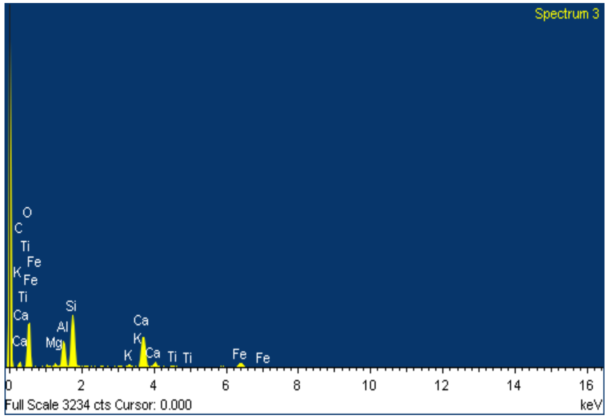
Sample 5: 10 % lime at 7 days - Area 1  (a1) Sample 5 SEM micrograph at 10 % lime	**Sample 5: 10 % lime at 7 days - Area 2**  (a2) Sample 5 SEM micrograph at 10 % lime	**Sample 5: 10 % lime at 7 days - Area 3**  (a3) Sample 5 SEM micrograph at 10 % lime
 (b1) Sample 5 EDS/EDX	 (b2) Sample 5 EDS/EDX	 (b3) Sample 5 EDS/EDX

Figure 97: (a1), (a2) and (a3): sample 5 SEM micrographs at 10 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

