

**COMPARISON OF DIFFERENT METHODS BY MEANS OF WHICH
WATER HOLDING CAPACITY OF SOIL IS DETERMINED AND
THE PREDICTION OF WATER HOLDING CAPACITY FROM SOIL
TEXTURE IN COARSE-TEXTURED SOIL**

By

C. L. HOWELL

Thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE



AGRICULTURE (SOIL SCIENCE)

at the

UNIVERSITY OF STELLENBOSCH

PROMOTER: DR. J. E. HOFFMAN

EXAMINERS

December 2004

DECLARATION

I the undersigned, hereby declare that the work contained in this thesis is my own work and has not been submitted to any University for a degree.

C. L. HOWELL

ABSTRACT

Irrigation scheduling is one of the most important cultural practices in irrigated vineyards. Water holding capacity of soil is arguably therefore one of the most important characteristics of a soil as it determines how much water can be made available to the plant. The measurement of water holding capacity of soils is time consuming and costly. *In situ* determinations are often impractical to determine.

For routine determinations, water holding capacity is therefore determined on disturbed samples. Such a method for example is the rubber ring method. A great deal of criticism surrounds this rubber ring method and results are often questioned.

The objectives of this study were therefore to determine what the relationship was between undisturbed and disturbed samples and to determine whether compacted samples could give a more accurate representation of the water holding capacity of soil. Soil textural factors influencing the volumetric water content of undisturbed, rubber ring and compacted samples at 5, 10 and 100 kPa were investigated. In addition, soil textural properties influencing water holding capacity of the respective samples between 5 and 100 kPa and 10 and 100 kPa were investigated. The final objective of the study was to develop simple models to predict the volumetric water content and water holding capacity of soil.

Undisturbed and disturbed soil samples were taken at various localities to ensure a wide range of textures. Water holding capacity of undisturbed and disturbed samples was determined at ARC Infruitec-Nietvoorbij using the standard air pressure and ceramic plate technique and the routine rubber ring method respectively. Soil samples were also compacted to a bulk density of approximately 1.5 g.cm^{-3} as a further treatment for determination of water holding capacity using the air pressure and ceramic plate technique.

To investigate aspects of soil texture that could possibly influence volumetric water content of the soil, correlations were done between different texture components and volumetric water content of undisturbed, rubber ring and compacted samples at 5, 10 and 100 kPa. In order to determine the effect of texture on water holding capacity of the soil, correlations were drawn between texture components and water holding capacity of undisturbed, rubber ring and compacted samples between matric potential ranges 5 and 100 kPa and 10 and 100 kPa. The results from this study were used to develop models to predict volumetric soil water content and water holding capacity of soils for a range of soils.

Volumetric water content of rubber ring samples at 5 kPa was more than the volumetric water content of undisturbed samples at 5 kPa. The volumetric water content of rubber ring samples at 5 kPa and the volumetric water content of undisturbed samples at 5 kPa was correlated by 87%. Volumetric water

content of compacted samples at 5 kPa had a 85% degree of correlation with the volumetric water content of undisturbed samples. At 10 kPa, the correlation between volumetric water content determined using rubber ring samples and undisturbed samples was 77%. This was identical to the correlation between volumetric water content of compacted samples at 10 kPa and undisturbed samples. At 100 kPa, most of the rubber ring samples' volumetric water content fell below the 1:1 line of volumetric water content of undisturbed samples. The volumetric water content of all the compacted samples was higher than that of the undisturbed samples.

Water holding capacity of all the rubber ring samples between 5 and 100 kPa was greater than the water holding capacity of the undisturbed samples between 5 and 100 kPa. Rubber ring samples therefore generally overestimated the water holding capacity of the soil. The water holding capacity of most of the rubber ring samples between 10 and 100 kPa was greater than the water holding capacity of the undisturbed samples. In contrast, the water holding capacity of compacted samples between 5 and 100 kPa was less than the water holding capacity of undisturbed samples between 5 and 100 kPa. Water holding capacity of compacted samples was therefore underestimated.

The results from this study confirmed that the influence of clay and silt content on volumetric water content of undisturbed, rubber ring and compacted samples increased as the suction on the respective samples is increased. The influence of fine sand content on volumetric water content of undisturbed, rubber ring and compacted samples decreased with an increase in matric potential to 100 kPa. Medium sand content of undisturbed, rubber ring and compacted samples had the greatest influence of all the textural components on the volumetric water content of the respective samples at 5 kPa and 10 kPa.

Water holding capacity of undisturbed, rubber ring and compacted samples between 5 and 100 kPa was greatly influenced by the fine sand content of the samples. Medium sand content of the samples also had an influence on the water holding capacity thereof.

To predict the volumetric water content of undisturbed samples at 5, 10 and 100 kPa, the independent variables were fine sand content, square root of medium sand content and \ln of medium sand content. In the case of models to predict the volumetric water content of rubber ring samples at 5, 10 and 100 kPa, the same variables were used as independent variables. Additional variables such as silt content, the \ln of silt content, square root of clay plus silt content and the medium sand content. To predict the volumetric water content of compacted samples at 5, 10 and 100 kPa the terms used were silt content, clay plus silt content, the $e^{-\text{clay plus silt content}}$, medium sand content and the square root of medium sand content. The models to predict volumetric water content of rubber ring samples gave the best correlation with the actual volumetric water content of rubber ring samples.

The final models to predict the water holding capacity of all the samples between 5 and 100 kPa and 10 and 100 kPa used only fine and medium sand parameters as independent variables.

Soil textural components do play an important role in determining the volumetric water content of undisturbed, rubber ring and compacted samples at 5, 10 and 100 kPa. The magnitude of the water holding capacity between 5 and 100 kPa and 10 and 100 kPa is also influenced by soil texture. The models developed to predict the volumetric water content of samples at 5, 10 and 100 kPa and the magnitude of the water holding capacity between 5 and 100 kPa and 10 and 100 kPa could be very useful. Both time and money can potentially be saved. Models that can be highly recommended are the models generated for the undisturbed samples.

These are:

$$\text{At 5 kPa, } \text{VWC}_u = 0.47259 - 0.04712 \text{ medium sand}^{0.5}$$

$$\text{At 10 kPa, } \text{VWC}_u = 0.41292 - 0.04221 \text{ medium sand}^{0.5}$$

$$\text{At 100 kPa, } \text{VWC}_u = 0.48080 - 0.00254 \text{ fine sand} - 0.0865 \ln \text{ medium sand}$$

$$\text{Between 5 and 100 kPa, } \text{WHC}_u = -29.523 + 3.394 \text{ fine sand}$$

$$\text{Between 10 and 100 kPa, } \text{WHC}_u = -891.794 + 232.326 \ln \text{ fine sand} + 38.006 \ln \text{ medium sand}$$

OPSOMMING

Besproeiingskedulering is een van die belangrikste wingerdverbouingspraktyke. Waterhouvermoë bepaal hoeveel water beskikbaar gestel kan word aan die plant en daarom is dit een van die belangrikste eienskappe van 'n grond. Die meting van waterhouvermoë van grond is tydsaam en duur. Boonop is *in situ* bepaling dikwels onprakties om te bepaal.

Waterhouvermoë word dus bepaal op versteurde monsters vir roetine ontleding. 'n Voorbeeld van so 'n metode is die rubberring metode. Daar bestaan groot kritiek teenoor hierdie rubberring metode en resultate word dikwels betwyfel deur die landboubedryf.

Die doel van hierdie studie was dus om te bepaal wat die verwantskap is tussen onversteurde monsters en rubberring monsters asook om te bepaal of gekompakteerde monsters 'n meer akkurate aanduiding sou gee as onversteurde monsters van die waterhouvermoë van die grond. Grondtekstuur faktore wat die volumetriese waterinhoud van onversteurde monsters, rubberring monsters en gekompakteerde monsters by 5, 10 and 100 kPa beïnvloed, was ondersoek. Grondtekstuur faktore wat waterhouvermoë van die onderskeie monsters tussen 5 en 100 kPa en tussen 10 en 100 kPa beïnvloed, was ook ondersoek. Die finale doelwit van die studie was om eenvoudige modelle te ontwikkel vir die voorspelling van volumetriese waterinhoud en waterhouvermoë van grond.

Onversteurde grond monsters en grond vir versteurde monsters is by verskeie lokaliteite geneem om 'n wye reeks teksture te verkry. Waterhouvermoë van onversteurde monsters is bepaal by LNR Infruitec-Nietvoorbij met die standaard drukplaat tegniek. Waterhouvermoë van versteurde grond is bepaal met die roetine rubberring metode van LNR Infruitec-Nietvoorbij. Grond was ook gekompakteer tot 'n bulkdigtheid van ongeveer 1.5 g.cm^{-3} en daarna is die waterhouvermoë bepaal by die LNR Infruitec-Nietvoorbij met die standaard drukplaat tegniek.

Om aspekte van grondtekstuur, wat moontlik die volumetriese waterinhoud van grond kan beïnvloed te ondersoek, is korrelasies tussen verskeie tekstuur komponente en die volumetriese waterinhoud van onversteurde monsters, rubberring monsters en gekompakteerde monsters by 5, 10 en 100 kPa bepaal. Om te bepaal watter tekstuur komponente waterhouvermoë van die grond kan bepaal, is korrelasies getrek tussen tekstuur komponente en waterhouvermoë van onversteurde monsters, rubberring monsters en gekompakteerde monsters tussen 5 en 100 kPa en tussen 10 en 100 kPa. Die data is verwerk met die SAS uitgawe 6.12 (SAS, 1990) om modelle vir die voorspelling van volumetriese waterinhoud en waterhouvermoë van grond met behulp van maklik kwantifiseerbare grondtekstuur veranderlikes te ontwikkel.

Die volumetriese waterinhoud van rubberring monsters by 5 kPa was meer as die volumetriese waterinhoud van onversteurde monsters by 5 kPa. Die volumetriese waterinhoud van rubberring monsters by 5 kPa en die volumetriese waterinhoud van onversteurde monsters by 5 kPa is gekorreleerd met 87%. Die volumetriese waterinhoud van gekompakteerde monsters by 5 kPa het 'n korrelasie van 85% met volumetriese waterinhoud van onversteurde monsters getoon. By 10 kPa, was die graad van korrelasie tussen volumetriese waterinhoud bepaal met rubberring monsters en onversteurde monsters, 77%. Dit was omtrent dieselfde as die graad van korrelasie tussen volumetriese waterinhoud van gekompakteerde monsters en onversteurde monsters by 10 kPa. By 100 kPa het die meeste van die rubberring monsters se volumetriese waterinhoud onderkant die 1:1 lyn van die volumetriese waterinhoud by 100 kPa van al die onversteurde monsters. Die volumetriese waterinhoud van al die gekompakteerde monsters was hoër as die van dië onversteurde monsters.

Die waterhou vermoë van al die rubberring monsters tussen 5 en 100 kPa was groter as dië van die onversteurde monsters tussen 5 en 100 kPa. Die rubberring monsters het dus oor die algemeen die grootte van die waterhou vermoë oorskry. Die waterhou vermoë van die meeste van die rubberring monsters tussen 10 en 100 kPa was groter as die waterhou vermoë van die onversteurde monsters. Die waterhou vermoë van gekompakteerde monsters tussen 5 en 100 kPa was minder as die waterhou vermoë van die onversteurde monsters tussen 5 en 100 kPa. Die waterhou vermoë van gekompakteerde grondmonsters is dus onderskat.

Die resultate van hierdie studie het die invloed van klei- en sliksand inhoud op die volumetriese waterinhoud van onversteurde monsters, rubberring monsters en gekompakteerde monsters bevestig. Die invloed van klei en sand op die volumetriese waterinhoud van onversteurde monsters, rubberring monsters en gekompakteerde monsters het toegeneem soos die matriks potensiaal op die onderskeie monsters toegeneem het. Die invloed van fynsand op die volumetriese waterinhoud van onversteurde monsters, rubberring monsters en gekompakteerde monsters was die grootste by 5 kPa en het afgeneem tot by 100 kPa. Die mediumsand inhoud van onversteurde monsters, rubberring monsters en gekompakteerde monsters het van al die tekstuur komponente die grootste invloed op die volumetriese waterinhoud van al die monsters by 5 kPa en 10 kPa gehad.

Die waterhou vermoë van onversteurde monsters, rubberring monsters en gekompakteerde monsters tussen 5 en 100 kPa is grootliks beïnvloed deur die fynsand inhoud van die monsters. Die mediumsand inhoud van die monsters het ook 'n invloed gehad op die waterhou vermoë daarvan.

Om die volumetriese waterinhoud van onversteurde monsters by 5, 10 en 100 kPa te voorspel, is onafhanklike veranderlikes soos fynsand inhoud, vierkantswortel van mediumsand inhoud en ln van mediumsand inhoud bepaal. In die geval van modelle om die volumetriese waterinhoud van rubberring monsters by 5, 10 en 100 kPa te voorspel, is dieselfde veranderlikes gebruik as onafhanklike

veranderlikes. Addisionele veranderlikes soos slijk inhoud, \ln van slijk inhoud, die vierkantswortel van die klei plus slijk inhoud en die mediumsand inhoud is ook gebruik. Om die volumetriese waterinhoud van gekompakteerde monsters by 5, 10 en 100 kPa te voorspel, is die terme slijk inhoud, klei plus slijk inhoud, $e^{-\text{klei plus slijk inhoud}}$, mediumsand inhoud en vierkantswortel van mediumsand inhoud gebruik. Die modelle om volumetriese waterinhoud van rubberring samples te voorspel het die akkuraatste voorspellings gegee.

Die finale modelle, om waterhouvermoë van alle monsters tussen 5 en 100 kPa en tussen 10 en 100 kPa te bepaal, het slegs fyn en mediumsand as onafhanklike veranderlikes gebruik.

Grondtekstuur komponente speel dus 'n belangrike rol in die volumetriese waterinhoud van onversteurde monsters, rubberring monsters en gekompakteerde monsters by 5, 10 en 100 kPa. Die grootte van die waterhouvermoë tussen 5 en 100 kPa en tussen 10 en 100 kPa is ook beïnvloed deur die grondtekstuur. Die modelle wat ontwikkel is om die volumetriese waterinhoud van monsters by 5, 10 en 100 kPa en die grootte van die waterhouvermoë tussen 5 en 100 kPa en tussen 10 and 100 kPa te voorspel, kan baie waardevol wees. Tyd en geld kan potensieel bespaar word. Die modelle wat hoogs aanbevole is, is die modelle vir onversteurde monsters.

Die modelle is:

$$\text{By 5 kPa, } VWI_o = 0.47259 - 0.04712 \text{ mediumsand}^{0.5}$$

$$\text{By 10 kPa, } VWI_o = 0.41292 - 0.04221 \text{ mediumsand}^{0.5}$$

$$\text{By 100 kPa, } VWI_o = 0.48080 - 0.00254 \text{ fynsand} - 0.0865 \ln \text{ mediumsand}$$

$$\text{Tussen 5 en 100 kPa, } WHV_o = -29.523 + 3.394 \text{ fynsand}$$

$$\text{Tussen 10 en 100 kPa, } WHV_o = -891.794 + 232.326 \ln \text{ fynsand} + 38.006 \ln \text{ mediumsand}$$

ACKNOWLEDGMENTS

I would like to thank:

- My Heavenly Father.
- My parents, Peter and Louise, for their encouragement and support.
- My sister, Phillippa, for her enthusiasm and patience.
- My friends, for all of their support.
- The Agricultural Research Council for the opportunity and financial assistance to further my education.
- The Deciduous Fruit Producers' Trust for the funding of the research project.
- The staff of the Soil Science section of the ARC Infruitec – Nietvoorbij for all the technical assistance. In particular, I would like to thank Dr. P. A. Myburgh for initiating the study, his guidance, interest and encouragement throughout the years.
- O. Beukes and H. Paardewaater for analysis of rubber ring samples.
- Karlien Breedt and Nellie Wagman from the library of the ARC Infruitec – Nietvoorbij for assistance with literature.
- Frikkie Calitz for all his assistance with the statistics and development of the prediction models.
- My promoter, Dr. J. E. Hoffman, for all of his encouragement, advice and support.

CONTENTS

ABSTRACT	i
OPSOMMING	iv
ACKNOWLEDGEMENTS	vii
CONTENTS	viii
LIST OF TABLES	xi
LIST OF FIGURES	xiii
CHAPTER 1-INTRODUCTION	1
CHAPTER 2- LITERATURE REVIEW	3
2.1 Introduction	3
2.2. <i>In situ</i> measurement of water holding capacity of soils	3
2.2.1 Description of field method to determine water retention curves	4
2.3 Laboratory methods of determining water holding capacity	5
2.3.1 Type of equipment used in determination of water holding capacity	6
2.3.2 Pressure plate and membrane apparatus	6
2.3.3 Sand baths	9
2.3.4 Weighable cells	10
2.3.5 Suction tables	10
2.3.6 Psychrometer method	10
2.3.7 Osmotic method	11
2.3.8 Dynamic methods	11
2.3.9 Rubber ring method	11
2.4 Sampling of soil for water holding capacity determination	12
2.5 Soil composition factors influencing water holding capacity	13
2.5.1 Texture	13
2.5.2 Soil structure	16
2.5.3 Organic matter content	18
2.5.4 Presence of stones	18
2.5.5 Agronomic aspects	19
2.5.6 Influence of stratification	19
2.5.7 Influence of clay minerals and exchangeable cations	20
2.6 Stochastic modeling of water holding capacity of soils	21
2.6.1 Additivity hypothesis	21
2.6.2 Fractal approach	22

2.6.3 Specific stochastic models	22
2.6.4 Pedo-transfer functions	27
CHAPTER 3 – MATERIALS AND METHODS	
3. Introduction	29
3.1 Undisturbed samples	29
3.2 Rubber ring samples	29
3.3 Compacted samples	29
3.4 Data analysis	30
CHAPTER 4 – RESULTS AND DISCUSSION: VOLUMETRIC WATER CONTENT AND WATER HOLDING CAPACITY OF UNDISTURBED, RUBBER RING AND COMPACTED SAMPLES	
4.1 Texture	33
4.2 Bulk density	33
4.3.1 Volumetric water content: undisturbed samples	33
4.3.2 Volumetric water content: rubber ring samples	41
4.3.3 Volumetric water content: compacted samples	45
4.3.4 Volumetric water content: a comparison	52
4.4.1 Water holding capacity	61
4.4.2 Water holding capacity: undisturbed samples	61
4.4.3 Water holding capacity: rubber ring samples	63
4.4.4 Water holding capacity: compacted samples	63
4.4.5 Water holding capacity: a comparison	69
CHAPTER 5 – RESULTS AND DISCUSSION: PROPOSED MODELS TO PREDICT VOLUMETRIC WATER CONTENT AND WATER HOLDING CAPACITY OF SOIL FROM TEXTURE IN COARSE-TEXTURED SOILS	
5.1 Introduction	75
5.2 Proposed models: volumetric water content	75
5.3 Proposed models: water holding capacity	81
5.4 Evaluation of rubber ring model and comparison to Hutson's equations for volumetric water content at 10 kPa and 100 kPa	86
CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS	93

LIST OF TABLES

Table 4.1. Texture classification of the range of soils that were used in the comparison of different methods of water holding capacity determination.	34
Table 4.2. Particle size distribution of the range of soils that were used in the comparison of different methods of water holding capacity determination.	35
Table 4.3. Bulk density of soil samples used in different methods to determine water holding capacity of soils.	36
Table 4.4. Volumetric water content of undisturbed samples used to determine water holding capacity of soils.	37
Table 4.5. Matrix table summerising the correlations of volumetric water content of undisturbed (VWC_u), rubber ring (VWC_{rr}) and compacted (VWC_c) samples at 5, 10 and 100 kPa with textural properties of the soils.	38
Table 4.6. Volumetric water content of rubber ring samples used to determine water holding capacity of soils.	44
Table 4.7. Volumetric water content of compacted samples used to determine water holding capacity of soils.	51
Table 4.8. Water holding capacity (mm.m^{-1}) of soils determined by means of undisturbed, rubber ring and compacted samples.	62
Table 4.9. Matrix table summerising the correlations of water holding capacity of undisturbed (WHC_u), rubber ring (WHC_{rr}) and compacted (WHC_c) samples at 5, 10 and 100 kPa with textural properties of the soils.	64
Table 5.1. Equations of models to predict volumetric water content of undisturbed samples (VWC_u), rubber ring samples (VWC_{rr}) and compacted samples (VWC_c) at 5 kPa, 10 kPa and 100 kPa and standard errors (SE) of coefficient variables.	76
Table 5.2. Actual (VWC_A) and predicted volumetric water content (VWC_P) of undisturbed samples used to determine water holding capacity of soils.	77

Table 5.3. Actual (VWC_A) and predicted volumetric water content (VWC_P) of rubber ring samples used to determine water holding capacity of soils.	78
Table 5.4. Actual (VWC_A) and predicted volumetric water content (VWC_P) of compacted samples used to determine water holding capacity of soils.	79
Table 5.5. Equations of models to predict water holding capacity of undisturbed samples (WHC_U), rubber ring samples (WHC_{rr}) and compacted samples (WHC_c) between 5 and 100 kPa and between 10 and 100 kPa and standard errors (SE) of coefficient variables.	82
Table 5.6. Actual (WHC_A) and predicted water holding capacity (WHC_P) of soils determined by means of undisturbed samples.	83
Table 5.7. Actual (WHC_A) and predicted water holding capacity (WHC_P) of soils determined by means of rubber ring samples.	84
Table 5.8. Actual (WHC_A) and predicted water holding capacity (WHC_P) of soils determined by means of compacted samples.	85
Table A.1. Actual rubber ring data used to evaluate models to predict volumetric water content of rubber ring samples at 10 and 100 kPa and water holding capacity between 10 and 100 kPa.	102

LIST OF FIGURES

Fig. 3.1. Compactor developed for compaction of soil samples.	32
Fig. 4.1. The influence of silt content (%) on the volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	39
Fig. 4.2. The influence of clay plus silt content (%) on the volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	40
Fig. 4.3. The influence of fine sand content (%) on the volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	42
Fig. 4.4. The influence of medium sand content (%) on the volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	43
Fig. 4.5. The influence of clay content (%) on the volumetric water content of rubber ring samples (VWC_r), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	46
Fig. 4.6. The influence of silt content (%) on the volumetric water content of rubber ring samples (VWC_r), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	47
Fig. 4.7. The influence of clay plus silt content (%) on the volumetric water content of rubber ring samples (VWC_r), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	48
Fig. 4.8. The influence of fine sand content (%) on the volumetric water content of rubber ring samples (VWC_r), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	49
Fig. 4.9. The influence of medium sand content (%) on the volumetric water content of rubber ring samples (VWC_r), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	50
Fig. 4.10. The influence of clay content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	53
Fig. 4.11. The influence of silt content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.	54

- Fig. 4.12. The influence of clay plus silt content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa. 55
- Fig. 4.13. The influence of fine sand content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa. 56
- Fig. 4.14. The influence of medium sand content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa. 57
- Fig. 4.15. Relationship between volumetric water content of rubber ring samples (VWC_{rr}) and volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa. 59
- Fig. 4.16. Relationship between volumetric water content of compacted samples (VWC_c) and volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa. 60
- Fig. 4.17. The influence of fine sand content (%) on the water holding capacity of undisturbed samples (WHC_u) between 5 and 100 kPa. 65
- Fig. 4.18. The influence of medium sand content (%) on the water holding capacity of undisturbed samples (WHC_u) between 5 and 100 kPa. 65
- Fig. 4.19. The influence of fine sand content (%) on the water holding capacity of undisturbed samples (WHC_u) between 10 and 100 kPa. 66
- Fig. 4.20. The influence of medium sand content (%) on the water holding capacity of undisturbed samples (WHC_u) between 10 and 100 kPa. 66
- Fig. 4.21. The influence of fine sand content (%) on the water holding capacity of rubber ring samples (WHC_{rr}) between 5 and 100 kPa. 67
- Fig. 4.22. The influence of medium sand content (%) on the water holding capacity of rubber ring samples (WHC_{rr}) between 5 and 100 kPa. 67
- Fig. 4.23. The influence of fine sand content (%) on the water holding capacity of rubber ring samples (WHC_{rr}) between 10 and 100 kPa. 68

- Fig. 4.24. The influence of medium sand content (%) on the water holding capacity of rubber ring samples (WHC_{rr}) between 10 and 100 kPa. 68
- Fig. 4.25. The influence of fine sand content (%) on the water holding capacity of compacted samples (WHC_c) between 5 and 100 kPa. 70
- Fig. 4.26. The influence of medium sand content (%) on the water holding capacity of compacted samples (WHC_c) between 5 and 100 kPa. 70
- Fig. 4.27. The influence of fine sand content (%) on the water holding capacity of compacted samples (WHC_c) between 10 and 100 kPa. 71
- Fig. 4.28. The influence of medium sand content (%) on the water holding capacity of compacted samples (WHC_c) between 10 and 100 kPa. 71
- Fig. 4.29. Relationship between water holding capacity of rubber ring samples (WHC_{rr}) and water holding capacity of undisturbed samples (WHC_u), as determined between (A) 5 and 100 kPa and (B) 10 and 100 kPa. 72
- Fig. 5.1. The relationship between actual and predicted volumetric water content of rubber ring samples at 10 kPa. 87
- Fig. 5.2. The relationship between actual and predicted volumetric water content of rubber ring samples at 100 kPa. 87
- Fig. 5.3. The relationship between actual water holding capacity of rubber ring samples between 10 and 100 kPa and the predicted water holding capacity thereof. 88
- Fig. 5.4. The relationship between predicted volumetric water content of undisturbed samples at 10 kPa and predicted volumetric water content of rubber ring samples at 10 kPa. 88
- Fig. 5.5. The relationship between actual volumetric water content of rubber ring samples at 10 kPa and predicted volumetric water content of samples at 10 kPa using the model of Hutson (1986). 90
- Fig. 5.6. The relationship between actual volumetric water content of rubber ring samples at 100 kPa and predicted volumetric water content of samples at 100 kPa using the model of Hutson (1986). 90

Fig. 5.7. The relationship between predicted volumetric water content of rubber ring samples at 10 kPa and predicted volumetric water content of samples at 10 kPa using the model of Hutson (1986). 91

Fig. 5.8. The relationship between predicted volumetric water content of rubber ring samples at 100 kPa and predicted volumetric water content of samples at 100 kPa using the model of Hutson (1986). 91

Fig. 5.9. The relationship between predicted volumetric water content of samples using the model of undisturbed samples at 10 kPa and predicted volumetric water content of samples at 10 kPa using the model of Hutson (1986). 92

Fig. 5.10. The relationship between predicted volumetric water content of samples using the model of undisturbed samples at 100 kPa and predicted volumetric water content of samples at 100 kPa using the model of Hutson (1986). 92

CHAPTER 1

INTRODUCTION

Water holding capacity of soil is the ability of soil to retain water. Water holding capacity is essential to characterise the availability of soil water to plants and to model movement of water and solutes in unsaturated soils (Gupta & Larson, 1979). Knowledge of water retention characteristics is therefore essential in describing soil water processes (Vereecken, Maes, Feyen & Darius, 1988).

Irrigation scheduling is one of the most important cultural practices in irrigated vineyards. Water holding capacity determines how much water can be stored in the soil for uptake by the plant. To irrigate correctly, the water holding capacity or the plant available water of the soil must be known. In order to determine the water holding capacity of soils, at least two important types of information should be known (Klute, 1986). The amount of water retained in the soil and the energy status of the soil water must be known.

According to Zeiliger, Pachepsky & Rawls (2000) and Kravchenko & Zhang (1998), soil water retention measurements are time consuming and costly. De Jong, Campbell & Nicholaichuk (1983) reiterated that high variability and soil complexity makes measurement time consuming and costly. Measuring soil water characteristic curves are expensive and time consuming (Gupta & Larson, 1979) and laboratory results do not always agree with field data. Both laboratory and field procedures are tedious, time consuming and expensive (Arya & Paris, 1981). *In situ* determinations of water holding capacity in the field are time consuming and often impractical. The relationship between soil water content and matric potential can be determined *in situ* by means of tensiometers and soil samples. The gravimetric method of determining soil water content of soils is the most basic method to determine soil water content (Hanks & Ashcroft, 1980). When soil samples are taken, tensiometer readings are taken. Taking these soil samples can be destructive as roots can be cut and infiltration and drainage behaviour altered (Marshall & Holmes, 1979).

Taking undisturbed samples requires specialised equipment and knowledge. According to Hall, Reeve, Thomasson & Wright (1977) samples are collected in, or as near as possible to an undisturbed state. However, it is often extremely difficult to take undisturbed samples in gravelly or stony soils.

For routine determinations, water holding capacity is therefore determined on disturbed samples. The method used by ARC Infruitec- Nietvoorbij to determine the water holding capacity of soils commercially (Beukes, 1990) is known as the rubber ring method. Pressure plates were used to determine the water holding capacity of soils between 10 and 100 kPa. A great deal of criticism surrounds this method in the agricultural industry and results are often questioned. If the rubber ring samples undermine the value of the water holding capacity of soils, then producers are in danger of under irrigating their crops. On the other hand, if the water holding capacity of soils are

overestimated, then soils are being over irrigated with negative consequences for the plant. This wastage of water is also not in accordance with the new Water Act where the judicious use and application of water will be enforced.

There are a number of factors that play an important role in determining the value of the water holding capacity. However, not all the factors influencing the water holding capacity of soils can be easily quantified. The main factors influencing the water holding capacity of soil are soil texture, pore size distribution and temperature (Hall *et al.*, 1977). The main field variables that influence water holding capacity are particle size distribution and bulk density (Hall *et al.*, 1977).

Several efforts have been made to predict water retention from easily and routinely determined textural and structural properties (Gupta & Larson, 1979). Soil water retention characteristics are not unique and are affected by a number of environmental and soil factors (Rawls, Gish & Brakensiek, 1991), therefore the relationship between easily measurable soil properties and water holding capacity is therefore of great importance (Vereecken *et al.*, 1988). An alternative to the experimental approach is the prediction of hydrologic properties from textural and structural soil properties (Arya & Paris, 1981). This consists of relating water contents at specified soil water pressures to soil texture, organic matter and/or bulk density using multiple regression analysis (Arya & Paris, 1981). Hutson (1983) concluded that both the laboratory and field measurements are laborious and time consuming and there is therefore the need for simpler methods of estimating retentivity from soil type, composition and bulk density.

The objectives of this study were therefore to:

- Determine the relationship between water holding capacity measurements in undisturbed and disturbed samples.
- Determine whether compacted samples could give a more accurate representation of water holding capacity of soil.
- Develop simple models to predict water holding capacity of soil from texture analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Soil consists of a mass of solid particles with a network of pores and channels in between (Howell, 2001). Water is held in the soil as films around soil particles and temporarily in pores (McCarthy, Jones & Due, 1988). The soil becomes saturated when all the pores are filled with water. If the soil is allowed to drain freely, then after a few days no more drainage will occur from the soil. The soil is then at field capacity. In the case of sands, field capacity is attained at approximately 5 kPa. For heavier soils, field water capacity is attained at 10 kPa. As the soil becomes drier, a point will be reached where plants will wilt by day and will no longer be able to take up water from the soil. Permanent wilting point occurs at a matrix potential of 1500 kPa (Beukes, 1985). The plant available water is the amount of water held in the soil between these two limits. It can be expressed as a depth of water in mm per meter of soil.

2.2 *In situ* measurement of water holding capacity of soils

In situ determination of water holding capacity takes a great deal of time as in the case of laboratory determinations of water holding capacity of soils. Laboratory methods however, give more accurate results than *in situ* determination of water holding capacity. *In situ* determination of water holding capacity do not disturb the natural state of the soil, while in the case of laboratory measurements, some researchers do use disturbed samples. Specialised equipment is also required for *in situ* determination of water holding capacity. Tensiometers used for *in situ* determination of water holding capacity can be used for irrigation scheduling. One of the greatest risks of *in situ* determinations is that the drying out cycle of the soil can be negated by rain, particularly if no rain shelter is present. *In situ* determinations of water holding capacity are destructive as soil samples have to be taken to determine their gravimetric soil water content. Labour is therefore required to take these samples.

The evaluation of the water content and matric potential relationship *in situ* requires sufficient time, effort and specialised equipment (Bruce & Luxmoore, 1986). Certain questions should be asked to ensure that the particular data requirements will be met. It is essential to define soil area and depth properly. Field determination of the water content – potential is done on relatively small areas and therefore the selection thereof is very important. Site related factors, such as whether the soil has horizons that restrict water flow and impede wetting and drainage, should be considered. Instruments used should also be reviewed and particular attention should be given to the sampling volume of the instrument or technique. It is also important to consider the nature and state of soil volume because it is necessary to make measurements over a large soil water range.

The relation between soil water content and matric potential can be determined *in situ* using tensiometers and soil samples. The gravimetric method of determining soil water content of soils is the most basic method to determine soil water content (Hanks & Ashcroft, 1980). Tensiometers consist of a ceramic porous cup, connected by a tube to a manometer, with all parts filled with water (Hillel, 1980). A tensiometer left in the soil for a long period of time tends to follow the changes in the matric suction of soil water. When soil gravimetric samples are taken, tensiometer readings are taken. Soil samples must then be taken close to the tensiometers.

The water content of soil can be determined by determining the mass of water lost when samples are dried in an oven at 105 °C to a constant mass (Marshall & Holmes, 1979). Once the soil water content of the gravimetric samples has been determined, one can determine the relationship between soil water content and soil matric potential.

The main advantage of *in situ* determinations is that determinations are done on soil in its natural state. There are disadvantages in determining the water holding capacity of soils in this manner (Marshall & Holmes, 1979). Taking soil samples is destructive and when holes are bored, roots are cut and infiltration and drainage behaviour can be altered. A large number of samples may also be required because of the interspatial variation within a site due to soil texture and structure.

According to Bruce & Luxmoore (1986) the area for measurement should be large enough to accommodate the sampling and instrument installation. A dyke must be installed around the perimeter of the plot sufficient to allow ponding of water on the surface. Layer or horizon thickness must be carefully assessed for each plot before installing any instruments.

2.2.1 Description of field method to determine water retention curves

To determine water retention curves for 0 to –50 kPa, a water supply is essential. A shovel, bucket soil auger and soil sample tins are needed for collection of samples. A balance and oven at 105 °C is required for determination of soil water content. Approximately three to four tensiometers per horizon and a neutron probe is necessary. A bulk density sampler is needed. A rainfall shelter, plastic sheet and insulation material is also required.

After site selection and before the dyke is constructed, vegetation must be destroyed and the soil surface prepared. Traffic should be kept off the plot during instrument installation. Tensiometers must be installed to determine matric potential measurements. The tensiometers should be located in the middle of each horizon that is to be monitored. Tensiometers can be installed vertically or horizontally. Vertically installed tensiometers should not allow free water to flow along the vertical shank or connection between the cup and pressure measuring device (Bruce & Luxmoore, 1986).

The tensiometers must then be read. The response time thereof depends on soil characteristics. To measure soil water content, either thermal neutron or dual- source gamma transmission methods

should be used (Bruce & Luxmoore, 1986). Calibrations applicable to soil situations must be obtained to ensure reliable water content evaluation.

When tensiometers and access tubes have been installed, a rainfall shelter may be needed. This is essential in rainy areas. After tensiometers and access tubes have been installed, the plot surface may require shallow hand tillage and levelling. Water can then be applied until a near steady state conditions is achieved and there is no further change in tensiometer readings. When all tensiometers are working properly, water application must be stopped and drainage allowed to proceed (Bruce & Luxmoore, 1986). Tensiometers and neutron probe readings should be determined frequently during early drainage. The frequency of determination can be reduced as drainage proceeds. A barrier to prevent evaporative water loss should be installed when free water leaves the soil surface. Soil samples must be taken that correspond with tensiometer positions. Bulk density should be determined to convert water content from mass units to volumetric units. When tensiometer readings don't change after seven to ten days, drainage is assumed to be complete.

The method can also be extended to the range determined to -1500 kPa. Three to four tensiometers per horizon and a neutron probe is necessary. A bulk density sampler is needed. A rainfall shelter, plastic sheet and insulation material is also required. Thermal psychrometers or electrical resistance sensors are needed.

After a suitable site has been selected, appropriate grass must be planted to develop a uniform, deep-rooting system for profile water extraction. When the vegetation is well established, instruments must be installed to measure soil water content and water potential. If the water-potential range from near saturation or early drainage to less than -1500 kPa requires characterization, and if completely *in situ* measurements are selected to measure to -1500 kPa, tensiometers can be installed along with the electrical resistance sensors or soil thermocouple psychrometers. Water content can then be determined by thermal neutron method, electrical resistance or psychrometers. When instruments have been installed, water must be applied uniformly over plot surface by sprinkling or ponding until the soil profile is wet. When a steady state has been achieved, the potential and water content must be measured. The application of water must be stopped. The water content and potential must be measured at intervals as drainage and drying proceeds. Measurements of soil water content and potential can continue until characterisation of the desired soil water range in each soil layer is achieved.

2.3 Laboratory methods of determining water holding capacity

The use of pressure plates and pressure membrane apparatus are in general use in laboratories and are commercially available (Marshall & Holmes, 1979). The pressure plate and pressure membrane methods differ from the tensiometer in that pressure is increased on the soil and its solution while the reference solution remains at atmospheric pressure (Taylor & Ashcroft, 1972).

According to Klute (1986), the traditional method of determining the water retention function involves establishing a series of equilibrium between water in the soil sample and a body of water at known potential. There are two basic measurement options available for the determination of the water retention function. If a nondestructive method for the determination of soil water content is available, one can plot a retention curve by carrying one or more samples through a series of equilibria. The curve can also be mapped by establishing a series of equilibria in a limited number of suction or pressure cells, using different samples for each equilibrium. The nature of the apparatus required will depend upon the range of matric pressure head in which the retention measurements are to be made. Generally, the lower the pressure head the higher the bubbling pressure requirement of the porous plate and the greater the strength requirements of the pressure chamber.

2.3.1 Type of equipment used in determination of water holding capacity

According to De Backer & Klute (1967) the water content pressure head function is one of the soil properties required in the analysis of unsaturated flow phenomena. The two methods by which these curves are usually obtained are the suction and pressure cell methods.

In the suction apparatus, the wet soil sample is in hydraulic contact with bulk water through a porous plate. Atmospheric pressure is applied to the soil and the pressure in the bulk water is reduced to subatmospheric levels, thereby reducing its hydraulic head (Klute, 1986). When hydraulic equilibrium is reached, water stops flowing from the sample. The water content and the matric pressure head at equilibrium are then determined. The suction, tension or hanging water column method is also known as the Haines' method (De Backer & Klute, 1967). A series of equilibria are established with successively longer water columns. The pressure head of the soil water is given by the elevation relative to the soil sample of the free water surface in the open arm of the manometer. At each equilibrium the water content is determined. A curve relating the two variables is then constructed.

Cavitation can occur when the hydrostatic pressure in the water in and below the porous plate approaches the vapour pressure of water. Cavitation can also result from nucleation of gas bubbles from dissolved gases. The pressure cell method was therefore developed by Richards to avoid cavitation (De Backer & Klute, 1967). The pressure cell apparatus keeps the body of water under the porous plate at about atmospheric pressure and raises the gas phase pressure applied to the soil sample so that no water in the system is actually subjected to pressures greatly less than atmospheric pressure (Klute, 1986). In the method of Richards, the cell gas pressure on the sample is increased while the water under the plate is maintained at atmospheric pressure.

2.3.2 Pressure plate and membrane apparatus

Pressure plate and membrane equipment consists of a pressure chamber in which soil samples are placed, a membrane through which soil solution passes but through which the soil matrix and air

cannot pass, a support for the porous membrane and an outlet for water (Taylor & Ashcroft, 1972). A source of pressure and a method for regulating and controlling it is of great importance.

