DEVELOPMENT OF FAST AND BOUNCY CRICKET PITCHES IN SRI LANKA

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The research thesis was submitted in partial fulfillment of the requirements for the Degree of Master of Science

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June, 2017

DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

Development of Fast and Bouncy cricket pitches in Sri Lanka

Most cricket batsmen in Indian subcontinent face a great difficulty in batting against fast bowlers on English and Australian fast and bouncy cricket pitches. The lack of having such practice pitches in home is the main reason for their lack of performances in fast pitches. It had been discovered that the pace and bounce of a cricket pitch is governed by clay content, clay mineralogy, sand content, organic matter content and grass content of the top layer of a cricket pitch.

Six local soils and one soil from India were tested for their index properties as the preliminary step. The soils which were fulfilling the requirement of the soil properties of fast and bouncy cricket pitch material were selected along with the currently used soil for Sri Lankan cricket pitch preparation and used for the laboratory model studies.

Six cubic samples for the friction and bounce comparison were prepared inside the laboratory from selected three soils varying the surface grass content.

The co-efficient of friction (μ value) and the co-efficient of restitution (e value) were determined by the bounce test and friction test respectively. Soils which had low "μ" value and high "e" value were selected as suitable soils for the further proceedings of the research.

MU and TY along with MT (Mixture of both MU and TY) were selected to carry on further studies in an actual cricket pitches in order to check their ability to generate pace and bounce.

Besides selected area of the cricket pitch was daily photographed and surface crack density was analysed using MATLAB software.

MU was selected as the most suitable soil from among all tests soils and recommended to be used for the development of local fast and bouncy cricket pitches in Sri Lanka.

Keywords: Pace, bounce, cricket pitch, clay

DEDICATION

To my parents, teachers and all cricket loving readers

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LIST OF ABBREVIATIONS

Abbreviation	Description
MU	Murunkan soil
TY	Tyronne Fernando Stadium soil
KO	Kotawehera soil
MT	Murunkan: Tyronne = 1:1 mixed Soil
+GR	with Grass
D.A.C	Days after compaction
PL_{MU}	Ball pitching line for MU strip
PL_{MT}	Ball pitching line for MT strip
PL_{TY}	Ball pitching line for TY strip
H_p	Height of the ball measured by the pole
H_{TY}	Corrected vertical ball height for TY soil
H_{MU}	Corrected vertical ball height for MU soil
HB	Hockey Ball
TCB	Test Cricket Ball
PM	Pitch Model
ms	milliseconds
T_{In}	Time when ball passes the 1st pole
T_{Out}	Time when ball passes the 2nd pole

T_p	Ball pitching time
g	gravitational acceleration 9.81 ms^{-1}
J	Joules
k	kilo
LPA	Laser Particle Analyser
Gs	Specific gravity
μ	Coefficient of Friction
e	Coefficient of Restitution
m	meters
cm	centimeters
ER%	Percentage reduction in total energy
MC%	Moisture Content
USCS	Unified Soil Classification System
SL	Sri Lanka / Sri Lankan
AUS	Australia / Australian
L/H	Light hand operated roller
H/H	Heavy hand operated roller
VR	Vibratory Rammer
WBR	Walk behind roller

1 INTRODUCTION

1.1 Game of Cricket

Cricket is a game played between two teams of eleven players each. The game has three distinct sub editions in terms of the duration of play within the international arena, namely "Test Cricket", One day internationals (ODI), and 20 over matches (T20). Each team bats and bowls so that the winner in terms of runs or wickets will be selected thereafter. The unpredictability of the game and the ever-changing cricket pitch conditions from one ground to another has influenced the popularity of the game of cricket. Cricket is more of a complex sport that several key factors such as weather, pitch conditions, outfield conditions influence on the playing conditions of a single game.

1.2 Cricket pitch and the need of Fast and bouncy cricket pitches in Sri Lanka

The surface on to which a bowler projects a ball in the game of cricket is made up of hard packed soil with sparse grass cover. This natural turf surface or the "pitch" will eventually lead to different playing conditions from one stadium to another, or from one country to another. Players have to adapt to the nature of the pitch in order to perform well with both bat and ball.

The well-compacted topmost clay layer or the "bully" of a cricket pitch helps the cricket ball to gain bounce and pace off the turf. The nature of the clay type and various other parameters improves or degrades the pace and bounce of the ball. To construct a fast and bouncy pitch, it is needed to find alternative soils other than what is being used in typical local context.

1.3 Pitch Characteristics and Need of fast and bouncy pitches in Sri Lanka.

Pitches usually categorized into two main sections, fast and bouncy wickets and slow and low, spinning wickets. Cricket playing nations usually construct pitches either fast and bouncy or slow and spinning. So, players find it difficult to play on conditions which they do not experience in their home soil. In Sri Lankan context, pitches are tailor-made to assist slow spin bowlers. Hence Sri Lankan batsman lack exposure to quality fast bowling which offers more pace and bounce. Adapting to the nature of the pitch determines the success of a batsman and at the same time needs some skill level. (Nawagamuwa, et al., 2009).

To make pitches which suits fast bowlers, either soil should be imported from overseas or a local soil has to be found with similar soil properties. This research addresses this issue by conducting field tests on a new local clayey soil for the possibility of making fast and bouncy pitches by comparing them with a normally used pitch preparation soil in Sri Lanka. These field tests which were carried out at an actual pitch after successful series of soil tests and model tests at the laboratory on the same soil.