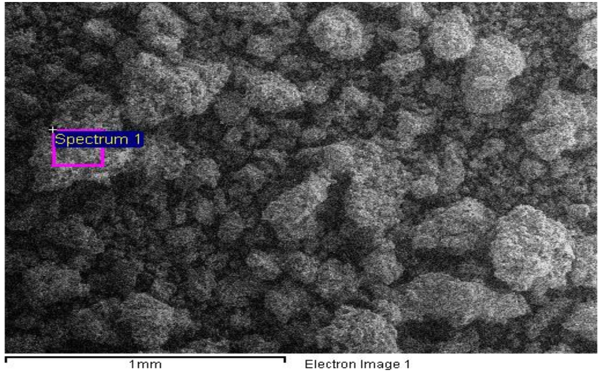
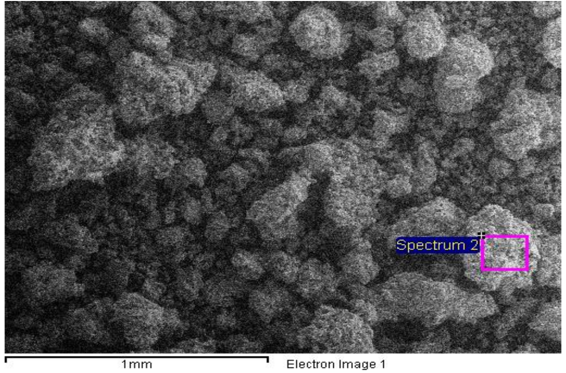
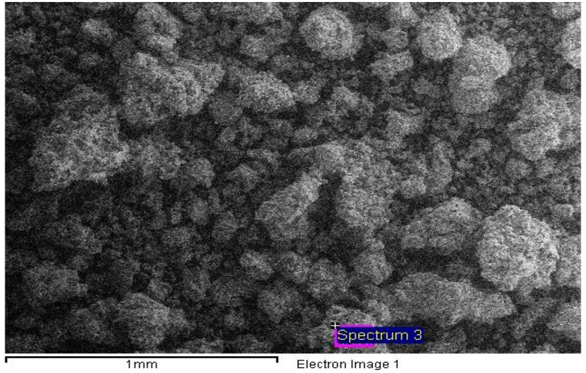
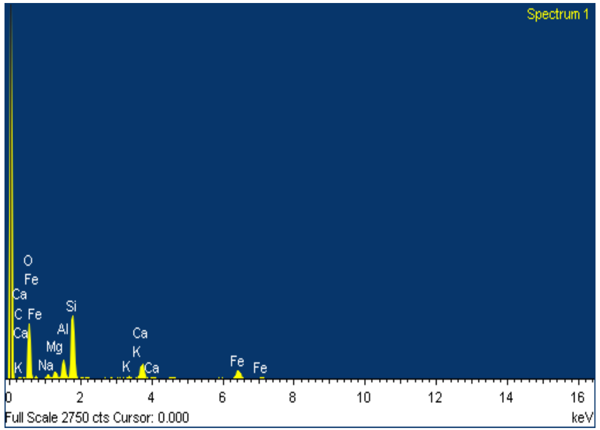
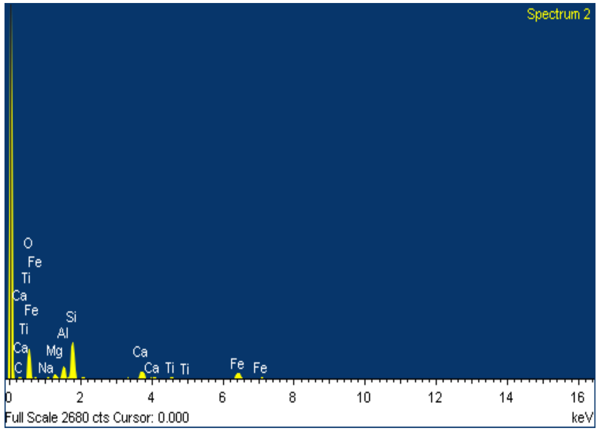
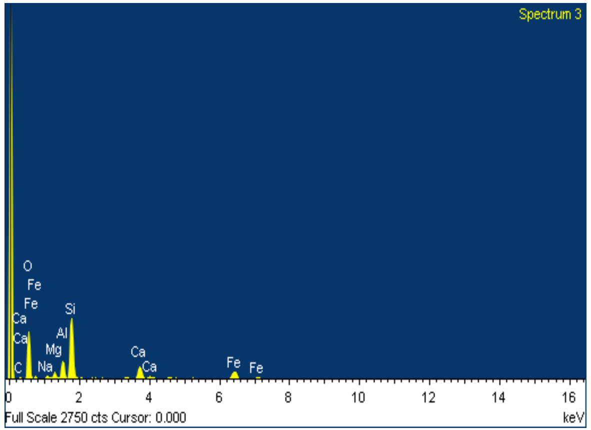
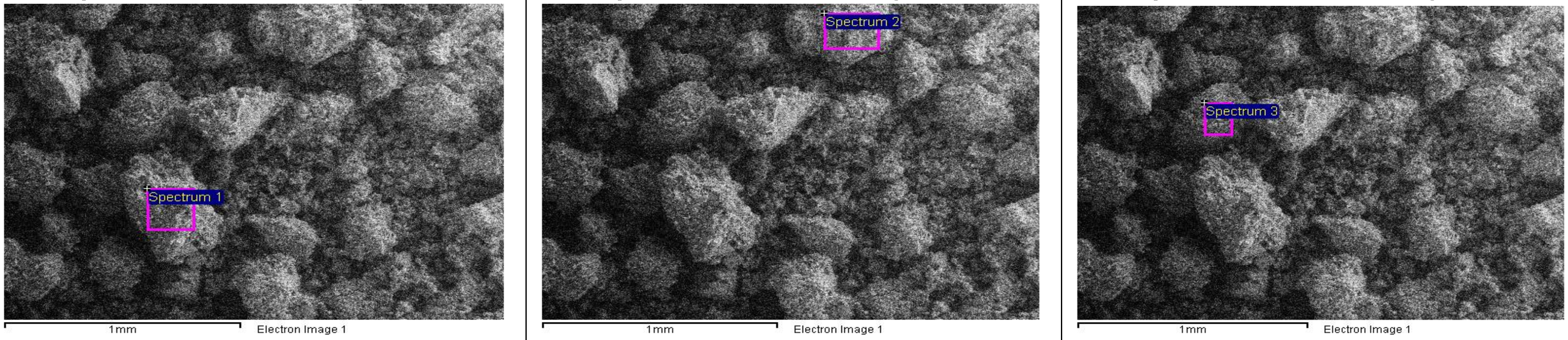
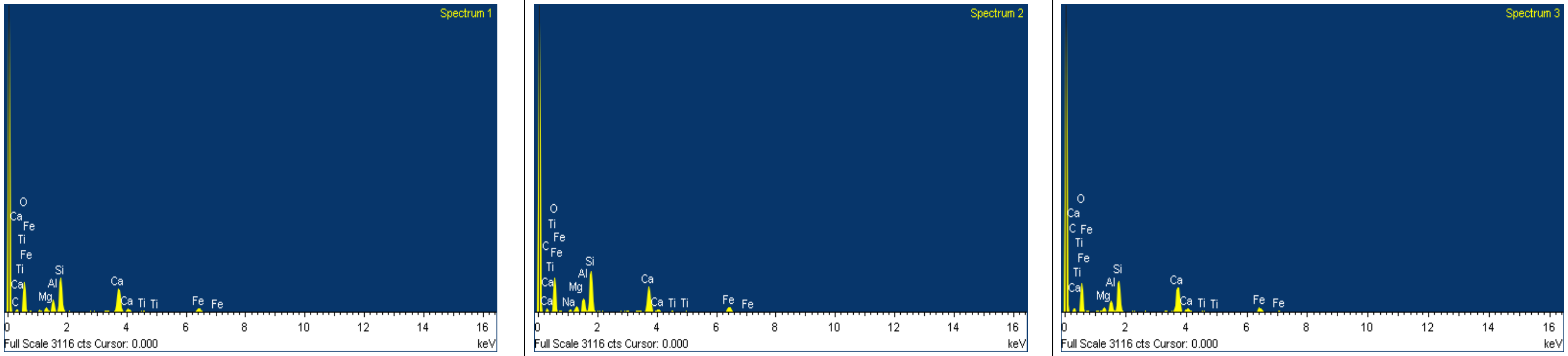
Sample 6: 2 % lime at 7 days - Area 1  (a1) Sample 6 SEM micrograph at 2 % lime	**Sample 6: 2 % lime at 7 days - Area 2**  (a2) Sample 6 SEM micrograph at 2 % lime	**Sample 6: 2 % lime at 7 days - Area 3**  (a3) Sample 6 SEM micrograph at 2 % lime
 (b1) Sample 6 EDS/EDX	 (b2) Sample 6 EDS/EDX	 (b3) Sample 6 EDS/EDX