The pressure plate and pressure membrane apparatus differ from each other in the kind of material composing the porous membrane and the resulting pressure range over which they operate. A ceramic plate is used in pressure plate equipment and such plates are limited by the air pressure that they can withstand without permitting air to pass. Such plates are generally limited to 100 or 200 kPa but developments have extended the range to 1500 kPa (Taylor & Ashcroft, 1972).

There are three systems that can be used (Klute, 1986), namely the low- range systems, mid- range system and a high- range system. The high- range system can be used for determinations from 100 kPa to 1500 kPa.

Porous plates containing water under suction are used to determine the relation between soil water content and matric potential for soil samples determined in the laboratory. Ceramic plates large enough so that several samples can be determined at once are generally used (Marshall & Holmes, 1979). According to Hillel (1971), the relation between soil water content and matric suction is often determined by means of a pressure plate assembly in the low suction range and by means of a pressure plate or pressure membrane apparatus in the higher suction ranges. Successive suction values can be applied to the soil samples and the equilibrium soil water content determined at each suction. The structure of the original soil needs to be maintained (Marshall & Holmes, 1979)

The maximum suction value obtainable by porous plate devices is limited to 100 kPa if the soil air is kept at atmospheric pressure and the pressure difference across the plate is controlled by a vacuum or a hanging water column (Hillel, 1971). Matric suction values greater than 100 kPa can be obtained by increasing the pressure of the air phase. This can be done by placing the porous plate assembly in the pressure chamber. The maximum matric suction obtainable with such a device would then be determined by the design of the chamber and the maximal air pressure difference the saturated porous plate can bear without allowing air to bubble through its pores. According to Marshall and Holmes (1979), water from the wet soil passes out through the plate into a body of water in contact with the underside of the plate. This water is at atmospheric pressure so that, when flow ceases, the pressure potential, P , of the soil water in the chamber will be zero.

The pressure potential, P , has two components (Marshall & Holmes, 1979), namely the matric potential Ψ , associated with water retention by the soil and the pneumatic potential arising from the imposed gas pressure. The pneumatic potential is equivalent to imposed gas pressure (p_g) when potentials are expressed per unit volume of water, and therefore at equilibrium

$$P = \Psi + p_g = 0 \text{ and } \Psi = -p_g. \quad 2.1$$

It is therefore possible to use the pressure chamber to determine the relation between matric potential and water content of a soil over a greatly extended range.

According to Hillel (1980), if a slight suction is applied to water in a saturated soil, no outflow may occur until, as suction is increased, a certain critical value is exceeded at which the largest pore of entry begins to empty. This critical suction is called the air entry suction. As suction is further increased, more water is drawn out of the soil and more of the relatively large pores, which cannot retain water against the suction applied, will empty out.

A gradual increase in suction will result in the emptying of progressively smaller pores, until, at high suction values, only the very narrow pores retain water (Hillel, 1980). Increased suction is associated with decreasing soil wetness. The amount of water remaining in the soil at equilibrium is a function of the sizes and volumes of the water filled pores and it is therefore a function of the matric suction. This function is usually determined experimentally and it is represented by a curve known as the soil moisture characteristic curve.

Pressure is increased on the soil and its solution in the pressure plate and pressure membrane methods. For equilibrium to be established, hydraulic potential (Ψ_h) must be uniform throughout the system (Taylor & Ashcroft, 1972). Pressure applied to a saturated soil sample causes the water potential of the soil sample to increase above the water potential of the dialyzate that the soil contact through the plate or membrane. Water therefore moves from the soil sample where the water potential is high to the dialyzate reservoir where the water potential is lower. As water moves from the soil sample the matric potential decreases and becomes more negative. Water continues to flow from the soil sample until the matric potential is reduced to a value that just compensates for the increased pressure potential caused by the applied pressure potential.

According to Richards & Fireman (1943), the apparatus they used to determine water holding capacity consisted of a closed chamber in which the soil sample under study rested on a porous ceramic plate, which was accurately grounded. During use the underside of the porous plate was kept in contact with water, the connection being made through a 9 mm tube soldered into the base. When water was extracted from the soil it passed into a burette, which was attached to the 9 mm brass delivery tube connected to the underside of the porous plate. For wetting a soil under given tensions, the burette supplies water under constant head to the porous plate through the 9 mm brass delivery tube. The soil chamber is completed by a section of brass tubing, rubber gaskets and a bolted-on cover plate. The air pressure in the cell was controlled accurately by slowly admitting compressed air through a micro adjustable valve to a chamber or line having two outlets. One outlet is connected to the soil chamber. The other outlet, which served as a pressure release, was connected to a tube immersed in water to the depth required to obtain the desired pressure in the soil chamber. The initial or final moisture content of a sample should be known or determined. Evaporation from burettes should be minimised. The selection of suitable porous plates for this apparatus involves a compromise between permeability and fineness of pores. Soil moisture is expressed as a percentage on the dry weight basis. Richards & Fireman (1943) obtained data with this apparatus that correlated with the suction plate apparatus.

In order to cover pressure ranges beyond the limits of operation of the pressure plates, a membrane containing smaller pore openings must be used (Taylor & Ashcroft, 1972). Visking sausage casing is most commonly used for the purpose although other membranes such as cellophane have been used satisfactorily.

Several precautions must be taken when using the apparatus (Taylor & Ashcroft, 1972). Air leaks in the system must be prevented because the air passing through the chamber may cause the samples to dry out. Precautions should also be taken to ensure that the soil remains firmly in contact with the membrane or plate. In order to get reproducible results with a pressure plate or pressure membrane, the temperature should be monitored carefully. When doing the laboratory determinations, it is important that the temperature of the room in which the determinations are done should be held to within one degree more or less of 20 °C. Excellent temperature control is essential for precise work. The chemical composition of the wetting fluid can affect the water retention of the samples, particularly fine textured soils that contain significant amount of swelling clays (Klute, 1986). A fluid with a similar composition to that of the soil water should be used. The wetting procedure will be determined by whether the initial drainage curve (IDC) or the main wetting curve (MWC) is required. The intensity of the forces retaining the water in the soil at a given matric pressure head is temperature dependent. Surface tension of soil water decreases with increasing temperature, which leads to a reduction of water content at a given pressure head.

2.3.3 Sand baths

If a fine capillary tube is lowered into water then water will rise up the tube until the surface tension force acting upwards between the liquid and the glass is equal to the weight of liquid downwards (Hall *et al.*, 1977). If a mass of fine particles packed together can be pictured, then the spaces between the particles can be considered as a system of fine capillary tubes.

A sand bath consists of particles with pores small enough to hold water in against an imposed force. The force is applied by means of a negative head of water below the bath. A bath filled with well packed particles of 20-100 μm will stay saturated under a negative head of 10 kPa and a bath with kaolin surface will support a suction of 50 kPa. Three separate baths are maintained at suctions of 5, 10 and 40 kPa. Tensiometers are used to monitor suction in a core sample of silt placed on the surface of each bath. After wetting, each sample is placed consecutively on the 5, 10 and 40 kPa baths, moving on to the next as it reaches equilibrium. Samples are weighed every two days and are considered to have reached equilibrium when they lose 100 mg or less between measurements.

Most problems with sand baths are due to air locks, either in the drain system of the bath itself, or in the monitoring tensiometer (Hall *et al.*, 1977).

2.3.4 Weighable cells

A soil sample in a cylindrical sleeve is held between two end caps (Klute, 1986). One of the caps contains a porous plate and the other cap may be connected to a source of regulated gas pressure. The cell may be operated either as a pressure or suction cell. The soil cores can be repacked or be of natural structure. Each cell is carried through a series of equilibria, and the weight determined at each. At the final equilibrium, the water content of the sample is determined. The cells are useful for determining the hysteresis of the water retention function. Excellent retention data can be obtained on each core. However, each core is carried sequentially through a series of equilibria and the time taken to obtain data is great.

2.3.5 Suction tables

These systems are designed to operate in the suction mode and can handle relatively large number of cores (Klute, 1986). Desk blotters and sand-silt packings are among the materials that have been used. This method has been used mainly for the determination of water retention, by drainage, at low suctions. According to Jamison (1958), the suction column serves the same purpose as the blotter or asbestos tension tables to determine moisture retention at low suction and estimate soil – air capacity. The column in use is 100 cm high and appears to give a closer estimate of field capacity in coarse textured soils than the more conventional 60 cm columns. The material of the column is retained in a walled brick container. If bricks are used the insides of the walls should be coated with asphalt paint to prevent losses due to evaporation. The base is set in a shallow pan or trough filled to a depth of about 25 mm with fine gravel. Wet fine sand, then coarse silt and finally medium silt layers are added in successive layers in the column. The silt can be washed in a barrel. The materials used should be washed or sedimented until reasonably free of clay. One surface of each soil core should be covered with cheese cloth held in place with rubber bands and the cores should be placed on top of the column. Water should be added to the top of the column until the cores are nearly emmersed. This should be repeated several times. The water should then be shut off, the cores covered and drainage allowed to proceed for 24 hours. The cores should then be removed and weighed to 0.2% of the dry weight. If the cores are very fine textured then a longer period may be needed for equilibrium. The core should then be dried and the moisture retention capacity determined.

2.3.6 Psychrometer method

Thermocouple psychrometers have been used to determine water retention as a function of the chemical potential of the chemical species water in the soil (Klute, 1986). The potential function measured by the psychrometer is not the same as that measured by porous plate apparatus. The psychrometer measures the energy status of the water, which includes an osmotic component. A thermocouple psychrometer is imbedded in a soil sample to determine the retention function. The

soil sample is wetted, then dried by evaporation. The chemical potential of the water in the soil sample and the water content of the sample are measured periodically.

2.3.7 Osmotic method

Polyethylene glycol (PEG) solutions, separated from a soil water system by a membrane that is impermeable to the PEG, have been used to control the soil water matric potential (Klute, 1986). Since the membrane is permeable to the normal soil solutes, the method controls the matric pressure head of the soil solution phase. By equilibrating a series of soil samples with PEG solutions of varying concentrations and determining the resulting water content of the soil, a water retention function can be determined. According to Zur (1966), a new method in which the osmotic pressure of a separate body of water is being manipulated in order to control the matric soil water potential. The results that they obtained established the osmotic system as a dependable method for the control of the matric soil water potential. The method is simple, easy to operate, inexpensive and can be operated in a laboratory.

2.3.8 Dynamic methods

If the water content and matric pressure head as a function of time at a given point in a soil water flow system can be measured, then a dynamic water retention function can be obtained by pairing the values of water content and pressure head at a given time (Klute, 1986).

Although procedures are available for obtaining the wetting moisture characteristics of soils, they often involve lengthy equilibration periods (Perroux, Raats & Smiles., 1982). A rapid, precise method for obtaining a wetting curve by supplying a small constant flux of water to the top of a thin section of soil fully occupying a cell of known volume, and measuring the pressure head at the bottom with a pressure transducer can also be used. The method makes the assumption that the increase in moisture content of the soil can be inferred from the influx, provided no water is lost from the sample. If the sample is thin and the rate of application of water is low enough, the pressure head across the sample will tend towards zero. This condition implies that the measured pressure head and a mean water content are applicable to the whole sample.

2.3.9 Rubber ring method

The rubber ring method was the method used by ARC Infruitec- Nietvoorbij to determine the water holding capacity of soils commercially (Beukes, 1990). Matro Laboratorium in Cape Town is currently the only laboratory in the Western Cape using this procedure. Results are available in approximately three weeks, which makes this method a very quick method in comparison to both the laboratory methods and the *in situ* methods of determining water holding capacity.

Pressure plates are used to determine the water holding capacity of soils between 10 and 100 kPa. This is then known as the readily available water. Soil is placed in rubber rings on the ceramic plates. The soil is pressed down evenly and gently. Twelve rings can be fitted onto a plate. Soil samples are saturated by letting them stand in distilled water 5 mm deep for approximately 16 hours. An empty soil sample tin and the lid is weighed and this mass is noted as A grams. Samples are put into the pressure chamber and are removed after three days or until no water comes out through the outlet pipe. Once the samples have equilibrated at 10 kPa, then the content of the rubber rings must be placed in the soil sample tin and this is closed tightly. The soil sample tin, lid and wet soil is weighed and this mass is noted as B gram. The lid must be removed and the soil tin, lid and wet soil must be placed in an oven at 105 ° C and dried for at least 16 hours. The lid must be placed back on the soil sample tin and this must be cooled in a desiccator. The soil tin, lid and dry soil is weighed and this mass is noted as C grams.

The calculation is as follows:

$$\begin{aligned} \text{Percentage moisture} &= \text{Mass of wet sample} / \text{Mass of dry sample} * 100 && 2.2 \\ &= (B-C)/(C-A)*100 \end{aligned}$$

Where A is mass of empty soil sample tin and lid;

B is mass of soil sample tin, lid and wet soil;

and C is mass of soil sample tin, lid and dry soil.

The water holding capacity of the soil is determined between 10 and 100 kPa by determining the volumetric water content of samples as 10 and at 100 kPa. The volumetric water content of samples at 100 kPa is subtracted from the volumetric water content of samples as 10 kPa. The water holding capacity is then calculated for the respective depth of the soil.

2.4 Sampling of soil for water holding capacity determination

One of the most important actions of determination of the water holding capacity of soils is the collection of representative soil samples. According to Hall *et al.* (1977), samples are collected in, or as near as possible, to an undisturbed state. Samples should preferably be taken in an undisturbed state so that the samples represent the natural field conditions in order to obtain the most accurate results.

Tensiometers may give different results from pressure plates or pressure membranes for soil at the same water content if the soil inside the cell is in a different structural state (Taylor & Ashcroft, 1972). When the structure is changed, the soil will have a different matrix. The soil samples can either be repacked samples or samples of natural structure (Klute, 1986). It is generally best to use samples of natural state and structure. A core sampler can be used to get undisturbed samples. Thin walled metal cylinders with a sharpened edge may be pressed into the soil, or soil cores may be obtained in metal cylinders that fit into a sleeve which has a sharpened edge. A metal sleeve is

supported in a heavy stainless steel tube of which a cutting ring is attached and the whole device is hammered carefully into a flat horizontal surface (Hall *et al.*, 1977). The corer is dug out very carefully and the core ejected by means of a spring-loaded plunger. The core is then trimmed roughly with a knife. Samples should be taken in spring or winter when the soil is near field capacity. In summer, clayey soils are difficult to sample when dry and contract and swell with varying water content. Many soils are also difficult to sample because of stones.

2.5 Soil composition factors influencing water holding capacity

2.5.1 Texture

Of all the factors influencing the water holding capacity of the soil, soil texture is the most important one. Texture is defined as the predominant size, or size range of the particles and refers to the feel of the soil material (Hillel, 1971). Soil texture refers to the relative proportions of various sizes of particles in the soil. The ability of soils to retain and transmit water is measured by the hydraulic properties of the soil that are determined by the geometry of the pore space (Klute, 1982). Water holding capacity is strongly influenced by soil texture (Hillel, 1980), which has an important effect on pore geometry and configuration (Beukes, 1984). Texture and structure will influence the amount of water retained in the soil (Buckman & Brady, 1969). Finer textured soils retain a greater percentage of water through the entire suction range, because they contain a greater percentage of total colloidal matter, greater total pore space and have a much greater adsorptive surface. As fineness of texture increases, so there is a general increase in available moisture storage although clays frequently have a smaller capacity than do well granulated silt loams.

Water retention in the higher suction range is due increasingly to adsorption and is influenced more by texture and specific surface of the soil material than structure (Hillel, 1971). The amount of water retained under low soil water suctions is dominated by the size, abundance and shape of the pore spaces in the soil (Rivers & Shipp, 1978). The influence of the finer portion of the sand fraction on distribution of pore spaces and water holding capacity of sandy soils becomes very important as the supply of water becomes scarcer. A positive influence on soil water retention by the very fine sand fraction has been reported. The higher the clay content, the greater the water holding capacity at any particular suction and the more gradual the slope of the curve of the soil water characteristic curve (Hillel, 1980). Sandy soils release more of their water at low suctions than soils that have more clay (Marshall & Holmes, 1979). A sand of fairly uniform particle size releases most of its water over a small range of suctions. In sandy soils the water content at a given suction depends on how much pore space there is of the right size to hold water (Marshall, 1959). In soils of high clay content, the filling and emptying of pores on wetting and drying may be less important than swelling and shrinking. The relation between water content and suction depends less upon the pore structure and more upon the size distribution of the particles and their surface properties. In coarse textured soils, the water holding capacity of the soil is mainly due to capillary forces determined by the amount of pores and their size distribution (El-Swaify & Henderson, 1967). In soils of high clay

content, water holding capacity is mainly determined by the inter-particle forces termed swelling pressures or osmotic pressures. The water holding capacity of a soil due to swelling pressure forces depends on the mineralogical composition, the amount of salt present and the saturating ionic species.

In a clayey soil, increasing the matric suction causes a more gradual decrease in water content because pore size distribution is more uniform than in sandy soils and more of the water is adsorbed (Hillel, 1980). Most of the pores in a sandy soil are relatively large. Once these pores have emptied at a given suction, only a small amount of water remains therein.

Correlation of water holding capacity with a single particle size parameter is fairly successful giving a significant positive correlation between clay content and water holding capacity at both the 5 and 1500 kPa suction (Hall *et al.*, 1977). Fine pores are mainly associated with the clay fraction of a soil, and the correlation between clay content and water holding capacity increases with increasing suction. Both silt and organic carbon content have more effect on the coarse pore distribution and therefore it is at the lower suctions that they are most significant in accounting for variation in retained water. Both are positively correlated with water holding capacity.

Salter & Williams (1965) determined the available water capacity of 27 soils, together with the moisture release characteristics of 20 of the soils. In their study, they came to the conclusion that the moisture contents at field capacity and permanent wilting point increased and the specific gravity decreased as soils became finer in texture. The increase in field capacity was, however, not accompanied by exactly the same increase in permanent wilting point.

Pore size distribution is the volume of different classes of pore sizes. Soil water holding capacity in the low suction range is strongly influenced by pore size distribution (Hillel, 1971). In a porous material, the volume of water retained at a given suction should be equivalent to the volume of pores having diameters (μm) smaller than approximately $3000 s^{-1}$, where s is the suction in millibars (Hall *et al.*, 1977). Pores having larger diameters will be filled with air at that suction. This relationship will only operate perfectly where the pore space consists of circular pores with few blind ends or random restrictions. However, real soils contain planar voids, pores with blind ends and restrictions. If pore volume is used to estimate water movement, continuity of pores above or below a given diameter is as important as their total volume. With a steadily decreasing rate of water loss per increment of suction, there is very little opportunity for an appreciable volume of pores having restricted exits to release water at a later suction without their presence being obvious. The distribution of relatively small or large volumes in the 5 to 40 kPa range is mainly related to particle-size distribution and horizon type. Clay soils release very little water in this range, while fine sands and finely structured topsoils release larger amounts of water at this range. This suggests that where pores in this size range are present, they are reasonably continuous between particles and peds. For most mineral soils and for pores greater than 30 μm diameter, the water retention technique gives an acceptable measurement of pore volume. In less clayey materials, the volume of

fine pores can also be measured. The calculation of pore size distribution from suction data depends on the conditions that loss or gain of water occurs without change in volume of the soil mass and that suction is dependent on the curvature of the air-water interface and not on adsorptive forces (Marshall, 1959). It appears that the geometry of the porous system could be the dominating factor in water holding capacity of soils.

Porosity is an index of the relative pore volume in the soil (Hillel, 1971). Porosity generally lies between 0.3 and 0.6. Fine textured soils are more porous than coarse textured soils, although the mean size of individual pores is greater in coarse textured soils. Clayey soils have a variable porosity as the soil alternately swells, shrinks, aggregates, disperses, compacts and cracks. The total porosity reveals nothing about the pore size distribution, which is another important property of the soil. The pore space of a soil is that portion occupied by air and water (Buckman & Brady, 1969). The total pore space is easy to determine but to determine the pore sizes is more difficult (Marshall, 1959). The arrangement of the solid particles determines this amount of pore space (Buckman & Brady, 1969). In the case of sands, the particles tend to lie close together and the total porosity is low. If the particles are arranged in porous aggregates, as is often the case in medium textured soils high in organic matter, the pore space per unit volume will be high. In the case of a sandy soil with a bulk density of 1.5 g.cm^{-3} and a particle density of 2.65 g.cm^{-3} , the pore space will be 43.3%. A silt loam with a bulk density of 1.3 g.cm^{-3} and a particle density of 2.65 g.cm^{-3} will have 50.9% pore space that can be occupied by air and water. It is therefore clear that there are considerable differences in the total pore space of various soils. Sandy soils have a total pore space of 35 to 50%, while medium to fine textured soils vary from 40 to 60% and sometimes even more in the case of soils with a high organic carbon content. The pore space also varies with depth and some compact subsoils can have pore space as low as 25 to 30%.

Two types of individual pore spaces occur in soils (Buckman & Brady, 1969). Macropores ($> 3 \text{ }\mu\text{m}$) allow the ready movement of air and percolating water, while micropores ($< 0.2 \text{ }\mu\text{m}$) impede air movement and water movement is restricted largely to slow capillary movement. In a sandy soil therefore, despite its low porosity, the movement of air and water is rapid because of the dominance of the macropores. Fine textured soils allow relatively slow gas and water movement in spite of the large amount of total pore space. The dominating micropores often keep themselves full of water. Water will move through, or drain out of, large pores more easily than small, and so the size of pores also has to be considered for water storage and movement, as well as amount of pore space (Marshall, 1959).

The amount of water retained at high soil water potentials ($> -10 \text{ kPa}$) depends primarily on the pore size distribution and is therefore strongly affected by soil structure, bulk density and porosity. As the soil dries out, water adsorption becomes critical and those soil properties that affect specific surface become important such as texture, organic matter content and clay mineralogy.

2.5.2 Soil structure

Soil structure is the second most important factor determining the water holding capacity of the soil. Structure is defined as the physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles and associated voids, including both the primary voids to form compounds themselves and the compound particles themselves (Sharma & Uehara, 1968). According to Buckman & Brady (1969), the structure of the soil is strictly a field term descriptive of the gross, over-all aggregation or arrangement of the soil solids. The term structure refers to the particular type of particle grouping that happens to predominate.

According to Rawls *et al.* (1991), when bulk density increases, so the water holding capacity of the soil decreases. The amount of water retained at relatively low values of matric suction depends mainly on the capillary effect and the pore size distribution and is therefore strongly influenced by soil structure (Hillel, 1971). Soil structure also affects the shape of the soil water characteristic curve. The effect of compaction is to decrease total porosity and, especially, to decrease the volume of the large interaggregate pores (Hillel, 1980). Saturation water content and the initial decrease of water content with application of low suction are reduced. Intermediate size pores is likely to be more in a compact soil while the intraaggregate pores remain unaffected and therefore the curves for the compacted and uncompacted soil may be nearly identical in the high suction range. At the very high suction range, water is held primarily by adsorption and therefore retention is a textural rather than a structural attribute of the soil (Hillel, 1971). The particles may be openly or closely packed together and so leave more or less pore space between them for water and air (Marshall, 1959). They form the porous matrix in which the water is embedded and the way in which they are arranged so as to leave much pore space or little, large pores or small.

In sands, increasing bulk density results in an increased capacity to retain moisture at a constant matric suction. The magnitude of the effect decreases with increasing matric suction. On the other hand, although increasing bulk density also results in an increased moisture holding capacity in clays and loams, the magnitude of the effect seems to increase with increasing matric suction. In the case of sandy loams and sandy clay loams, increases in bulk density result in a decreased capacity for retaining moisture at low matric suctions, whereas at high matric suctions the reverse occurs. According to Salter *et al.* (1966), structure as well as texture influences the available water capacity of soils and the variation in available water capacity of soils in the same textural class may also be the result of structural differences between the soils. Soil structure is one of the most important factors influencing the capacity of soils to hold water. It has a much bigger effect on the quantity of water held at low tensions than at high tensions. The reason for this is that larger pores, holding water under low tensions, are more affected by structural changes than the smaller, capillary pores. Hill & Sumner (1966) investigated the effects of bulk density on moisture characteristics of soil. Topsoil samples of nine Natal soil series were collected and air dried. Air dried, disturbed soil was compacted to various bulk densities by mechanical pressure.

When a soil sample has been compacted, the following changes in porosity will occur. The total porosity is reduced and the total number and relative volume of small pores increase while the total number and relative volume of larger pores decreases (Hill & Sumner, 1966). Bulk density is therefore an important factor affecting both moisture characteristics and derived values of total available moisture.

Yang and de Jong found that above 10 kPa moisture content by mass was unaffected by bulk density changes (quoted after Archer & Smith, 1972). At lower suctions, the moisture content increased as the bulk density decreased because the volume of pores increased. Archer & Smith (1972) studied the relationships between bulk density, field capacity, available water and air capacity of soils. Samples were taken from the surface horizon of four soils covering a wide range of textures and were sieved through a 6 mm sieve to remove stones. The samples were packed to different bulk densities ranging from 0.7 to 1.9 g.cm⁻³. The water holding capacity of the samples was determined using sand tension tables. The 50 kPa moisture contents of each of the four soils studied increased linearly with density up to approximately zero air capacity (Archer & Smith, 1972). The results suggested that a constant volume of water is associated with each soil particle or ped until a critical bulk density is reached and beyond which the volume of associated water decreases. As bulk density increases, so air capacity progressively decreases. According to Archer & Smith (1972) the bulk density of the soil is an important field property, but its significance for a particular soil must be related to texture. Changes in bulk density affect available water and strongly influence permeability, drainage rate and penetration of plant roots. Assessment of the optimum bulk density for a soil must be taken into account.

Bulk density is one of the easiest properties to control in the field (Reeve, Smith & Thomasson, 1973). Soil structure is expected to exert an influence on the physical properties of the soil. Structure includes the closeness of packing of aggregates and particles as well as their shape and this is partly expressed by bulk density. Bulk density can be increased by shallow ploughing, rolling or minimum tillage (Archer & Smith, 1972). Reducing the bulk density of heavier soils is difficult but can be done by subsoiling and improving timeliness of field preparation will all decrease local compaction and therefore decrease bulk density.

Compaction affects the pore size distribution in soils with larger particle sizes more than in the fine (Klute, 1982). Increasing the bulk density tends to decrease the total porosity and therefore the amount of water retained at lower suctions is decreased. The amount of water held at higher suctions is increased.

Soil morphology, particularly aggregation, has a distinct effect on the pore size distribution by dominating the soil water characteristic curve as the soil approaches saturation (Rawls *et al.*, 1991). As soil water content decreases, the water films around the aggregates and soil grains become the dominating soil characteristic influencing water retention. In natural soils, aggregation tends to

dominate soil water retention only at high water contents, and clay mineralogy becomes more important at low water contents.

According to the Canola Connection (2001), soil structure only has a small effect on the ability of soil to hold water. It, however, controls water entry into the soil. Soil structure refers to the way in which mineral and organic particles are arranged into granules or aggregates of different shapes, sizes and volumes of pores. Soils that are well aggregated have more pore space for soil air and water.

2.5.3 Organic matter content

The organic carbon content of the soil plays an important role in determining the water holding capacity of the soil (Buckman & Brady, 1969). Organic matter content and composition in the solution phase also plays a role in determining the water holding capacity of the soil (Klute, 1986). Organic carbon or organic matter content has a strong effect on soil structure and soil surface area (Rawls *et al.*, 1991). Organic matter has a direct effect on the retention function because of its hydrophilic nature and has an indirect effect because of the modification of soil structure.

A well drained soil containing 5% organic matter will probably have a higher available moisture capacity than a comparable soil with 3% organic matter. The organic matter has a favourable influence on soil structure and porosity (Buckman & Brady, 1969).

Burns & Rawitz (1981) investigated the effects of organic matter in sewage effluent on water retention properties of soil. They observed that the water holding capacity of soils was increased under effluent irrigation. The effluent sodium absorption ratio increased the amount of water held by deflocculating the soil. Soil drying created conditions which enhanced organic matter-clay complex formation between soil clay colloids and the organic solids introduced by the sewage effluent. These complexes were found to be very stable in finer soils. In coarser soils, less stable, organic matter-clay complexes were formed and these were easily destroyed by simulated rain application.

Usually water retention of all matric potentials improves with an increase in organic matter content (Rawls *et al.*, 1991).

2.5.4 Presence of stones

The effect of coarse fragments on soil water characteristics has received very little attention (Ravina & Magier, 1984). Stones refer to material greater than 2 mm in diameter. Soils containing stones pose special problems for the determination of water holding capacity. Core sampling of an entire soil mass is usually not possible if there are many stones in the soil. Stony material may retain water which could be important in estimating the water available to plants growing in such soils (Klute, 1986). This is, however, debateable. The effect of rock fragments on moisture retention of aggregated clay soils cannot be adequately accounted for by simple corrections for the total pore

volume, especially at the low suction range (Ravina & Magier, 1984). Pore and aggregate size distributions are affected by the degree of compaction or consolidation that the soil has undergone and this depends on rock fragment content.

2.5.5 Agronomic aspects

Field properties affecting water retention and other properties of a soil are not constant and can be modified by land use, cultivation and drainage measures (Hall *et al.*, 1977). The main properties varying with land use are bulk density and organic matter content.

The cultivation of a soil can have a great effect on its pore space (Buckman & Brady, 1969). Air capacity decreases regularly with increasing density. Available water initially decreases slightly. Greater organic carbon content will increase the water holding capacity of the soil. Continuous cropping and cultivation, particularly of soils with high organic carbon content, often results in a reduction of large or macropore spaces. This is accompanied by a more or less proportional rise in the micropores. The decrease in pore size is also associated with a corresponding decrease in organic matter content.

Tillage tends to decrease the bulk density and increase the total porosity of the surface soil. At the same time, the soil just below the ploughed or tilled layer may be increased in bulk density by the stresses applied to that layer by tillage machinery (Klute, 1982). Tillage can change the pore size distribution of the soil. The pore size distribution represents the volume of pores of a given size as a function of the size. The pore size distribution function may display one or more maxima or peaks. A uni-modal pore size distribution function is characteristic of a number of soils, especially sandy soils with single grain structure. Bi-modal pore size distributions are found in soils with well developed structure. In soils with a uni-modal pore size distribution, the tillage process may produce changes in the mean pore size. Compaction and increase of bulk density requires a decrease on the total porosity and decreases the mean pore size. The fraction of the porosity that is made up of larger pores is reduced. Tillage may also change the pore size distribution of the soil from uni-modal to bi-modal. The changes in the geometry of the pore space produced by tillage and reflected in the total porosity and pore size distribution will have important effects on the hydraulic functions.

2.5.6 Influence of stratification

Stratification has a marked influence on the movement of water into and through soils and therefore has an influence on the amount of water retained in the soil. Soils have varying degrees of stratification depending on soil formation processes and profile development (Taylor & Ashcroft, 1972). Deep soils will have greater available moisture capacities than shallow ones. Soil stratification or layering will influence the available water and its movement in the soil (Buckman & Brady, 1969).

2.5.7 Influence of clay minerals and exchangeable cations

According to Rawls *et al.* (1991), clay mineralogy is an important factor determining the water holding capacity of soils containing more than 10% clay. Generally the greater the clay content, the more water will be retained by the soil at a given stage of wetting or drying, but the type of clay mineral and the nature of the exchangeable cations can also affect the water holding capacity (Marshall, 1959). The 2:1 layer silicates, especially montmorillonite, have the greatest effect, whereas the 1:1 nonexpandable clays have the least influence (Rawls *et al.*, 1991).

Kutilek (1973) investigated the behaviour of moisture in swelling clays in comparison to its behaviour in sands and non swelling clays. The experimental work was performed with clay fractions of kaolinites and montmorillonites, alternatively saturated with exchangeable calcium and sodium. When the moisture retention curves of kaolinites and montmorillonites were compared, the following facts had to be considered. The affinity of water to kaolinites is higher than to montmorillonites in terms of unit specific surface area. The specific surface area of montmorillonites is greater than that of kaolinites. From a comparison of the retention curves when comparing various clay minerals, the specific surface area plays a dominant role while the quality of the solid surface is a subordinate factor. When the mineralogical composition is kept constant, the quality of the solid surface as influenced by exchangeable cations plays a more important role.

The exchangeable cations in a water layer occupying the space between two parallel clay plates give rise to a higher osmotic pressure than exists in bulk water free from exchangeable cations. Since the exchangeable ions are not free to migrate, there is a tendency for more water to be drawn into the layer between the particles (Marshall, 1959).

There is a great deal of literature available on the influence of clay content, bulk density, organic matter and silt content on the water holding capacity of soils but little has been reported on the quantitative influence of clay mineralogy on water holding capacity of soils (Lambooy, 1983). There is, however, no significant correlation between water holding capacity and percentage kaolinite, illite, vermiculite, chlorite and interlayered minerals in the soil. It is often, however, impossible to determine the types of clay quantitatively and accurately on a routine basis. Specific surface has an influence on the amount of water retained by a soil and can be used as an indicator of the type of mineral in the soil. Often a high correlation between specific surface and CEC is found. Lambooy (1983) investigated the effect of CEC on the water retention of soils. Water content is dependent on adsorption and capillary forces. However, clay content alone does not always indicate the total extent of these forces. When both clay content and CEC are used highly significant multiple correlation coefficients are obtained. As clay mineralogy and therefore the CEC of the clay fraction generally varies among soils, adsorption forces will vary too. Therefore, soils with low CEC values do not have the same adsorption forces as soils with high CEC values, irrespective of clay content. The water holding capacities of such soils will vary accordingly.

In South African soils, where organic matter content is very low, clay content and type dominate soil water properties. According to Botha & Eisenberg (1993), clay content and CEC accounted for more than 93% of the variability in soil water.

2.6 Stochastic modelling of water holding capacity of soils

Soil water retention models can be subdivided into four categories based on their functional relationships, namely exponential; power, cosine hyperbolic and error function (Rawls *et al.*, 1991). Most authors use a power function relationship to characterize soil water retention.

According to Rawls *et al.* (1991) two approaches have been used for estimating soil water retention characteristics from soil properties. The first approach estimates soil water retention values from soil physical properties and characteristics using regression analysis (Rawls *et al.*, 1991).

The second approach estimates parameters for water retention models from soil physical properties and characteristics using regression analysis (Rawls *et al.*, 1991). The need for a continuous function describing the soil water retention curve has become very important as interest in modeling of the soil water retention curve has increased.

Model parameters can be related to soil parameters by developing average parameter values as a function of soil textural classes (Rawls *et al.*, 1991). Brooks and Corey, Campbell, Rawls *et al.*, De Jong and Clapp and Hornberger used such an approach to develop parameter values for their models (as quoted by Rawls *et al.*, 1991). There is considerable variation in parameter estimations among researchers, which could be a result of the database used to develop the parameters.

Water retention models can be fitted to raw data and then regression analysis used to relate the parameters to soil physical properties (Rawls *et al.*, 1991). Examples of this approach being used are Brooks & Corey model and the van Genuchten model (as quoted by Rawls *et al.*, 1991).

The most popular method for estimating soil water retention at specific water potentials has been to relate soil properties to soil water retention at specific water potentials using regression analysis (Rawls *et al.*, 1991). The most frequently estimated water contents are those corresponding to soil water potential levels of -33 kPa and -1500 kPa, because they are commonly measured (Rawls *et al.*, 1991). Other methods include the development of soil water retention curves based on bulk density and particle-size distribution (Rawls *et al.* 1991).

2.6.1 Additivity hypothesis

According to Zeiliger *et al.* (2000), yet another approach to soil water retention estimation that is not based on regression is that of determining soil water retention from water retention of soil constituents. The hypothesis is that soil water retention can be approximated by summing up water

retention of pore subspaces related to the soil components. Arya and Paris and Haverkamp and Parlange, according to Zeiliger *et al.* (2000), formulated this additivity hypothesis in terms of relative water saturation of soil and relative saturation of the pore subspaces

$$S(h) = \sum w_i S_i(h) \quad (\text{Zeiliger } et al., 2000) \quad 2.2$$

where N is the number of textural components; $S(h)$ is the relative saturation of soil and $S_i(h)$ the relative saturation of the pore subspace related to the i^{th} textural components.

Another way to apply the additivity hypothesis is to use measured soil water retention of soil constituents. Measurements are made with porous materials constituting the i^{th} constituent.

2.6.2 Fractal approach

It is important to utilise other available information such as soil texture and structure to estimate the soil hydraulic properties (Kravchenko & Zhang, 1998). Soil physical properties, such as particle-size and aggregate size distributions exhibit fractal behaviour and can be characterized by mass fractal dimension values. The interface between particles forming soil pores and the pores themselves is a fractal as well, with a corresponding surface fractal dimension.

According to Kravchenko & Zhang (1998), representing the soil pore structure by means of a theoretical fractal, such as a Menger sponge and a Sierpinski carpet, allows one to introduce physically based models of the soil water retention function. The models include the fractal dimension as one of the equation parameters. The fractal dimension remains just one of the fitting parameters of experimental water retention data. It is therefore critical to develop procedures that allow estimation of the fractal dimensions, based on the other easily measured soil properties, for the soil water retention prediction. In their study a procedure was developed for estimating the soil water retention based on the fractal theory and particle-size distribution. Their second objective was to use the fractal dimensions for prediction of the soil water retention function.

2.6.3 Specific stochastic models

Many models have been developed to estimate soil water retention from soil properties such as particle-size distribution, particle density, pore size distribution, bulk density, mineralogy and soil morphology (Kern, 1995). Some models have used measured water retention data to predict the entire soil moisture curve. The use of measured water retention data with measured physical properties has been shown to increase model effectiveness.

Gupta & Larson (1979) used soil samples from each of ten geographic locations in eastern and central United States of America. Particle-size distribution and organic carbon content of the samples was determined. The water retention of the soils was determined in the laboratory on artificially prepared cores. Soil water retention values were obtained using a pressure plate

apparatus. Experimental data was not determined at exactly the same pressures for all samples and therefore water content values used in the regression analyses were taken from the smoothed curve of

$$\theta_p = a (\text{sand } \%) + b (\text{silt } \%) + c (\text{clay } \%) + d (\text{organic matter } \%) + e (\rho_b \text{ g/cm}^3) \quad 2.3$$

where θ_p is the predicted water content ($\text{cm}^3 \cdot \text{cm}^{-3}$) for a given matric potential and a, b, c, d and e are regression coefficients.

The basic data used in developing the regression equations included soils with a wide range of sand (5-98%), silt (1-72%), clay (0-65%), organic matter (0-23%) and bulk density (0.74-1.74 $\text{g}\cdot\text{cm}^{-3}$). At all matric potentials, correlation coefficients were 0.94 or greater (Gupta & Larson, 1979). The authors concluded that the regression models presented in their article may be used to estimate water retention characteristics from particle-size distribution, percentage of organic matter and bulk density with reasonable accuracy. Water retention curves obtained from these regression equations may also be used to approximate hydraulic conductivity-water content relationships.

According to Saxton, Rawls, Romberger & Papendick (1986), soil texture is the dominant factor in the soil water potential-content relationship of which clay content is the most important texture factor. For the range greater than 10 kPa, Rawls' regression equation with an average organic matter content of 0.66% to generate moisture content values was used. The objective of their study was to provide mathematical equations for continuous estimates over broad range of soil texture, water potentials and hydraulic conductivity. The soil texture triangle was divided into grids of 10% sand and 10% clay increments. For potentials less than 10 kPa, saturation moisture contents and air entry tension was correlated with soil texture. The following regression equation was obtained

$$\Theta_s = 0.332 - 7.251 * 10^{-4} (\% \text{ sand}) + 0.1276 \log_{10} (\% \text{ clay}) \quad 2.4$$

where Θ_s is the moisture content at saturation.