1.4 Objective

Objective of this research is to find a locally available soil(s) having approximately same soil properties of a fast and bouncy cricket pitch soil and determine the co-efficient of friction and co-efficient of restitution values of a laboratory model made from the afore-mentioned soil(s) and compare the bounce and the pace of an actual cricket pitch made from the afore-mentioned soil(s) with currently used soil in SL cricket pitch preparation.

1.5 Research approach

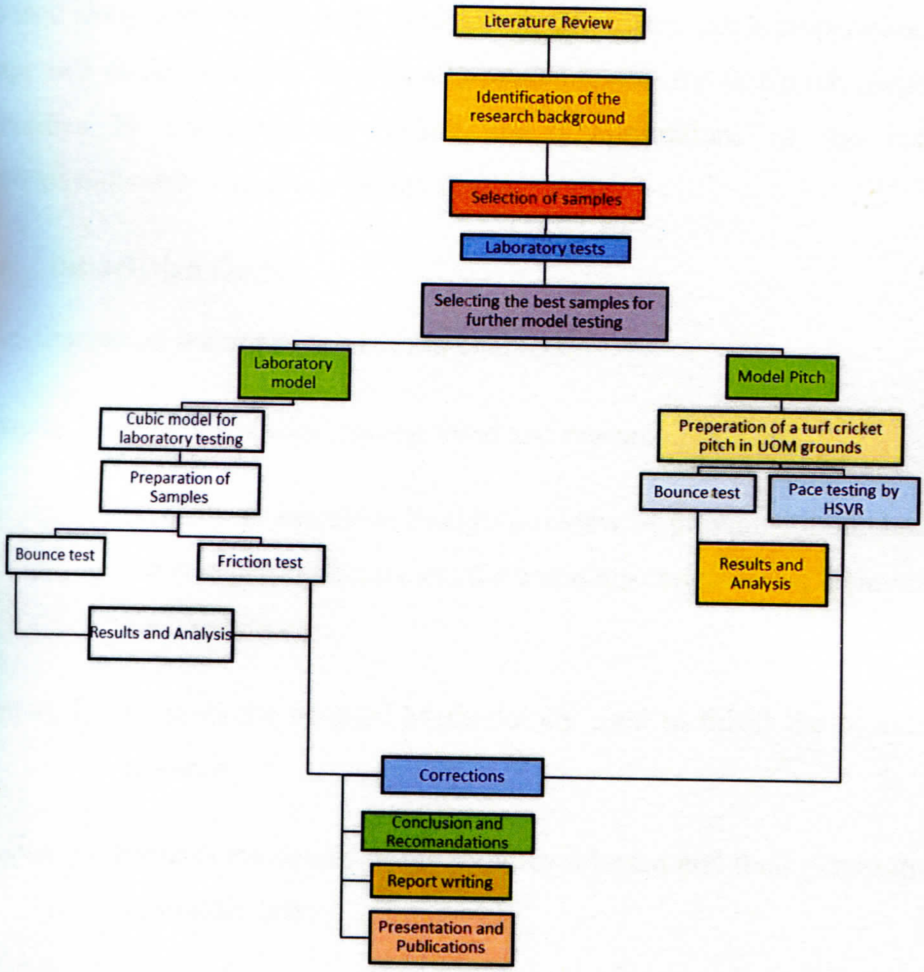


Figure 1.1 Schematic view of the research approach

In this research "Development of Fast and Bouncy cricket pitches", literature review was done as the first step to identify the research background. After selecting the suitable soils by the literature review, index property tests were carried out for the soil samples. Soils having desired properties of a fast and bouncy pitch preparation material was used for further laboratory model tests. Friction test and bounce test were carried out for the selected samples during laboratory model tests which was the stage 1 of the research. The coefficient of Friction (μ value) and Coefficient of Restitution (e value) was determined respectively by each tests.

The soil giving high e value and low μ value was selected and used in actual cricke pitch preparation. The prepared pitch using the selected soil was tested for pace an bounce along with the currently used soil in SL cricket pitch preparation during th stage two of the research. Best locally available soil for fast pitch preparation wa identified by analyzing the results and limitations of the research anc recommendations were given for the further studies

1.6 Dissertation Outline

The dissertation is comprised of seven chapters.

Chapter 1 – Explains research background and research problem.

Chapter 2 – Presents an extensive literature review of previous researches regarding the research problems and the associated engineering techniques used in such researches.

Chapter 3 – Presents the adopted Methodology used to fulfill the objectives of the research.

Chapter 4 – Presents the details of the samples selected and their preparations for the laboratory tests

Chapter 5 – Explains the laboratory experiments done for the samples and the results.

Chapter 6 – Explains the laboratory model studies done for the selected soils.

Chapter 7 – Explains the pace and bounce tests done for the selected soils in actual field conditions

Chapter 8 – Presents the summary of the research and the conclusion with limits and recommendations of the research.

Chapter 9 – List of the References

Chapter 10 – Appendix

2 LITERATURE REVIEW

2.1 Previous approaches for fast and bouncy cricket pitches

One of the key factor for fast and bouncy pitches is the clay content present in the top-dressing soil. But, the clay content alone does not show a universal correlation with pace and bounce. A perfect counter example is the case of English pitches. Cricket pitches in England have very low clay contents, about 30% (Carré, et al., 1999) which is comparable to Sri Lankan pitches. But, these pitches are faster than Sri Lankan pitches and what even more surprising is that they lose pace when the clay content is increased. To understand this phenomenon a study has to be done on how the clay content affects the mechanics and physical properties of a pitch. It has to be found whether other variables besides the clay content have an effect on the effort mentioned behaviour.