Figure 98: (a1), (a2) and (a3): sample 6 SEM micrographs at 2 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Sample 6: 4 % lime at 7 days - Area 1 **Sample 6: 4 % lime at 7 days - Area 2** **Sample 6: 4 % lime at 7 days - Area 3**

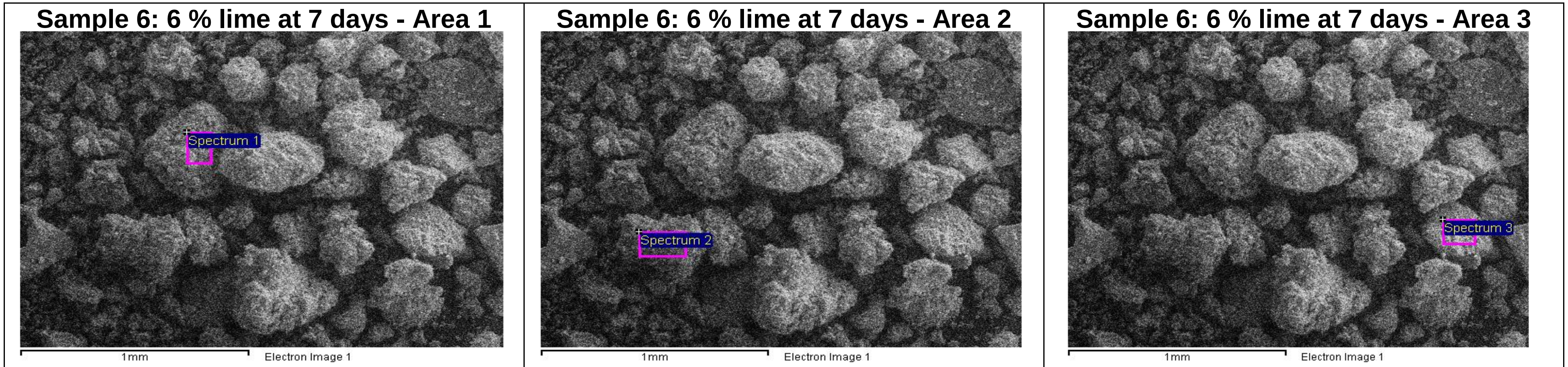


(a1) Sample 6 SEM micrograph at 4 % lime (a2) Sample 6 SEM micrograph at 4 % lime (a3) Sample 6 SEM micrograph at 4 % lime



(b1) Sample 6 EDS/EDX (b2) Sample 6 EDS/EDX (b3) Sample 6 EDS/EDX

Figure 99: (a1), (a2) and (a3): sample 6 SEM micrographs at 4 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively



Sample 6: 6 % lime at 7 days - Area 1

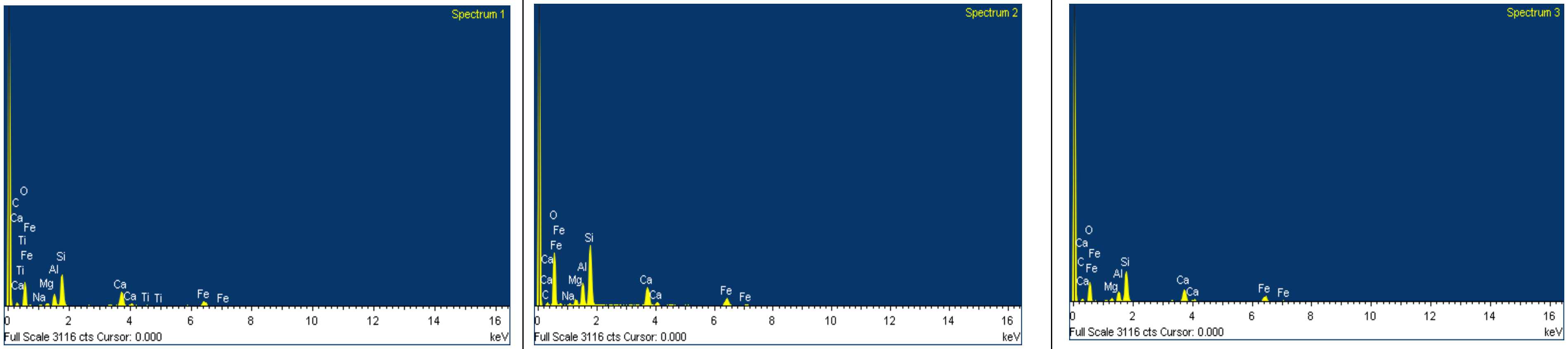
Sample 6: 6 % lime at 7 days - Area 2

Sample 6: 6 % lime at 7 days - Area 3

(a1) Sample 6 SEM micrograph at 6 % lime

(a2) Sample 6 SEM micrograph at 6 % lime

(a3) Sample 6 SEM micrograph at 6 % lime



(b1) Sample 6 EDS/EDX

(b2) Sample 6 EDS/EDX

(b3) Sample 6 EDS/EDX

Figure 100: (a1), (a2) and (a3): sample 6 SEM micrographs at 6 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