Air entry tension was then correlated to saturation moisture content using reported air entry potential values for ten texture classes as reported by Rawls *et al.* in 1982 (according to Saxton *et al.*, 1986).

This resulted in the following equation

$$\Psi_e = 100 [-0.108 + 0.341 * (\Theta_s)] \quad 2.5$$

where Ψ_e is air entry potential in kPa.

The complete characteristic curve can therefore be estimated from soil texture data (Saxton *et al.*, 1986).

Results were used to calculate water potentials for a wide range of soil textures (Saxton *et al.*, 1986). These were then fitted by multivariate analysis to provide continuous potential estimates for all textures (Saxton *et al.*, 1986).

In South African soils where organic carbon content is low, clay content and type dominate soil water properties (Botha & Eisenberg, 1993). The most important properties of clay are its surface area and negative charge. One hundred disturbed samples were used to develop models to describe the relationship between soil water retention, clay content and CEC. The formulae were then validated.

The regression equations are as follows:

$$\text{At } -33 \text{ kPa, } 2.913 + 0.274 (\text{clay}) + 0.0756 (\text{CEC}) \quad 2.6$$

$$\text{At } -80 \text{ kPa, } 1.679 + 0.2803 (\text{clay}) + 0.06109 (\text{CEC}) \quad 2.7$$

$$\text{At } -500 \text{ kPa, } 0.689 + 0.2266 (\text{clay}) + 0.05725 (\text{CEC}) \quad 2.8$$

$$\text{At } -1500 \text{ kPa, } 0.489 + 0.2452 (\text{clay}) + 0.0443 (\text{CEC}) \quad 2.9$$

where clay is % and CEC is me kg^{-1} soil.

It is not always possible to go back to samples or to field samples to resample and it is therefore useful to utilise other available data such as clay content and CEC to estimate the water content at a retention of -33kPa and -1500 kPa . According to Botha & Eisenberg (1993), clay content and CEC accounted for more than 93% of the variability in soil water. As this model requires data on the chemical status of the soil, it requires more laboratory work than some of the other models. The use thereof to predict soil water retention on a routine basis can therefore not be recommended.

According to Zwolinski, Dondald, van Laar & van der Merwe (1995), the area of commercial tree planting in South Africa is restricted by limited water supply and low water storage capacity of soils. The objective of the authors' study was to develop retention models for soil and to predict soil retentivity based on pressure potential, soil characteristics and soil cultivation practices. The experiments were located on two sites representative for the Tsitsikamma and Harkerville plateaux. The non-linear three parameter Gompertz model was fitted to several data sets defined for individual treatments and specific soil depths or all treatments and depths combined. Multiple regression analysis was used to determine the extent of water retention variability that could be explained by soil physical properties, organic matter content and soil cultivation technique.

The general form of the final model is

$$\theta_{\psi} = \beta_0 + \beta_1 \text{GOMP} + \beta_2 \text{BULK} + \beta_3 \text{ORG} + \beta_4 \text{TEXTURE} + [\alpha_1 \text{DUM}_1 + \alpha_2 \text{DUM}_2 + \alpha_3 \text{DUM}_3 + \alpha_4 \text{DUM}_4] + \varepsilon \quad 2.10$$

where θ is the estimated volume fraction of water held at a given pressure potential, β_0 to β_4 model parameters, GOMP is water retention with $P =$ pressure applied to balance pressure potential, TEXTURE has been introduced either as a percentage of single grain size class or a total percentage of a combination of several classes, each being significant when tested in a separate model, BULK is bulk density in kg.m^{-3} , ORG is organic matter content (%), α are parameters, DUM are dummy variables and ε is an error term.

According to Zwolinski *et al.* (1995), the Gompertz model proved to be suitable for modelling water retention as a function of pressure applied. The authors concluded that the soil characteristic variables were of minor importance in explaining water retention in regression models.

Hall *et al.* (1977) correlated water retention with a single particle-size parameter. This gave a significant positive correlation between clay content and water retention at 5 kPa and 1 500 kPa. By using multiple linear regression, it was possible to show the effect of these variables on water retention at five different suctions. The regression equations are as follows:

For topsoils,

$$\theta_v(5)=47.0 + 0.25 (C) + 0.10 (Z) + 1.12 (X) - 16.52 (D_b) \quad 2.11$$

$$\theta_v(10)=37.47 + 0.32 (C) + 0.12 (Z) + 1.15 (X) - 1.25 (D_b) \quad 2.12$$

$$\theta_v(40)=28.66 + 0.36 (C) + 0.12 (Z) + 1.00 (X) - 7.64 (D_b) \quad 2.13$$

$$\theta_v(200)=8.7 + 0.45 (C) + 0.11 (Z) + 1.03 (X) \quad 2.14$$

$$\theta_v(1500)=2.94 + 0.83 (C) - 0.0054 (C)^2 \quad 2.15$$

For subsoils,

$$\theta_v(5)=37.2 + 0.35 (C) + 0.12 (Z) - 11.73 (D_b) \quad 2.16$$

$$\theta_v(10)=27.87 + 0.41 (C) + 0.15 (Z) - 8.32 (D_b) \quad 2.17$$

$$\theta_v(40)=20.81 + 0.45 (C) + 0.13 (Z) - 5.96 (D_b) \quad 2.18$$

$$\theta_v(200)=7.57 + 0.48 (C) + 0.11 (Z) \quad 2.19$$

$$\theta_v(1500)=1.48 + 0.84 (C) - 0.0054 (C)^2 \quad 2.20$$

where C is clay content (%), Z is silt content (%), X is organic carbon (%) and D_b is bulk density (g. cm^{-3}).

According to Hutson (1983), most models neglect poorly defined facets of soil water behaviour such as hysteresis, vapour diffusion, swelling, temperature and solute effects. It is often acceptable to estimate retentivity relationships, ensuring that predominant soil profile features are reflected in the estimated data. Retentivity functions, or equations relating water content to water potential, are essential for modelling purposes. In order to use soil survey data to predict hydrological properties it is necessary to investigate retentivity of South African soils in relation to their physical composition and classification.

Retentivity data from several sources were combined and used to derive equations relating water content at several potentials to particle-size criteria and bulk density. Three thousand samples from the Land Type Survey were used. This consisted of water retentivity at -500 kPa and -1500 kPa determined on sieved samples and retentivity determined at a range of potentials on five hundred samples using cores or clods (Hutson, 1983). Each retentivity curve was plotted on semi-logarithmic axes and the points were joined with a smooth curve. Values of θ at -1 , -3 , -10 , -30 , -100 , -500 and -1500 kPa were obtained directly by interpolation (Hutson, 1983). Histograms and scatter diagrams were prepared to establish the range of soils in the database (Hutson, 1983). According to Hutson

(1983), simple and multiple regression analyses were used to determine the proportion of the variance of retentivity at each potential that can be explained by particle size criteria and bulk density.

The multiple regression model used was:

$$Y_{\psi} = \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \dots + \beta_n Z_n + \varepsilon \quad 2.21$$

where Y is θ or W at potential ψ , β_i are independent variables and ε is an error term.

According to Hutson (1983), as pressure potential decreases, the proportion of the variance of water content accounted for by the regression increases since retentivity is increasingly related to water film thickness and surface area whereas pore size distribution, aggregation and the geometry of the solid matrix play a lesser role. Of all the independent variables included in the regression, clay content accounts for the greatest proportion of the variance in θ and W . As potential increases, so does the importance of the silt content increase but bulk density has a negligible influence until saturation is approached. Including fine sand in the regression analysis increased R^2 values slightly at pressure potentials of -1 kPa and -3 kPa. The equations do not enable very precise predictions. Standard errors of the estimates of θ (core samples) and W (sieved samples) are about 0.05 or 5% of volumetric water content. Hutson (1983) came to the conclusion that precise predictions of retentivity are difficult from soil survey data. If accurate measurements are required, field or laboratory measurements must be done.

Hutson (1986) published regression equations whereby volumetric water content of soils could be predicted at -10 , -100 , -500 and -1500 kPa, using only the clay and silt content of the soil.

These equations are:

$$\theta_{-10} = 0.112 + 0.00380 (Cl + Si) \quad 2.22$$

$$\theta_{-100} = 0.038 + 0.00372 (Cl + Si) \quad 2.23$$

$$\theta_{-500} = 0.0185 + 0.00366 (Cl + Si) \quad 2.24$$

$$\theta_{-1500} = 0.0187 + 0.00337 (Cl + Si) \quad 2.25$$

where Cl is clay content and Si is silt content.

A two-part retentivity function was proposed by Hutson (1983), based upon a widely used exponential function. The two-part function is ideal for use in mathematical simulation modelling as it is applicable over the whole range of water content, from saturation to beyond wilting point. It is sigmoidal. Hutson (1983) investigated the precision with which the function can be fitted to measured retentivity data and the relationship between soil properties and the function parameters. The function was fitted to two sets of retentivity data. The data for the sand contained all available retentivity data between saturation and -50 kPa, while the data for the sandy loam consisted of interpolated values at 0, -10 , -30 and -50 kPa. To show the relationship between soil properties and function parameters a number of retentivity curves were generated using regression equations relating retentivity to some properties of South African soils. All combinations of clay content,

silt/clay ratio and bulk density were used to generate θ values at 0, -10, -30, -100, -500 and -1500 kPa. For each combination a retentivity curve was generated. The two-part retentivity function was fitted to each generated curve to obtain values for a and b . Hutson (1983) stated that methods of determining retentivity are important and that the best means of obtaining data forming a smooth progression of points is to use a pressure cell, in which the core is not disturbed at all between pressure increments. The precision of fit of the retentivity function to the available measured retentivity data is indicated by the distribution of standard errors of the estimate of θ_{ψ} , which was calculated separately for each set of data. The retentivity function fits the majority of the sets of experimental data satisfactorily.

Hutson (1983) concluded that the range of a and b values is far wider than reported by previous investigations. Both a and b influence the shape of a retentivity curve and therefore the claim can not be made that the value of b is related to texture class. According to Hutson (1983), one must know how to predict the values of the constants a and b from a knowledge of bulk density, particle size distribution and soil type. One way of estimating retentivity constants is to calculate all combinations of parameters leading to a particular value of the ratio θ/θ_s at any desired potential Ψ . Regression equations may be used to predict θ at various potentials for several combinations of bulk density, clay and silt content. Hutson (1983) concluded that regression equations used for predicting the retentivity curves and therefore retentivity parameters, account for only between 60 and 80% of the variance of θ_{ψ} , depending on the pressure potentials. Predictions may vary markedly from actual measured retentivity at a particular site.

2.6.4 Pedo-transfer functions

Because of soil spatial variability, an assessment of soil water retention over a site demands expensive and extensive fieldwork, which is not feasible over larger areas (Tomasella & Hodnett, 1998). There is therefore a great interest in developing pedo-transfer functions (PTF) that predict retention characteristics from soil properties routinely surveyed. Pedo-transfer functions can be classified into three groups. Pedo-transfer functions can estimate parameters of an analytical retention function, there are those that use regression functions to estimate water contents at selected pressure heads and the estimated water contents are subsequently used in curve-fitting procedures and there are PTF that estimate the soil water retention characteristic using a physical conceptual model approach. Most PTF have been devised and validated using information from soils of temperate regions and have not yet been tested for soils of the tropical regions.

Soil water release and texture data sets were obtained from a review of literature. Data included location, Brazilian soil classification, soil profile description, soil texture and chemical data. Detailed water retention data were available for some sites but for other sites data was limited to water contents at matric potentials of -33 kPa and -1 500 kPa. To predict water release curve parameters, a pedo-transfer function was derived in five stages. Water content at the matric potentials were related to texture using the following equation

$$\theta(\Psi_i) = a_i \text{OC} + b_i \text{Si} + c_i \text{Cl} + d_i \quad 2.26$$

where θ is the volumetric water content at matric potential Ψ_i , OC is the percentage organic carbon, Si and Cl are the percentage of silt and clay respectively and a_i , b_i , c_i and d_i are empirical coefficients that depend on the matric potential.

The textural triangle was then divided into increments of silt and clay to give a total of 59 incremental textural classes. For each of these classes, values of porosity and of water content were generated. This produced a set of water retention data for each of the textural classes. The parameters of the Brooks and Corey soil water retention curve were then derived by nonlinear optimization. The 59 sets of Brooks-Corey parameters were then correlated independently with the percentage of silt and clay. Finally, the variance of the results was then analyzed to produce expressions to estimate each Brooks-Corey parameter using only those terms that explained a significant proportion of the variation of the parameter.

A PTF to predict Brooks-Corey parameters from texture using data from Amazon soils was therefore developed. Multiple linear regressions were fitted to estimate water retention capacity from texture. Bulk density and the water content at a range of matric potentials. Brooks-Corey parameters were then derived and correlated independently with soil texture, making this a straight forward method for deriving soil water retention parameters from clay and silt content.

CHAPTER 3

MATERIALS AND METHODS

Undisturbed soil samples and soil for disturbed samples were taken at various localities to ensure a wide range of textures.

Particle size analysis was determined using the hydrometer method as this was the standard method at the laboratory of ARC Infruitec-Nietvoorbij (Gee & Bauder, 1986). The clay and silt were determined using this method. Individual sand fractions were determined after the hydrometer analysis. The texture chart (Soil Classification Work Group, 1991) was used to classify the texture of the soil.

Bulk density of undisturbed samples was calculated by dividing the mass of dry soil in the soil core by its volume. The bulk density of rubber ring samples was determined by calculating the amount of dry soil in the rubber ring. Compacted samples were compacted to a bulk density of approximately 1.5 g. cm^{-3} .

3.1 Undisturbed samples

The water holding capacity of undisturbed samples was determined at ARC Infruitec-Nietvoorbij using the standard pressure plate technique (Klute, 1986). Volumetric water content (mm. mm^{-1}) was determined at 5, 10 and 100 kPa. The water holding capacity of the soil was determined between 5 and 100 kPa and between 10 and 100 kPa.

3.2 Rubber ring samples

Water holding capacity of disturbed soil was determined using the routine laboratory method at the laboratory of the ARC Infruitec-Nietvoorbij. This method is known as the rubber ring method (Beukes, 1990). Further details can be found in Chapter 2.

3.3 Compacted samples

Soil was also compacted to a bulk density of approximately 1.5 g. cm^{-3} . Air dried soil, that had been sifted through a 2 mm sieve, was used. The amount of soil required to pack a soil core to a specific bulk density was calculated and this was then weighed and put into a plastic bag. Water was added to the soil and mixed until all the soil was wet. The soil and water was then left to equilibrate overnight. The following day, the soil was compacted using a specially designed soil compactor (Fig. 3.1) that can compact soils with ease. A copper cylinder with a filter paper attached to one of its ends, was placed onto a foot piece. A guide and soil loading ring, which served as a guide for the piston and for putting the soil into was placed onto a copper cylinder. This guide and soil loading

ring fitted snugly onto a copper cylinder. The soil was quantitatively transferred into the guide and soil loading ring. The piston was then placed into this guide and soil loading ring. A handle was then lowered onto the piston and pressure applied until the piston could not move any further into soil loading ring. The cylinder with the compacted soil was placed into an oven at 105 °C and dried for approximately sixteen hours. The compacted samples were then placed into a desiccator and allowed to cool. When the compacted samples were cool, they were weighed and thereafter saturated.

Volumetric water content of the compacted samples was determined at 5, 10 and 100 kPa using the standard pressure plate technique (Klute, 1986). The water holding capacity of the soil was determined between 5 and 100 kPa and between 10 and 100 kPa.

3.4 Data analysis

To compare the different methods of determining water holding capacity, the volumetric water contents were compared. Using the volumetric water content of undisturbed soil samples as the norm, the different methods of determining water holding capacity were compared. Thereafter, the water holding capacity of the soils between 5 and 100 kPa and between 10 and 100 kPa as determined by the different methods were compared. The water holding capacity of the undisturbed samples was used as the norm.

To investigate aspects of soil texture that could possibly influence the volumetric water content of the soil, graphs were drawn of different texture components versus volumetric water content of undisturbed samples, rubber ring samples and compacted samples at 5, 10 and 100 kPa. In order to compare the different graphs, only straight line graphs were drawn. In order to determine what textural components influenced the water holding capacity of the soil, correlations were drawn between texture components and water holding capacity of undisturbed samples, rubber ring samples and compacted samples between 5 and 100 kPa and between 10 and 100 kPa. These graphs were also straight line graphs in order for accurate comparison.

To develop models to predict volumetric soil water content and water holding capacity of soils from easily quantified variables, the data was analysed using SAS version 6.12 (SAS, 1990). Total sand content, clay content, silt content, clay and silt content, fine sand content, medium sand content, coarse sand content and stone content served as independent variables. The volumetric water contents of undisturbed samples, rubber ring samples and compacted samples at 5, 10 and 100 kPa were recorded as dependent variables. The water holding capacity of undisturbed samples, rubber ring samples and compacted samples between 5 and 100 kPa and 10 and 100 kPa were also recorded as dependent variables.

The measurements were analysed with SAS version 6.12 (SAS, 1990), using the method of Cochran and Cox. Pearson's correlation coefficients were calculated between the above independent and

dependent variables and scatter plots were examined for trends. For each dependent variable a forward stepwise regression procedure were performed with a specified significance level of at least 10% for a independent variable to enter and a significance level more than 5% to remove.

In order to evaluate models of water holding capacity, it was essential to obtain a good database of water holding capacity. Due to the fact that particle size distribution is determined in conjunction with water holding capacity determined by means of the rubber ring method, it was decided to use such data. Data available was volumetric water content at 10 kPa, volumetric water content at 100 kPa, the water holding capacity between 10 and 100 kPa and the clay, silt and sand content of the soil. The percentage of stones in the soil was also determined before sieving. This data was then subjected to the models that had been developed for rubber ring samples.

Hutson (1986) published regression equations whereby volumetric water content of soils could be predicted at -10, -30, -100, -500 and -1500 kPa, using only the clay and silt content of the soil.

These equations for predicting volumetric water content of soils at 10 and 100 kPa are:

$$\theta_{-10}=0.112 + 0.00380 (Cl + Si) \quad 3.2$$

$$\theta_{-100}=0.038 + 0.00372 (Cl + Si) \quad 3.3$$

where Cl is clay content and Si is silt content.

The predicted volumetric water content at 10 kPa and 100 kPa, according to the model of Hutson (1986), was then compared to actual and predicted volumetric water content of rubber ring samples at 10 and 100 kPa.

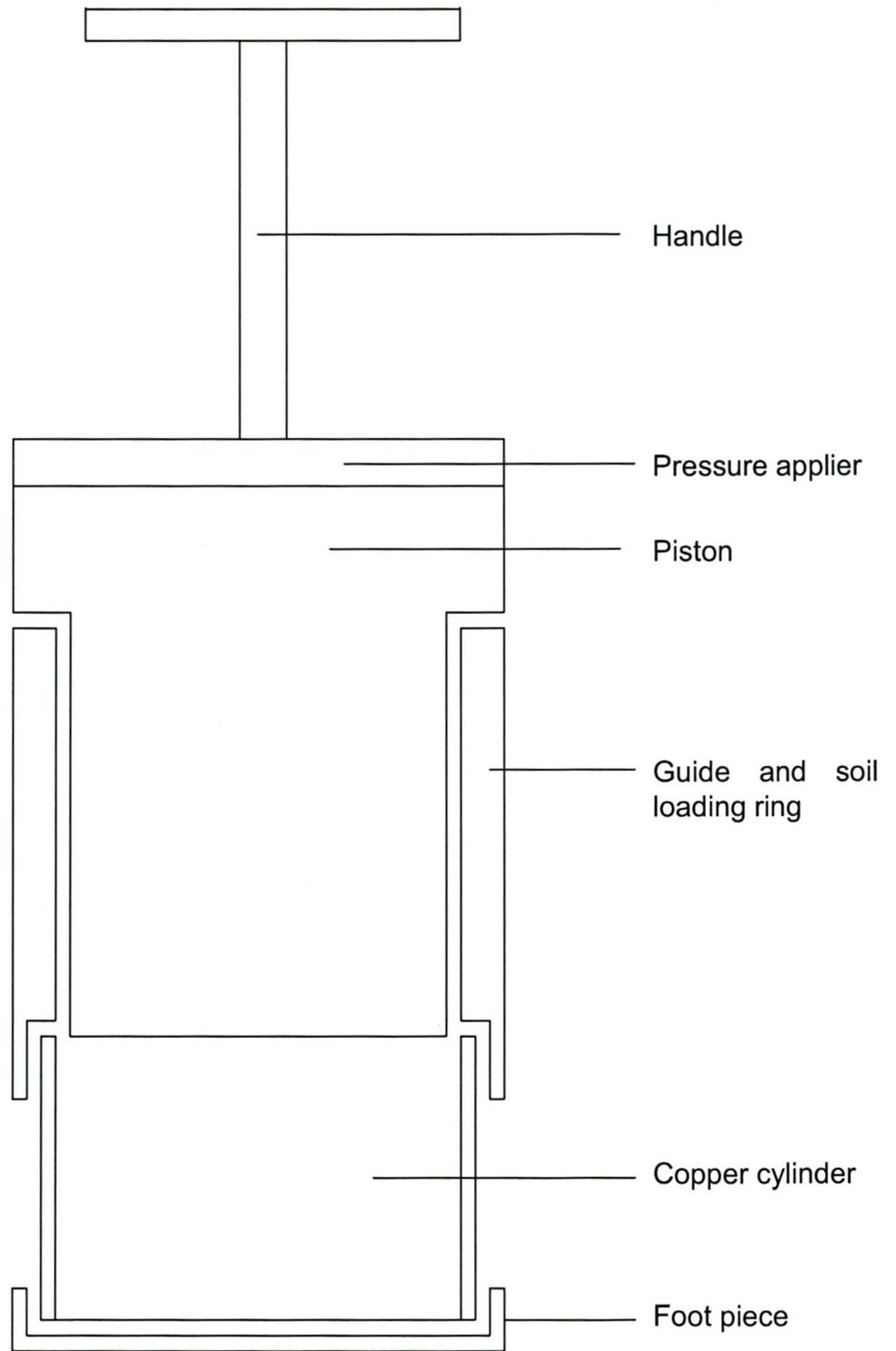


Figure 3.1. Compactor developed for the compaction of soil samples.

CHAPTER 4

RESULTS AND DISCUSSION: VOLUMETRIC WATER CONTENT AND WATER HOLDING CAPACITY OF UNDISTURBED, RUBBER RING AND COMPACTED SAMPLES

4.1 Texture

The clay content of the soils varied from 0.8% clay to 26.2% clay (Table 4.1). The soil with the highest clay content of 26.2% also had the highest silt content of 17.2%. The sand content of the soils varied from 56.6% sand to 98.8% sand. Sand fractions were also determined. The fine sand content of the soils varied from 26.4% to 88.8% (Table 4.2). The medium sand content of the soils was lower than that of the fine sand and varied from 2.4% to 69.2% (Table 4.2). Most of the soils had a very low coarse sand content and some of the soils even had no coarse sand present. The highest coarse sand content from samples used in this study was 23.9% (Table 4.2).

The soils were classified according to the texture triangle (Table 4.1) (Soil Classification Work Group, 1991). Fourteen of the soils were classified as sand, while four of the soils were classified as pure sand. Three of the soils had a sandy loam texture. The remaining three soils were classified as loamy sand.

4.2 Bulk density

The average bulk density (Table 4.3) of the undisturbed samples was 1.54 g.cm^{-3} , rubber ring samples 1.55 g.cm^{-3} and compacted samples 1.48 g.cm^{-3} . The bulk density of the undisturbed samples ranged from 1.24 g.cm^{-3} to 1.82 g.cm^{-3} . Bulk density of the rubber ring samples ranged from 1.21 g.cm^{-3} to 1.90 g.cm^{-3} . The bulk density of compacted samples varied between 1.45 g.cm^{-3} and 1.50 g.cm^{-3} . This was expected as the aim had been to compact the soils to 1.50 g.cm^{-3} .

4.3.1 Volumetric water content: undisturbed samples

Volumetric water content of undisturbed samples at 5, 10 and 100 kPa is given in Table 4.4. Volumetric water content of undisturbed samples at 5 kPa ranged from $0.0766 \text{ mm.mm}^{-1}$ to approximately $0.4178 \text{ mm.mm}^{-1}$. Volumetric water content of undisturbed samples at 10 kPa ranged from $0.0509 \text{ mm.mm}^{-1}$ to $0.3892 \text{ mm.mm}^{-1}$. At 100 kPa, volumetric water content of undisturbed samples ranged from $0.0165 \text{ mm.mm}^{-1}$ to $0.2599 \text{ mm.mm}^{-1}$.

Table 4.5 consists of a matrix table summarising the data that will be discussed hereafter. The correlation between clay content of undisturbed samples and volumetric water content thereof at 5 kPa was 15% (graph not shown). Volumetric water content of undisturbed samples at 5 kPa shows a 11% correlation with silt (Fig. 4.1A). Clay plus silt content of undisturbed samples explained 15% of the variation in volumetric water content of undisturbed samples at 5 kPa (Fig. 4.2A). At 5 kPa,

Table 4.1. Texture classification of the range of soils that were used in the comparison of different methods of water holding capacity determination.

Site number	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture classification
1	0-70	4.8	1.0	94.2	Pure sand
1	70-100	7.2	0.8	92.0	Sand
2	0-30	4.0	7.6	88.4	Sand
2	30-90	6.4	4.8	88.8	Sand
3	0-30	17.0	5.2	77.8	Sandy loam
3	30-100	6.4	3.6	90.0	Sand
4	0-30	18.8	16.2	65.0	Loamy sand
4	30-90	6.0	3.2	90.8	Sand
5	0-25	11.6	5.6	82.8	Loamy sand
5	25-90	2.4	2.8	94.8	Pure sand
6	0-20	3.3	1.5	95.2	Pure sand
6	20-60	4.1	1.5	94.4	Pure sand
7	0-50	17.0	10.0	73.0	Sandy loam
7	50-80	9.2	4.4	86.4	Sand
8	0-30	5.6	3.8	90.6	Sand
8	30-90	7.2	2.4	90.4	Sand
9	0-30	1.6	1.7	96.7	Sand
10	0-30	0.8	0.4	98.8	Sand
11	0-30	1.6	0.4	98.0	Sand
12	0-30	5.5	5.3	89.2	Sand
13	0-30	16.8	9.0	74.2	Loamy sand
14	0-30	26.2	17.2	56.6	Sandy loam
15	20-40	11.0	14.0	75.0	Sand
16	20-40	11.5	15.2	73.5	Sand

Table 4.2. Particle size distribution of the range of soils that were used in the comparison of different methods of water holding capacity determination.

Site number	Depth (cm)	Clay (%)	Silt (%)	Fine sand (%)	Medium sand (%)	Coarse sand (%)
1	0-70	4.8	1.0	84.2	10.0	0.0
1	70-100	7.2	0.8	88.8	3.2	0.0
2	0-30	4.0	7.6	85.4	3.0	0.0
2	30-90	6.4	4.8	86.4	2.4	0.0
3	0-30	17.0	5.2	74.8	3.0	0.0
3	30-100	6.4	3.6	86.0	4.0	0.0
4	0-30	18.8	16.2	60.8	4.0	0.2
4	30-90	6.0	3.2	83.6	6.4	0.8
5	0-25	11.6	5.6	74.4	7.2	1.2
5	25-90	2.4	2.8	79.8	14.0	1.0
6	0-20	3.3	1.5	34.1	38.3	22.8
6	20-60	4.1	1.5	33.2	37.3	23.9
7	0-50	17.0	10.0	68.2	4.6	0.2
7	50-80	9.2	4.4	77.4	9.0	0.0
8	0-30	5.6	3.8	81.2	9.4	0.0
8	30-90	7.2	2.4	76.8	13.4	0.2
9	0-30	1.6	1.7	26.4	55.7	14.6
10	0-30	0.8	0.4	27.2	69.2	12.4
11	0-30	1.6	0.4	26.4	65.6	6.0
12	0-30	5.5	5.3	52.5	36.2	0.5
13	0-30	16.8	9.0	56.0	14.2	4.0
14	0-30	26.2	17.2	42.4	11.0	3.2
15	20-40	11.0	14.0	63.7	8.5	2.8
16	20-40	11.5	15.2	60.8	11.9	0.6

Table 4.3. Bulk density of soil samples used in different methods to determine water holding capacity of soils.

Site number	Depth (cm)	Bulk density (g. cm ⁻³)		
		Undisturbed samples	Rubber ring samples	Compacted samples
1	0-70	1.45	1.57	1.48
1	70-100	1.52	1.55	1.48
2	0-30	1.50	1.51	1.48
2	30-90	1.47	1.49	1.49
3	0-30	1.40	1.48	1.46
3	30-100	1.47	1.45	1.46
4	0-30	1.60	1.49	1.45
4	30-90	1.49	1.55	1.47
5	0-25	1.45	1.50	1.48
5	25-90	1.47	1.63	1.48
6	0-20	1.63	1.84	1.49
6	20-60	1.82	1.90	1.50
7	0-50	1.50	1.37	1.45
7	50-80	1.56	1.56	1.47
8	0-30	1.64	1.52	1.48
8	30-90	1.53	1.56	1.48
9	0-30	1.48	1.69	1.50
10	0-30	1.66	1.74	1.50
11	0-30	1.65	1.81	1.50
12	0-30	1.66	1.50	1.49
13	0-30	1.73	1.56	1.48
14	0-30	1.41	1.21	1.46
15	20-40	1.24	1.38	1.47
16	20-40	1.51	1.39	1.48

Table 4.4. Volumetric water content of undisturbed samples used to determine water holding capacity of soils.

Site number	Depth (cm)	Volumetric water content (mm.mm ⁻¹)		
		5 kPa	10 kPa	100 kPa
1	0-70	0.3064	0.2766	0.1236
1	70-100	0.3557	0.2420	0.1144
2	0-30	0.4178	0.3839	0.2397
2	30-90	0.3933	0.3360	0.1749
3	0-30	0.3753	0.3304	0.1691
3	30-100	0.4152	0.3258	0.1185
4	0-30	0.4138	0.3892	0.2599
4	30-90	0.3581	0.2727	0.0469
5	0-25	0.3750	0.3350	0.0830
5	25-90	0.3798	0.3526	0.1056
6	0-20	0.1482	0.1242	0.0618
6	20-60	0.1601	0.1184	0.0570
7	0-50	0.3814	0.3397	0.1341
7	50-80	0.3079	0.2957	0.0913
8	0-30	0.3678	0.3653	0.0460
8	30-90	0.2735	0.2225	0.0927
9	0-30	0.0954	0.0667	0.0324
10	0-30	0.0766	0.0509	0.0180
11	0-30	0.1731	0.1597	0.1093
12	0-30	0.1763	0.1314	0.0165
13	0-30	0.2520	0.2270	0.1141
14	0-30	0.2889	0.2661	0.2068
15	20-40	0.3041	0.2586	0.1597
16	20-40	0.2853	0.2248	0.1207

Table 4.5. Matrix table summerising the correlations of volumetric water content of undisturbed (VWC_u), rubber ring (VWC_{rr}) and compacted (VWC_c) samples at 5, 10 and 100 kPa with textural properties of the soils.

Sample	Soil textural property	Coefficient of determination (r^2)		
		5 kPa	10 kPa	100 kPa
VWC_u	Clay	15	17	34
VWC_u	Silt	11	11	41
VWC_u	Clay plus silt	15	18	41
VWC_u	Total sand	15	18	41
VWC_u	Fine sand	75	64	10
VWC_u	Medium sand	82	74	32
VWC_{rr}	Clay	21	36	55
VWC_{rr}	Silt	13	35	62
VWC_{rr}	Clay plus silt	19	39	64
VWC_{rr}	Total sand	19	39	64
VWC_{rr}	Fine sand	77	48	21
VWC_{rr}	Medium sand	82	79	60
VWC_c	Clay	28	37	53
VWC_c	Silt	23	34	46
VWC_c	Clay plus silt	29	39	55
VWC_c	Total sand	29	39	55
VWC_c	Fine sand	63	51	34
VWC_c	Medium sand	83	80	69

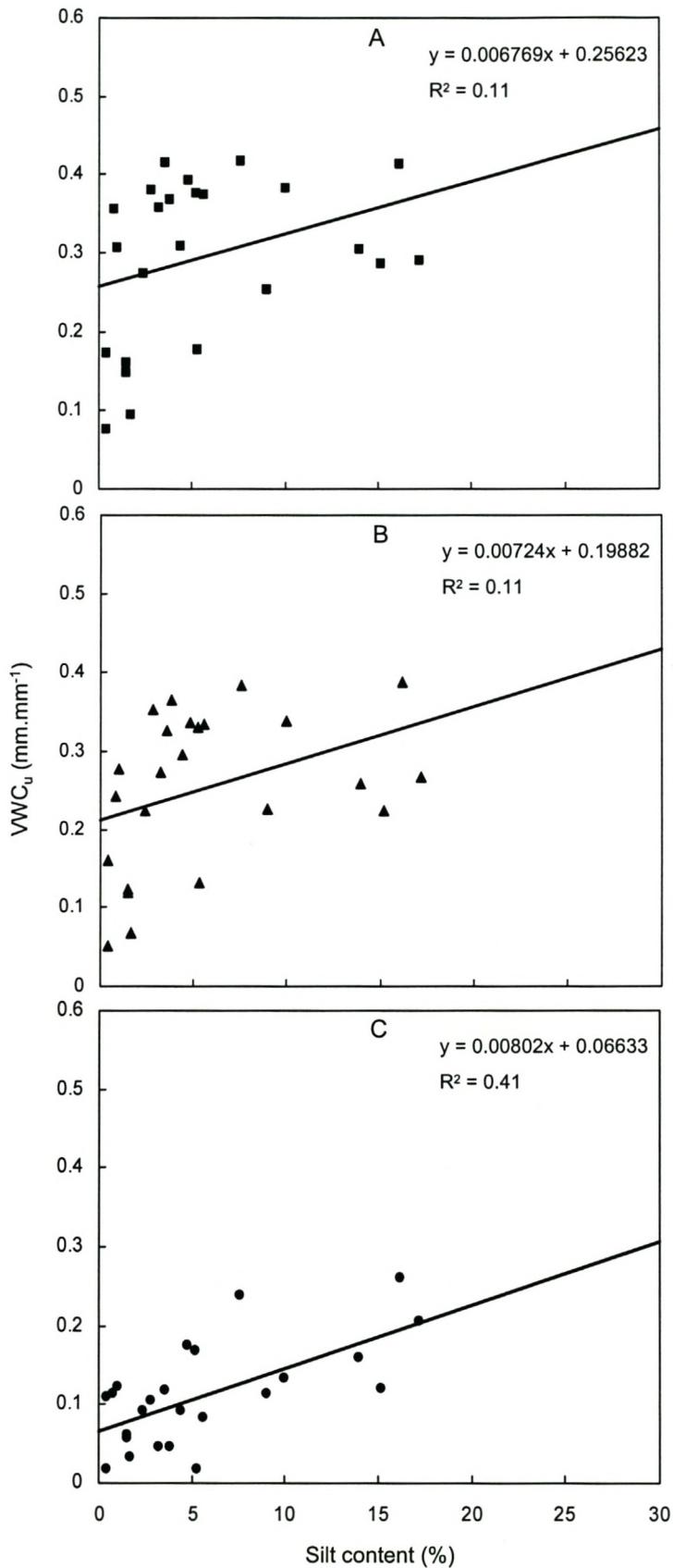


Figure 4.1. The influence of silt content (%) on the volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

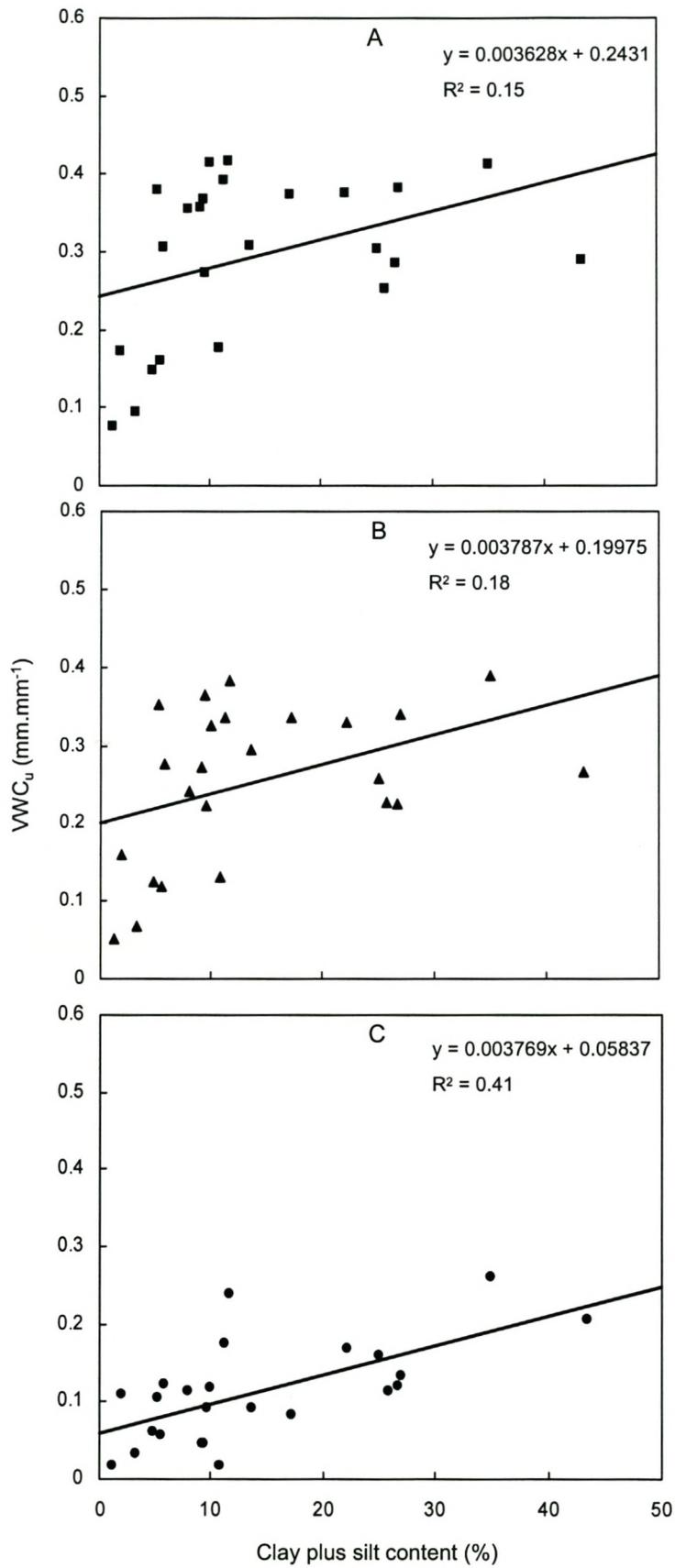


Figure 4.2. The influence of clay plus silt content (%) on the volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

volumetric water content of undisturbed samples had a 15% correlation with total sand contents (graph not shown). However, if the individual sand components are used instead of the total sand contents, fine sand content explained 75% of the variation in volumetric water content of undisturbed samples at 5 kPa (Fig. 4.3A). As fine sand content increased, so did the volumetric water content of undisturbed samples. Medium sand content explained 82% of the variation in volumetric water content of undisturbed samples at 5 kPa (Fig. 4.4A). As the medium sand content of the soil samples increased, so the volumetric water content thereof decreased. Sandy soil has the smallest amount of pore space and many pores are so large that water readily drains from them. A sandy soil will have large pore spaces through which water can move easily. Soils with a high medium sand content will therefore have large pore spaces through which water can move easily. The volumetric water content thereof will not be as high as a soil that has a lower medium sand content. Soils containing a high fine sand content will have more smaller pores than a soil with a low fine sand content, therefore soils with a high fine sand content will have a higher volumetric water content than soils with less fine sand.