In addition to that, soil sample taken from Mannar area which is named as "Murunkan soil sample" has been tested for its ability to be used as a fast and bouncy cricket pitch soil. After doing the index property tests and classifications for the soil it had been concluded that soil sample from Mannar area is suitable for a fast and bouncier pitch material (Perera, et al., 2015).

2.2 Layers of a typical Sri Lankan cricket pitch (Fernando, 2016)

Typical cricket pitch in Sri Lanka consists with five notable layers as shown below.

- Layer 1 : Compacted clay layer (Bully) of 125mm
- Layer 2 : Compacted ant clay layer of 100mm
- Layer 3 : Compacted gravel layer ("*Makula boralu*") of 750mm
- Layer 4 : Crushed and compacted brick tiles layer of 50mm
- Layer 5 : Compacted rubble layer (150mm x 225mm), voids filled with river sand, 225mm side of the rubble is kept in vertical direction.

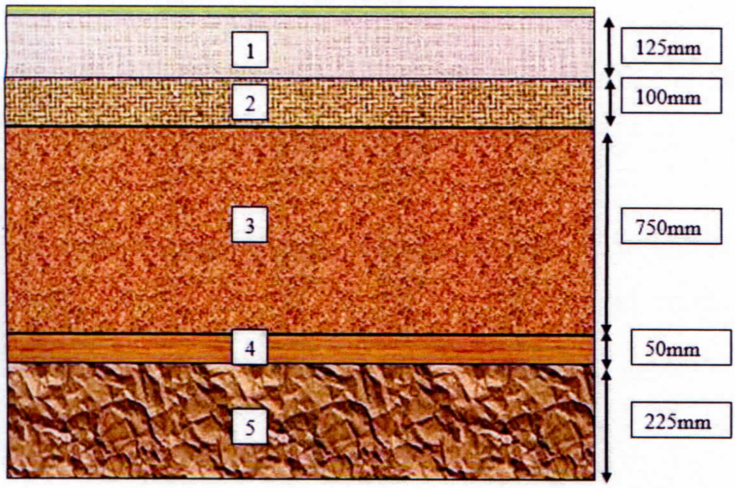


Figure 2.1 Layers of a typical SL pitch

On top of all layers there is grass whe : its stems are starting from the ant clay layer. There are two types of grass types can be seen in SL wickets. "*Blue grass*" is planted inside the ant clay layer through the clay layer while "*Running grass*" is planted on the pitch surface.

2.3 Typical pitch preparation procedure (Fernando, 2016)

During test matches, before the commencement of play on first day, moisture is allowed to be added and thereafter, the condition of the pitch is only modified via the roller compaction during the period of play. So, due to the drying process during playing days allows the clay layer to shrink allowing the cracks to open up. As the drying continues, cracking of the pitch may improve and these cracks may disappear after the pitch is wetted and rolled again.

During the five-day test matches, roller compaction is done in three situations

1. Before the start of the game on each day's play.
2. During innings break.

   In both these situations, batting team will decide the type of roller to be used in terms of light or heavy roller.

2.4 Playing characteristics of cricket pitches

According to the authors, playing characteristics can be classified as follows,

- **Pace**

Quantitative measurement on how much speed does the cricket ball retains during a delivery by a bowler after bouncing off the turf. Horizontal velocity component governs this factor.

- **Bounce**

Quantitative measurement on comparing the rebound height and the delivered height during a delivery by a bowler before and after bouncing off the turf. Vertical velocity component governs this factor.

- **Spin**

Spin depends on the number of revolutions of the ball which the bowler provides in the delivery stride and the seam presentation of the leather ball. Pitch condition and the weather also affect the spinning ability of the ball.

- **Consistency**

Consistency means how the above characteristics vary along the pitch surface. If the playing conditions differ in different parts of the same pitch, it becomes unsuitable to play. So, consistency should be maintained for a fair game of cricket.

- **Deterioration**

Although a pitch is prepared to meet the standards, with time, it will start to deteriorate. Deterioration due to opening up cracks will cause unpredictable movements of the ball and uneven bounce which will thereby cause dismissals of batsman.

As per the comparison between Sri Lankan (and most Indian subcontinent pitches) pitches with Australian, South African and English pitches, three of the above characteristics show significance variation. They are "pace", "bounce" and "deterioration". Sri Lankan pitches offer lower pace and bounce while they deteriorate quicker than the other pitches in Australia, England and South Africa.

There are several factors which govern the above characteristics of a cricket pitch (Nawagamuwa, et al., 2009)

- Clay content of the soil and clay minerology
- Moisture content and degree of compaction of soil
- Amount of grass cover on the pitch
- Organic content of clayey soil
- Cracking of the surface (Crack widths)
- Silt content of the soil

2.4.1 Clay content of the soil, clay minerology and the impact

Soil properties of the ICC test venues in AUS was shown below in Table 2.1

Table 2.1 Properties of clay used in Australian pitches (Nawagamuwa,et al.,2009)

Soil	Adelaide	Brisbane	MCG	Perth	SCG
Clay	51	68	53	82	52
Silt	14	6	21	6	22
Fine Sand	25	5	20	6	15
Coarse sand	7	1	1	2	7
Organic matter	2.2	5.5	5.4	2.1	5.7
Type	Smectite-Illite	Smectite-Illite	Smectite-Kaolinite	Smectite-Illite	NA