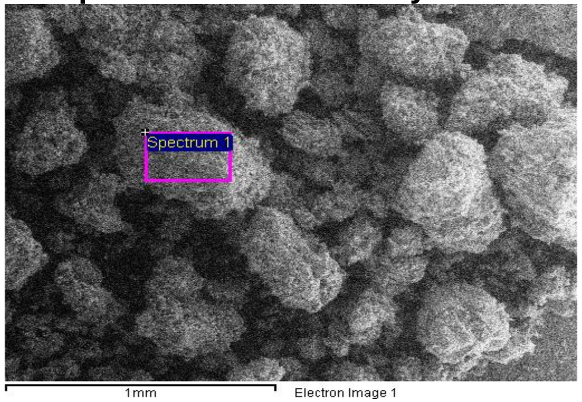
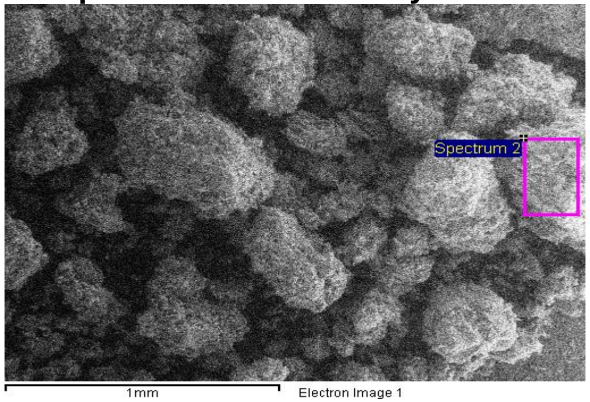
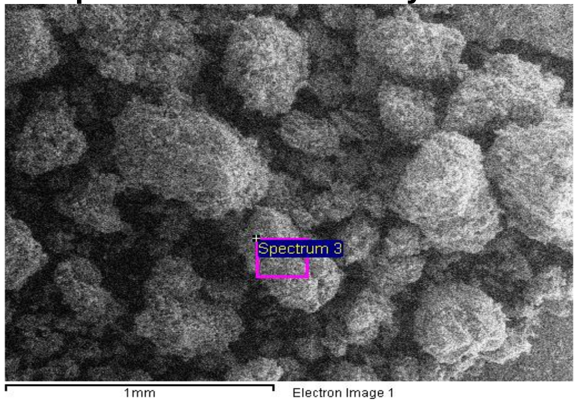
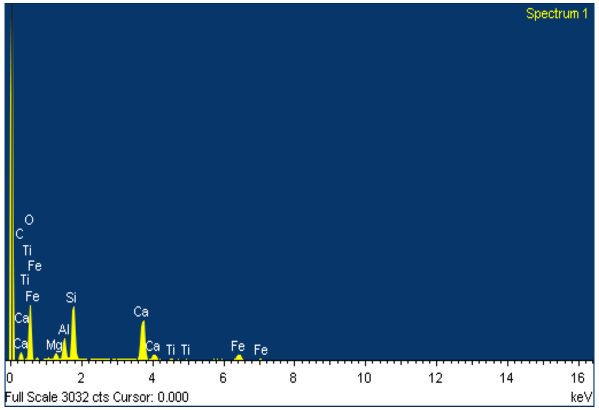
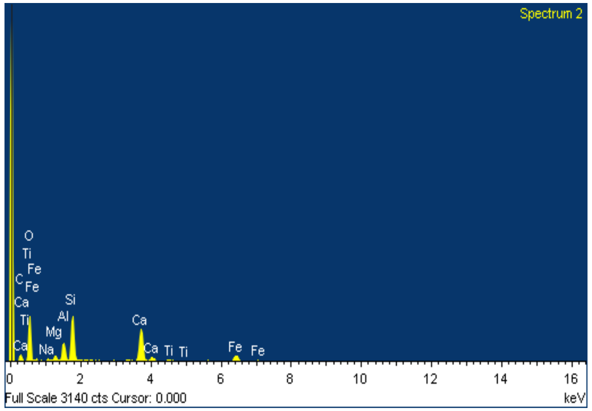
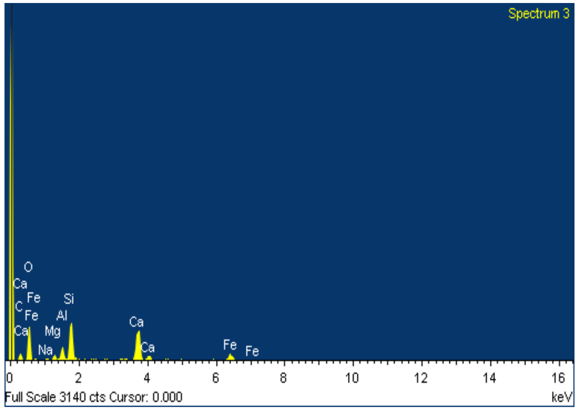
Sample 6: 8 % lime at 7 days - Area 1	**Sample 6: 8 % lime at 7 days - Area 2**	**Sample 6: 8 % lime at 7 days - Area 3**
 (a1) Sample 6 SEM micrograph at 8 % lime	 (a2) Sample 6 SEM micrograph at 8 % lime	 (a3) Sample 6 SEM micrograph at 8 % lime
 (b1) Sample 6 EDS/EDX	 (b2) Sample 6 EDS/EDX	 (b3) Sample 6 EDS/EDX