Volumetric water content of undisturbed samples at 10 kPa had a 17% correlation with clay content (graph not shown). The silt content of undisturbed samples explained 11% of the variation in volumetric water content of undisturbed samples (Fig. 4.1B). The clay plus silt content together gave a correlation of 18% for undisturbed samples (Fig. 4.2B). The total sand content of the samples gave a correlation of 18% with the volumetric water contents of the samples at 10 kPa (graph not shown). Fine sand content of undisturbed samples explained 64% of the variation in the volumetric water contents thereof (Fig. 4.3B). Volumetric water content of undisturbed samples at 10 kPa had a 74% correlation with medium sand content (Fig. 4.4B).

At 100 kPa, the volumetric water content of undisturbed samples at 100 kPa had a 34% correlation with clay content of the soil (graph not shown). Pore spaces in a clay soil are small, causing water to move slowly. At a greater clay content, there will be more small pores, and therefore the volumetric water content of the samples will be greater. The silt content also showed a better correlation with volumetric water content of undisturbed samples at 100 kPa and this was approximately 41% (Fig. 4.1C). The clay plus silt content of the undisturbed samples showed a 41% correlation with volumetric water contents thereof (Fig. 4.2B). Total sand contents accounted for 41% of the variation in volumetric water content of undisturbed samples at 100 kPa (graph not shown). Fine sand content of undisturbed samples showed a correlation of 10% with volumetric water content at 100 kPa (Fig. 4.3C), while medium sand content showed a correlation of 32% with volumetric water of undisturbed samples at 100 kPa (Fig. 4.4C).

4.3.2 Volumetric water content: rubber ring samples

Volumetric water content of rubber ring samples at 5, 10 and 100 kPa is given in Table 4.6. Volumetric water content of rubber ring samples at 5 kPa ranged from $0.0766 \text{ mm.mm}^{-1}$ to approximately $0.5230 \text{ mm.mm}^{-1}$. Volumetric water content of rubber ring samples at 10 kPa ranged

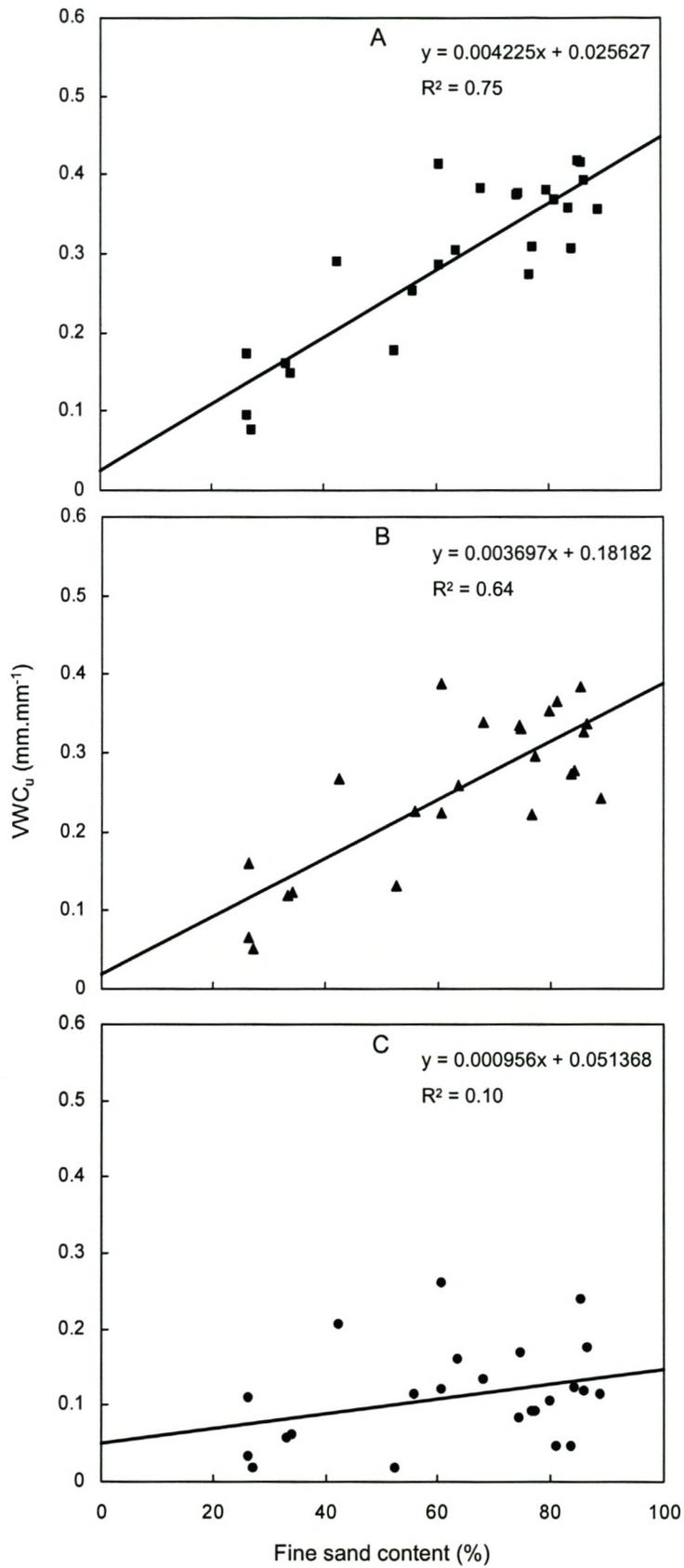


Figure 4.3. The influence of fine sand content (%) on the volumetric water content of undisturbed samples (WwC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

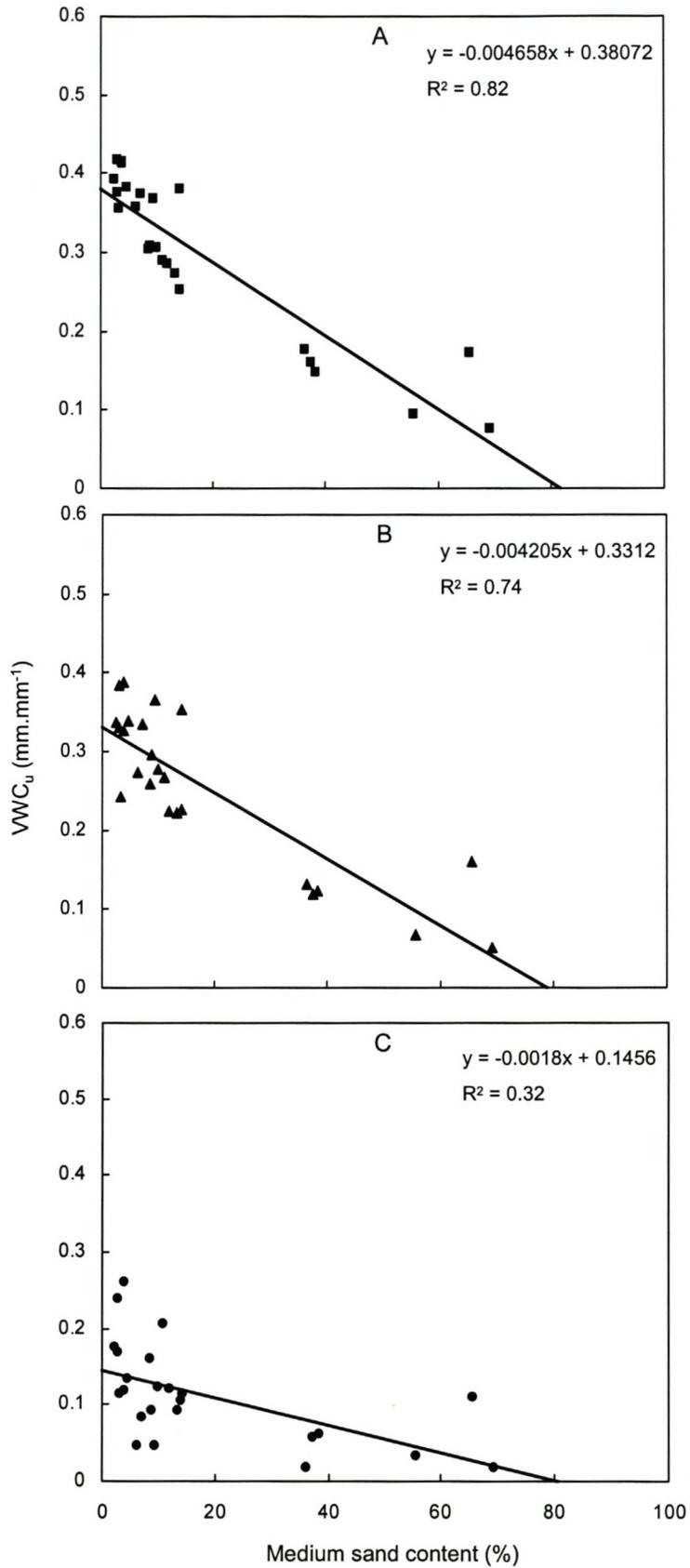


Figure 4.4. The influence of medium sand content (%) on the volumetric water content of undisturbed samples (WVC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

Table 4.6. Volumetric water content of rubber ring samples used to determine water holding capacity of soils.

Site number	Depth (cm)	Volumetric water content (mm.mm ⁻¹)		
		5 kPa	10 kPa	100 kPa
1	0-70	0.4650	0.2360	0.0670
1	70-100	0.4730	0.2560	0.0760
2	0-30	0.5230	0.4150	0.1660
2	30-90	0.4700	0.3990	0.1210
3	0-30	0.5040	0.3990	0.1700
3	30-100	0.4640	0.4460	0.1110
4	0-30	0.5030	0.4520	0.1860
4	30-90	0.4830	0.2990	0.0870
5	0-25	0.5050	0.3600	0.1390
5	25-90	0.4410	0.2890	0.0830
6	0-20	0.2780	0.1490	0.0560
6	20-60	0.2780	0.1520	0.0490
7	0-50	0.4700	0.4270	0.1070
7	50-80	0.4490	0.3530	0.0870
8	0-30	0.4560	0.2780	0.0860
8	30-90	0.4260	0.2330	0.0880
9	0-30	0.1350	0.0750	0.0140
10	0-30	0.1030	0.0460	0.0150
11	0-30	0.1210	0.0500	0.0140
12	0-30	0.2670	0.1630	0.0540
13	0-30	0.3520	0.2310	0.1050
14	0-30	0.4240	0.3730	0.1773
15	20-40	0.4400	0.4110	0.1760
16	20-40	0.3730	0.2870	0.1333

from $0.0460 \text{ mm.mm}^{-1}$ to $0.4520 \text{ mm.mm}^{-1}$, whilst volumetric water content of rubber ring samples at 100 kPa ranged from $0.0140 \text{ mm.mm}^{-1}$ to $0.1860 \text{ mm.mm}^{-1}$.

The correlation between clay content of the soil samples and volumetric water content of rubber ring samples at 5 kPa was 21% (Fig. 4.5A). Rubber ring samples gave a slightly better correlation between clay content and volumetric water content than the undisturbed samples. Volumetric water content of rubber ring samples at 5 kPa had only a 13% correlation with silt content (Fig. 4.6A). At 5 kPa, clay plus silt content of rubber ring samples explained 19% of the variation in volumetric water content of the soil samples (Fig. 4.7A). Fine sand content explained almost 77% of the variation in volumetric water content of rubber ring samples at 5 kPa (Fig. 4.8A). Volumetric water content of rubber ring samples at 5 kPa had a 82% correlation with medium sand content (Fig. 4.9A). As medium content of the soil samples increased, so the volumetric water content thereof decreased.

At 10 kPa, volumetric water content of rubber ring samples was correlated 36% with clay content thereof (Fig. 4.5B). This was almost the same as the correlation between silt content of rubber ring samples and volumetric water content of rubber ring samples at 10 kPa (Fig. 4.6B). Clay plus silt content together gave a correlation of 39% between clay plus silt content and volumetric water content of rubber ring samples at 10 kPa (Fig. 4.7B). Volumetric water content at 10 kPa had a 39% correlation with total sand content (graph not shown). Volumetric water content of rubber ring samples at 10 kPa had a poor correlation of 48% with fine sand content (Fig. 4.8B). Medium sand content of rubber ring samples explained 79% of the variation in the volumetric water content of rubber ring samples (Fig. 4.9B).

At 100 kPa, the correlation between clay content and volumetric water content of rubber ring samples was 55% (Fig. 4.5C). Silt content of rubber ring samples showed a 62% correlation with volumetric water contents thereof (Fig. 4.6C). Volumetric water content of rubber ring samples at 100 kPa had a 64% correlation with clay plus silt content (Fig. 4.7C). Total sand content of rubber ring samples and volumetric water contents thereof was correlated by 64% (graph not shown). Volumetric water content had only a 21% correlation with fine sand content (Fig 4.8C). Medium sand content, however, showed a correlation of 60% with volumetric water content of rubber ring samples at 100 kPa (Fig 4.9C).

4.3.3 Volumetric water content: compacted samples

Volumetric water content of compacted samples at 5, 10 and 100 kPa is given in Table 4.7. Volumetric water content of compacted samples at 5 kPa ranged from $0.0806 \text{ mm.mm}^{-1}$ to approximately $0.4622 \text{ mm.mm}^{-1}$. Volumetric water content of compacted samples at 10 kPa ranged from $0.0443 \text{ mm.mm}^{-1}$ to $0.4212 \text{ mm.mm}^{-1}$, whilst volumetric water content of compacted samples at 100 kPa ranged from $0.0196 \text{ mm.mm}^{-1}$ to $0.3860 \text{ mm.mm}^{-1}$.

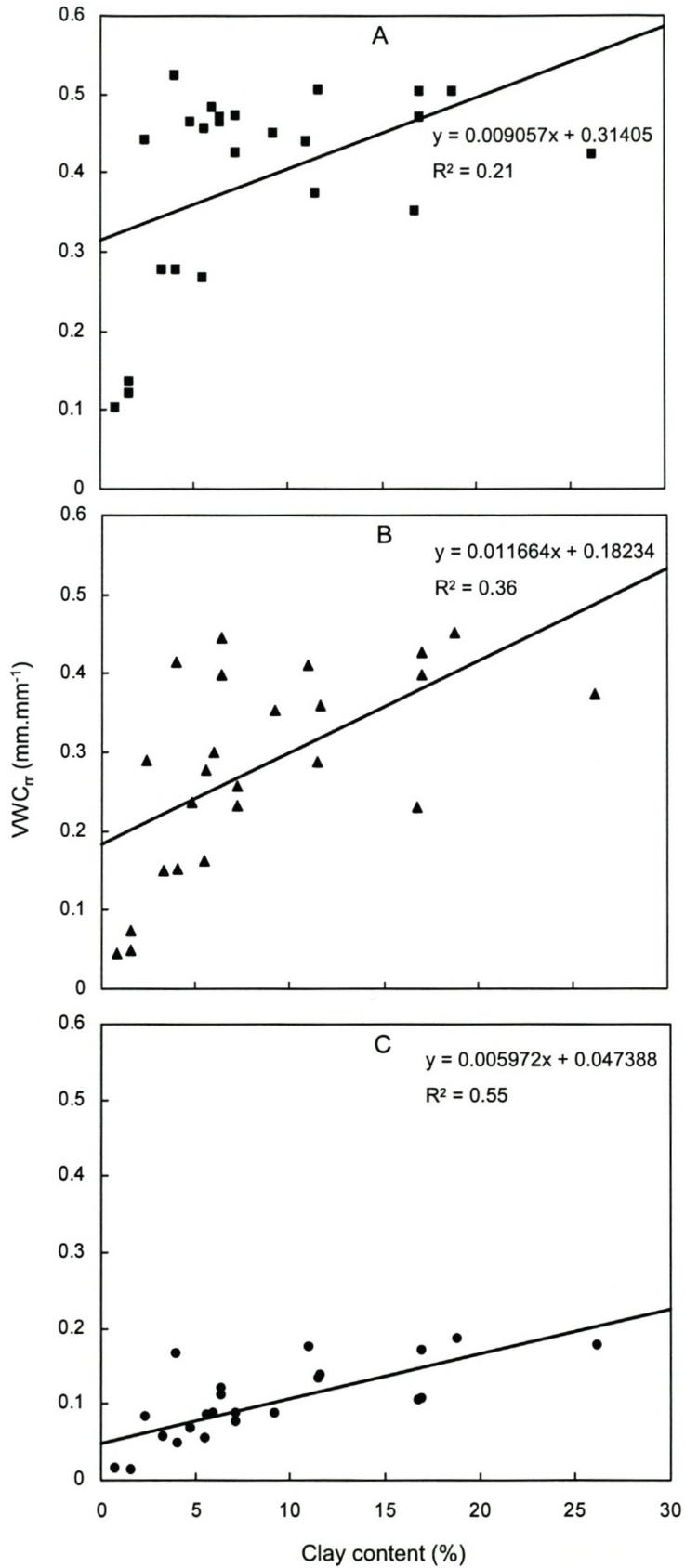


Figure 4.5. The influence of clay content (%) on the volumetric water content of rubber ring samples (VWC_r), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

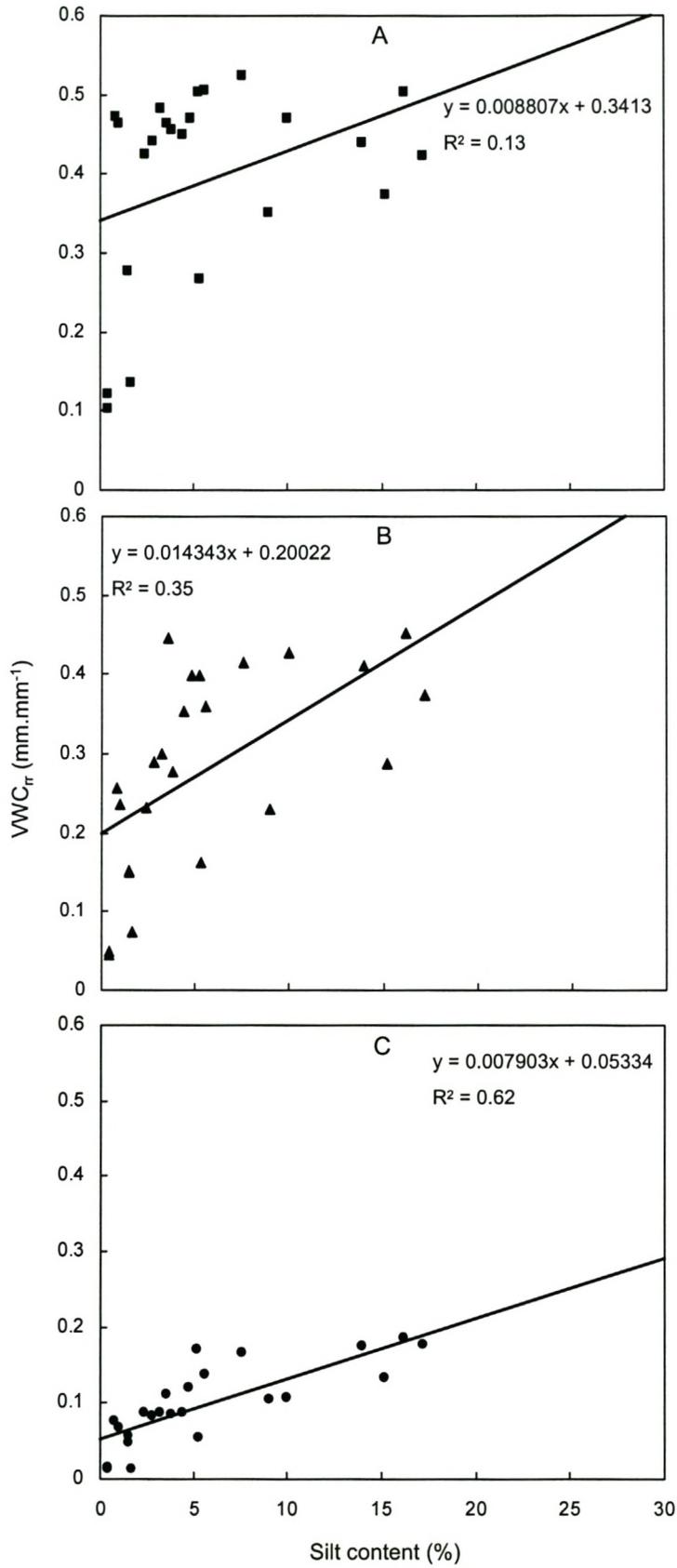


Figure 4.6. The influence of silt content (%) on the volumetric water content of rubber ring samples (WVC_{rr}), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

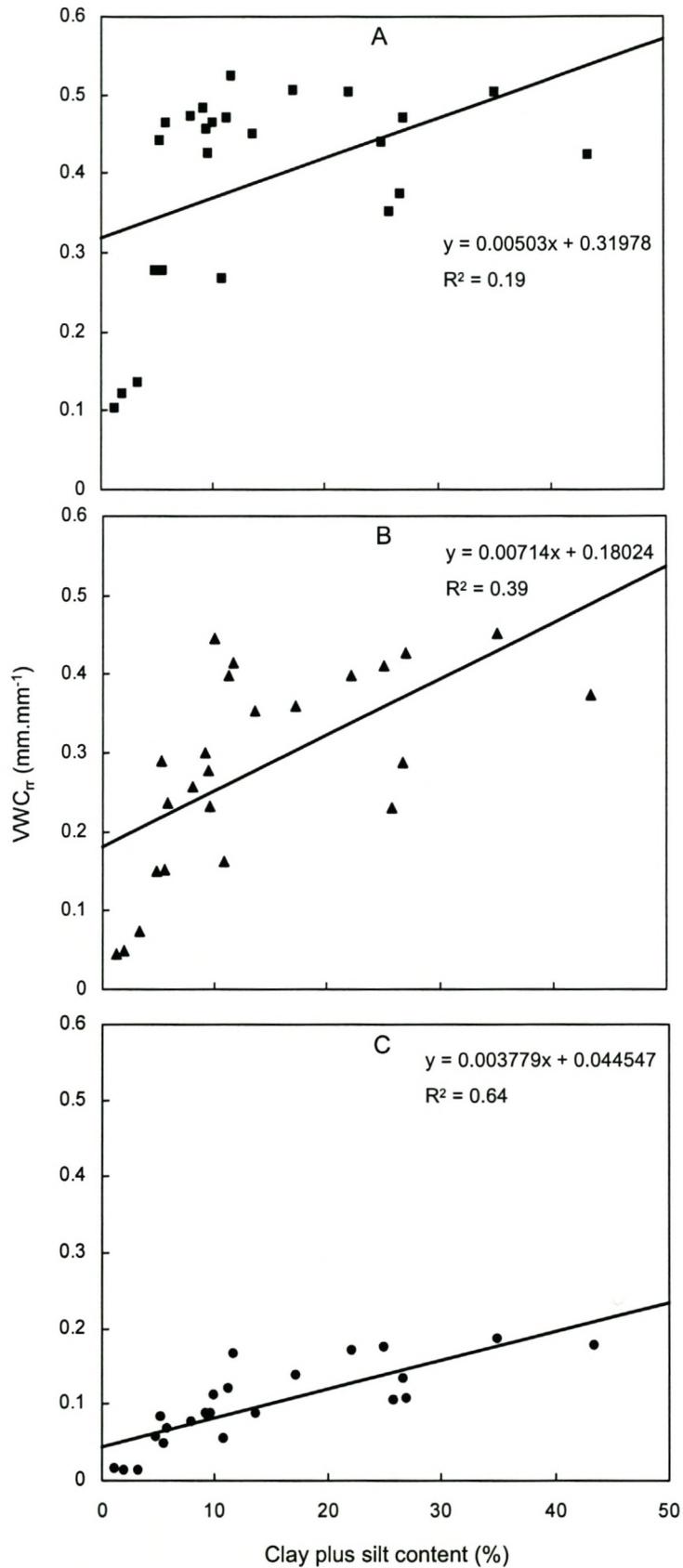


Figure 4.7. The influence of clay plus silt content (%) on the volumetric water content of rubber ring samples (VWC_{rr}), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

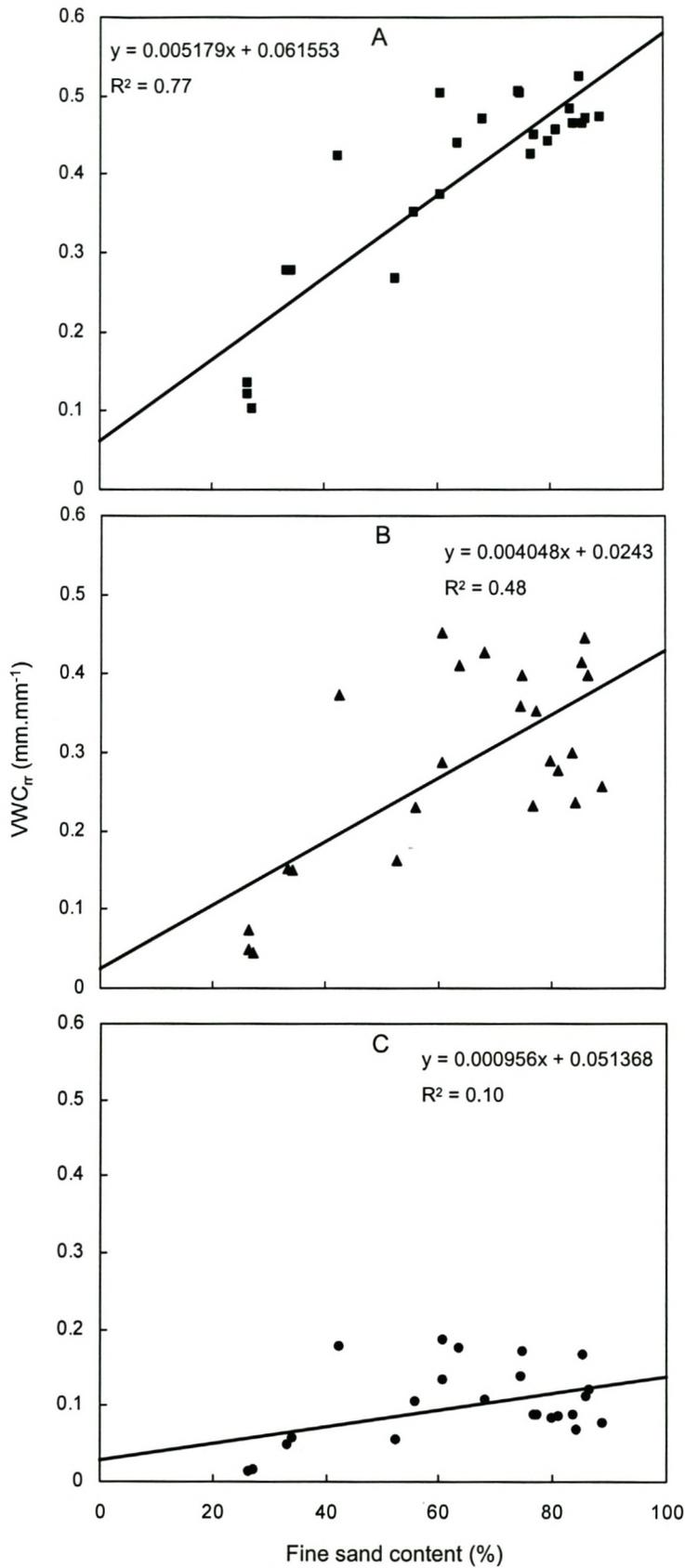


Figure 4.8. The influence of fine sand content (%) on the volumetric water content of rubber ring samples (VWC_r), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

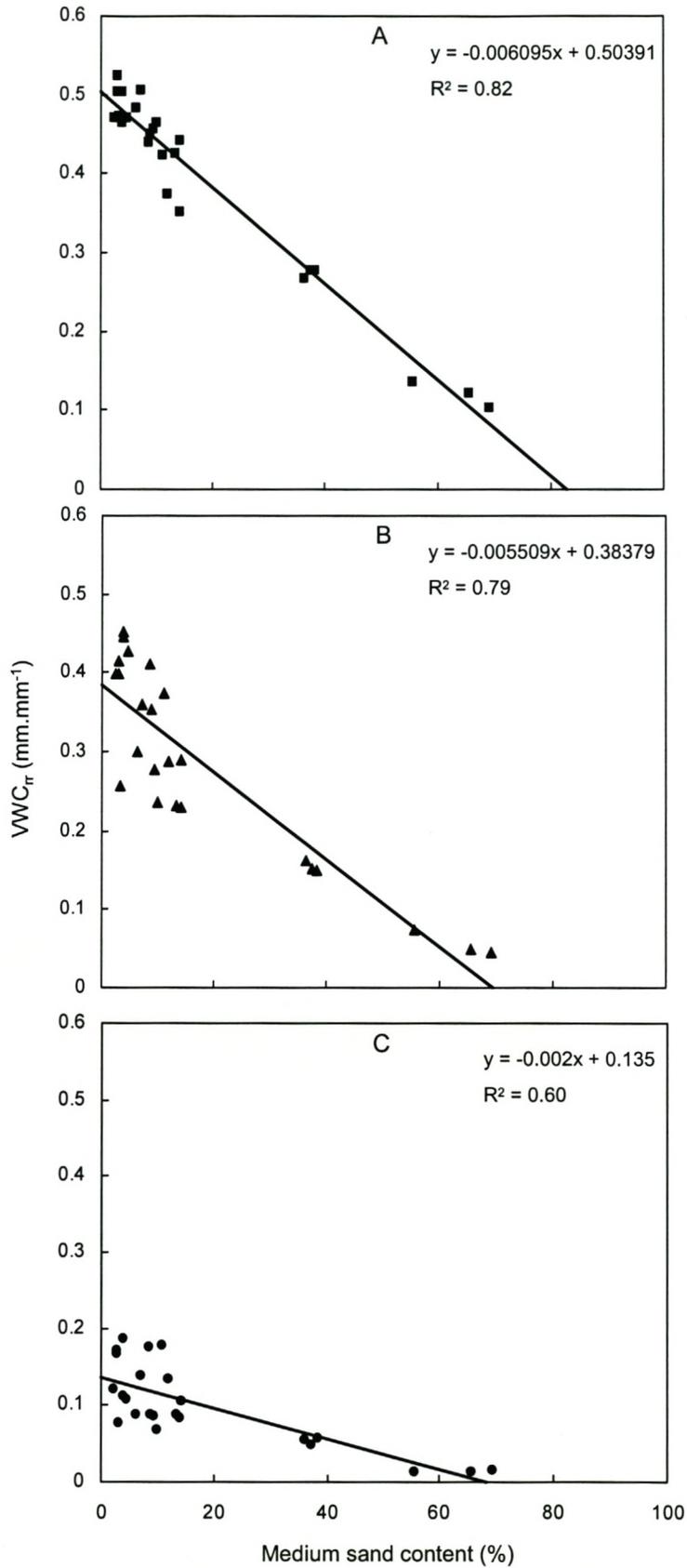


Figure 4.9. The influence of medium sand content (%) on the volumetric water content of rubber ring samples (VWC_{rr}), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

Table 4.7. Volumetric water content of compacted samples used to determine water holding capacity of soils.

Site number	Depth (cm)	Volumetric water content (mm.mm ⁻¹)		
		5 kPa	10 kPa	100 kPa
1	0-70	0.3086	0.2296	0.1549
1	70-100	0.3503	0.2882	0.2265
2	0-30	0.4358	0.3933	0.2607
2	30-90	0.4245	0.3754	0.2451
3	0-30	0.4622	0.3560	0.2410
3	30-100	0.4461	0.3789	0.2879
4	0-30	0.4375	0.4212	0.3860
4	30-90	0.3531	0.2324	0.1280
5	0-25	0.4217	0.3440	0.1913
5	25-90	0.2805	0.2218	0.1702
6	0-20	0.1171	0.1015	0.0710
6	20-60	0.1337	0.1096	0.0630
7	0-50	0.3528	0.3140	0.2709
7	50-80	0.3536	0.2707	0.2040
8	0-30	0.3404	0.2884	0.2121
8	30-90	0.2761	0.2380	0.1328
9	0-30	0.0887	0.0610	0.0299
10	0-30	0.0864	0.0443	0.0196
11	0-30	0.0806	0.0456	0.0241
12	0-30	0.1817	0.1437	0.0952
13	0-30	0.2357	0.2286	0.2069
14	0-30	0.3789	0.3656	0.3213
15	20-40	0.4343	0.3719	0.2235
16	20-40	0.2863	0.2315	0.1790

The correlation between clay content of compacted samples and volumetric water content thereof at 5 kPa was 28% (Fig. 4.10A). The silt content of compacted soil samples explained 23% of the variation of volumetric water content at 5 kPa (Fig. 4.11A). At 5 kPa, clay plus silt content of compacted samples explained 29% of the variation in the volumetric water content (Fig. 4.12A). Fine sand content explained 63% of the variation in volumetric water content of compacted samples at 5 kPa (Fig. 4.13A). Medium sand content explained 83% of the variation in volumetric water content of compacted samples at 5 kPa (Fig. 4.14A).

At 10 kPa, volumetric water content of compacted samples had a 37% correlation with clay content (Fig. 4.10B). Silt content of compacted samples explained 34% of the variation in volumetric water content at 10 kPa (Fig. 4.11B). Clay plus silt content together gave a correlation of 39% between clay plus silt content and volumetric water content of compacted samples at 10 kPa (Fig. 4.12B). Total sand content of the samples gave a correlation of 39% with volumetric water content at 10 kPa (graph not shown). Volumetric water content of compacted samples at 10 kPa had a 51% correlation with fine sand content (Fig. 4.13B). Medium sand content of compacted samples explained 80% of the variation in volumetric water content thereof (Fig. 4.14B).

At 100 kPa, the correlation between clay contents and volumetric water content of the compacted samples was 53% (Fig. 4.10C). Silt content of the compacted samples showed a slightly poorer correlation with volumetric water contents thereof (Fig. 4.11C). Clay plus silt content together accounted for 55% of the variation in volumetric water content of compacted soil samples at 100 kPa (Fig. 4.12C). Total sand content of compacted samples and volumetric water contents thereof was correlated by 55% (graph not shown). Fine sand content of compacted samples at 100 kPa showed a 34% degree of correlation with volumetric water content thereof (Fig. 4.13C). Medium sand content, however, showed a correlation of approximately 69% with volumetric water content of compacted samples at 100 kPa (Fig. 4.14C).