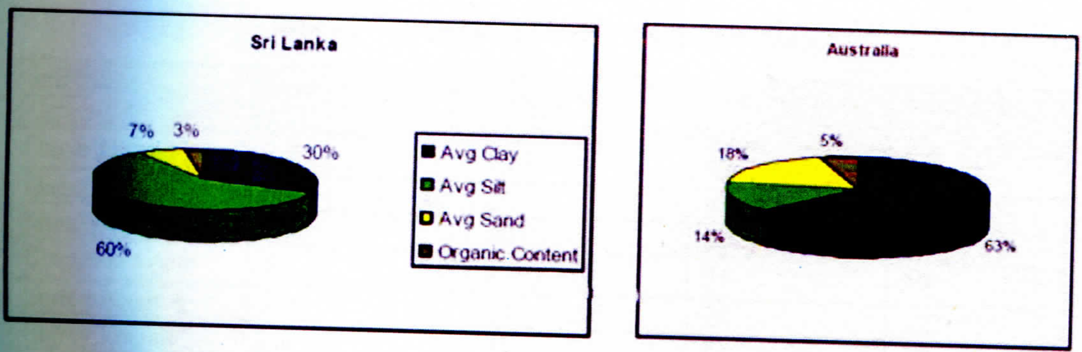


Figure 2.2 Data courtesy of SLC and NZSTI, (Nawagamuwa, et al., 2009)

Average grading of cricket pitch soils in AUS and SL is shown in **Error! Reference source not found.**. When interpreting the numbers in this table, the Australian soils which are used to prepare turf wickets, all the soils have high amount of clay percentage and a less amount of silt and sand. In Perth, clay content is as high as 82% and this shows why the WACA (Western Australia Cricket Association) ground is renowned for its' pace and bounce over the years. The presence of loose particles such as sand will absorb kinetic energy of a delivered leather ball reducing the velocity and the rebound height. Also, the presence of sand will decrease the cohesion of the soil mixture and thereby can cause the soil to be power and crumble. Therefore, to make fast and bouncy pitches, the topmost clayey layer should have higher clay content with a minimum sand content. (Perera, et al., 2015)

When considering the soils used by Sri Lanka Cricket to construct pitches, average silt percentage is as high as 60% while the clay content is only around 30%. So, in terms on clay content, which allows the pitch to bond together, Sri Lankan and Australian practice of pitch making have a definite difference which influence on the playing conditions of the game.

Table 2.2 illustrates the soils used in preparation of pitches of England and Wales. (Carré, et al., 1999)

Table 2.2: Soil properties used in England pitches

Soil Name	Organic matter (%)	Clay (%)	Silt (%)	Sand (%)
Ongar Loam Plus	3.8	31	42	27
Ongar Loam	3.8	32	41	27
Mendip loam	7.8	30	57	13
Boughton Loam	7.1	30	31	39
Surrey Loam A	3.0	24	24	52
Surrey Loam C	2.8	31	31	38
Kaolam	2.5	30	53	17

But in contrast England, which is also home to the game of cricket, uses soil with less amount of clay content for pitch making when compared to Australian continent. In general, it is through the larger voids that the water seeps through and the smaller voids are the ones which retains moisture i a soil. So, clayey soils are water retaining soils as they have smaller voids than other granular soils. Therefore, if a pitch made out of soils consisting greater percentage of clay, it should be exposed to drier conditions to dry up until a hard surface is achieved. But in England, due to the seasonal changes of climate, persistent rainy conditions even in summer and limited duration of sunlight within a day, does not offer good drying conditions for clayey soil rich pitches. So, they've opted for soils with average amount of clay for cricket pitch making to strike a balance in between assistance for pace and bounce and duration for drying of pitches under uncontrollable climatic conditions. (Carré, et al., 1999)

2.4.2 Smectite clay minerology and properties

All the major Australian grounds except MCG (Melbourne Cricket Ground), have been using Smectite-Illite type clayey soil for pitch making. Smectite is an expansive clay which tends to shrink in low moisture conditions. (Herath, 1973) Hence it shows a significant cracking when subjected to drying conditions. Another inherent quality of this smectite type clay is the highest compressive strength shown among clayey type soils. So, after drying, it produces hardest possible surfaces which paves the way for a faster and bouncier cricket pitch.

In Sri Lankan pitches, the soils used are predominantly kaolinite type clayey soils. Kaolinite carries a low plasticity index and has low plasticity characteristics. So, the chance for a strong bonding between particles with cohesion is low and thus tends to crumble when drying the pitch with time. These pitches show dusty surfaces and premature breaking which assists more for spin rather than for fast bowling. (Nawagamuwa, et al., 2009)

Therefore, finding local soils which shows familiar characteristics as soils such as smectite-illite will open a path in developing a fast and bouncy cricket pitch in local scenario. Two such identified locations of clay deposits which can be used for making of pitches are Kotawehera area in Nikaweratiya region and Murunkan in Mannar district. Both these locations have a clay deposit which shows a clay percentage more than 50% and the plasticity index is beyond the limit of most of the common clayey soils in Sri Lanka. Above these two, Murunkan sample has shown the highest clay content, highest liquid limit and highest plasticity index. (Perera, et al., 2015) This Murunkan soil is a soil type of the grumusol group which covers about 17000ha in the Mannar and Jaffna region, northern parts of the island (Sobana, et al., 2014). The soil is rich in nutrients for cultivation and carries a minimum permeability and high capability of water retention for longer periods. Hence it is classified as one of the best available soils for paddy cultivation (Sobana, et al., 2014) . These grumusol soil is a highly active soil, hence belongs to the Smectite clay group. From the soils classified to date in Sri Lanka, grumusol soil deposits happen to be one of the clayey soil with the high percentage of clay.