Figure 101: (a1), (a2) and (a3): sample 6 SEM micrographs at 8 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

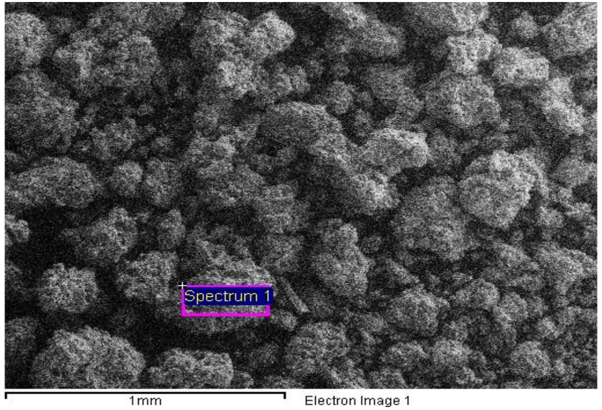
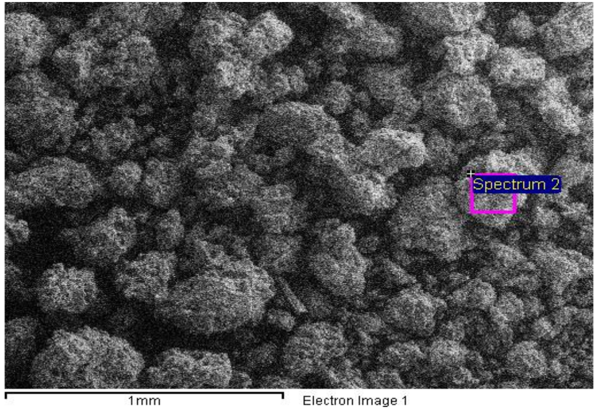
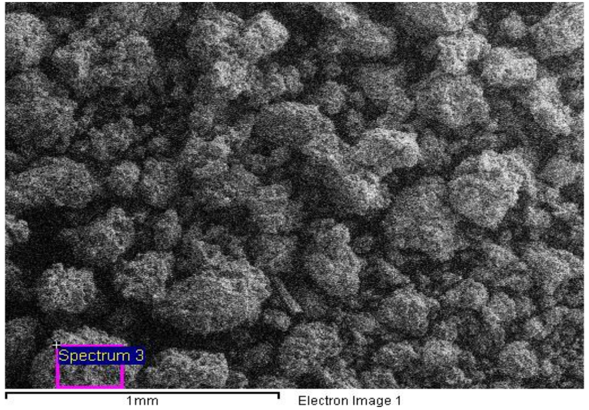
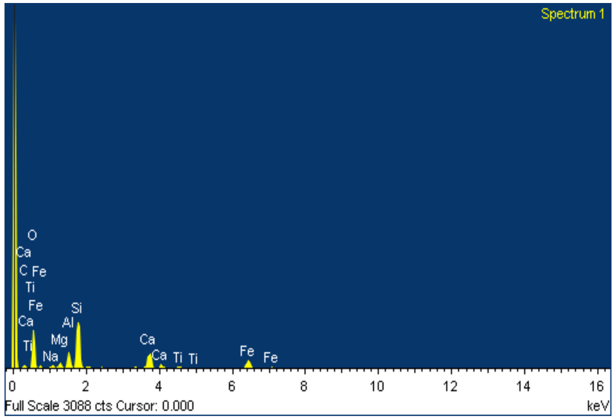
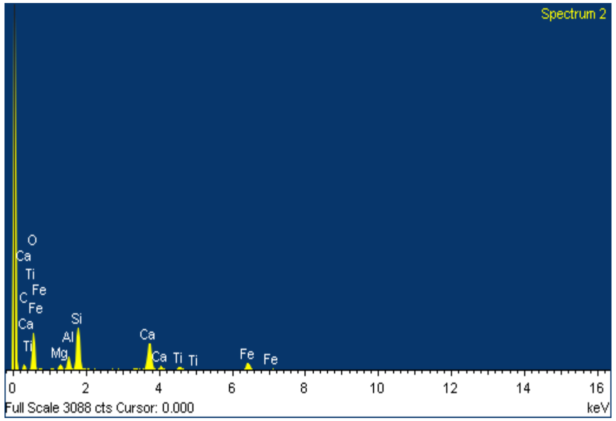
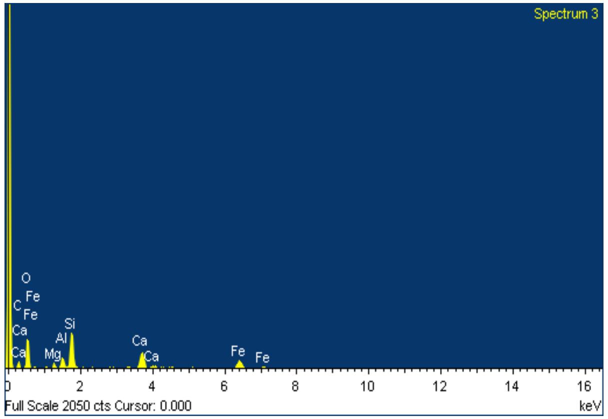
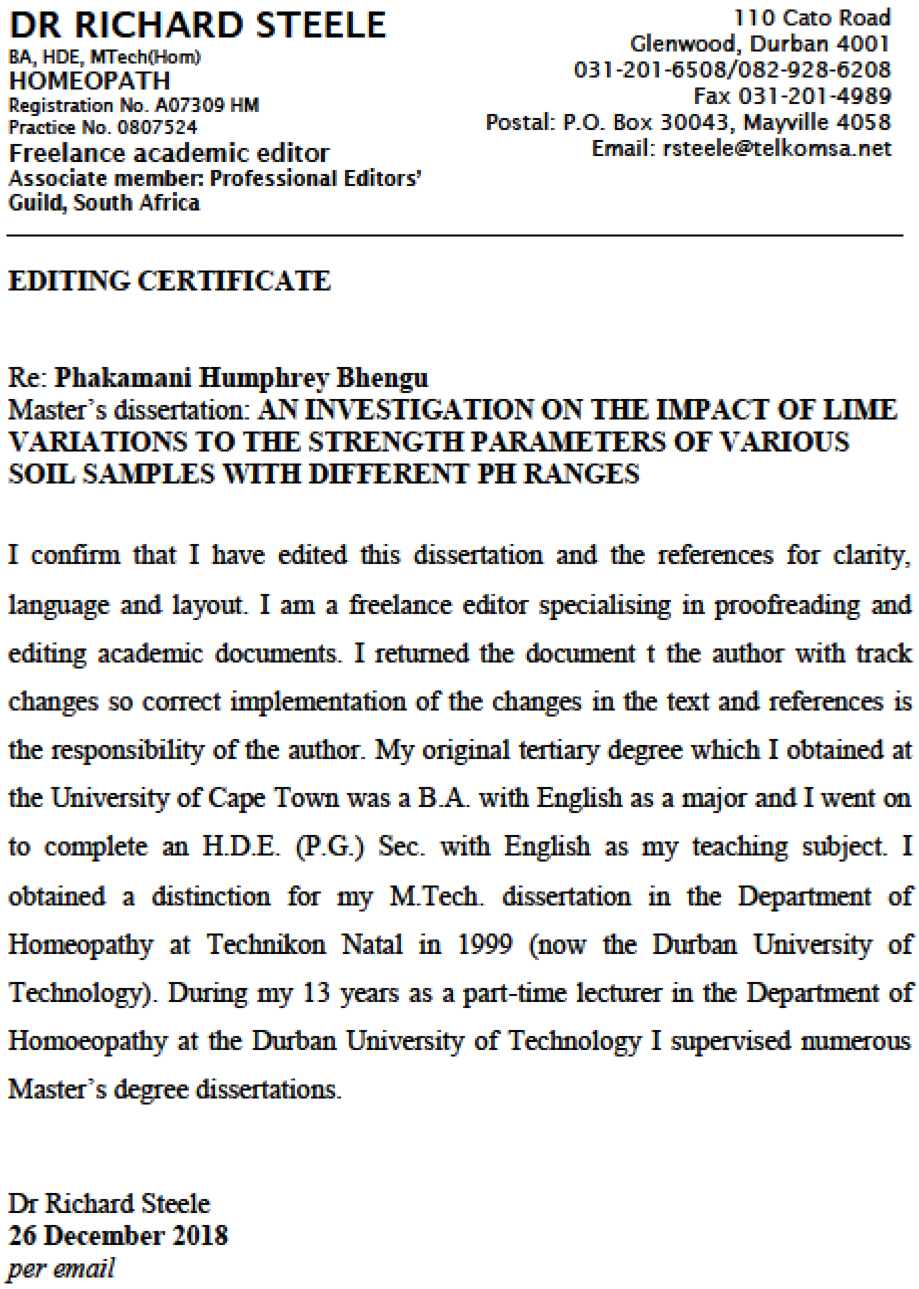
Sample 6: 10 % lime at 7 days - Area 1	**Sample 6: 10 % lime at 7 days - Area 2**	**Sample 6: 10 % lime at 7 days - Area 3**
 (a1) Sample 6 SEM micrograph at 10 % lime	 (a2) Sample 6 SEM micrograph at 10 % lime	 (a3) Sample 6 SEM micrograph at 10 % lime
 (b1) Sample 6 EDS/EDX	 (b2) Sample 6 EDS/EDX	 (b3) Sample 6 EDS/EDX

Figure 102: (a1), (a2) and (a3): sample 6 SEM micrographs at 10 % lime, areas 1, 2 and 3 respectively. (b1), (b2) and (b3): sample 2 EDS/EDX images, areas 1, 2 and 3 respectively

Appendix E: Editing certificate



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EDITING CERTIFICATE

Re: **Phakamani Humphrey Bhengu**
Master's dissertation: **AN INVESTIGATION ON THE IMPACT OF LIME VARIATIONS TO THE STRENGTH PARAMETERS OF VARIOUS SOIL SAMPLES WITH DIFFERENT PH RANGES**

I confirm that I have edited this dissertation and the references for clarity, language and layout. I am a freelance editor specialising in proofreading and editing academic documents. I returned the document t the author with track changes so correct implementation of the changes in the text and references is the responsibility of the author. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homeopathy at Technikon Natal in 1999 (now the Durban University of Technology). During my 13 years as a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology I supervised numerous Master's degree dissertations.

Dr Richard Steele
26 December 2018
per email