4.3.4 Volumetric water content: a comparison

According to Salter *et al.* (1966), regression analyses indicated that the plant available water content of the soils they studied were linearly correlated to the percentages of sand, silt and organic carbon content in the soils. From the above results, it was clear that the influence of clay content on the volumetric water content of undisturbed samples increased as the suction on the undisturbed samples was increased. The same tendency was observed in the case of rubber ring samples and compacted samples. The influence of clay content on volumetric water content of both rubber ring samples and compacted samples at 5 kPa and 10 kPa was comparable and was greater than observed for the undisturbed samples. The influence of clay and silt content on volumetric water content of undisturbed samples at 5 kPa and 10 kPa did not differ but volumetric water of undisturbed samples at 100 kPa is clearly influenced more by both clay and silt content. The effect of fine and medium sand on volumetric water content of undisturbed samples, rubber ring samples and compacted samples is the greatest at 5 kPa and decreased remarkably to 100 kPa. This

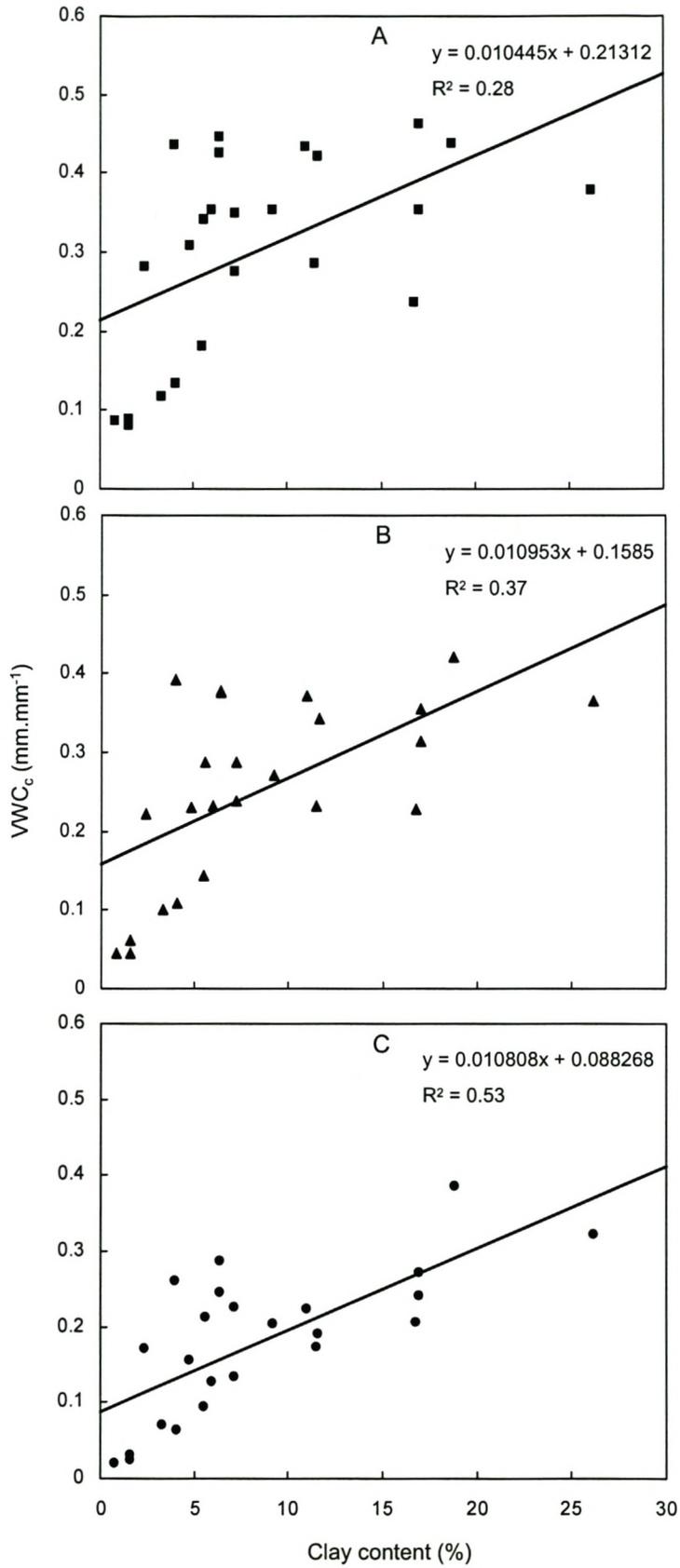


Figure 4.10. The influence of clay content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

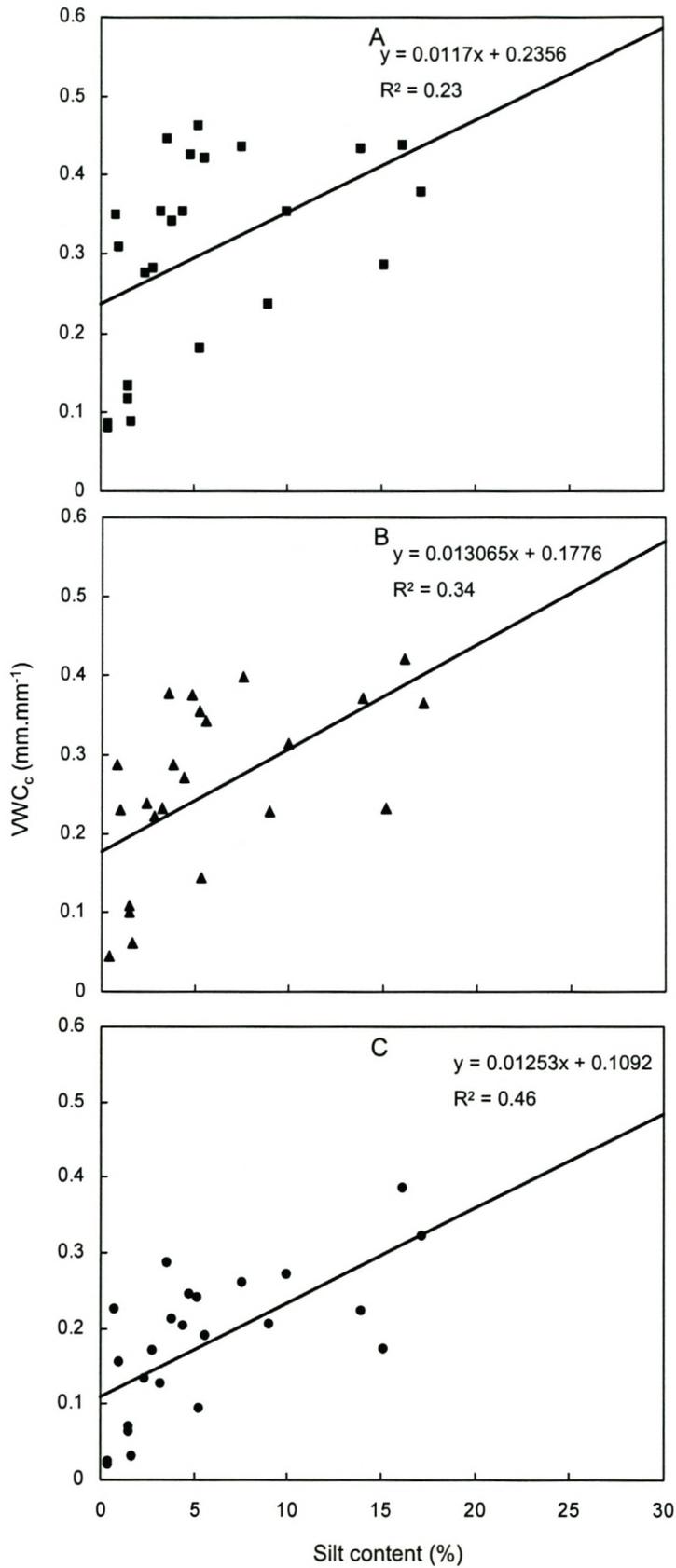


Figure 4.11. The influence of silt content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

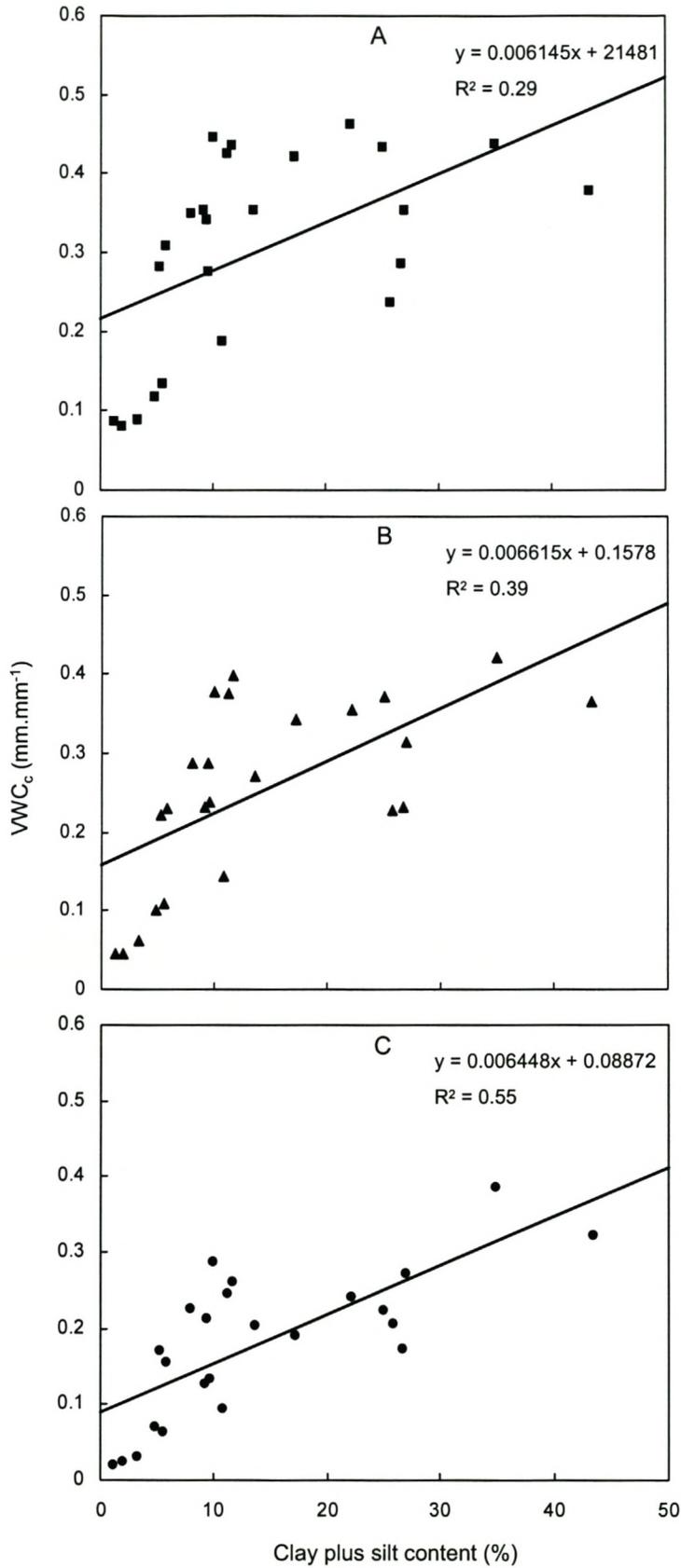


Figure 4.12. The influence of clay plus silt content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

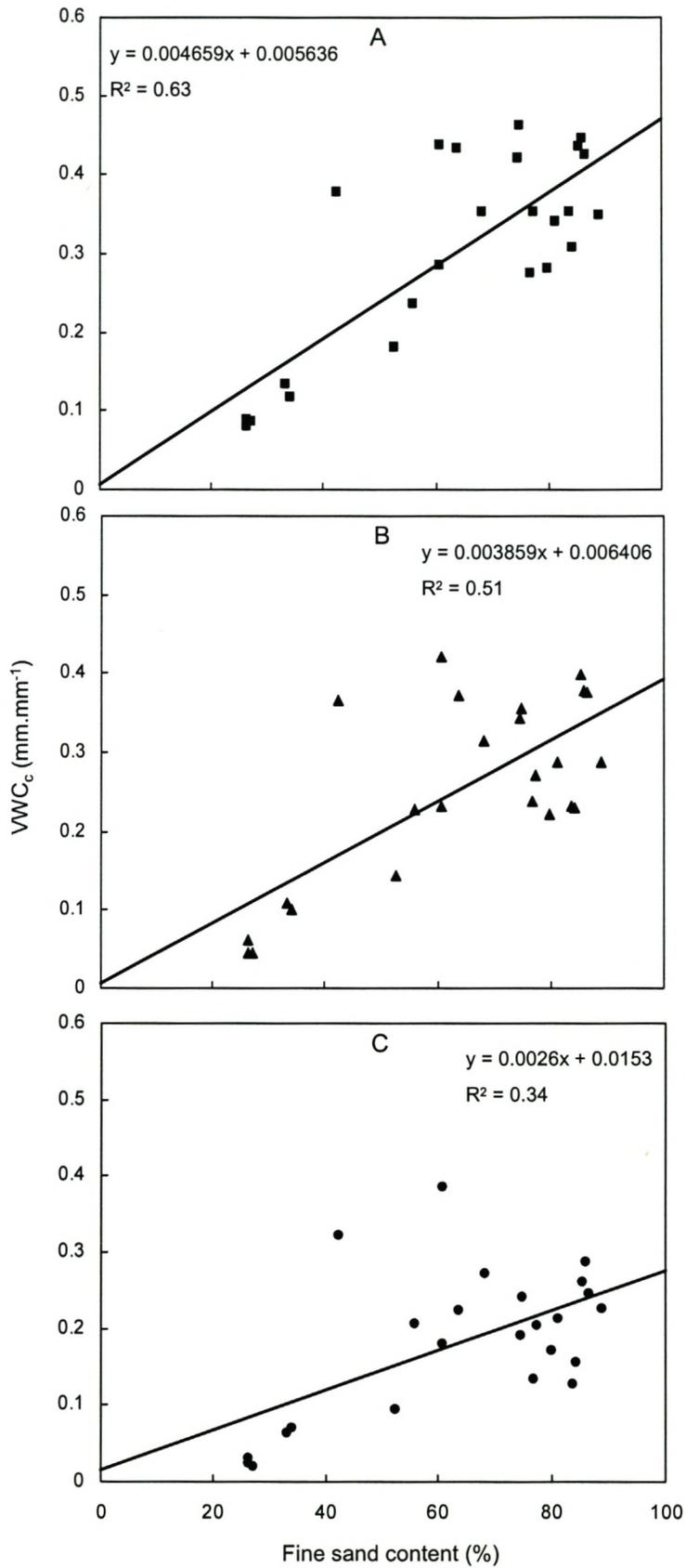


Figure 4.13. The influence of fine sand content (%) on the volumetric water content of compacted samples (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

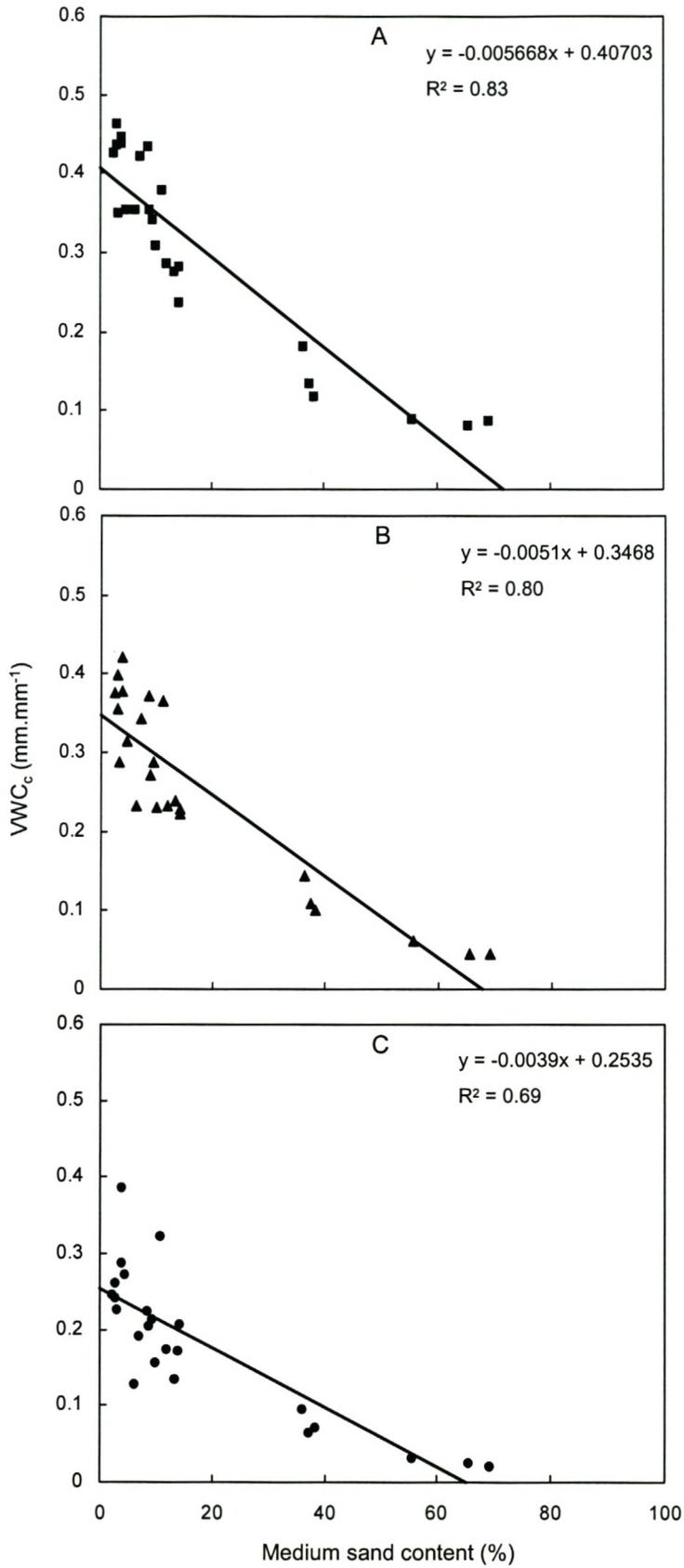


Figure 4.14. The influence of medium sand content (%) on the volumetric water content of compacted (VWC_c), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

confirms the statement of Rivers & Shipp (1978) that the amount of water retained under low soil water suctions is dominated by the size, abundance and shape of the pore spaces in the soil. However, in the case of compacted soils, the medium sand content still has the greatest influence on the volumetric water content at 100 kPa. These results confirm the conclusion drawn by Marshall (1959) that the relation between water content and suction depends less upon the pore structure and more upon the size distribution of the particles and their surface properties.

Volumetric water content of rubber ring samples at 5 kPa was more than the volumetric water content of undisturbed samples at 5 kPa, with the exception of one site (Fig. 4.15A). According to Buckman & Brady (1969), two types of individual pore spaces occur in soils, namely macropores and micropores. Air and water readily moves in macropores, while micropores restrict air and water movement mainly because of slow capillary movement (Buckman & Brady, 1969). Water will move through, or drain out of, large pores more easily than small, and so the size of pores also has to be considered for water storage and movement, as well as amount of pore space (Marshall, 1959). Undisturbed samples probably had more macropores and micropores than the rubber ring samples which had gently been pushed into the rubber rings and therefore had more intermediate sized pores. These macropores of the undisturbed samples drained their water more easily than the mesopores of the rubber ring samples. The volumetric water content of undisturbed samples at 5 kPa was therefore greater than the volumetric water content of the rubber ring samples at 5 kPa. The volumetric water content determined with rubber ring samples at 5 kPa had a 87% degree of correlation with the volumetric water content of undisturbed samples (Fig. 4.15A).

At 10 kPa, volumetric water content of rubber ring samples had a 77% correlation with volumetric water content of undisturbed samples (Fig. 4.15B). Approximately four samples were below the 1:1 line of the volumetric water content of the undisturbed samples.

At 100 kPa, most of the rubber ring samples' volumetric water content fell below the 1:1 line of volumetric water content of undisturbed samples (Fig. 4.15C). This was probably due to the micropores of the undisturbed samples which held the water more tightly than the mesopores of the rubber ring samples. Fine textured soils allow relatively slow gas and water movement in spite of the large amount of total pore space. The volumetric water content at 100 kPa of rubber ring samples was correlated to a degree of 65% to the volumetric water content of undisturbed samples (Fig. 4.15C).

Approximately half of the compacted samples' volumetric water content at 5 kPa was more than the volumetric water content of undisturbed samples at 5 kPa (Fig. 4.16A). Volumetric water content of compacted samples determined at 5 kPa had a 85% correlation with volumetric water content of undisturbed samples. At 10 kPa, the correlation between volumetric water content determined using compacted samples and undisturbed samples was 77% (Fig. 4.16B). Volumetric water content at 100 kPa of compacted samples and volumetric water content of undisturbed samples at 100 kPa was correlated by 64% (Fig. 4.16C). With the exception of one sample, volumetric water content of

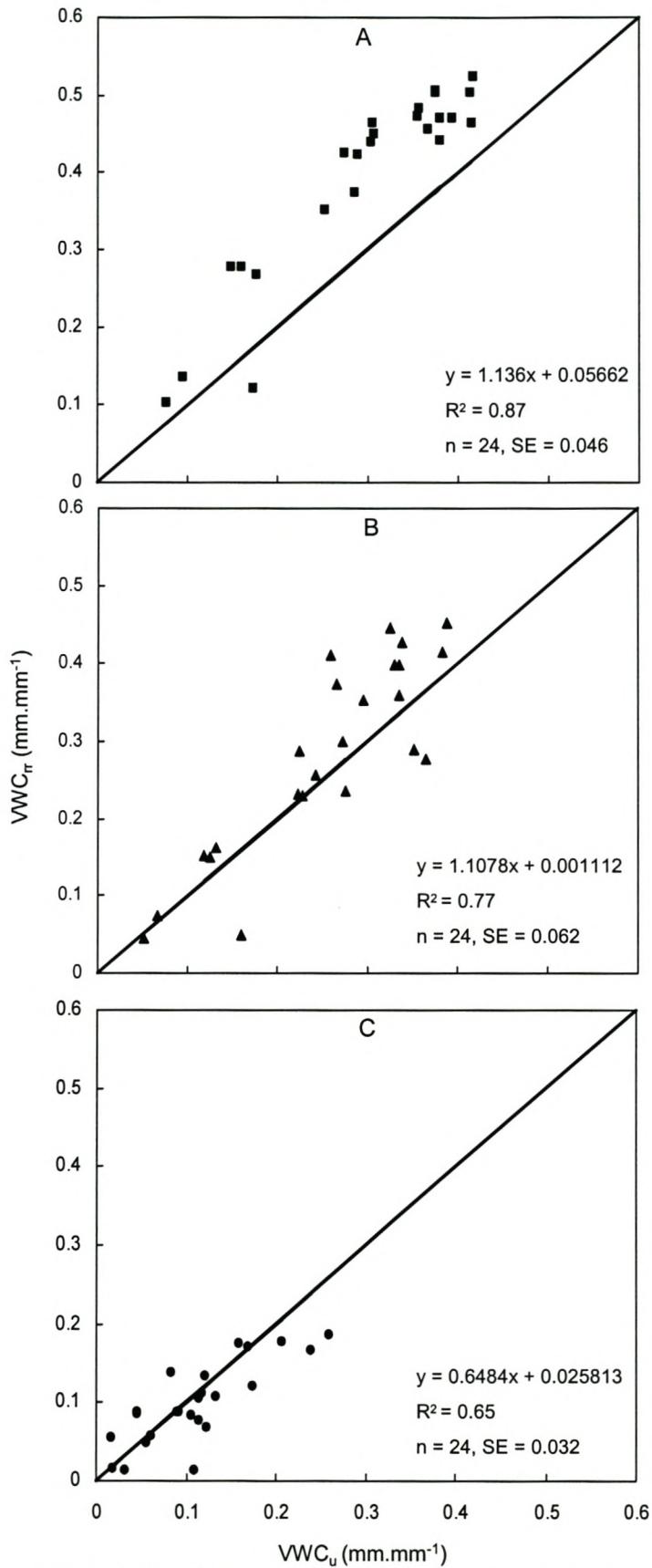


Figure 4.15. Relationship between volumetric water content of rubber ring samples (VWC_r) and volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

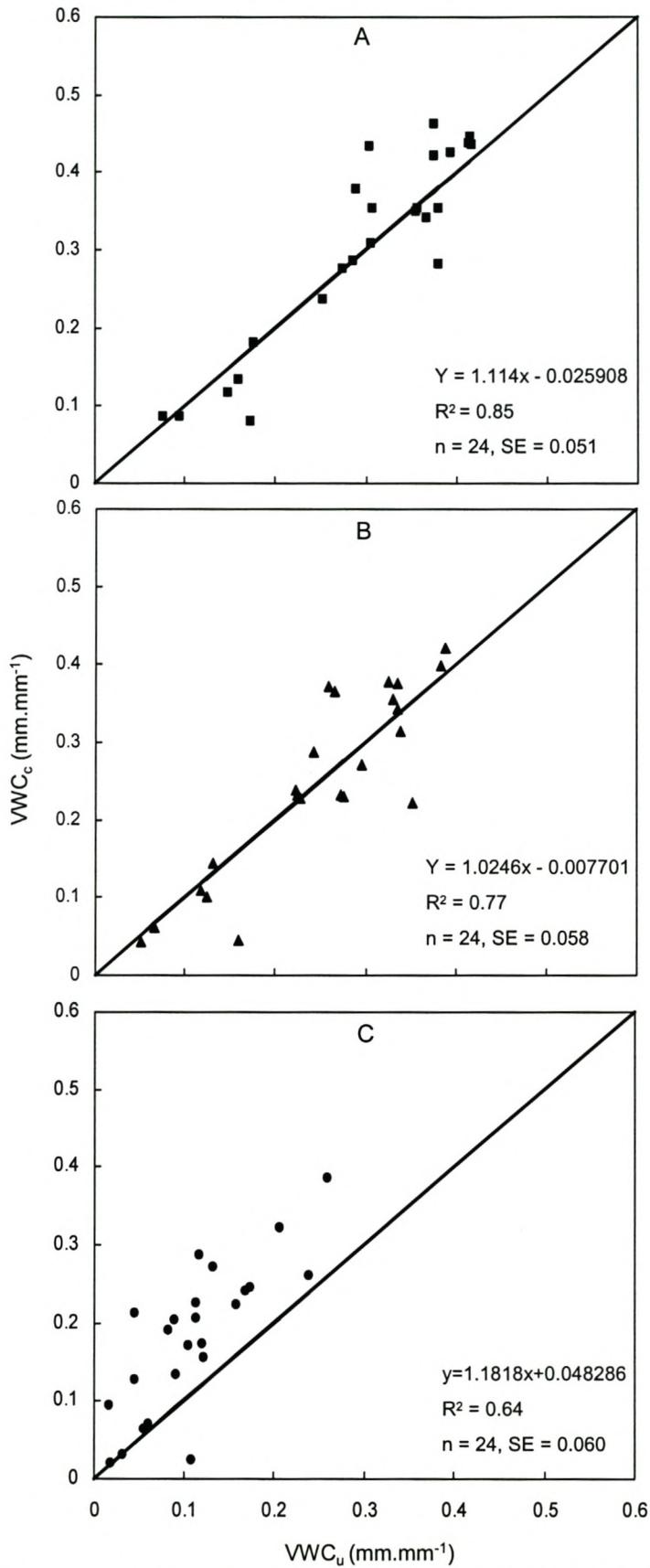


Figure 4.16. Relationship between volumetric water content of compacted samples (VWC_c) and volumetric water content of undisturbed samples (VWC_u), as determined at (A) 5 kPa, (B) 10 kPa and (C) 100 kPa.

all compacted samples was higher than that of undisturbed samples. This was probably due to the presence of more micropores in the case of compacted samples which resulted in a greater volumetric water content of compacted samples at 100 kPa. Pores of the compacted samples also had a more even distribution than the pores of undisturbed samples.

The standard error of the relationship between volumetric water content of undisturbed samples at 5 kPa and volumetric water content of rubber ring samples at 5 kPa was 0.046. This was almost the same as the standard error of the relationship between volumetric water content of undisturbed samples at 5 kPa and volumetric water content of compacted samples at 5 kPa which was 0.051. The standard error of the relationship between volumetric water content of undisturbed samples at 10 kPa and volumetric water content of rubber ring samples at 10 kPa was 0.062. This was slightly higher than the standard error of the relationship between volumetric water content of undisturbed samples at 10 kPa and volumetric water content of compacted samples at 10 kPa which was 0.058. The standard error of the relationship between volumetric water content of undisturbed samples at 100 kPa and volumetric water content of compacted samples at 100 kPa was 0.060. This was almost twice the standard error of the relationship between volumetric water content of undisturbed samples at 100 kPa and volumetric water content of rubber ring samples at 100 kPa which was 0.032.

4.4.1 Water holding capacity

Water holding capacity of undisturbed, rubber ring and compacted samples is given in Table 4.8. Water holding capacity of undisturbed samples between 5 and 100 kPa ranged from 58.7 mm.m⁻¹ to approximately 318.0 mm.m⁻¹. Water holding capacity of undisturbed samples between 10 and 100 kPa ranged from 32.9 mm.m⁻¹ to 315.0 mm.m⁻¹. Water holding capacity of rubber ring samples between 5 and 100 kPa ranged from 88.1 mm.m⁻¹ to 397.2 mm.m⁻¹. Water holding capacity of rubber ring samples between 10 and 100 kPa ranged from 30.7 mm.m⁻¹ to approximately 334.8 mm.m⁻¹. Water holding capacity of compacted samples between 5 and 100 kPa ranged from 30.3 mm.m⁻¹ to approximately 225.0 mm.m⁻¹. Water holding capacity of compacted samples between 10 and 100 kPa ranged from 23.1 mm.m⁻¹ to approximately 148.1 mm.m⁻¹.

4.4.2 Water holding capacity: undisturbed samples

Water holding capacity is strongly influenced by soil texture (Hillel, 1980), which has an important effect on pore geometry and configuration (Beukes, 1984). Texture is an expression of the predominant size, or size range of the particles in the soil (Hillel, 1971) and refers to the feel of soil material. According to the Canola Connection (2001), the amount of water that can be stored varies widely among soils and depends on the number and size of pore spaces they contain. The number and size of pore spaces in a soil depends on its texture, organic matter content and structure.

Table 4.8. Water holding capacity ($\text{mm}\cdot\text{m}^{-1}$) of soils determined by means of undisturbed, rubber ring and compacted samples.

Clay (%)	Silt (%)	Undisturbed		Rubber ring		Compacted	
		samples		samples		samples	
		5-100 kPa	10-100 kPa	5-100 kPa	10-100 kPa	5-100 kPa	10-100 kPa
4.8	1.0	195.4	165.5	397.2	168.4	153.8	74.7
7.2	0.8	233.2	119.6	397.0	180.0	201.6	91.5
4.0	7.6	178.1	144.2	353.4	248.6	175.1	137.6
6.4	4.8	215.1	157.8	345.5	278.4	179.4	130.3
17.0	5.2	204.0	159.1	334.0	229.0	221.2	114.9
6.4	3.6	296.7	207.3	352.6	334.8	158.2	91.0
18.8	16.2	166.2	141.5	317.0	265.5	51.4	36.0
6.0	3.2	311.2	225.8	395.9	211.8	225.0	104.3
11.6	5.6	294.4	254.4	351.4	220.6	201.8	124.1
2.4	2.8	287.9	260.6	347.3	205.9	110.3	51.6
3.3	1.5	86.6	62.4	221.8	92.7	61.5	45.8
4.1	1.5	103.1	61.3	228.5	102.8	73.5	49.3
17.0	10.0	265.7	224.0	363.4	319.8	117.7	91.0
9.2	4.4	236.3	224.0	361.6	265.5	149.6	77.5
5.6	3.8	318.0	315.0	370.0	192.0	128.3	76.6
7.2	2.4	246.2	217.6	339.0	145.0	143.3	105.1
1.6	1.7	63.0	34.3	121.6	61.3	58.8	31.1
0.8	0.4	58.7	32.9	88.1	30.7	66.7	24.7
1.6	0.4	63.8	45.8	106.9	35.6	56.5	21.5
5.5	5.3	159.8	114.9	213.0	109.0	86.4	48.5
16.8	9.0	137.8	113.6	247.4	125.7	30.3	23.1
26.2	17.2	83.8	59.1	246.7	195.2	97.0	31.1
11.0	14.0	144.4	98.8	264.0	235.0	210.8	148.1
11.5	15.2	136.6	104.1	239.7	153.7	107.3	52.5

Table 4.9 is a summary of the data that will be discussed in the following paragraphs. Water holding capacity of undisturbed samples between 5 and 100 kPa was poorly correlated with the clay and silt contents thereof (graphs not shown). Clay plus silt content together also did not give a good correlation with water holding capacity of undisturbed samples between 5 and 100 kPa (graph not shown). Fine sand content gave a good correlation with the water holding capacity of undisturbed samples between 5 and 100 and was 75% (Fig. 4.17). Medium sand content explained only 50% of the variation in the water holding capacity of undisturbed samples between 5 and 100 kPa (Fig. 4.18).

Water holding capacity of undisturbed samples between 10 and 100 kPa was also extremely poorly correlated with clay, silt, clay plus silt and sand contents thereof (graphs not shown). Water holding capacity of undisturbed samples between 10 and 100 had a 62% correlation with fine sand content (Fig. 4.19). Medium sand content explained 42% of the variation in water holding capacity of undisturbed samples between 10 and 100 kPa (Fig. 4.20).

4.4.3 Water holding capacity: rubber ring samples

Water holding capacity of rubber ring samples between 5 and 100 kPa was very poorly correlated with the clay and silt contents thereof (graphs not shown). There was no correlation between total sand content of rubber ring samples and water holding capacity thereof between 5 and 100 kPa (graph not shown). However, fine sand content and water holding capacity of rubber ring samples between 5 and 100 had a 87% correlation (Fig. 4.21). Medium sand content was also extremely well correlated with water holding capacity of rubber ring samples between 5 and 100 kPa (Fig. 4.22). Water holding capacity had a 81% correlation with medium sand.

Water holding capacity of rubber ring samples between 10 and 100 kPa had a 19% correlation with clay content (graph not shown). Silt content explained only 16% of the variation in the water holding capacity of rubber ring samples between 10 and 100 kPa (graph not shown). Clay plus silt content together gave a correlation of 20% between clay plus silt content and water holding capacity of rubber ring samples between 10 and 100 kPa (graph not shown). Total sand content of rubber ring samples gave a correlation of 20% between water holding capacity of rubber ring samples between 10 and 100 kPa and total sand content of rubber ring samples (graph not shown). The correlation between fine sand content and water holding capacity of rubber ring samples between 10 and 100 was 57% (Fig. 4.23). Medium sand content of rubber ring samples showed a better correlation with water holding capacity of these samples between 10 and 100 kPa and explained 74% of the variation in the water holding capacity thereof (Fig. 4.24).

4.4.4 Water holding capacity: compacted samples

Water holding capacity of compacted samples between 5 and 100 kPa was not at all correlated with the clay, silt, clay plus silt and total sand contents thereof (graphs not shown). Water holding

Table 4.9. Matrix table summarising the correlations of water holding capacity of undisturbed (WHC_u), rubber ring (WHC_{rr}) and compacted (WHC_c) samples between 5 and 100 kPa and 10 and 100 kPa 100 kPa with textural properties of the soils.

Sample	Soil textural property	Coefficient of determination (r^2)	
		5-100 kPa	10-100 kPa
WHC_u	Clay	0	0
WHC_u	Silt	1	0
WHC_u	Clay plus silt	0	0
WHC_u	Total sand	0	0
WHC_u	Fine sand	75	62
WHC_u	Medium sand	50	42
WHC_{rr}	Clay	5	19
WHC_{rr}	Silt	0	16
WHC_{rr}	Clay plus silt	2	20
WHC_{rr}	Total sand	2	20
WHC_{rr}	Fine sand	87	57
WHC_{rr}	Medium sand	81	74
WHC_c	Clay	0	3
WHC_c	Silt	0	2
WHC_c	Clay plus silt	0	3
WHC_c	Total sand	0	3
WHC_c	Fine sand	57	46
WHC_c	Medium sand	40	46

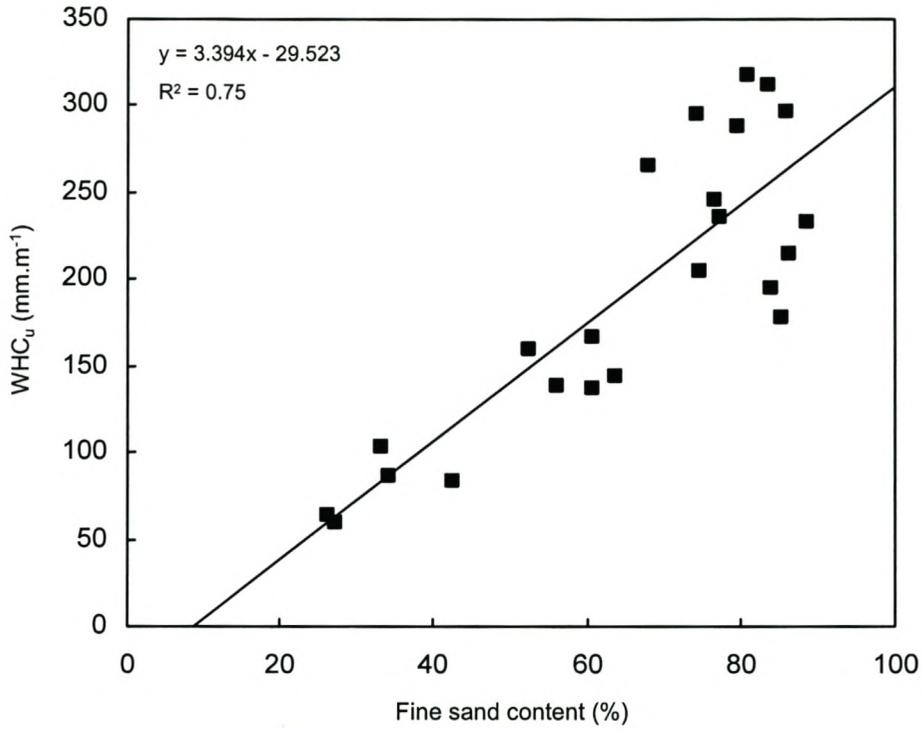


Figure 4.17. The influence of fine sand content (%) on the water holding capacity of undisturbed samples (WHC_u) between 5 and 100 kPa .

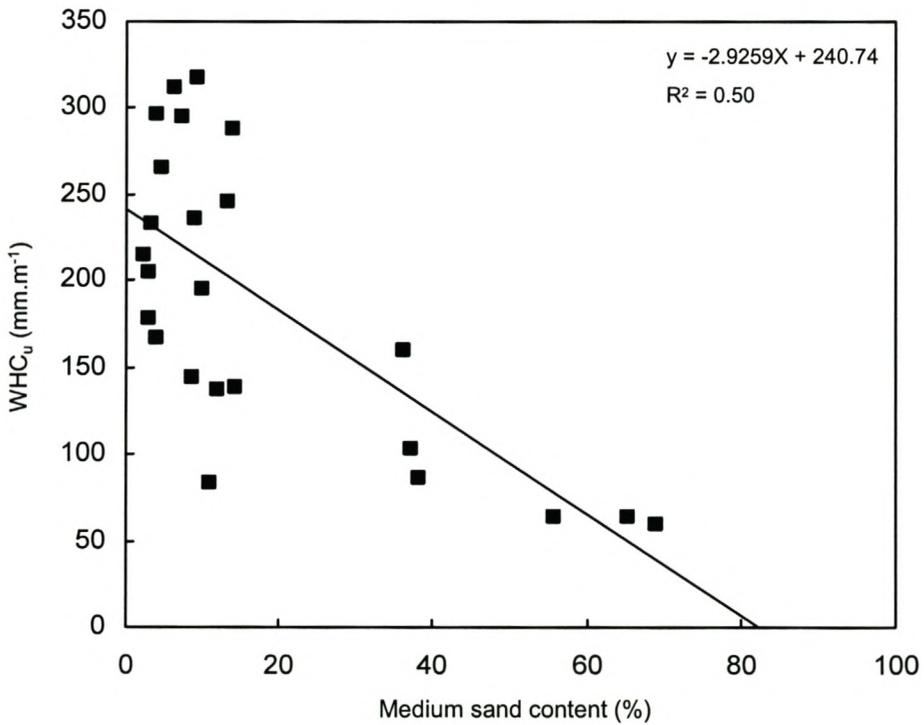


Figure 4.18. The influence of medium sand content (%) on the water holding capacity of undisturbed samples (WHC_u) between 5 and 100 kPa .

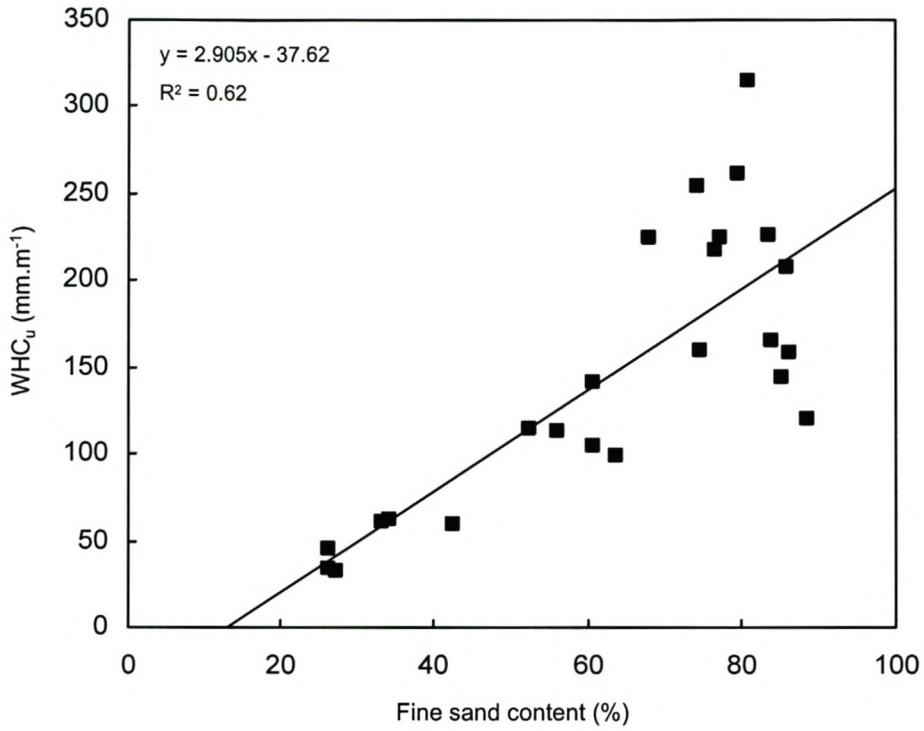


Figure 4.19. The influence of fine sand content (%) on the water holding capacity of undisturbed samples (WHC_u) between 10 and 100 kPa.

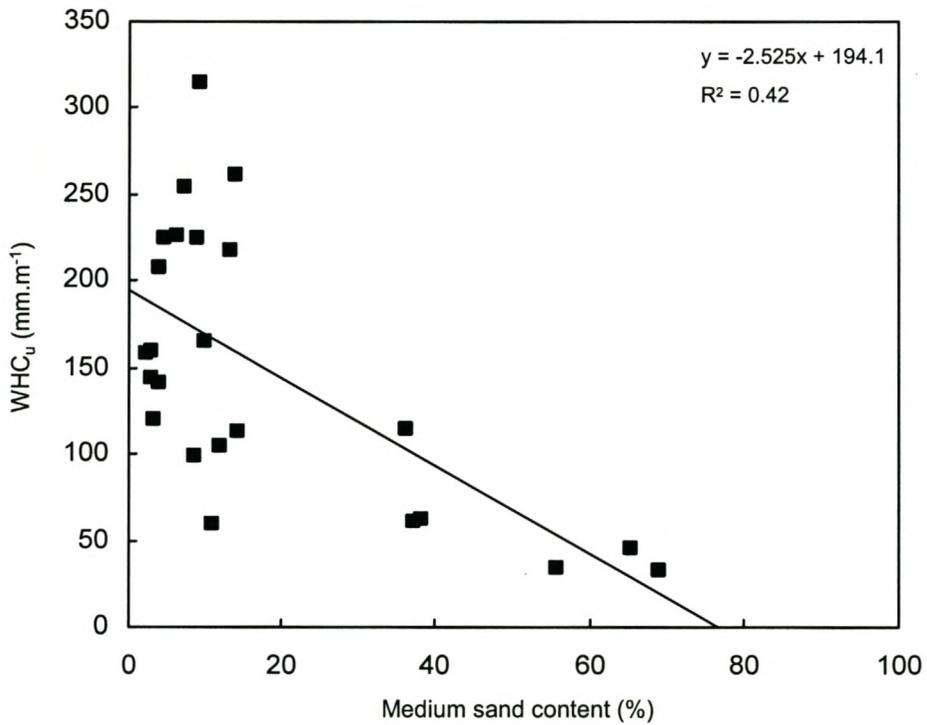


Figure 4.20. The influence of medium sand content (%) on the water holding of undisturbed samples (WHC_u) between 10 and 100 kPa.