2.4.3 Correlations between pitch characteristics and behaviour of ball

The coefficient of friction, μ, has a strong negative correlation with velocity ratio. Therefore, higher the friction coefficient, velocity ratio becomes lower and for a given releasing speed of the ball, the rebound velocity will be lower (Carré, et al., 1999).

Carré et al., (1999) have found out that bulk density has a strong negative correlation with moisture content. The correlation between hardness and moisture content has found out to be strongly negative. Pitch hardness has a direct impact for the behaviour of the ball at impacts. Further, the authors state that moisture content shows a strong negative correlation with velocity ratio and strong positive correlation with coefficient of friction. At the same time Carré et al., (1999) points out that repeated measurements on pace and bounce should be made over a period of time due to large number of factors which contributed to the variations of results (wear of the ball, deterioration of pitch, change in weather conditions, inconsistency of the deliveries, etc.

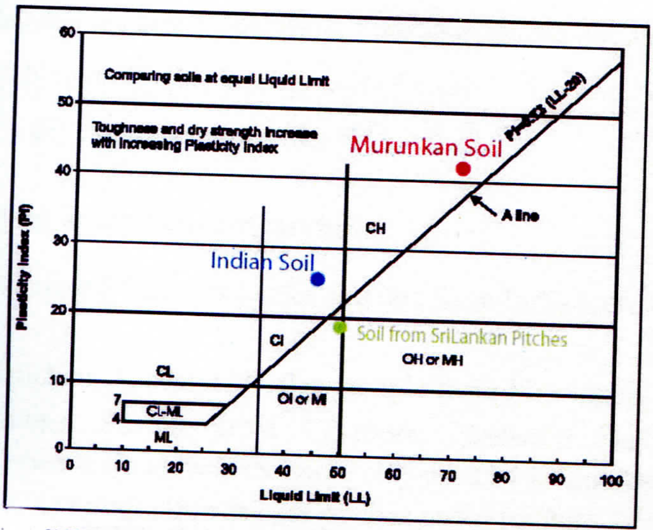
2.5 Previous tests on soils

2.5.1 Laboratory tests (Perera & Nawagamuwa, 2015)

"Grumusol" clay was discovered in Murunkan with comparatively high clay content which is fulfilling most of the required clay properties in a Fast and Bouncy Wicket. Typical Sri Lankan clay sample use 'o prepare wickets, Clay sample from Bangalore and the local "Grumusol" sample from Murunkan was tested for the clay properties. Results showed that "Grumusol" is highly suitable for constructing a Fast and Bouncy.

Series of experiments were conducted according to appropriate guidelines such as BS and ASTM. Soil classification of three samples were done by performing particle size distribution using wet sieve analysis and Hydrometer test, Atterberg limit test, specific gravity test and Proctor compaction test.

Particle size distribution and Atterberg limit tests were done in order to classify the selected soil samples. Rather than using the ordinary sieve analysis here a wet sieve analysis is done because the soil is mostly clay. The primary objective of wet sieve analysis test was to separate the particles greater than 0.075mm and doing the sieve analysis for the greater size particles. Liquid limits, Plastic limits and Plasticity Index were found by Atterberg limit tests which were conducted according to the BS 1377-2 standards.



PLASTICITY CHART FOR LABORATORY CLASSIFICATION OF FINE-GRAINED SOILS.

Figure 2.3 USCS chart , Perera et al. 2015

Ash content test was used to determine the organic matter content (ASTM D 2974-87 of the selected clayey soil samples. Classifications of the soils were done with Unified Soil Classification method.

Highlighted results can be shown as follows

- Three samples (MU, TY, BAN) were tested for the soil properties and the "Grumusol" sample from Murunkan shows its higher ability to be a fast pitch soil.
- The soil from Bangalore meets the requirement in to some extent by having higher amount of Silt and Clay particles and high plasticity
- In contrast the currently using soil in Sri Lanka is having higher silt, sand and Organic impurities which gives the reason of being Slow and Low.
- To keep the clay particles together while maintaining the strong bond and reduce the crack openings in extreme hot temperature and low humid conditions Crouch grass is ideal to use in Sri Lankan pitches

Since importing soil is a costly operation, finding a reliable source such as "Grumusol" in Murunkan which meets the requirement of a soil in fast and bouncy wicket is great advantage for a developing country like Sri Lanka.

2.5.1 Soils used in previous researches

Seven soils including 6 from Sri Lanka and one from India were used in this research.

- Murunkan- "Grumusol" clay sample from Murunkan, Mannar, Sri Lanka
- Tyronne- Sample from "Tyronne Fernando Stadium" cricket pitch Katubedda which was the same clay used by Sri Lanka Cricket Association (SLCA) for all other cricket pitches in Sri Lanka
- Ant clay- Typical Ant clay sample from Batticaloa, Sri Lanka

2.5.1.1 Murunkan soil (MU), (Sobana, et al., 2014)

This soil type mainly belongs to Smectite soil group with high clay content. Murunkan series occurred on the back slope of the Yoda wewa flood plain in Sri Lanka. This was a deep, very poorly drained soil rich with clay. Surface soil was clayey and black in colour. The soil group, Grumusol covers about 17000 ha in the Mannar and Jaffna districts of Sri Lanka.

Shrinkage cracks on the surface soil were a marked feature during dry season of this soil deposition of calcium and magnesium carbonate rich soil.

2.5.1.2 Ant clay (Fernando, 2016)

Ant clay layer is an essential layer in every pitch which is added beneath the clay layer. This brown coloured ant clay is used as base the layer for the grass which is enrich with nutrients. Stems of the grass is inserted to this soil (Four plants per one hole) and clay layer is filled on top of this layer which is compacted layer by layer afterwards mean while the growth of the grass. Usually the layer thickness of the ant clay will be around 100mm. This soil can be usually found near river banks, paddy fields, forests or earth embankments where termites live.

2.5.2 Laser Particle Analyser (LPA) test

Low-angle laser light scattering, or laser diffraction, has been well known as a reliable laboratory technique since the 1960s. It is conventionally used in the laboratory, when wide distributions need to be analysed in quick time. (Crawley, 2001).

The size analysis is based on an intensity distribution measurement of coherent laser light scattered by the particles. The form of the scattering pattern is described by the Mie theory and the width of the pattern is dependent on the size of the particles. When laser light meets a group of particles, volumetric size distribution can be calculated back from the scattered light distribution. (Burrows, 2013)

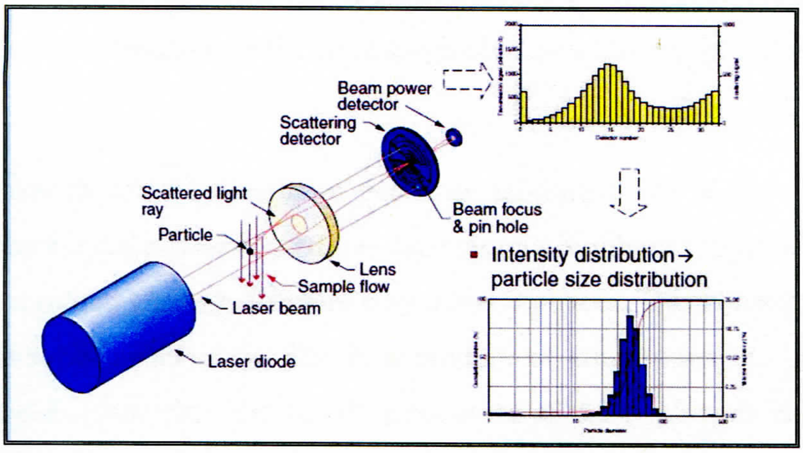


Figure 2.4 The principle of laser diffraction analysis (Burrows, 2013)

Laser diffraction method depends upon the diffracted light produced when a laser beam passes through a dispersion of particles in air or in liquid. The angle of diffraction increases as the particle size increases. Therefore, this method is reliable and accurate when measuring particle sizes distributions between 0.1 and 192 μm (Rathnayake, et al., 2005). Also, this method is relatively fast and can be performed on very small sized samples.

Laser diffraction measures particle size distributions by measuring the angular variation in intensity of light scattered as a laser beam passes through a dispersed particulate sample. Larger particles scatter light at smaller angles relative to the laser beam and smaller particles scatter light at larger angles relative to the laser beam. The angular scattering intensity data is then analysed to calculate the size of particles responsible for creating the scattering pattern. The particle size is reported as a volume equivalent sphere diameter.

2.5.3 X-Ray Diffraction (XRD) test

Clay mineralogy is one of the governing factors which influences the pace and bounce of a cricket pitch. Clays which belong to Smectite clay mineralogy group in Australia generates higher ball bounce than currently used clay in Sri Lankan pitches which belong to Kaolinite Clay mineralogy group (Nawagamuwa, et al., 2009). XRD test was adopted in this research in order to find the clay mineralogy of each clay. Powder XRD provides detailed information on the crystallographic structure and physical properties of materials.

Soil clay minerals almost invariably occur as mixtures. The signal intensity of individual clay mineral phases in mixtures depends on a number of physical properties, which are not constant among different clay mineral phases. This consequently leads to the well-known phenomenon that in a mixture of equal parts of, i.e. smectite, muscovite and kaolinite the relative 001 peak areas of these minerals are not equal. This evidence together with what is known about the theory of X-ray diffraction. (Moore & Reynolds, 1997)

2.6 Previous tests for pace and bounce

2.6.1 The friction test

Challenger, (1986) stated that while a major proportion of the research undertaken in England had been concerned with the bounce test, pitch pace was not determined by bounce alone. Movement in the horizontal plane, representing pace at which the ball comes onto the bat, and in the lateral plane, representing sideways movement off the pitch, are also important. To measure the influence of these factors, a friction test was developed by Murphy (1985). The test involved the measuring the force required to move a sledge and series of weights on the surface of the pitch. Following on from the lead given by Stewart & Adams in England in the 1960's, Challenger, (1986) has, for the last few years been testing pitch playability of all of New Zealand's first class pitches. This was done by two tests. First the bounce test developed by Stewart and Adams, which involves dropping a cricket ball from a height of 4 m onto a pitch and measuring the rebound. The higher the bounce, the faster the pitch. This determines the pace on a vertical plane. To measure the horizontal plane (the pace of the ball onto the bat) a friction test was developed which measures both pace onto the bat and sideways movement. This involves measuring 'the force required to move a small sledge (15 x 20 cm) on the surface of the pitch. A series of weights ranging from 3-12 kg were used on the sledge. The higher the friction the greater the resistance of the pitch on the ball, and thus the slower the forward pace. Also, the higher the friction, the higher the sideways movement of the ball. An overall pace rating was worked out by incorporating the two values into the following equation: The bounce and friction tests were incorporated by Murphy (1985) into an overall pace rating scale.