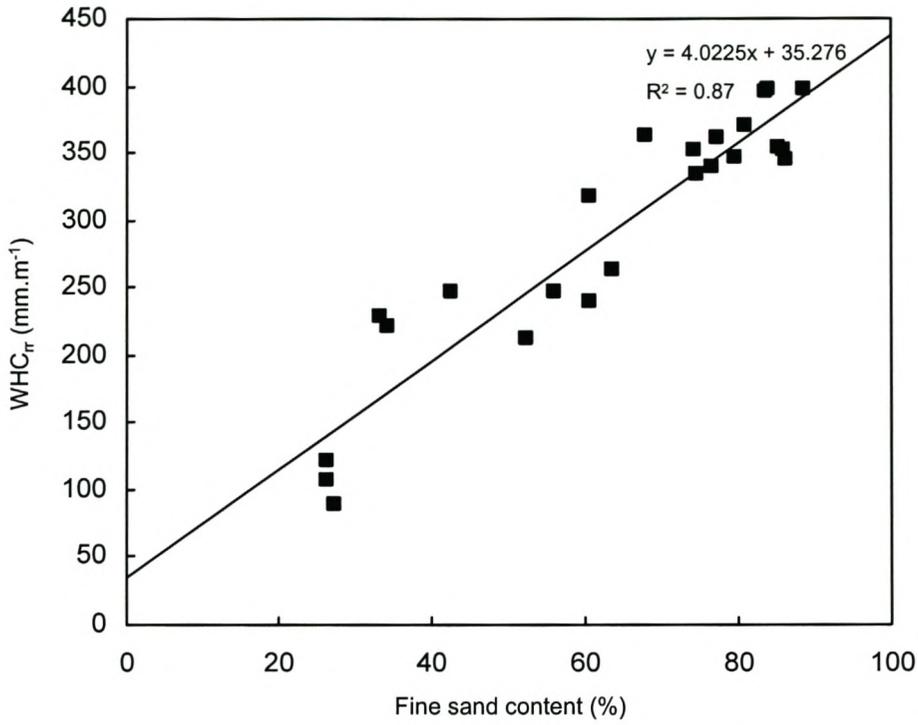


Figure 4.21. The influence of fine sand content (%) on the water holding capacity of rubber ring samples (WHC_{rr}) between 5 and 100 kPa.

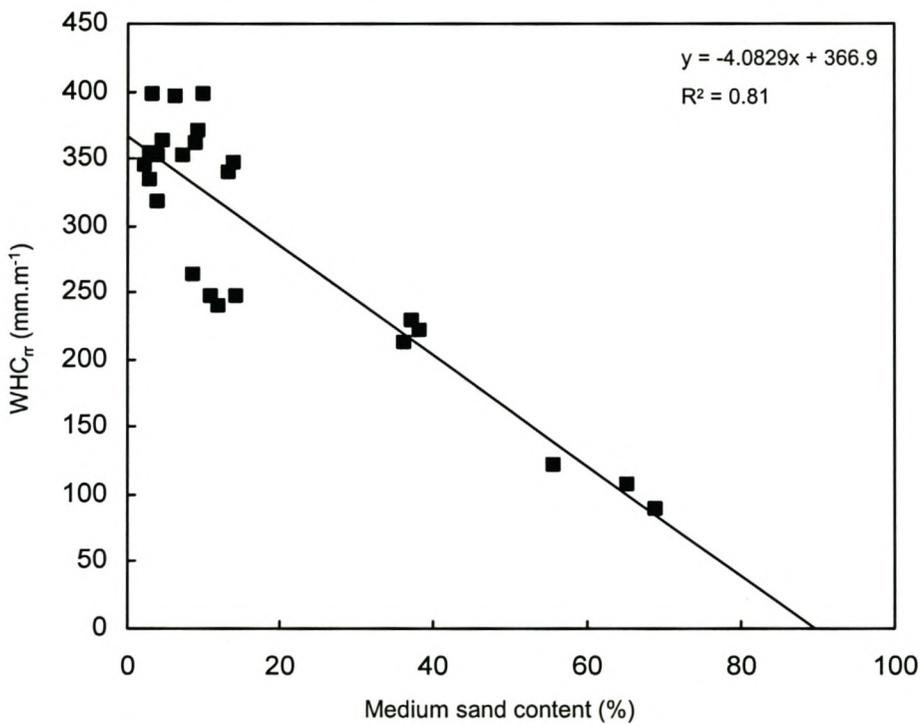


Figure 4.22. The influence of medium sand content (%) on the water holding capacity of rubber ring samples (WHC_{rr}) between 5 and 100 kPa.

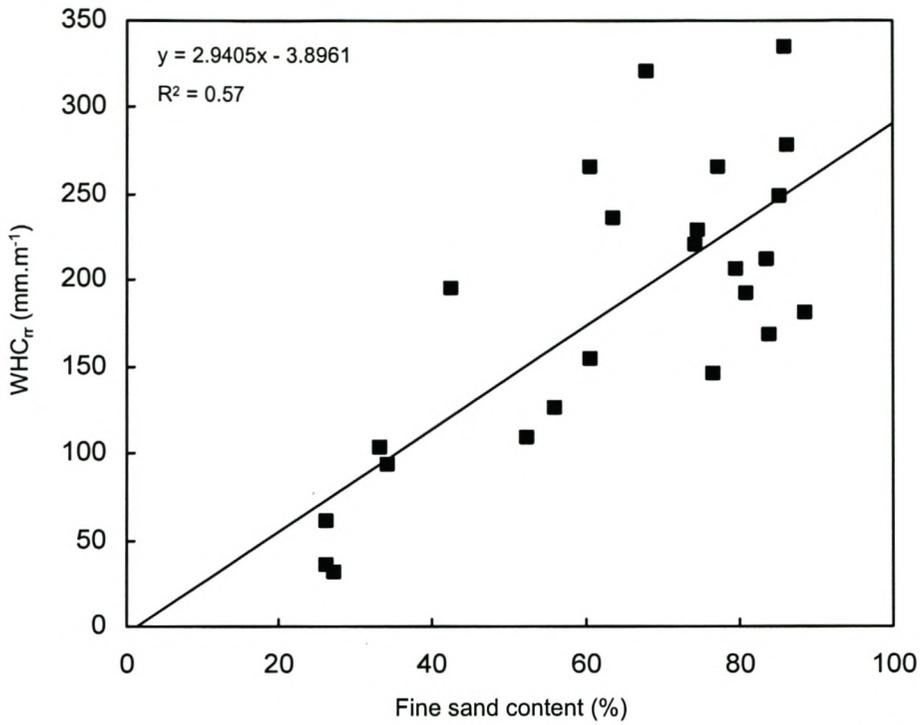


Figure 4.23. The influence of fine sand content (%) on the water holding capacity of rubber ring samples (WHC_{rr}) between 10 and 100 kPa .

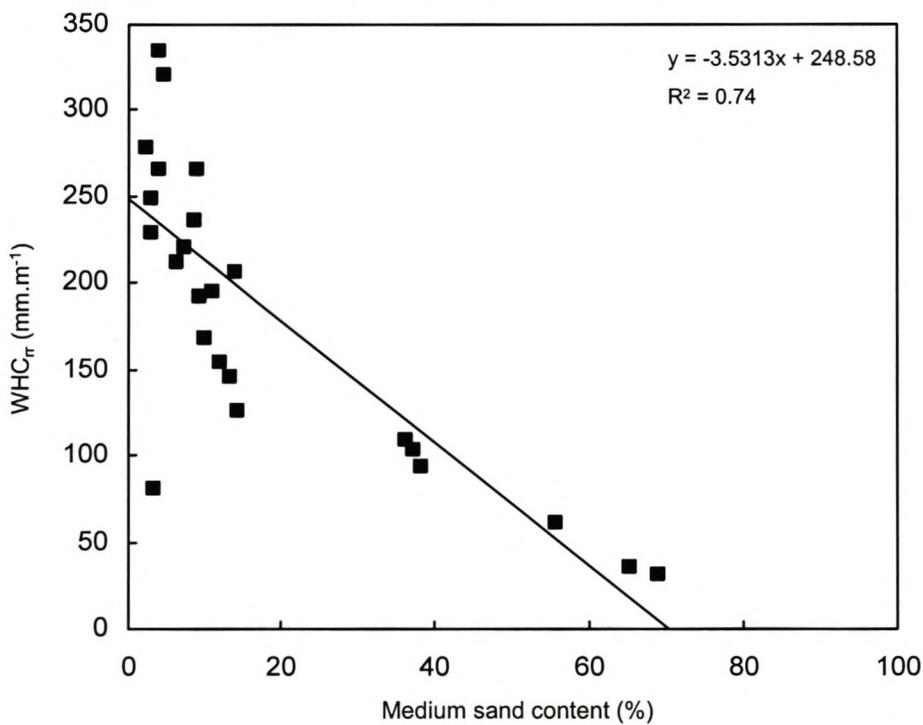


Figure 4.24. The influence of medium sand content (%) on the water holding capacity of rubber ring samples (WHC_{rr}) between 10 and 100 kPa .

capacity of compacted samples between 5 and 100 kPa had a 57% correlation with fine sand content (Fig. 4.25). Medium sand content explained only 40% of the variation in water holding capacity of compacted samples between 5 and 100 kPa (Fig. 4.26).

Water holding capacity of compacted samples between 10 and 100 kPa was not at all correlated with clay content thereof (graph not shown). Silt content of compacted samples was extremely poorly correlated with water holding capacity of compacted samples between 10 and 100 kPa (graph not shown). Clay plus silt content together gave no correlation between clay plus silt content and water holding capacity of compacted samples between 10 and 100 kPa (graph not shown). Total sand content of compacted samples gave no correlation between water holding capacity of compacted samples between 10 and 100 kPa and total sand content thereof (graph not shown). Water holding capacity of compacted samples between 10 and 100 kPa had a 46% correlation with fine and medium sand content (Fig. 4.27 and Fig. 4.28).

4.4.5 Water holding capacity: a comparison

Water holding capacity in the low suction range is strongly influenced by pore size distribution (Hillel, 1971). From the above results, it was clear that clay, silt and clay plus silt content did not influence the water holding capacity of undisturbed samples and compacted samples. In the case of the water holding capacity of rubber ring samples between 5 and 100 kPa, clay, silt and clay plus silt content also did not influence the water holding capacity of the soils. However, in the case of the water holding capacity of rubber ring samples between 10 and 100 kPa, clay, silt and clay plus silt content slightly influenced the water holding capacity of the samples.

Water holding capacity of undisturbed samples, rubber ring samples and compacted samples between 5 and 100 kPa was strongly influenced by fine sand content of the samples. In the case of rubber ring samples between 5 and 100 kPa, medium sand content also had a strong influence on the water holding capacity thereof.

Water holding capacity of all the rubber ring samples between 5 and 100 kPa was greater than that of the undisturbed samples between 5 and 100 kPa (Fig. 4.29A). Water holding capacity of rubber ring samples therefore generally overestimated the water holding capacity of the soil. This was mainly because volumetric water content of the rubber ring samples at 5 kPa was greater than the volumetric water content of the undisturbed samples at 5 kPa. Volumetric water content of rubber ring samples at 100 kPa was also generally less than the volumetric water content of undisturbed samples at 100 kPa. Water holding capacity of rubber ring samples between 5 and 100 kPa had a 75% correlation with water holding capacity of undisturbed samples between 5 and 100 kPa (Fig. 4.29A).

Water holding capacity of rubber ring samples between 5 and 100 kPa was on average 1.7 times greater than water holding capacity of undisturbed samples between 5 and 100 kPa. The degree by

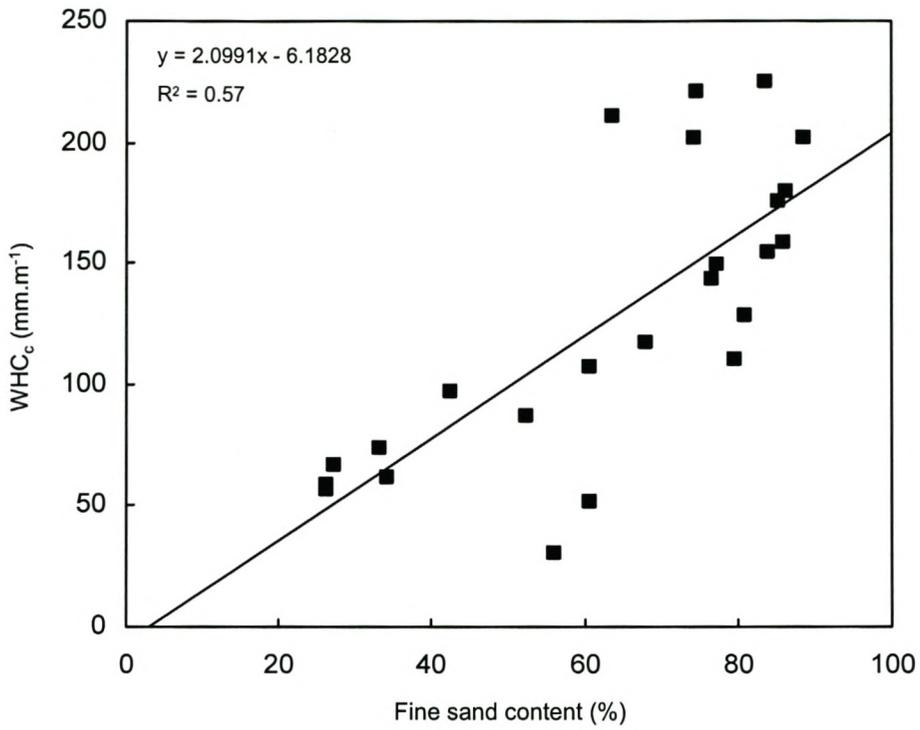


Figure 4.25. The influence of fine sand content (%) on the water holding capacity of compacted samples (WHC_c) between 5 and 100 kPa .

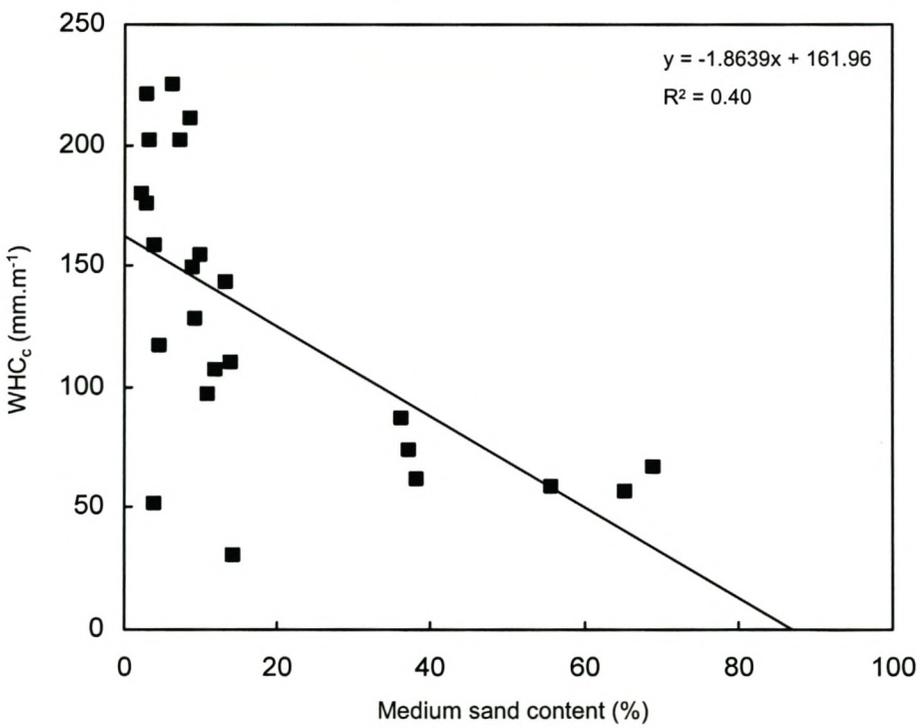


Figure 4.26. The influence of medium sand content (%) on the water holding capacity of compacted samples (WHC_c) between 5 and 100 kPa .

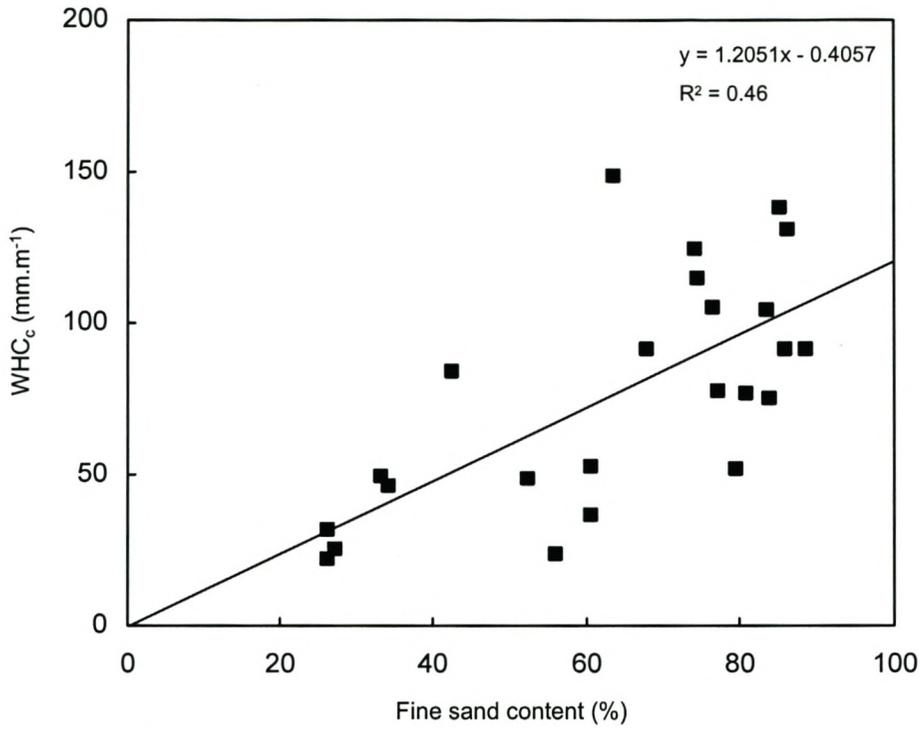


Figure 4.27. The influence of fine sand content (%) on the water holding capacity of compacted samples (WHC_c) between 10 and 100 kPa.

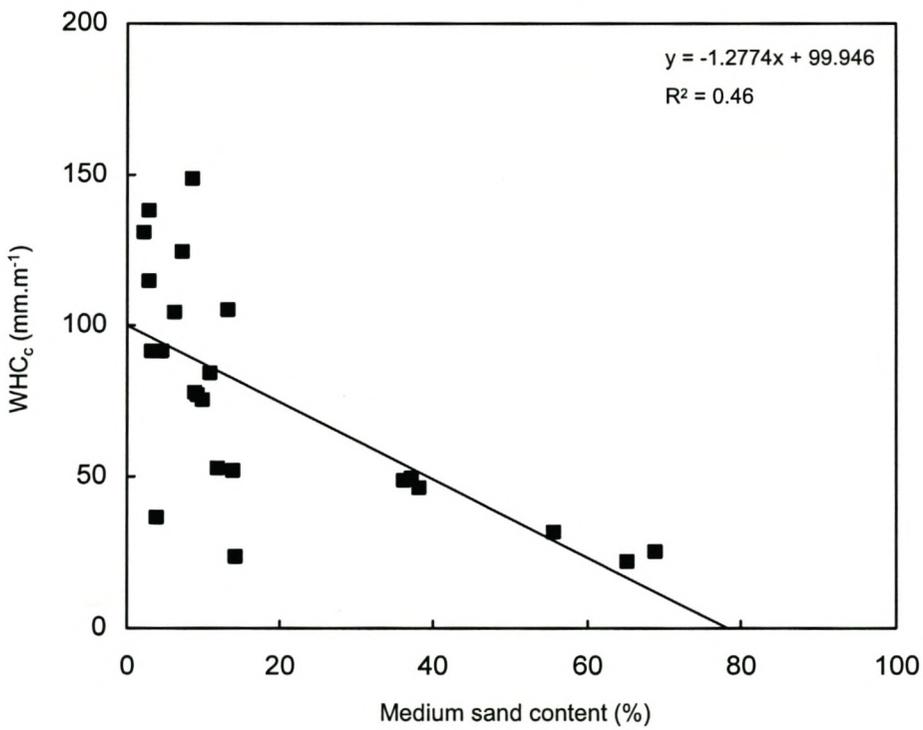


Figure 4.28. The influence of medium sand content (%) on the water holding capacity of compacted samples (WHC_c) between 10 and 100 kPa .

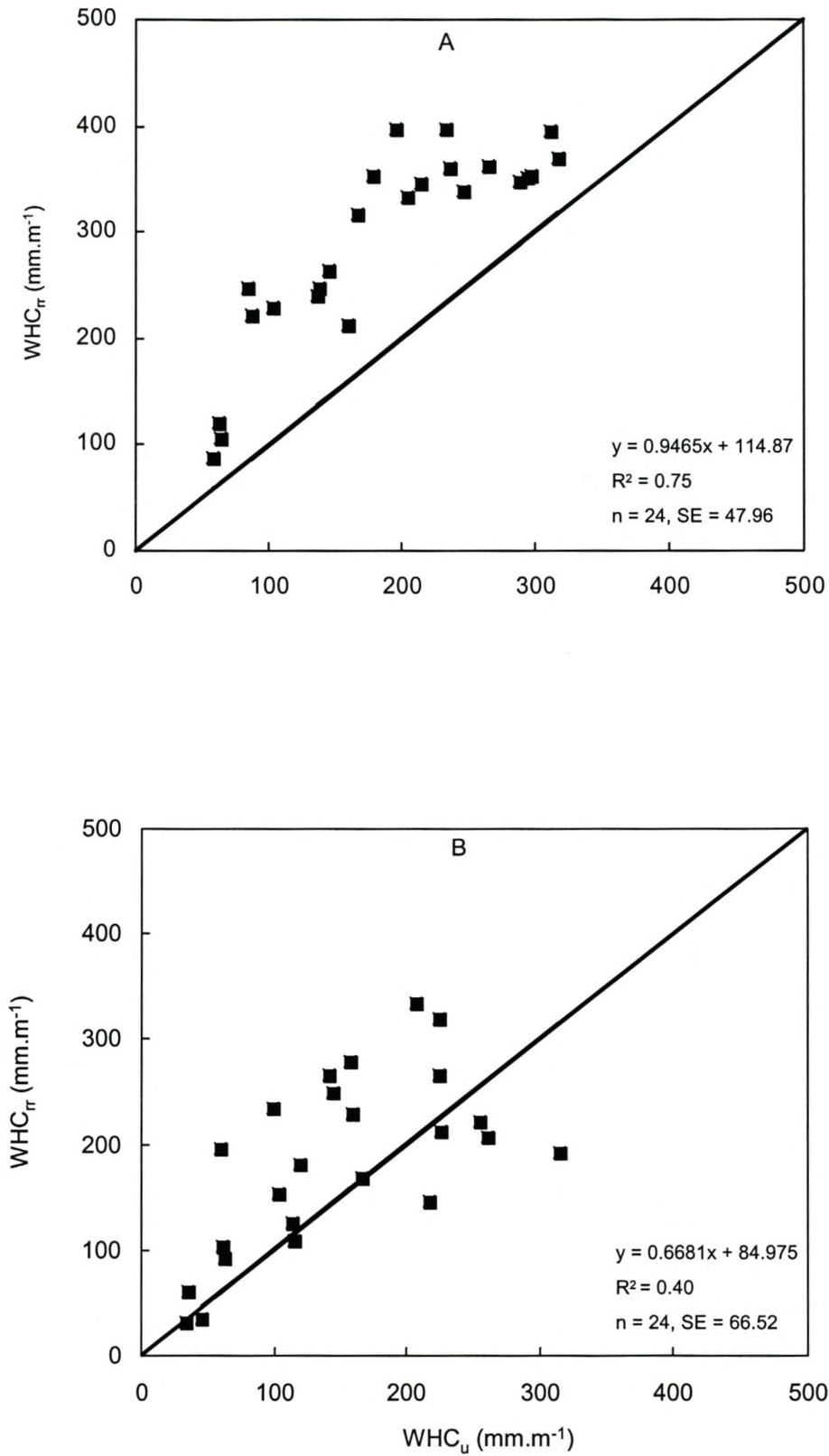


Figure 4.29. Relationship between water holding capacity of rubber ring samples (WHC_r) and water holding capacity of undisturbed samples (WHC_u), as determined between (A) 5 and 100 kPa and (B) 10 and 100 kPa.

which the water holding capacity of undisturbed samples between 5 and 100 kPa was overestimated by rubber ring samples ranged from 1.2 to 2.9. The average overestimation of the water holding capacity of the rubber ring samples in relation to the water holding capacity of undisturbed samples, was 104 mm.m^{-1} , with the minimum overestimation of 29.44 mm.m^{-1} and the maximum overestimation approximately 201.8 mm.m^{-1} .

Water holding capacity of most of the rubber ring samples between 10 and 100 kPa was greater than the water holding capacity of undisturbed samples (Fig. 4.29B). There were, however, eight rubber ring samples whose water holding capacity between 10 and 100 kPa was lower than that of the undisturbed samples. Water holding capacity of rubber ring samples between 10 and 100 kPa had only a 40% correlation with water holding capacity of undisturbed samples between 10 and 100 (Fig. 4.29B). This was not as good as the correlation between water holding capacity of rubber ring samples between 5 and 100 kPa and water holding capacity of undisturbed samples between 5 and 100 kPa.

The rubber ring samples that underestimated the water holding capacity between 10 and 100 kPa on average generally gave a water holding capacity of the soil that was 0.82 of the water holding capacity of undisturbed samples. In the case of the water holding capacity of rubber ring samples between 10 and 100 kPa that was greater than that of the undisturbed samples, the water holding capacity of the rubber ring samples between 10 and 100 kPa was on average 1.7 times greater than that of the undisturbed samples between 10 and 100 kPa. The water holding capacity determined by the rubber ring samples between 10 and 100 kPa ranged from being in the same range as the water holding capacity of the undisturbed samples between 10 and 100 kPa to approximately three times the water holding capacity of the undisturbed samples between 10 and 100 kPa.

Water holding capacity of compacted samples between 5 and 100 kPa was less than the water holding capacity of undisturbed samples between 5 and 100 kPa (graph not shown). Compacted samples therefore generally underestimated the water holding capacity of the soil. This was probably due to the fact that volumetric water content of compacted samples at 100 kPa was greater than the volumetric water content of undisturbed samples at 100 kPa. Water holding capacity of compacted samples between 5 and 100 kPa was correlated 39% with water holding capacity of undisturbed samples between 5 and 100 kPa (graph not shown).

The water holding capacity of compacted samples between 5 and 100 kPa was on average 0.74 times the magnitude of the water holding capacity of the undisturbed samples between 5 and 100 kPa. The maximum overestimation of the water holding capacity of the compacted samples between 5 and 100 kPa in relation to the water holding capacity of undisturbed samples between 5 and 100 kPa was 66.4 mm.m^{-1} , with the maximum underestimation of 189.7 mm.m^{-1} .

The water holding capacity of most of the compacted samples between 10 and 100 kPa was less than the water holding capacity of the undisturbed samples between 10 and 100 kPa (graph not

shown). There were, however, two compacted samples whose water holding capacity between 10 and 100 kPa was greater than that of the undisturbed samples. Water holding capacity of compacted samples between 10 and 100 kPa had only a 18% correlation with water holding capacity of undisturbed samples between 10 and 100 kPa (graph not shown). Water holding capacity of compacted samples between 10 and 100 kPa were generally 62% that of the water holding capacity of the undisturbed samples between 10 and 100 kPa.

The standard error of the relationship between water holding capacity of undisturbed samples between 5 and 100 kPa and water holding capacity of rubber ring samples between 5 and 100 kPa was 47.95. This was almost the same as the standard error between water holding capacity of undisturbed samples between 5 and 100 kPa and water holding capacity of compacted samples between 5 and 100 kPa and was 47.70. Rubber samples and compacted samples therefore determined the water holding capacity between 5 and 100 kPa with the same degree of accuracy. The standard error of the relationship between water holding capacity of undisturbed samples between 10 and 100 kPa and water holding capacity of rubber ring samples between 10 and 100 kPa was 66.52. This was almost twice the standard error of the relationship between water holding capacity of undisturbed samples between 10 and 100 kPa and water holding capacity of compacted samples between 10 and 100 kPa which was 35.28. Rubber ring samples therefore proved to be less accurate than the compacted samples when determining the water holding capacity between 10 and 100 kPa.

CHAPTER 5

RESULTS AND DISCUSSION: PROPOSED MODELS TO PREDICT VOLUMETRIC WATER CONTENT AND WATER HOLDING CAPACITY OF SOIL FROM TEXTURE IN COARSE-TEXTURED SOILS

5.1 Introduction

After examining the scatter plots (not shown), it became clear that clay, silt, clay plus silt, total sand, fine sand and medium sand content variables showed non-linear trends. It was therefore essential to add additional terms before the data were subjected to the stepwise regression procedure.

The following additional terms were added, namely $e^{-\text{clay content}}$, the inverse of clay content, the inverted square root of clay content, $e^{-\text{silt content}}$, the inverse of silt content, the ln of silt content and the inverted square root of silt content. Four additional terms were added for the clay plus silt content variable. These were $e^{-\text{clay plus silt content}}$, the inverse of clay plus silt content, the ln of clay plus silt content and the inverted square root of clay plus silt content.

Two additional terms were added to the total sand content variable, namely the cube of the total sand content and $e^{\text{total sand content}}$. Additional terms were also added to the fine sand variable. These terms were the inverted square of fine sand content, the inverse of fine sand content, the ln of fine sand content and the inverted square root of fine sand content. Only two additional terms were added to the medium sand content variable, namely the square root of medium sand content and the ln of medium sand content.

The stone content variable also showed non-linear trends and two additional terms were added. These two terms were $e^{-\text{stone content}}$ and the square root of stone content.

5.2 Proposed models: volumetric water content

The final models produced by the stepwise regression to predict volumetric water content of undisturbed samples, rubber ring samples and compacted samples at 5, 10 and 100 kPa are given in Table 5.1. The predicted volumetric water content for undisturbed samples, rubber ring samples and compacted samples at 5, 10 and 100 kPa was calculated by means of these models (Tables 5.2, 5.3 and 5.4).

The actual volumetric water content of undisturbed samples at 5 kPa ranged from 0.0766 mm.mm⁻¹ to approximately 0.4178 mm.mm⁻¹, whilst the predicted volumetric water content of undisturbed samples at 5 kPa ranged from 0.0806 mm.mm⁻¹ to approximately 0.3910 mm.mm⁻¹ (Table 5.2). The actual volumetric water content of undisturbed samples at 10 kPa ranged from 0.0509 mm.mm⁻¹ to

Table 5.1. Equations of models to predict volumetric water content of undisturbed samples (VWC_u), rubber ring samples (VWC_{rr}) and compacted samples (VWC_c) at 5 kPa, 10 kPa and 100 kPa.

kPa	Equations	R^2 (%)
	$VWC = a + b (s) + c (t) + d (t)^{0.5} + e \ln (t) + f (\ln x) + g (x) + h (e^y) + i (y)^{-0.5}$	
5	$VWC_u = 0.47259 - 0.04712 \text{ medium sand}^{0.5}$	88.4
10	$VWC_u = 0.41292 - 0.04221 \text{ medium sand}^{0.5}$	78.0
100	$VWC_u = 0.48080 - 0.00254 \text{ fine sand} - 0.0865 \ln \text{ medium sand}$	63.9
5	$VWC_{rr} = 0.47940 + 0.13866 (\text{clay plus silt})^{0.5} - 0.00712 \text{ medium sand}$	96.7
10	$VWC_{rr} = 0.48282 + 0.046 \ln \text{ silt} + 0.00595 \text{ medium sand} - 0.0978 \text{ medium sand}^{0.5}$	92.2
100	$VWC_{rr} = 0.12958 + 0.00603 \text{ silt} - 0.0274 \ln \text{ medium sand}$	87.8
5	$VWC_c = 0.5360 + 0.293 e^{\text{clay plus silt}} - 0.0636 \text{ medium sand}^{0.5}$	90.9
10	$VWC_c = 0.4660 + 0.00622 \text{ silt} + 0.00437 \text{ medium sand} - 0.0874 \text{ medium sand}^{0.5}$	92.5
100	$VWC_c = 0.2410 + 0.0037 \text{ clay plus silt} - 0.0300 \text{ medium sand}^{0.5}$	87.4

Table 5.2. Actual (VWC_A) and predicted volumetric water content (VWC_P) of undisturbed samples used to determine water holding capacity of soils.

Site number	Depth (cm)	5 kPa		10 kPa		100 kPa	
		VWC_A	VWC_P	VWC_A	VWC_P	VWC_A	VWC_P
1	0-70	0.3064	0.3236	0.2766	0.2794	0.1236	0.0678
1	70-100	0.3557	0.3883	0.2420	0.3374	0.1144	0.1546
2	0-30	0.4178	0.3910	0.3839	0.3398	0.2397	0.1689
2	30-90	0.3933	0.3996	0.3360	0.3475	0.1749	0.1856
3	0-30	0.3753	0.3910	0.3304	0.3398	0.1691	0.1958
3	30-100	0.4152	0.3784	0.3258	0.3285	0.1185	0.1424
4	0-30	0.4138	0.3784	0.3892	0.3285	0.2599	0.2065
4	30-90	0.3581	0.3534	0.2727	0.3061	0.0469	0.1079
5	0-25	0.3750	0.3462	0.3350	0.2997	0.0830	0.1211
5	25-90	0.3798	0.2962	0.3526	0.2550	0.1056	0.0498
6	0-20	0.1482	0.1810	0.1242	0.1517	0.0618	0.0789
6	20-60	0.1601	0.1848	0.1184	0.1551	0.0570	0.0834
7	0-50	0.3814	0.3715	0.3397	0.3223	0.1341	0.1756
7	50-80	0.3079	0.3312	0.2957	0.2862	0.0913	0.0941
8	0-30	0.3678	0.3281	0.3653	0.2835	0.0460	0.0807
8	30-90	0.2735	0.3001	0.2225	0.2584	0.0927	0.0612
9	0-30	0.0954	0.1209	0.0667	0.0979	0.0324	0.0660
10	0-30	0.0766	0.0806	0.0509	0.0618	0.0180	0.0452
11	0-30	0.1731	0.0909	0.1597	0.0710	0.1093	0.0518
12	0-30	0.1763	0.1890	0.1314	0.1590	0.0165	0.0370
13	0-30	0.2520	0.2950	0.2270	0.2539	0.1141	0.1091
14	0-30	0.2889	0.3163	0.2661	0.2729	0.2068	0.1657
15	20-40	0.3041	0.3352	0.2586	0.2899	0.1597	0.1339
16	20-40	0.2853	0.3100	0.2248	0.2673	0.1207	0.1121

Table 5.3. Actual (VWC_A) and predicted volumetric water content (VWC_P) of rubber ring samples used to determine water holding capacity of soils.

Site number	Depth (cm)	5 kPa		10 kPa		100 kPa	
		VWC _A	VWC _P	VWC _A	VWC _P	VWC _A	VWC _P
1	0-70	0.4650	0.4658	0.2360	0.2330	0.0670	0.0725
1	70-100	0.4730	0.5056	0.2560	0.3166	0.0760	0.1025
2	0-30	0.5230	0.4988	0.4150	0.4246	0.1660	0.1453
2	30-90	0.4700	0.5037	0.3990	0.4177	0.1210	0.1345
3	0-30	0.5040	0.4875	0.3990	0.4071	0.1700	0.1308
3	30-100	0.4640	0.4948	0.4460	0.3699	0.1110	0.1133
4	0-30	0.5030	0.4744	0.4520	0.4391	0.1860	0.1893
4	30-90	0.4830	0.4795	0.2990	0.3270	0.0870	0.0980
5	0-25	0.5050	0.4616	0.3600	0.3425	0.1390	0.1093
5	25-90	0.4410	0.4405	0.2890	0.2475	0.0830	0.0742
6	0-20	0.2780	0.2700	0.1490	0.1241	0.0560	0.0387
6	20-60	0.2780	0.2724	0.1520	0.1261	0.0490	0.0395
7	0-50	0.4700	0.4733	0.4270	0.4064	0.1070	0.1481
7	50-80	0.4490	0.4529	0.3530	0.3111	0.0870	0.0959
8	0-30	0.4560	0.4577	0.2780	0.3003	0.0860	0.0911
8	30-90	0.4260	0.4287	0.2330	0.2448	0.0880	0.0729
9	0-30	0.1350	0.1591	0.0750	0.1087	0.0140	0.0297
10	0-30	0.1030	0.1133	0.0460	0.0388	0.0150	0.0159
11	0-30	0.1210	0.1104	0.0500	0.0389	0.0140	0.0174
12	0-30	0.2670	0.2638	0.1630	0.1864	0.0540	0.0632
13	0-30	0.3520	0.4056	0.2310	0.2998	0.1050	0.1112
14	0-30	0.4240	0.4221	0.3730	0.3548	0.1773	0.1676
15	20-40	0.4400	0.4466	0.4110	0.3697	0.1760	0.1554
16	20-40	0.3730	0.4215	0.2870	0.3414	0.1333	0.1534

Table 5.4. Actual (VWC_A) and predicted volumetric water content (VWC_P) of compacted samples used to determine water holding capacity of soils.

Site number	Depth (cm)	5 kPa		10 kPa		100 kPa	
		VWC _A	VWC _P	VWC _A	VWC _P	VWC _A	VWC _P
1	0-70	0.3086	0.3358	0.2296	0.2395	0.1549	0.1677
1	70-100	0.3503	0.4223	0.2882	0.3286	0.2265	0.2171
2	0-30	0.4358	0.4258	0.3933	0.3750	0.2607	0.2321
2	30-90	0.4245	0.4374	0.3754	0.3709	0.2451	0.2361
3	0-30	0.4622	0.4258	0.3560	0.3601	0.2410	0.2713
3	30-100	0.4461	0.4088	0.3789	0.3311	0.2879	0.2181
4	0-30	0.4375	0.4088	0.4212	0.4094	0.3860	0.3106
4	30-90	0.3531	0.3751	0.2324	0.2928	0.1280	0.1992
5	0-25	0.4217	0.3653	0.3440	0.2978	0.1913	0.2242
5	25-90	0.2805	0.2996	0.2218	0.2176	0.1702	0.1480
6	0-20	0.1171	0.1448	0.1015	0.1018	0.0710	0.0731
6	20-60	0.1337	0.1487	0.1096	0.1045	0.0630	0.0785
7	0-50	0.3528	0.3996	0.3140	0.3609	0.2709	0.2767
7	50-80	0.3536	0.3452	0.2707	0.2705	0.2040	0.2014
8	0-30	0.3404	0.3410	0.2884	0.2628	0.2121	0.1839
8	30-90	0.2761	0.3032	0.2380	0.2195	0.1328	0.1668
9	0-30	0.0887	0.0721	0.0610	0.0677	0.0299	0.0292
10	0-30	0.0864	0.0952	0.0443	0.0438	0.0196	-0.0043
11	0-30	0.0806	0.0605	0.0456	0.0472	0.0241	0.0530
12	0-30	0.1817	0.1533	0.1437	0.1313	0.0952	0.1004
13	0-30	0.2357	0.2963	0.2286	0.2547	0.2069	0.2234
14	0-30	0.3789	0.3251	0.3656	0.3312	0.3213	0.3021
15	20-40	0.4343	0.3506	0.3719	0.3354	0.2235	0.2461
16	20-40	0.2863	0.3166	0.2315	0.3110	0.1790	0.2364

0.3892 mm.mm⁻¹. The actual volumetric water content of undisturbed samples at 100 kPa ranged from 0.0165 mm.mm⁻¹ to 0.2599 mm.mm⁻¹ (Table 5.2). The predicted volumetric water content of undisturbed samples at 10 kPa ranged from 0.0618 mm.mm⁻¹ to 0.3475 mm.mm⁻¹ and the predicted volumetric water content of undisturbed samples at 100 kPa from 0.0370 mm.mm⁻¹ to 0.2065 mm.mm⁻¹ (Table 5.2).