2.6.2 Pace Rating

During the 1984/85 and 1985/86 seasons, pitches in New Zealand were assessed by this objective playability method. A pace rating scale was developed. Murphy, (1985) found that a good relationship existed between pace rating and the subjective assessment of pitch pace. (Challenger, 1986)

$$Pace\ rating = \frac{Ball\ bounce}{Coefficient\ of\ friction}$$

(Murphy, 1985)

Table 2.3: Pace rating categorization

Pace Rating	Pace
0 - 50	Very Slow
50-100	Slow
100-300	Easy
> 300	Fast

2.6.3 Condition of the cricket ball during testing (James, et al., 2012)

The author in his research on the effect of atmospheric conditions for swinging of the cricket ball, have used four distinct types of cricket balls. They are,

Ball 1: Brand new, **Ball 2**: Lacquer removed, **Ball 3**: Shine removed on one side, **Ball 4**: Lacquer removed, gently knocked for 20 overs

Removing shine on one side of the ball aims at simulating the swinging conditions adapted by professional players

2.7 Energy input to the soil in compaction

Although there are very few researches on roller compaction of cricket pitches, most of the curators around the world adapt their own met ods and measures to quantify the level of compaction according to their past experiences. The compaction of soil under the roller is dependent upon roller factors (including rigidity, load, contact area, contact shape) and soil properties (in particular water content and bulk density) which determine the stress distribution beneath the roller and the soil response to this stress. (James & Shipton, 2012)

The number of passes required to compact a cricket pitch will depend on the initial dry bulk density and the compacting potential of the roller (Shipton, 2008). Soil moisture content is another important aspect of optimization of rolling cricket pitches. The calculation of field compaction energy has proved to be a very difficult task. Caterpillar, (2001) received a patent for the calculation of field compaction energy.

$$CE = \frac{R}{T \times W} \quad \text{--Equation (1.1)}$$

CE= Compaction energy R= Machine Rolling resistance

T= Lift Thickness W= compaction width

Selig,(1971) Published an extensive essay meant to quantitatively evaluate compactor performance. The purpose of the research was to develop a method in which different compaction machines (smooth-drum, pneumatic-tire, tamping (sheeps-foot), vibratory) could be evaluated.

For smooth wheel rollers,

$$E = \frac{f \times w \times p}{B \times T} \text{ --- Equation (1.2)}$$

E = Compaction effort per unit volume (ft lb/ft^3)

w = Total weight (lb)

B= Roller width (ft)

f = coefficient of compaction

p = No. of passes

t = compacted lift thickness (ft)

2.8 Effect of roller compaction on soil (Shipton, et al., 2006)

Shipton et al., (2006) has done experiments on roller compaction with two rollers weighting 4.75 and 5.71 kN. The effect of subsequent passes of 4.75 and 5.71 kN on soil dry density was also determined in the soil dynamics laboratory. Maximum dry density was achieved after 20 and 10 passes of each roller, respectively. The roller did not have a significant effect on dry density below 50 mm in the profile.

2.9 Camera set up and videography of deliveries

James et al., (2004) used a Kodak motion camcorder with a frame rate of 120 frames per second and an exposure time of 1/8000 second to analyse the ball movement on a cricket pitch. To relate the measurements taken from video footages and the actual distance travelled, the author has measured some known distances in the plane of the ball impact. The main parallax error is the error occurred due to the positioning of the camera away from the direction perpendicular to the trajectory of the moving ball which overlaps with the point of impact of the ball on the pitch.

Typical a and b values of ball positioning considered by James et al., (2004) was 0.3m and 0.25m respectively. The actual camera position has a distance d away from the ideal camera position, parallel to the centreline of the pitch. The ideal camera position lies on the XX line which crosses the impact position and perpendicular to the ball trajectory. The maximum value considered for "d" is 3m and the minimum distance to the camera from the impact plane was 50m. These two value had caused the maximum error of the angle θ = 3.5°. It had been calculated that the maximum uncertainty due to the misalignment of the camera on the calculation of the pace of the ball was $0.1 ms^{-1}$ ($3.6 kmh^{-1}$).