The model to predict the volumetric water content of undisturbed samples at 5 kPa generally overestimated the volumetric water content of the undisturbed samples when the volumetric water content ranged from 0.1 mm.mm⁻¹ to 0.3 mm.mm⁻¹. The volumetric water content of undisturbed samples was generally underestimated by the model when the volumetric water content was more than 0.3 mm.mm⁻¹. The same tendency was observed in the case of the prediction of the volumetric water content of undisturbed samples at 10 kPa. At 100 kPa, approximately half of the volumetric water content of undisturbed samples was overestimated.

The actual volumetric water content of rubber ring samples at 5 kPa ranged from 0.1030 mm.mm⁻¹ to approximately 0.5230 mm.mm⁻¹, whilst the predicted volumetric water content of rubber ring samples at 5 kPa ranged from 0.1104 mm.mm⁻¹ to approximately 0.5037 mm.mm⁻¹ (Table 5.3). The actual volumetric water content of rubber ring samples at 10 kPa ranged from 0.0460 mm.mm⁻¹ to 0.4520 mm.mm⁻¹, whilst the actual volumetric water content of rubber ring samples at 100 kPa ranged from 0.0140 mm.mm⁻¹ to 0.1860 mm.mm⁻¹ (Table 5.3). The predicted volumetric water content of rubber ring samples at 10 kPa ranged from 0.0388 mm.mm⁻¹ to 0.4391 mm.mm⁻¹, whilst the predicted volumetric water content of rubber ring samples at 100 kPa ranged from 0.0159 mm.mm⁻¹ to 0.1893 mm.mm⁻¹ (Table 5.3).

The model to predict the volumetric water content of rubber ring samples at 5 kPa generally overestimated the volumetric water content of the undisturbed samples when the volumetric water content was between 0.1 mm.mm⁻¹ and 0.5 mm.mm⁻¹. When the volumetric water content was more than 0.5 mm.mm⁻¹, the volumetric water content of the rubber ring samples was underestimated by the model. At 10 kPa, approximately half of the rubber ring samples' volumetric water content was overestimated. The same tendency was observed in the case of the prediction of the volumetric water content of rubber ring samples at 100 kPa.

The actual volumetric water content of compacted samples at 5 kPa ranged from 0.0806 mm.mm⁻¹ to approximately 0.4622 mm.mm⁻¹, whilst the predicted volumetric water content of compacted samples at 5 kPa ranged from 0.0605 mm.mm⁻¹ to approximately 0.4374 mm.mm⁻¹ (Table 5.4). The actual volumetric water content of compacted samples at 10 kPa ranged from 0.0443 mm.mm⁻¹ to 0.4212 mm.mm⁻¹. The predicted volumetric water content of compacted samples at 10 kPa ranged from 0.0438 mm.mm⁻¹ to 0.4094 mm.mm⁻¹ (Table 5.4). The actual volumetric water content of compacted samples at 100 kPa ranged from 0.0196 mm.mm⁻¹ to 0.3860 mm.mm⁻¹ (Table 5.4). The predicted volumetric water content of compacted samples at 100 kPa ranged from 0 mm.mm⁻¹ to 0.3106 mm.mm⁻¹ (Table 5.4).

At 5, 10 and 100 kPa, the models to predict the volumetric water content of compacted samples at 5 kPa, 10 and 100 kPa generally overestimated half of the compacted samples' volumetric water content.

5.3 Proposed models: water holding capacity

The final models produced by the stepwise regression to predict the water holding capacity of undisturbed samples, rubber ring samples and compacted samples between 5 and 100 kPa and 10 and 100 kPa are given in Table 5.5. The predicted water holding capacity of undisturbed samples, rubber ring samples and compacted samples between 5 and 100 kPa and 10 and 100 kPa was calculated by means of these models (Tables 5.6, 5.7 and 5.8).

The actual water holding capacity of undisturbed samples between 5 and 100 kPa ranged from approximately 58.7 mm.m⁻¹ to 318.0 mm.m⁻¹. The actual water holding capacity of undisturbed samples between 10 and 100 kPa ranged from 32.9 mm.m⁻¹ to approximately 315.0 mm.m⁻¹ (Table 5.6). The predicted water holding capacity of undisturbed samples between 5 and 100 kPa ranged from 60.1 mm.m⁻¹ to 271.9 mm.m⁻¹, whilst the predicted water holding capacity of undisturbed samples between 10 and 100 kPa ranged from 27.7 mm.m⁻¹ to approximately 226.0 mm.m⁻¹ (Table 5.6).

The model to predict the water holding capacity of undisturbed samples between 5 and 100 kPa generally overestimated the water holding capacity thereof, until an approximate water holding capacity of 236 mm.m⁻¹. As the water holding capacity of undisturbed samples became more than 236 mm.m⁻¹, so there was a tendency of the model to underestimate the water holding capacity of the soil. The predicted water holding capacity of undisturbed samples between 10 and 100 kPa was generally an overestimation. All the undisturbed samples' predicted water holding capacity was underestimated when the actual water holding capacity was more than 165 mm.m⁻¹.

In the case of the actual water holding capacity of the rubber ring samples between 5 and 100 kPa, the values ranged from 88.1 mm.m⁻¹ to 397.2 mm.m⁻¹ (Table 5.7). The actual water holding capacity of rubber ring samples between 10 and 100 kPa ranged from 30.7 mm.m⁻¹ to approximately 334.8 mm.m⁻¹. The predicted water holding capacity of the rubber ring samples between 5 and 100 kPa ranged from 91.2 mm.m⁻¹ to 380.3 mm.m⁻¹, whilst the predicted water holding capacity of rubber ring samples between 10 and 100 kPa ranged from 21.1 mm.m⁻¹ to 262.9 mm.m⁻¹ (Table 5.7).

The model to predict the water holding capacity of rubber ring samples between 5 and 100 kPa generally overestimated the water holding capacity thereof of half the samples. The predicted water holding capacity of rubber ring samples between 10 and 100 kPa was very accurate when the actual water holding capacity of samples ranged from 30.7 mm.m⁻¹ to 109 mm.m⁻¹. When the actual water holding capacity of rubber ring samples between 10 and 100 kPa was more than 109 mm, the model generally overestimated and underestimated the water holding capacity of the samples.

Table 5.5. Equations of models to predict water holding capacity of undisturbed samples (WHC_u), rubber ring samples (WHC_{rr}) and compacted samples (WHC_c) between 5 and 100 kPa and between 10 and 100 kPa.

kPa	Equations $WHC = a + b (x) + c (\ln x) + d (\ln y) + f (y)^{0.5} + e (z)$	R^2 (%)
5 - 100	$WHC_u = -29.523 + 3.394$ fine sand	74.8
10 - 100	$WHC_u = -891.794 + 232.326 \ln$ fine sand + 38.006 \ln medium sand	69.1
5 - 100	$WHC_{rr} = -749.534 + 251.847 \ln$ fine sand + 3.670 coarse sand	92.0
10 - 100	$WHC_{rr} = 318.191 - 35.712$ medium sand ^{0.5}	79.2
5 - 100	$WHC_c = -6.183 + 2.099$ fine sand	56.8
10 - 100	$WHC_c = 140.589 - 26.865 \ln$ medium sand	52.3

Table 5.6. Actual (WHC_A) and predicted water holding capacity (WHC_P) of soils determined by means of undisturbed samples.

Site number	Depth (cm)	5-100 kPa		10-100 kPa	
		WHC _A	WHC _P	WHC _A	WHC _P
1	0-70	195.4	256.3	165.5	225.7
1	70-100	233.2	271.9	119.6	194.7
2	0-30	178.1	260.3	144.2	183.2
2	30-90	215.1	263.7	157.8	177.4
3	0-30	204.0	224.3	159.1	152.4
3	30-100	296.7	262.4	207.3	195.8
4	0-30	166.2	176.8	141.5	115.2
4	30-90	311.2	254.2	225.8	207.0
5	0-25	294.4	223.0	254.4	184.4
5	25-90	287.9	241.3	260.6	226.0
6	0-20	86.6	86.2	62.4	66.7
6	20-60	103.1	83.2	61.3	59.5
7	0-50	265.7	201.9	224.0	147.2
7	50-80	236.3	233.2	224.0	202.1
8	0-30	318.0	246.1	315.0	214.9
8	30-90	246.2	231.1	217.6	215.4
9	0-30	63.0	60.1	34.3	21.5
10	0-30	58.7	62.8	32.9	36.7
11	0-30	63.8	60.1	45.8	27.7
12	0-30	159.8	148.7	114.9	164.8
13	0-30	137.8	160.5	113.6	144.2
14	0-30	83.8	114.4	59.1	169.9
15	20-40	144.4	186.7	98.8	154.7
16	20-40	136.6	176.8	104.1	156.6

Table 5.7. Actual (WHC_A) and predicted water holding capacity (WHC_P) of soils determined by means of rubber ring samples.

Site number	Depth (cm)	5-100 kPa		10-100 kPa	
		WHC _A	WHC _P	WHC _A	WHC _P
1	0-70	397.2	367.0	168.4	205.3
1	70-100	397.0	380.3	180.0	254.3
2	0-30	353.4	370.5	248.6	256.3
2	30-90	345.5	373.4	278.4	262.9
3	0-30	334.0	337.1	229.0	256.3
3	30-100	352.6	372.3	334.8	246.8
4	0-30	317.0	285.7	265.5	246.8
4	30-90	395.9	368.1	211.8	227.8
5	0-25	351.4	340.2	220.6	222.4
5	25-90	347.3	357.1	205.9	184.6
6	0-20	221.8	223.0	92.7	97.2
6	20-60	228.5	220.3	102.8	100.1
7	0-50	363.4	314.6	319.8	241.6
7	50-80	361.6	345.7	265.5	211.1
8	0-30	370.0	357.8	192.0	208.7
8	30-90	339.0	344.5	145.0	187.5
9	0-30	121.6	128.4	61.3	51.7
10	0-30	88.1	191.2	30.7	21.1
11	0-30	106.9	96.9	35.6	28.9
12	0-30	213.0	249.8	109.0	103.3
13	0-30	247.4	278.9	125.7	183.6
14	0-30	246.7	205.9	195.2	199.7
15	20-40	264.0	307.7	235.0	214.1
16	20-40	239.7	287.2	153.7	195.0

Table 5.8. Actual (WHC_A) and predicted water holding capacity (WHC_P) of soils determined by means of compacted samples.

Site number	Depth (cm)	5-100 kPa		10-100 kPa	
		WHC _A	WHC _P	WHC _A	WHC _P
1	0-70	153.8	170.6	74.7	78.7
1	70-100	201.6	180.2	91.5	109.3
2	0-30	175.1	173.1	137.6	111.1
2	30-90	179.4	172.2	130.3	117.1
3	0-30	221.2	150.8	114.9	111.1
3	30-100	158.2	174.3	91.0	103.3
4	0-30	51.4	121.4	36.0	103.3
4	30-90	225.0	169.3	104.3	90.7
5	0-25	201.8	150.0	124.1	87.6
5	25-90	110.3	161.3	51.6	69.7
6	0-20	61.5	65.4	45.8	42.7
6	20-60	73.5	63.5	49.3	43.4
7	0-50	117.7	137.0	91.0	99.6
7	50-80	149.6	156.3	77.5	81.6
8	0-30	128.3	164.3	76.6	80.4
8	30-90	143.3	155.0	105.1	70.9
9	0-30	58.8	49.2	31.1	32.6
10	0-30	66.7	50.9	24.7	26.8
11	0-30	56.5	49.2	21.5	28.2
12	0-30	86.4	104.0	48.5	44.2
13	0-30	30.3	111.4	23.1	69.3
14	0-30	97.0	82.8	83.7	76.2
15	20-40	210.8	127.5	148.1	83.1
16	20-40	107.3	121.4	52.5	74.1

The actual water holding capacity of compacted samples between 5 and 100 kPa ranged from 30.3 mm.m⁻¹ to approximately 225.0 mm.m⁻¹. The actual water holding capacity of compacted samples between 10 and 100 kPa ranged from 23.1 mm.m⁻¹ to approximately 148.1 mm.m⁻¹ (Table 5.8). The predicted water holding capacity of compacted samples between 5 and 100 kPa ranged from 49.2 mm.m⁻¹ to approximately 180.2 mm.m⁻¹. The predicted water holding capacity of compacted samples between 10 and 100 kPa ranged from 26.8 mm.m⁻¹ to approximately 117.1 mm.m⁻¹ (Table 5.8).

The model to predict the water holding capacity of compacted samples between 5 and 100 kPa generally gave a very accurate prediction thereof until the actual water holding capacity of compacted samples became more than 179.0 mm.m⁻¹. Above this, the model underestimated the water holding capacity of the compacted samples between 5 and 100 kPa. The predicted water holding capacity of compacted samples between 10 and 100 kPa generally underestimated the water holding capacity thereof when the actual water holding capacity was more than 104.3 mm.m⁻¹.

5.4 Evaluation of rubber ring model and comparison to Hutson's equations for volumetric water content at 10 and 100 kPa

The volumetric water content of 220 rubber ring samples at 10 kPa and 100 kPa and the water holding capacity between 10 and 100 kPa (Table A.1), together with their particle size distribution were used to validate the proposed rubber ring models to predict volumetric water content at 10 and 100 kPa and the water holding capacity of soils between 10 and 100 kPa.

The degree of correlation between the actual volumetric water content of rubber ring samples at 10 kPa and the predicted volumetric water content thereof at 10 kPa was 74% (Fig. 5.1). The actual volumetric water content of rubber ring samples at 100 kPa showed a slightly poorer degree of correlation with the predicted volumetric water content at 100 kPa and was approximately 62% (Fig. 5.2).

The percentage of stones present in the soils had been taken into account when determining the water holding capacity of the soils using the rubber ring method. Therefore, in order to compare the water holding capacity of the soils determined using the rubber ring method and the predicted water holding capacity of the soils, it was decided to also take the percentage of stones present in the soil into account when using the prediction model. The actual water holding capacity of the rubber ring samples was correlated 71% with the predicted water holding capacity thereof (Fig. 5.3).

Using the particle size distribution of the 220 rubber ring samples and the proposed models to predict volumetric water content of undisturbed samples and rubber ring samples, the degree of correlation between the predicted volumetric water content using the model for undisturbed samples at 10 kPa and the predicted volumetric water content of rubber ring samples at 10 kPa was excellent and was 93% (Fig. 5.4). The predicted volumetric water content of undisturbed samples at 100 kPa

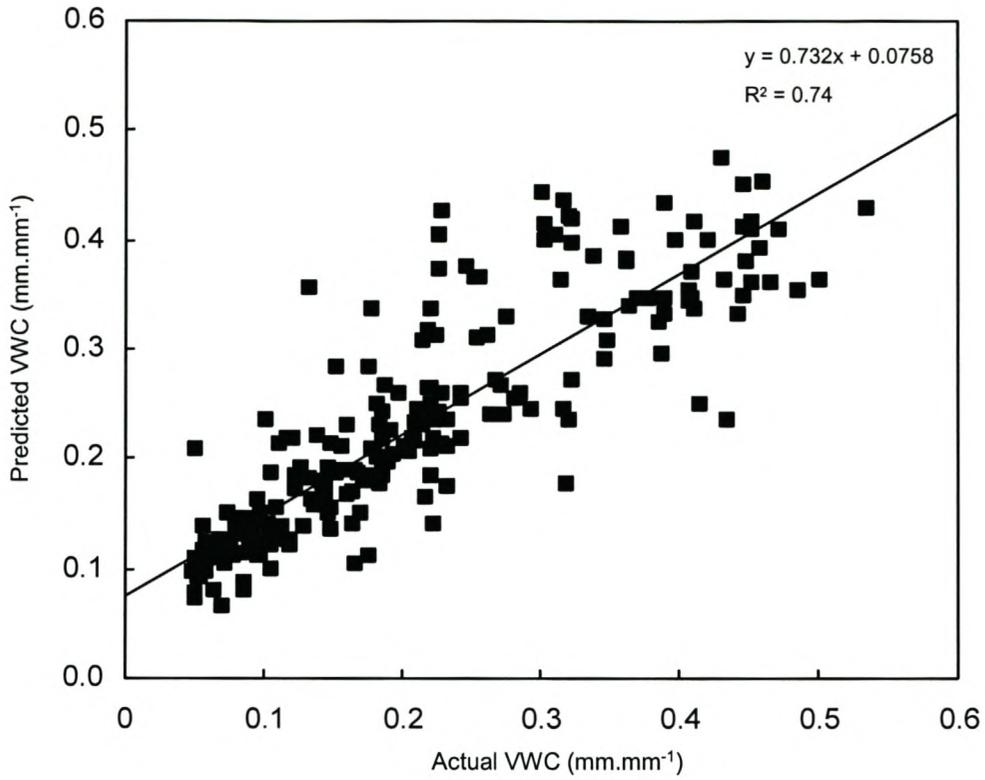


Figure 5.1. The relationship between actual and predicted volumetric water content of rubber ring samples at 10 kPa.

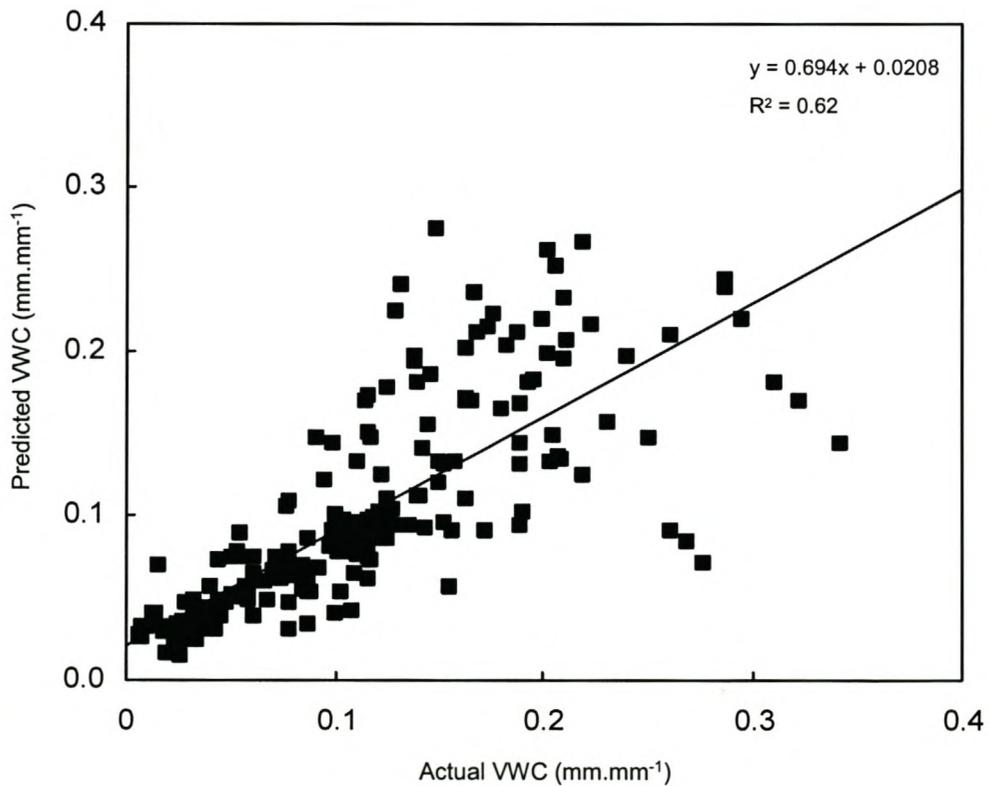


Figure 5.2. The relationship between actual and predicted volumetric water content of rubber ring samples at 100 kPa.

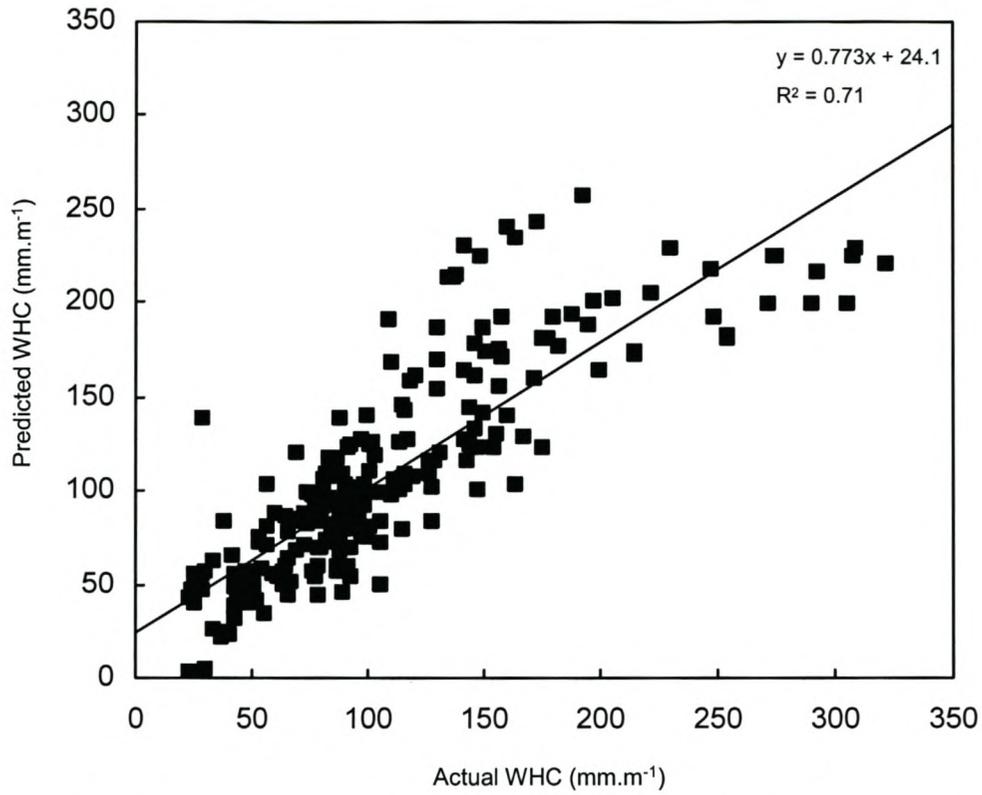


Figure 5.3. The relationship between actual water holding capacity of rubber ring samples between 10 and 100 kPa and predicted water holding capacity thereof.

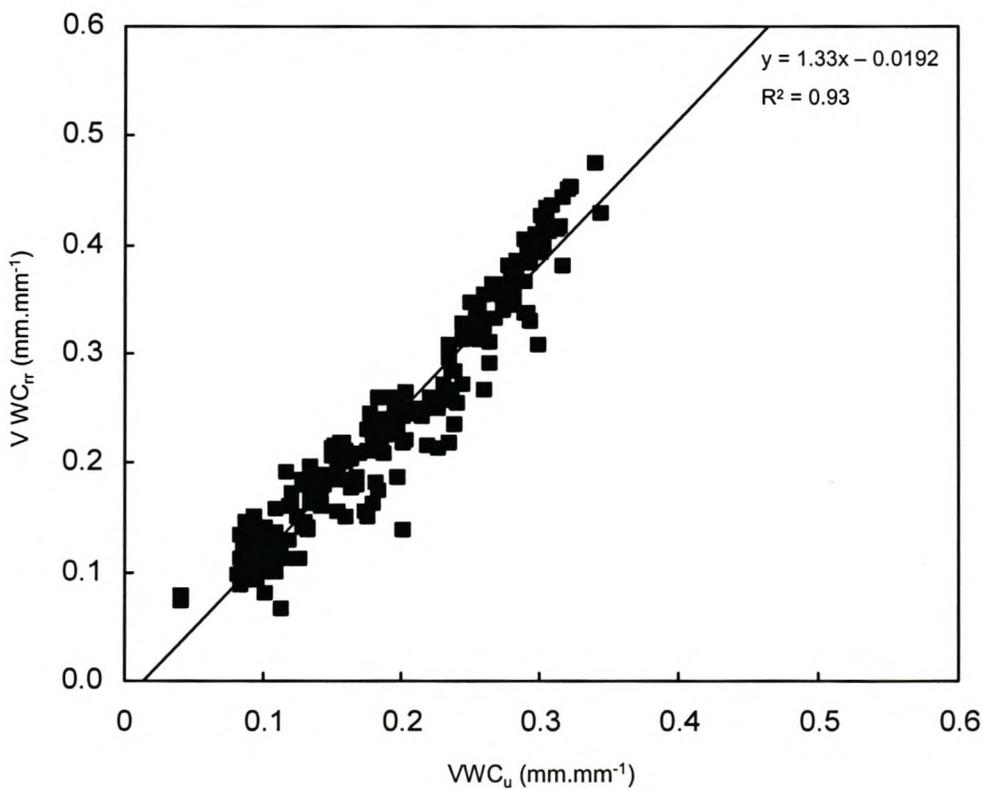


Figure 5.4. The relationship between predicted volumetric water content of undisturbed samples at 10 kPa and predicted volumetric water content of rubber ring samples at 10 kPa.

showed a 61% degree of correlation with the predicted volumetric water content of rubber ring samples at 100 kPa (data not shown).

The predicted water holding capacity of undisturbed samples and actual water holding capacity of the rubber ring samples was only correlated by 21% (data not shown). The predicted water holding capacity of approximately 57 of the soils using the model to predict water holding capacity of undisturbed samples between 10 and 100 kPa was less than zero. This was probably because of a high coarse sand content which in effect meant that the fine sand and medium sand content was lower. The ln of these two terms was used in the model to predict the water holding capacity of undisturbed samples between 10 and 100 kPa and if these two terms were lower, then the equation would have resulted in a negative result. If only the predicted water holding capacity of undisturbed samples between 10 and 100 kPa above zero was considered and correlated with the predicted water holding capacity of rubber ring samples between 10 and 100 kPa, then there was a correlation of approximately 45% between the two variables. This correlation is very similar to the correlation obtained in Chapter 4 between water holding capacity of undisturbed samples between 10 and 100 kPa and water holding capacity of rubber ring samples between 10 and 100 kPa.

The actual and predicted rubber ring volumetric water content data at 10 and 100 kPa and undisturbed volumetric water content data at 10 and 100 kPa data was also compared to the volumetric water content of the soils at 10 and 100 kPa as predicted by the model of Hutson (1986). The main input parameters into this model of Hutson (1986) are clay and silt. The volumetric water content of the soils at 10 kPa, predicted using the Hutson model, showed a correlation of 58% with the actual volumetric water content of rubber ring samples at 10 kPa (Fig. 5.5). The correlation between volumetric water content of soils at 100 kPa estimated using the model of Hutson, and actual volumetric water content of the rubber ring samples at 100 kPa was better and was 78% (Fig. 5.6). If the model to predict volumetric water content of rubber ring samples at 10 kPa are used, then there is a correlation of almost 72% between volumetric water content of soils at 10 kPa using the model of Hutson (1986) and the predicted volumetric water content of rubber ring samples at 10 kPa (Fig. 5.7). At 100 kPa, there was a correlation of 69% between the volumetric water content of soils predicted using the Hutson (1986) model and the predicted volumetric water content of rubber ring samples (Fig. 5.8).

The predicted volumetric water content of the soils using the model for volumetric water content of undisturbed samples at 10 kPa and the predicted volumetric water content of soils at 10 kPa using Hutson's (1986) prediction model was approximately 67% (Fig. 5.9). This was higher than the correlation between volumetric water content of the soils at 10 kPa, predicted using the Hutson model, and the actual and predicted volumetric water content of rubber ring samples at 10 kPa. The correlation between predicted volumetric water content of soils at 100 kPa using Hutson's (1986) prediction model and the estimated volumetric water content of the soils using the model for volumetric water content of undisturbed samples at 100 kPa was 78% (Fig. 5.10) .

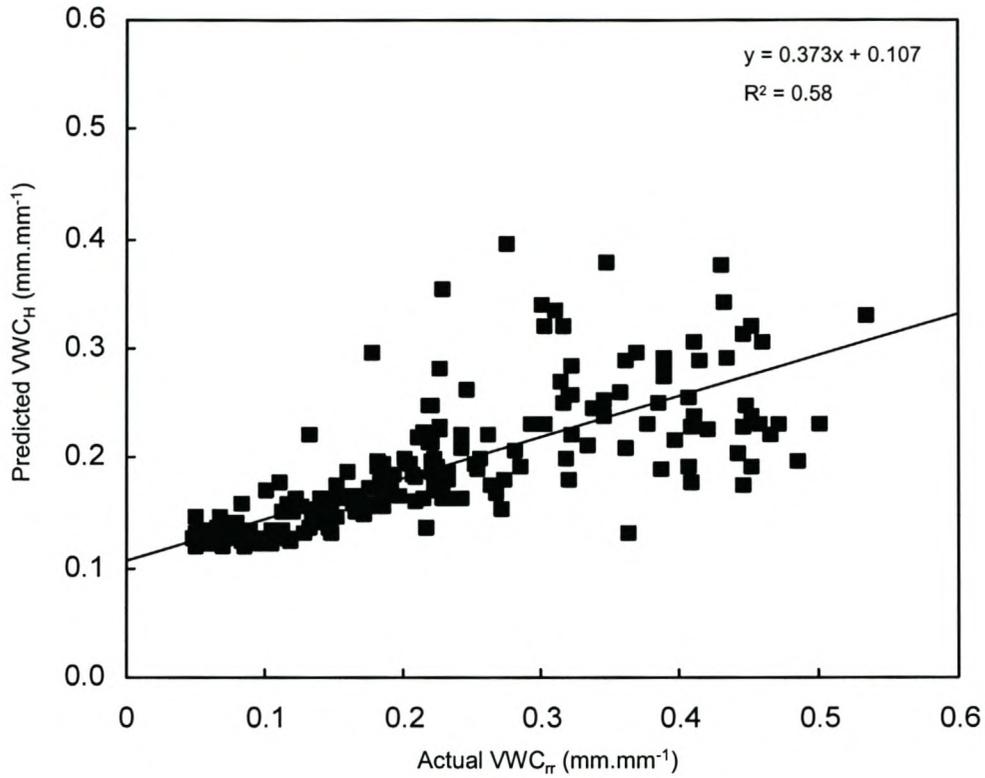


Figure 5.5. The relationship between actual volumetric water content of rubber ring samples at 10 kPa and predicted volumetric water content of samples at 10 kPa using the model of Hutson (1986).

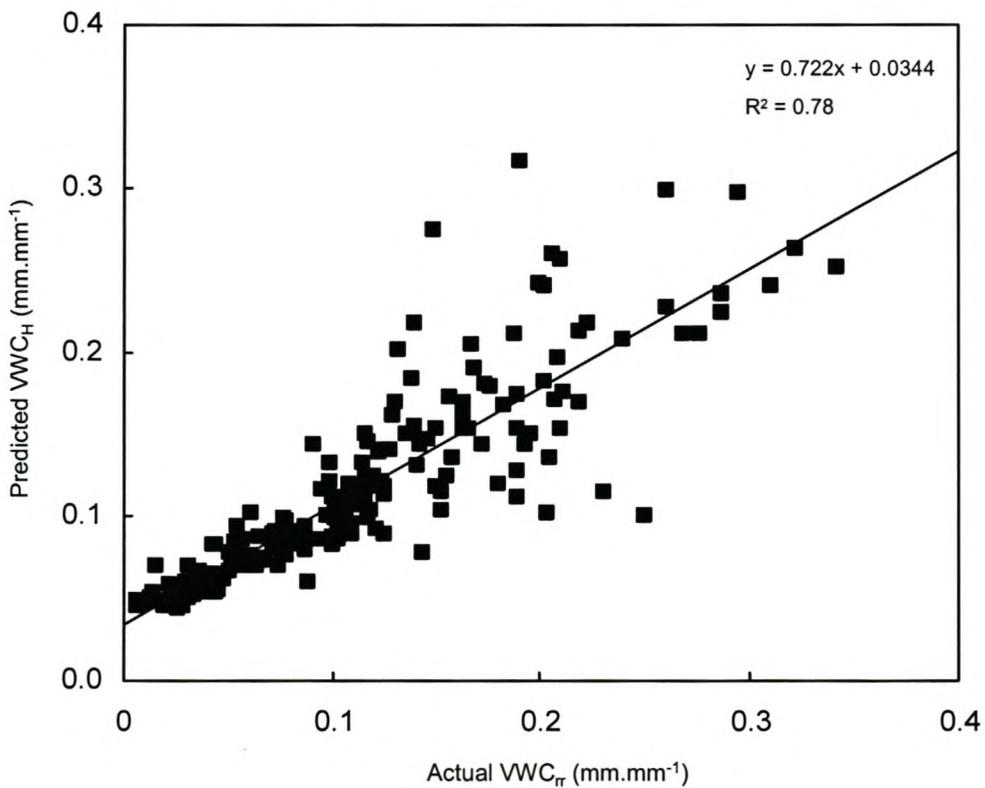


Figure 5.6. The relationship between actual volumetric water content of rubber ring samples at 100 kPa and predicted volumetric water content of samples at 100 kPa using the model of Hutson (1986).

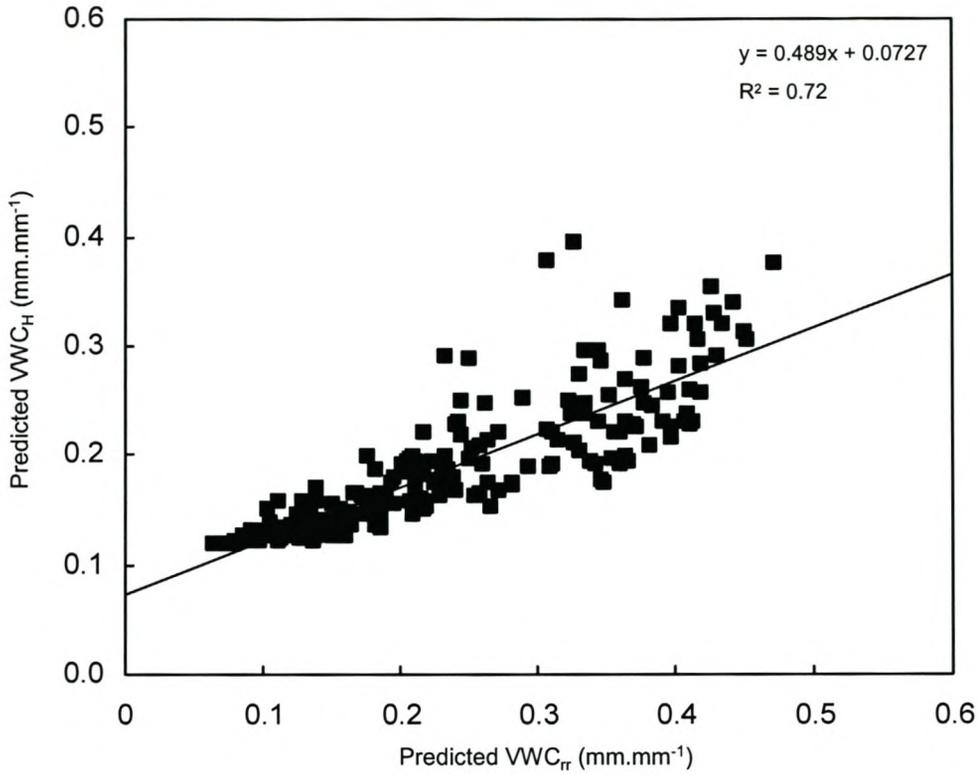


Figure 5.7. The relationship between predicted volumetric water content of rubber ring samples at 10 kPa and predicted volumetric water content of samples at 10 kPa using the model of Hutson (1986).

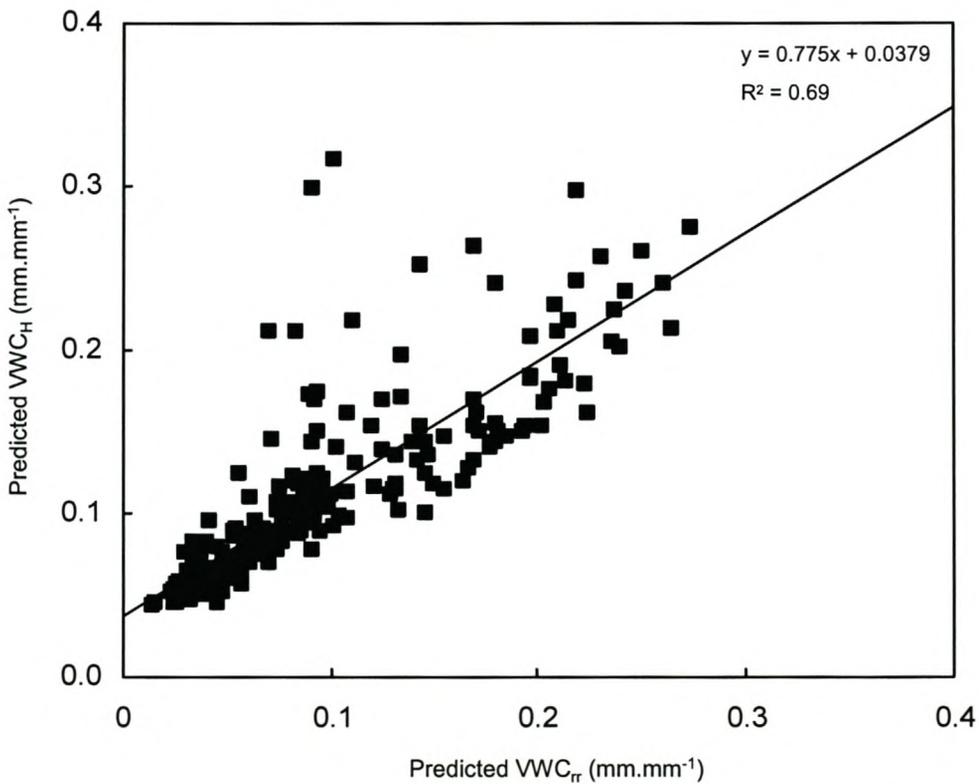


Figure 5.8. The relationship between predicted volumetric water content of rubber ring samples at 100 kPa and predicted volumetric water content of samples at 100 kPa using the model of Hutson (1986).

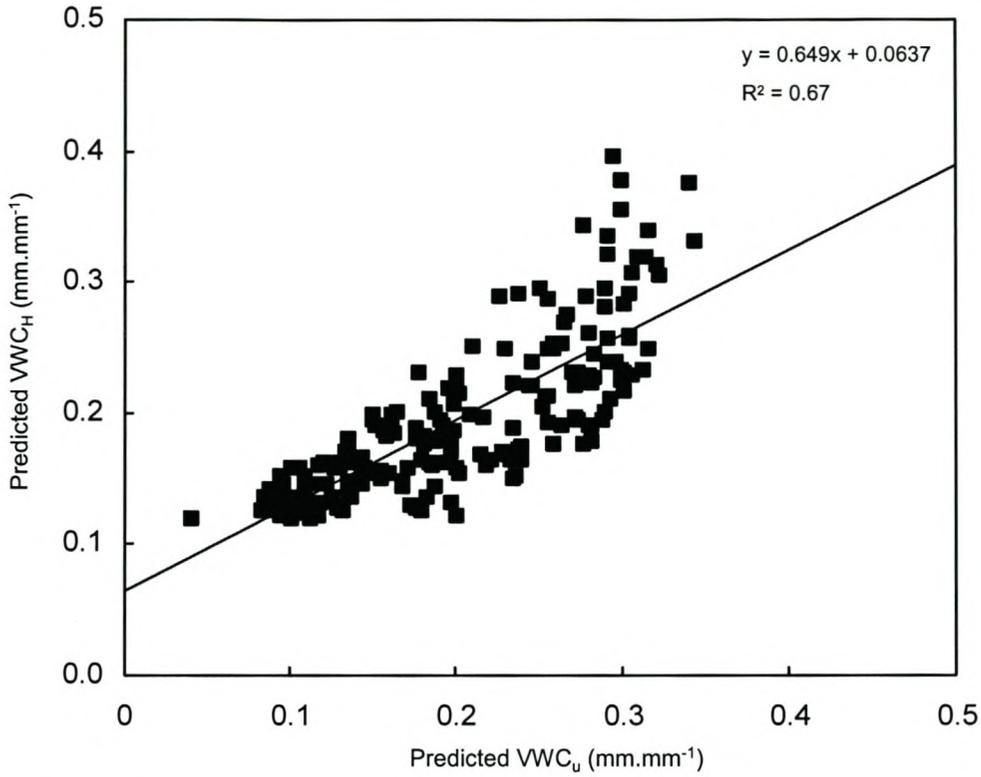


Figure 5.9. The relationship between predicted volumetric water content of samples using the model of undisturbed samples at 10 kPa and predicted volumetric water content of samples at 10 kPa using the model of Hutson (1986).

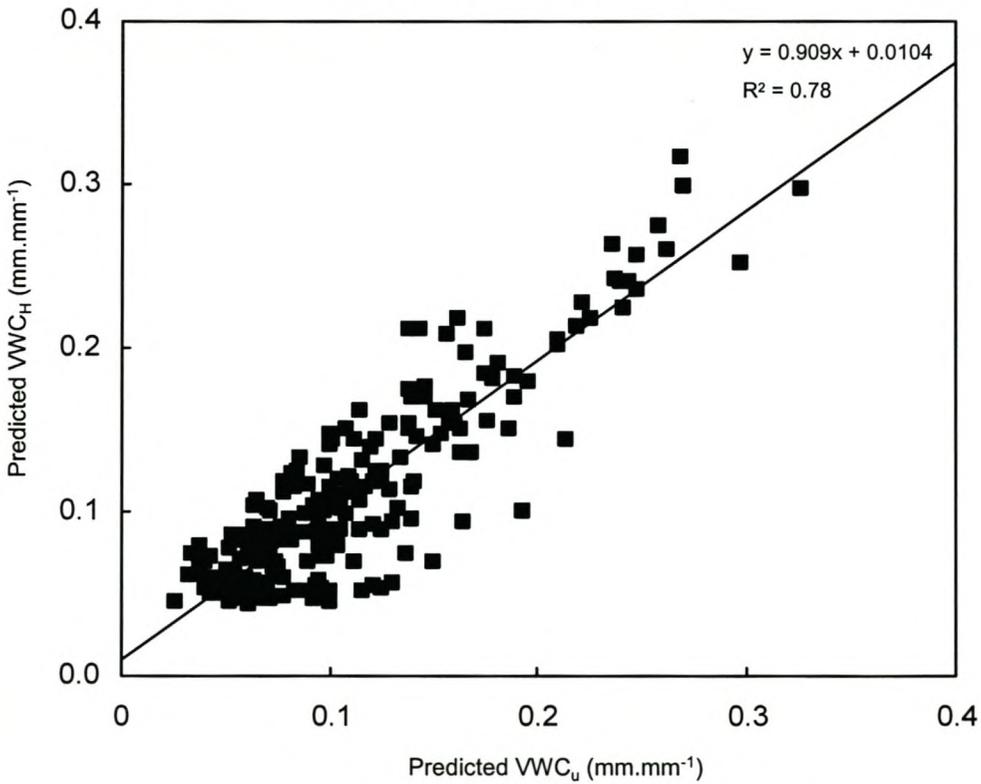


Figure 5.10. The relationship between predicted volumetric water content of samples using the model of undisturbed samples at 100 kPa and predicted volumetric water content of samples at 100 kPa using the model of Hutson (1986).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Volumetric water content of rubber ring samples at 5 kPa was more than the volumetric water content of undisturbed samples at 5 kPa. However, volumetric water content of rubber ring samples at 5 kPa had a very good correlation with volumetric water content of undisturbed samples at 5 kPa and this was almost 87%. Almost half the compacted samples' volumetric water content at 5 kPa was more than the volumetric water content of undisturbed samples at 5 kPa. Volumetric water content of compacted samples at 5 kPa had an 85% correlation with volumetric water content of undisturbed samples. This result was therefore similar to that of rubber ring samples. At 10 kPa, the correlation between volumetric water content determined using rubber ring samples and undisturbed samples was 77%. This was identical to the correlation between volumetric water content of compacted samples at 10 kPa and undisturbed samples. At 100 kPa, most of the rubber ring samples' volumetric water content fell below the 1:1 line of volumetric water content of undisturbed samples. Volumetric water content at 100 kPa of rubber ring samples was correlated 65% with volumetric water content of undisturbed samples. This was almost the same as the correlation between volumetric water content of compacted samples and undisturbed samples. Volumetric water content of most of the compacted samples was higher than that of undisturbed samples.

The standard error of the relationship between volumetric water content of undisturbed samples at 5 kPa and volumetric water content of rubber ring samples at 5 kPa was 0.046. This was almost the same as the standard error of the relationship between volumetric water content of undisturbed samples at 5 kPa and volumetric water content of compacted samples at 5 kPa which was 0.051. Compacted samples therefore tended to be slightly less accurate in determining the volumetric water content of samples at 5 kPa. The standard error of the relationship between volumetric water content of undisturbed samples at 10 kPa and volumetric water content of rubber ring samples at 10 kPa was 0.062. This was slightly higher than the standard error of the relationship between volumetric water content of undisturbed samples at 10 kPa and volumetric water content of compacted samples at 10 kPa which was 0.058. Rubber ring samples proved to be less accurate in determining the volumetric water content of samples at 10 kPa. The standard error of the relationship between volumetric water content of undisturbed samples at 100 kPa and volumetric water content of rubber ring samples at 100 kPa was 0.032. This was half the magnitude of the standard error of the relationship between volumetric water content of compacted samples at 100 kPa and volumetric water content of undisturbed samples at 100 kPa. Volumetric water content of rubber ring samples at 100 kPa were therefore correlated more closely with that of undisturbed samples.

The water holding capacity of rubber ring samples generally overestimated the water holding capacity of the soil. The implication is that if irrigation is scheduled according to the water holding

capacity determined by means of rubber ring samples, too much water will be applied. Water will then be wasted due to loss of water from the soil by drainage. In Africa and indeed, the entire world's current situation, this is unacceptable. Closer to home, producers' applying too much water could face the wrath of environmental workers and could face huge fines for the wastage of water. The water holding capacity of most of the rubber ring samples between 10 and 100 kPa was greater than the water holding capacity of the undisturbed samples. Currently recommendations for producers are being given on the results of the water holding capacity of rubber ring samples between 10 and 100 kPa. As in the case of the water holding capacity of rubber ring samples between 5 and 100 kPa, producers are still in danger of irrigating their soils with too much water and could possibly face penalties for such actions.

In contrast, water holding capacity of compacted samples was generally underestimated. Water holding capacity of compacted samples between 5 and 100 kPa was correlated 39% with water holding capacity of undisturbed samples between 5 and 100 kPa. This correlation was not as good as the correlation between water holding capacity of rubber ring samples between 5 and 100 kPa and water holding capacity of undisturbed samples between 10 and 100 kPa. Water holding capacity of most of the compacted samples between 10 and 100 kPa was less than the water holding capacity of the undisturbed samples between 10 and 100 kPa.

The standard error of the relationship between water holding capacity of undisturbed samples between 5 and 100 kPa and water holding capacity of rubber ring samples between 5 and 100 kPa was 47.95. The standard error of the relationship between water holding capacity of undisturbed samples between 5 and 100 kPa and water holding capacity of compacted samples between 5 and 100 kPa was 47.70. The standard error of the relationship between water holding capacity of undisturbed samples between 10 and 100 kPa and water holding capacity of rubber ring samples between 10 and 100 kPa was 66.52. This was almost twice the standard error of the relationship between water holding capacity of undisturbed samples between 10 and 100 kPa and water holding capacity of compacted samples between 10 and 100 kPa. The rubber ring samples therefore proved to be less accurate than the compacted samples when determining the water holding capacity between 10 and 100 kPa.

The results from this study confirm that the influence of clay content on the volumetric water content of undisturbed, rubber ring and compacted samples increases as the suction on the respective samples is increased. Silt content also had a marked effect on the volumetric water content of undisturbed, rubber ring and compacted samples at 100 kPa. In the case of both undisturbed and rubber ring samples, silt content had a greater influence on the volumetric water content of the respective samples at 100 kPa than the clay content had. This is probably due to the fact that the clay particles occur as coatings on the silt and sand particles. Combining the clay and silt content together to do correlations between volumetric water content of samples and the clay plus silt contents thereof did not particularly increase the correlation coefficients remarkably.

The influence of fine sand content on volumetric water content of undisturbed, rubber ring and compacted samples was the greatest at 5 kPa and decreased to 100 kPa. Volumetric water content of both undisturbed and rubber ring samples at 5 kPa were influenced more by the fine sand contents thereof than volumetric water of compacted samples at 5 kPa. At 100 kPa, volumetric water content of both undisturbed and rubber ring samples were influenced less by the fine sand content thereof than the volumetric water of compacted samples at 100 kPa. This was probably due to a more even pore size distribution in the case of the compacted samples. Medium sand content of undisturbed, rubber ring and compacted samples had the greatest influence of all the textural components on volumetric water content of the respective samples at 5 kPa and 10 kPa. From the results, it was therefore clear that fine sand and medium sand content of samples could be useful parameters in the prediction of volumetric water contents thereof.

However, water holding capacity of undisturbed, rubber ring and compacted samples between 5 and 100 kPa was greatly influenced by the fine and medium sand content of the samples. These were promising results which could be used to develop models to predict the water holding capacity of undisturbed, rubber ring and compacted samples.

Independent variables such as fine sand content, the square root of medium sand content and \ln of medium sand content were used to predict the volumetric water content of undisturbed samples at 5, 10 and 100 kPa. The same variables were used to predict volumetric water content of rubber ring samples at 5, 10 and 100 kPa. However, additional variables such as silt content, the \ln of silt content, the square root of clay plus silt content and medium sand content were also used. To predict volumetric water content of compacted samples at 5, 10 and 100 kPa the terms used were silt content, clay plus silt content, $e^{-\text{clay plus silt content}}$, medium sand content and square root of medium sand content. Models to predict volumetric water content of rubber ring samples at 5, 10 and 100 kPa gave the best correlation with the respective laboratory determinations.

The final models produced by the stepwise regression to predict the water holding capacity of undisturbed, rubber ring and compacted samples between 5 and 100 kPa and 10 and 100 kPa used only sand parameters as independent variables. This was expected as only fine and medium sand content of the respective samples had an influence on the water holding capacity thereof.

The volumetric water content of 220 rubber ring samples at 10 kPa and 100 kPa and the water holding capacity between 10 and 100 kPa, together with their particle size distribution were used to validate the proposed rubber ring models to predict volumetric water content at 10 and 100 kPa and the water holding capacity of soils between 10 and 100 kPa. The results indicated that degree of correlation between the actual volumetric water content of rubber ring samples at 10 kPa and the predicted volumetric water content thereof at 10 kPa was 74%. The actual volumetric water content of rubber ring samples at 100 kPa showed a slightly poorer degree of correlation with the predicted volumetric water content at 100 kPa and was approximately 62%. The actual water holding capacity of the rubber ring samples was correlated 71% with the predicted water holding capacity thereof.

This in effect means that if a particle size analysis of the soil is obtained, a reasonably accurate prediction can be made of the volumetric water content thereof at 10 and 100 kPa and the water holding capacity of the samples between 10 and 100 kPa, by means of the rubber ring models.

The predicted water holding capacity of approximately 57 of the soils using the model to predict water holding capacity of undisturbed samples between 10 and 100 kPa was less than zero. This suggests that the model to predict water holding capacity of undisturbed samples between 10 and 100 kPa needs further refining, particularly where the fine sand and medium sand of the soil is not very high.

If the model to predict volumetric water content of rubber ring samples at 10 kPa is used, then there is a correlation of almost 72% between volumetric water content of soils at 10 kPa using the model of Hutson (1986) and the predicted volumetric water content of rubber ring samples at 10 kPa.

The equations of Hutson (1986) used were

$$\theta_{-10}=0.112 + 0.00380 (Cl + Si) \quad 6.1$$

$$\theta_{-100}=0.038 + 0.00372 (Cl + Si) \quad 6.2$$

where Cl is clay content and Si is silt content.

At 100 kPa, there was a correlation of 69% between the volumetric water content of soils predicted using the Hutson (1986) model and the predicted volumetric water content of rubber ring samples. The model of Hutson (1986) can therefore be used as an alternative to predict the volumetric water content of samples at 10 and 100 kPa. Only clay content and silt content of the samples will then have to be determined.

The predicted volumetric water content of the soils using the model for volumetric water content of undisturbed samples at 10 kPa and the predicted volumetric water content of soils at 10 kPa using Hutson's (1986) prediction model was approximately 67%. This was higher than the correlation between volumetric water content of the soils at 10 kPa, predicted using the Hutson model, and the actual volumetric water content of rubber ring samples at 10 kPa. The correlation between predicted volumetric water content of soils at 100 kPa using Hutson's (1986) prediction model and the estimated volumetric water content of the soils using the model for volumetric water content of undisturbed samples at 100 kPa was 78%.

In conclusion, it is therefore clear that soil textural components play an important role in determining the volumetric water content of undisturbed samples, rubber ring samples and compacted samples at 5, 10 and 100 kPa. Soil texture also influences the magnitude of the water holding capacity between 5 and 100 kPa and 10 and 100 kPa. The most accurate method to determining water holding capacity is by using undisturbed samples. As mentioned previously, it is often difficult and impractical to take these samples. Prediction models to determine water holding capacity of undisturbed samples should be used to estimate water holding capacity of soils when undisturbed samples are unavailable

The models developed to predict the volumetric water content of undisturbed samples, rubber ring samples and compacted samples at 5, 10 and 100 kPa and the magnitude of the water holding capacity between 5 and 100 kPa and 10 and 100 kPa could be very useful and save both time and money.

In particular the use of the following models for undisturbed samples can be recommended:

At 5 kPa, $VWC_u = 0.47259 - 0.04712 \text{ medium sand}^{0.5}$

At 10 kPa, $VWC_u = 0.41292 - 0.04221 \text{ medium sand}^{0.5}$

At 100 kPa, $VWC_u = 0.48080 - 0.00254 \text{ fine sand} - 0.0865 \ln \text{ medium sand}$

Between 5 and 100 kPa, $WHC_u = -29.523 + 3.394 \text{ fine sand}$

Between 10 and 100 kPa, $WHC_u = -891.794 + 232.326 \ln \text{ fine sand} + 38.006 \ln \text{ medium sand}$

In order to utilize the models, only a particle size distribution analysis would have to be performed on a soil sample and the data then subjected to the models. A very quick estimate of the water holding capacity can then be produced. The use of the prediction models for undisturbed samples and rubber ring samples can be recommended. However, because undisturbed samples are the most accurate method to determine water holding capacity of soils, the use of the models to predict volumetric water content and water holding capacity of undisturbed samples can be highly recommended.

REFERENCES

- Archer, J. R. & P. D. Smith., 1972. The relation between bulk density, available water capacity, and air capacity of soils. *J. Soil Sc.* 23: 475-480.
- Arya, L. M. & J. F. Paris., 1981. A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data. *Soil Sci. Soc. Am. J.* 45: 1023-1030.
- Beukes, D. I., 1984. Invloed van sekere grondeienskappe op matrikspotensiaal by, en tydsverloop tot, veldkapasiteit. *S. Afr. J. Plant Soil* 1: 125-131.
- Beukes, O., 1990. Bepaling van grondwaterinhoud met behulp van drukplaat ekstraheerders. Infruitec Procedures en Tegniek - Nommer 67. LNR Infruitec, Nietvoorbij, Stellenbosch, Suid Afrika.
- Botha, A. D. P. & B. E. Eisenberg., 1993. Estimation of soil water retention from clay content and cation exchange capacity values of soils. *S. Afr. J. Plant Soil* 10: 141-143.
- Bruce, R. R & R. J. Luxmoore., 1986. Water retention: Field Methods. p 663-686. In: *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*. Madison, USA.
- Buckman, H. O. & N. C. Brady., 1969. *The nature and properties of soils*. The Macmillan Company, London.
- Burns, S. & E. Rawitz., 1981. The effects of sodium and organic matter in sewage effluent on water retention properties of soils. *Soil Sci. Soc. Am. J.* 45: 487-493.
- Canola Connection., 2001. Soil moisture storage capacity.
<http://www.canola-council.org/production/soilmois.html>
- De Backer, L. & A. Klute., 1967. Comparison of pressure and suction methods for soil-water content-pressure-head determinations. *Soil Sci.* 104: 46-55.
- De Jong, R., C. A. Campbell & W. Nicholaichuk., 1983. Water retention equations and their relationship to soil organic matter and particle size distribution for disturbed samples. *Can. J. Soil Sci.* 63: 291-302.
- El-Swaify, S. A. & D. W. Henderson., 1967. Water retention by osmotic swelling of certain colloidal clays with varying ionic composition. *J. Soil Sci.* 18: 223-232.

- Gee G. W. & J. W. Bauder., 1986. Particle-size analysis. p 383-411. In: Methods of soil analysis. Part 1. Physical and mineralogical methods. American Society of Agronomy, Madison, Wisconsin, U.S.A.
- Gupta, S. C & W. E. Larson., 1979. Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. *Water Resour. Res.* 15: 1633-1635.
- Hall, D. G. M, M. J. Reeve, A. J. Thomasson & V. F. Wright., 1977. Water retention, porosity and density of field soils. Bartholomew Press, Dorking, England.
- Hanks, R. J. & G. L. Ashcroft., 1980. Applied Soil Physics. Springer – Verlag, Germany.
- Hill, J. N. S & M. E. Sumner., 1966. Effect of bulk density on moisture characteristics of soils. *Soil Sci.* 103: 234-238.
- Hillel, D., 1971. Physiological ecology. Soil and Water. Physical Principles and processes. Academic Press, New York and London.
- Hillel, D., 1980. Fundamentals of Soil Physics. Academic Press, USA.
- Howell, C. L., 2001. Waterhouvermoë en grondwateronttrekkingspeile. In: Grondkundige aspekte vir optimum wynkwaliteit in die Breëriviervallei.
- Hutson, J. L., 1983. Estimation of hydrological properties of South African soils. Ph.D. Thesis, University of Natal, Pietermaritzburg.
- Hutson, J. L., 1986. Water retentivity of some South African soils in relation to particle size criteria and bulk density. *S. Afr. J. Plant Soil* 3: 151-155.
- Jamison, V. C., 1958. Sand-silt suction column for determination of moisture retention. *Soil Sci. Soc. Am. Proc.* 22: 82-83.
- Kern, J. S., 1995. Evaluation of soil water retention models based on basic soil physical properties. *Soil Sci. Soc. Am. J.* 59: 1134-1141.
- Klute, A., 1982. Tillage effects on the hydraulic properties of soil: A review. p 29-45. In: Predicting tillage effects on soil physical properties and processes, ASA Special Publication Number 44. Madison, USA.
- Klute, A., 1986. Water retention: Laboratory Methods. p 635-662. In: Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods. Madison, USA.

- Kravchenko, A. & R. Zhang., 1998. Estimating the soil water retention from particle-size distributions: a fractal approach. *Soil Sci.* 163: 171-179.
- Kutilek, M., 1973. The influence of clay minerals and exchangeable cations on soil moisture potential. In: *Ecological studies*. Berlin, Germany.
- Lambooy, A. M., 1983. Relationship between cation exchange capacity, clay content and water retention of Highveld soils. *S. Afr. J. Plant Soil* 1: 33-38.
- Marshall, T. J., 1959. *Relations between water and soil*. Commonwealth Agricultural Bureaux, England.
- Marshall, T. J. & J. W. Holmes., 1979. *Soil Physics*. Cambridge University Press, England
- McCarthy, M. G, L. D. Jones & G. Due. 1988. Irrigation – Principles and Practices. p 104-128. In: *Viticulture Volume 2 Practices*, Winetitles, Adelaide, Australia.
- Perroux, K. M., A. C. Raats & D. E. Smiles., 1982. Wetting moisture characteristic curve derived from constant- rate infiltration into thin soil samples. *Soil Sci. Soc. Am. J.* 46: 231-234.
- Ravina, I. & J. Magier., 1984. Hydraulic conductivity and water retention of clay soils containing coarse fragments. *Soil Sci. Soc. Am. J.* 48: 736-740.
- Rawls, W. J. , T. J. Gish & D. L. Brakensiek., 1991. Estimating soil water retention from soil physical properties and characteristics. p 213-234. In: *Advances in Soil Science*, Volume 16. Springer – Verlag, New York.
- Reeve, M. J., P. D. Smith & A. J. Thomasson., 1973. The effect of density on water retention properties of field soils. *J. Soil Sci.* 24: 355-367.
- Richards, L. A. & M. Fireman., 1943. Pressure plate apparatus for measuring moisture sorption and transmission by soils. *Soil Sci.* 56: 395-404.
- Rivers, E. D. & R. F. Shipp., 1978. Soil water retention as related to particle size in selected sands and loamy sands. *Soil Sci.* 126: 94-100.
- Rogowski, A. S., 1971. Watershed physics: Model of the Soil Moisture Characteristic. *Water Resour. Res.* 7: 1575-1582.

Salter, P. J. & J. B. Williams., 1965. The influence of texture on the moisture characteristics of soils. I. A critical comparison of techniques for determining the available- water capacity and moisture characteristic curve of a soil. *J. Soil Sci.* 16: 1-15.

Salter, P. J., G. Berry & J. B. Williams., 1966. The influence of texture on the moisture characteristics of soils. III. Quantitative relationships between particle size, composition, and available- water capacity. *J. Soil Sci.* 17: 93-98.

SAS, 1990. SAS/STAT User's Guide, Version 8, 1st printing, Volume 3. SAS Institute Inc., SAS Campus Drive, Cary, North Carolina 27513.

Saxton, K. E., W. J. Rawls, J. S. Romberger & R. I. Papendick., 1986. Estimating generalized soil-water characteristics from texture. *Soil Sci. Soc. Am. J.* 50: 1031-1036.

Sharma, M. L & G. Uehara., 1968. Influence of soil structure on water relations in low humic latosols: I. Water retention. *Soil Sci. Soc. Am. Proc.* 32: 765-770.

Soil Classification Work Group, 1991. Soil classification – A taxonomic system for South Africa. Memoirs on natural resources of South Africa no. 15. Dept. Agric. Developm., Pretoria.

Taylor, S. A. & G. L. Ashcroft., 1972. Physical Edaphology. The Physics of Irrigated and Nonirrigated Soils. W. H. Freeman and Company, San Fransisco.

Thomas, G. W. & J. E. Moody., 1962. Chemical relationships affecting the water holding capacity of clays. *Soil Sc. Soc. Am. Proc.* 22: 575-576.

Tomasella, J. & M. G. Hodnett., 1997. Estimating soil water retention characteristics from limited data in Brazilian Amazona. *Sci. Soc.* 163: 190-202.

Vereecken, H., J. Maes, Feyen, J. & P. Darius., 1988. Estimating soil water retention from texture, bulk density and carbon content. *Sci. Soc* 148: 389-403.

Zeiliguer, A. M., Y. A. Pachepsky & W. J. Rawls., 2000. Estimating water retention of sandy soils using the additivity hypothesis. *Sci. Soc* 165: 373-383.

Zur, B., 1966. Osmotic control of the matric soil water potential I. Soil water system. *Soil Sci.* 102: 394-398.ff

Zwolinski, J. B., D.G.M. Dondald, A. van Laar & L. van der Merwe., 1995. Water retention in cultivated forest soils of the Southern Cape province. *Suid-Afrikaanse Bosboutydskrif* 174: 1-8.

APPENDIX

Table A.1. Actual rubber ring data used to evaluate models to predict volumetric water content of rubber ring samples at 10 and 100 kPa and water holding capacity between 10 and 100 kPa.

No.	Clay content (%)	Silt content (%)	Sand content (%)	Fine sand content (%)	Medium sand content (%)	Coarse sand content (%)	VWC 10 kPa	VWC 100 kPa	WHC 10-100 kPa
1	15	16	69	61	6	2	0.304	0.140	165
2	11	12	77	68	8	0	0.257	0.118	139
3	8	13	22	78	9	2	0.253	0.116	137
4	11	10	79	65	14	0	0.226	0.095	131
5	17	11	72	38	27	8	0.211	0.128	83
6	21	9	70	37	25	8	0.227	0.136	91
7	3	1	95	35	56	4	0.059	0.031	29
8	4	1	95	34	57	4	0.054	0.029	25
9	2	2	96	37	54	4	0.059	0.030	30
10	4	2	95	37	54	4	0.059	0.030	30
11	9	3	88	27	55	7	0.164	0.100	64
12	7	3	90	28	57	6	0.113	0.062	51
13	14	9	77	35	36	7	0.201	0.116	85
14	14	7	79	36	36	7	0.183	0.111	72
15	9	9	83	47	29	7	0.185	0.102	83
16	8	9	83	45	30	8	0.192	0.100	92
17	15	7	78	36	28	15	0.186	0.109	76
18	11	7	82	36	30	16	0.187	0.112	74
19	6	7	88	35	45	7	0.124	0.071	53
20	7	6	87	37	45	6	0.141	0.075	66
21	3	2	95	37	54	4	0.056	0.030	25
22	4	2	94	38	53	4	0.061	0.030	31
23	3	1	96	29	59	7	0.054	0.029	26
24	2	1	96	27	61	8	0.049	0.024	26
25	6	2	93	35	52	6	0.077	0.043	34
26	4	2	94	34	55	6	0.066	0.038	28
27	4	1	95	34	55	6	0.056	0.031	26
28	3	1	95	30	59	7	0.050	0.027	23
29	13	3	85	29	44	12	0.224	0.109	115
30	19	4	77	35	35	7	0.319	0.156	164
31	7	6	87	31	41	16	0.186	0.081	106
32	15	5	81	26	36	19	0.222	0.116	106

Table A.1. Actual rubber ring data used to evaluate models to predict volumetric water content of rubber ring samples at 10 and 100 kPa and water holding capacity between 10 and 100 kPa cont.

No.	Clay content (%)	Silt content (%)	Sand content (%)	Fine sand content (%)	Medium sand content (%)	Coarse sand content (%)	VWC 10 kPa	VWC 100 kPa	WHC 10-100 kPa
33	3	3	94	26	60	8	0.081	0.032	49
34	3	2	95	28	60	7	0.077	0.032	45
35	3	2	95	24	60	10	0.078	0.034	44
36	4	2	95	29	57	9	0.073	0.030	44
37	11	2	88	27	46	16	0.177	0.088	89
38	9	1	90	26	52	12	0.166	0.078	87
39	5	4	91	25	41	25	0.146	0.059	88
40	5	4	91	26	41	24	0.139	0.059	80
41	9	4	86	24	42	21	0.161	0.088	74
42	9	5	86	23	43	20	0.164	0.085	79
43	6	6	89	23	39	27	0.180	0.088	92
44	6	5	88	23	40	25	0.175	0.086	89
45	6	7	87	23	43	21	0.156	0.085	71
46	6	7	87	24	43	20	0.166	0.079	87
47	13	9	78	21	39	18	0.221	0.124	97
48	12	9	79	21	39	19	0.206	0.118	87
49	8	11	81	27	37	17	0.206	0.105	101
50	10	11	80	26	38	16	0.224	0.125	99
51	8	8	84	25	43	16	0.190	0.102	88
52	9	9	82	25	43	15	0.190	0.107	83
53	6	5	89	25	41	22	0.185	0.088	97
54	7	7	86	24	41	22	0.169	0.078	91
55	3	9	88	27	49	12	0.148	0.054	93
56	4	5	91	32	48	12	0.136	0.052	84
57	4	6	91	44	44	4	0.144	0.067	76
58	3	5	91	45	43	3	0.145	0.064	80
59	7	10	83	35	28	20	0.274	0.119	155
60	10	3	87	36	29	22	0.234	0.103	131
61	12	8	80	40	26	15	0.233	0.106	127
62	28	7	64	32	19	13	0.220	0.131	89
63	11	7	82	32	31	19	0.233	0.103	130
64	29	8	64	26	23	15	0.318	0.157	161

Table A.1. Actual rubber ring data used to evaluate models to predict volumetric water content of rubber ring samples at 10 and 100 kPa and water holding capacity between 10 and 100 kPa cont.

No.	Clay	Silt	Sand	Fine	Medium	Coarse	VWC	VWC	WHC
	content	content	content	sand	sand	sand	10	100	10-100
	(%)	(%)	(%)	content	content	content	kPa	kPa	kPa
65	13	9	78	34	23	21	0.221	0.116	105
66	43	17	40	17	10	12	0.433	0.323	109
67	5	4	91	31	34	27	0.173	0.057	116
68	24	5	71	24	25	22	0.244	0.117	127
69	13	12	75	33	26	16	0.283	0.141	142
70	13	14	73	33	25	16	0.222	0.123	100
71	12	17	71	52	18	17	0.215	0.145	70
72	17	19	65	45	14	6	0.221	0.164	57
73	19	20	61	52	6	3	0.359	0.202	157
74	15	24	62	47	8	7	0.324	0.174	150
75	18	22	61	43	10	8	0.248	0.139	109
76	16	25	59	33	12	14	0.316	0.168	148
77	30	24	45	24	8	13	0.304	0.200	104
78	16	28	56	34	8	14	0.227	0.132	95
79	32	27	41	20	8	14	0.312	0.211	101
80	14	24	62	49	6	7	0.321	0.176	145
81	24	30	46	32	6	7	0.317	0.202	115
82	16	31	53	40	6	7	0.391	0.219	172
83	32	28	40	30	5	5	0.301	0.206	95
84	12	22	65	48	9	8	0.340	0.183	157
85	50	20	30	25	3	2	0.431	0.296	135
86	7	6	87	41	18	27	0.243	0.125	118
87	2	2	96	23	32	42	0.099	0.045	54
88	10	11	80	57	10	13	0.407	0.153	254
89	10	11	79	53	11	15	0.365	0.150	215
90	12	8	80	53	12	14	0.254	0.126	128
91	3	2	95	23	32	40	0.110	0.046	65
92	6	9	86	43	18	25	0.269	0.121	148
93	5	8	87	41	20	25	0.229	0.110	119
94	2	5	95	27	26	42	0.105	0.040	66
95	2	2	96	28	30	38	0.097	0.033	64
96	7	10	90	52	37	0	0.149	0.068	81

Table A.1. Actual rubber ring data used to evaluate models to predict volumetric water content of rubber ring samples at 10 and 100 kPa and water holding capacity between 10 and 100 kPa cont.

No.	Clay	Silt	Sand	Fine	Medium	Coarse	VWC	VWC	WHC
	content	content	content	sand	sand	sand	10	100	10-100
	(%)	(%)	(%)	content	content	content	kPa	kPa	kPa
				(%)	(%)	(%)			
97	41	6	53	34	19	0	0.416	0.269	146
98	9	5	87	66	17	4	0.244	0.103	141
99	9	3	87	65	21	2	0.209	0.093	117
100	31	6	63	49	12	2	0.348	0.190	158
101	8	6	86	67	17	2	0.198	0.088	111
102	4	7	90	72	17	1	0.273	0.144	130
103	22	6	72	55	16	1	0.323	0.173	151
104	9	2	89	52	36	1	0.170	0.079	91
105	44	3	53	36	17	0	0.436	0.277	158
106	29	7	65	58	5	1	0.449	0.219	231
107	51	7	43	40	3	0	0.536	0.343	193
108	16	16	69	61	7	1	0.459	0.166	294
109	27	6	67	58	8	1	0.412	0.163	249
110	8	25	67	59	7	1	0.452	0.130	322
111	9	16	75	66	8	1	0.363	0.115	248
112	11	19	70	63	6	1	0.447	0.138	309
113	11	17	73	65	7	1	0.399	0.125	274
114	10	21	69	61	7	1	0.473	0.164	308
115	11	18	71	62	7	1	0.422	0.147	276
116	27	26	47	39	5	3	0.447	0.287	160
117	38	16	45	37	5	3	0.453	0.311	141
118	26	25	50	43	4	2	0.460	0.287	173
119	30	21	49	40	6	3	0.411	0.262	149
120	9	22	69	56	11	2	0.502	0.211	291
121	14	19	67	51	16	1	0.347	0.164	182
122	5	17	78	66	11	1	0.486	0.180	306
123	6	18	76	60	14	1	0.444	0.190	254
124	9	19	72	59	11	1	0.466	0.194	272
125	23	24	53	42	10	1	0.363	0.188	175
126	6	6	88	29	37	22	0.127	0.072	55
127	4	5	92	25	34	33	0.152	0.074	78
128	12	7	81	23	35	24	0.194	0.116	78

Table A.1. Actual rubber ring data used to evaluate models to predict volumetric water content of rubber ring samples at 10 and 100 kPa and water holding capacity between 10 and 100 kPa cont.

No.	Clay content (%)	Silt content (%)	Sand content (%)	Fine sand content (%)	Medium sand content (%)	Coarse sand content (%)	VWC 10 kPa	VWC 100 kPa	WHC 10-100 kPa
129	11	6	83	23	29	32	0.112	0.061	51
130	9	11	80	28	31	21	0.160	0.100	61
131	3	2	95	26	59	10	0.106	0.039	66
132	3	3	94	22	55	18	0.114	0.046	68
133	3	4	94	37	47	10	0.148	0.048	100
134	3	2	95	35	48	12	0.111	0.041	70
135	12	10	78	34	38	6	0.224	0.126	98
136	5	5	91	35	48	8	0.137	0.056	81
137	6	5	90	28	52	10	0.138	0.059	79
138	4	4	92	46	44	3	0.139	0.051	88
139	8	7	85	32	22	31	0.187	0.088	99
140	8	2	90	38	18	35	0.121	0.062	59
141	13	3	85	34	19	32	0.229	0.110	119
142	13	4	83	25	13	45	0.188	0.098	90
143	11	8	82	39	26	17	0.210	0.112	98
144	15	7	78	36	21	21	0.182	0.099	83
145	14	12	74	35	14	25	0.272	0.158	114
146	15	13	71	28	10	34	0.134	0.092	42
147	31	33	36	21	7	8	0.230	0.149	81
148	7	7	87	31	30	25	0.157	0.072	84
149	6	6	87	35	29	24	0.149	0.058	91
150	5	15	80	44	27	9	0.287	0.111	175
151	3	5	92	17	18	47	0.050	0.016	34
152	23	13	64	45	13	6	0.387	0.208	178
153	31	12	57	40	12	6	0.390	0.290	181
154	11	15	74	34	14	26	0.335	0.205	130
155	7	9	84	55	17	12	0.177	0.079	98
156	8	9	84	51	17	16	0.152	0.077	74
157	41	7	52	28	8	16	0.179	0.140	39
158	4	2	94	33	54	8	0.091	0.042	50
159	3	1	96	24	61	12	0.086	0.034	53
160	8	18	74	40	29	5	0.244	0.099	145

Table A.1. Actual rubber ring data used to evaluate models to predict volumetric water content of rubber ring samples at 10 and 100 kPa and water holding capacity between 10 and 100 kPa cont.

No.	Clay content (%)	Silt content (%)	Sand content (%)	Fine sand content (%)	Medium sand content (%)	Coarse sand content (%)	VWC 10 kPa	VWC 100 kPa	WHC 10-100 kPa
161	8	9	84	43	26	14	0.265	0.118	147
162	6	8	87	42	27	18	0.216	0.101	114
163	5	7	88	48	33	8	0.179	0.078	101
164	6	5	89	55	25	10	0.139	0.051	88
165	7	5	88	50	25	13	0.117	0.045	73
166	67	3	30	16	7	7	0.349	0.261	88
167	70	5	25	13	8	4	0.276	0.191	85
168	2	3	95	43	44	8	0.090	0.033	58
169	3	3	94	61	30	3	0.134	0.041	93
170	1	2	97	14	54	28	0.072	0.023	50
171	1	1	98	14	55	30	0.086	0.025	61
172	1	1	98	17	55	27	0.065	0.023	43
173	3	4	93	22	57	14	0.075	0.037	38
174	6	3	91	22	56	13	0.068	0.031	37
175	9	3	88	22	53	13	0.084	0.043	41
176	2	2	96	14	56	26	0.096	0.040	56
177	2	2	96	13	55	28	0.071	0.029	43
178	3	2	95	15	56	24	0.058	0.022	37
179	1	3	96	16	58	22	0.093	0.027	66
180	1	3	96	16	55	25	0.113	0.035	78
181	1	2	97	18	58	21	0.120	0.028	93
182	2	3	95	29	55	12	0.130	0.041	90
183	1	2	97	30	55	12	0.118	0.025	93
184	1	2	97	34	53	10	0.119	0.027	92
185	2	4	94	43	43	9	0.217	0.089	128
186	1	3	97	43	44	10	0.092	0.013	79
187	1	3	96	40	45	11	0.104	0.015	89
188	1	2	97	33	50	14	0.102	0.014	88
189	1	2	98	36	49	13	0.099	0.010	89
190	1	1	98	35	51	13	0.071	0.007	65
191	2	3	95	27	52	16	0.149	0.042	106
192	1	1	97	30	52	16	0.105	0.018	87

Table A.1. Actual rubber ring data used to evaluate models to predict volumetric water content of rubber ring samples at 10 and 100 kPa and water holding capacity between 10 and 100 kPa cont.

No.	Clay content (%)	Silt content (%)	Sand content (%)	Fine sand content (%)	Medium sand content (%)	Coarse sand content (%)	VWC 10 kPa	VWC 100 kPa	WHC 10-100 kPa
193	1	2	97	30	52	15	0.084	0.008	76
194	1	1	97	21	57	19	0.057	0.006	52
195	1	1	98	25	56	17	0.053	0.006	47
196	1	1	98	23	57	18	0.053	0.008	45
197	3	13	83	71	10	2	0.448	0.251	197
198	7	13	80	61	18	2	0.389	0.189	200
199	18	13	69	54	11	4	0.379	0.190	189
200	11	19	70	57	10	3	0.410	0.196	215
201	6	11	83	71	10	3	0.410	0.204	205
202	8	9	82	51	28	4	0.321	0.153	168
203	6	15	80	66	10	4	0.453	0.231	222
204	14	14	72	51	16	5	0.263	0.142	121
205	4	7	89	28	38	23	0.186	0.076	110
206	13	25	63	44	13	6	0.407	0.212	195
207	14	9	77	26	28	23	0.223	0.120	102
208	1	1	98	17	78	4	0.050	0.026	24
209	1	1	98	17	78	4	0.050	0.019	31
210	1	1	98	69	25	4	0.057	0.029	29
211	13	17	70	40	9	21	0.228	0.116	112
212	18	26	55	41	7	7	0.323	0.167	156
213	7	8	85	14	26	45	0.102	0.055	48
214	7	6	87	31	48	9	0.123	0.065	57
215	17	14	69	21	31	17	0.294	0.150	144
216	7	7	86	33	41	13	0.153	0.073	79
217	22	27	52	34	15	3	0.371	0.224	147
218	23	23	54	38	14	2	0.391	0.241	151
219	8	11	82	41	36	4	0.224	0.108	116
220	4	4	93	22	59	12	0.08	0.037	43