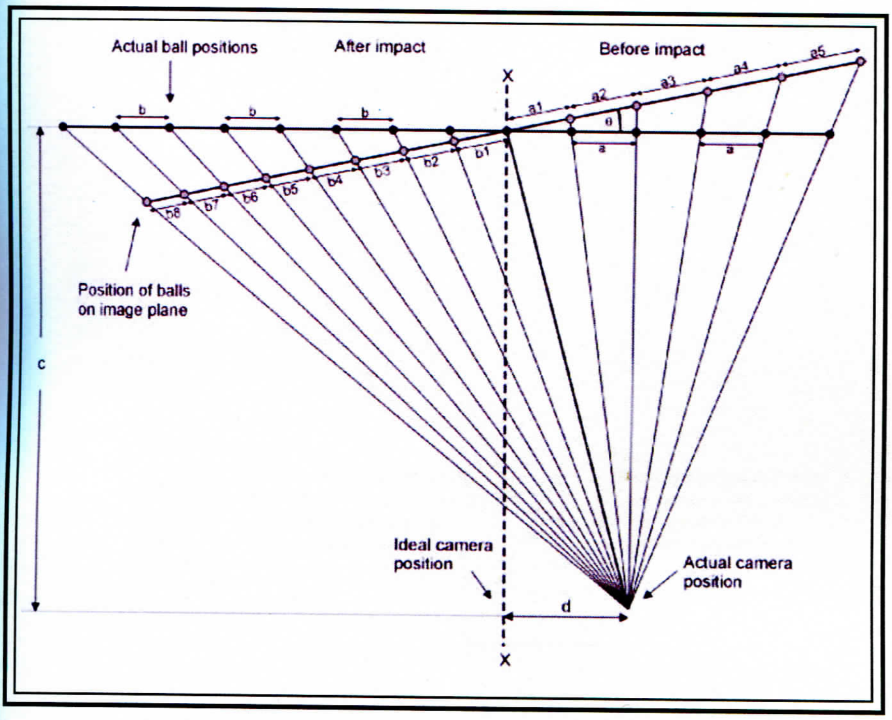


Figure 2.5 Camera positioning - (James , et al., 2004)

This error is analysed by assuming that the trajectory of the ball before and after the impact on the pitch, is parallel to the centreline of the pitch. But if the path of the delivered ball has an offset angle with the centreline of the pitch, there occurs another parallax error. James et al. (2004) has found out that the error due to this scenario is very similar to the error due to misalignment of the video camera system.

2.9.1 Camera

The need of a high-speed camera system was essential for this experiment in order to track the movement of the ball trajectory. (James , et al., 2004) used a Kodak motion coder with a frame rate of 120fps.

2.9.2 Positioning of the camera

Angle of view varies with the focal length.

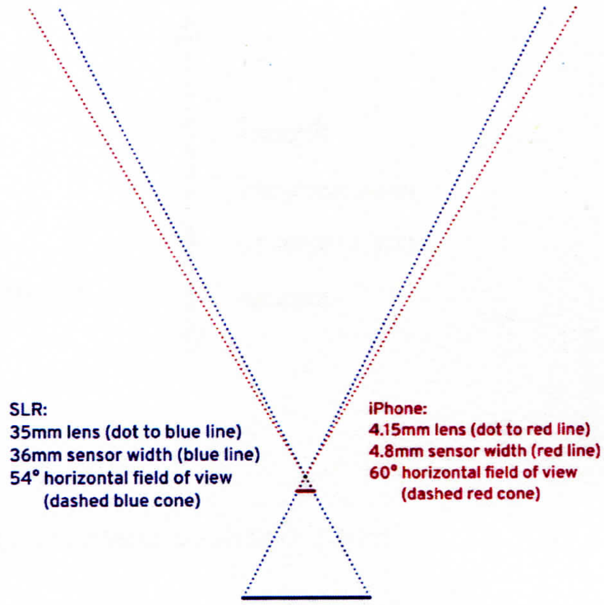


Figure 2.6:Angle of view in iPhone 6S

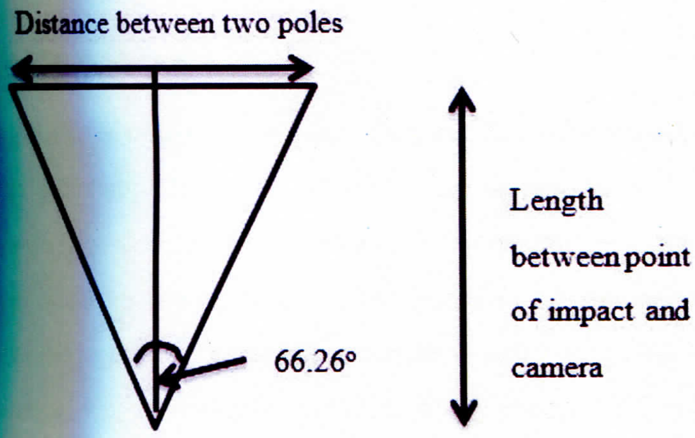
$$Angle\ of\ view = \frac{180 \times d}{\pi \times f}$$ where,

$$d = chosen\ dimension\ \&\ f = focal\ length$$

for I phone 6S , d=4.8mm f=4.15mm

$$Angle\ of\ view = \frac{180 \times 4.8}{\pi \times 4.15} = 66.26$$

By trigonometry,



Length from point of impact to camera position = 2.44m

During the testing, the camera was placed 3.5m away in the perpendicular direction from the central y axis in Tyronne soil area to sufficiently allocate clear space out of the range between two poles within the video frame.

3 SAMPLE SELECTION AND PREPARATION FOR LABORATORY TESTS

3.1 Introduction

The top layer of the cricket pitch (90mm-125mm) consists of a clayey material which is called "bully" (Shannon, 2010). Early researches had revealed that the pace and bounce depend on the clay mineralogy. (Nawagamuwa, et al., 2009) Therefore, the top layer of the cricket pitch had to be changed and the pace and bounce tests test were separately carried out for those selected soils. Smectite and Kaolinite are the two common, locally available clay mineralogy groups Sri Lanka (Herath, 1973). Most of the locally available clays in wet zone are in Kaolinite group however, some soils in the dry and semi-arid zones are found to be in Smectite group (Herath, 1973).

3.2 Selection of samples

Six locally available soil samples and one sample from India were selected for laboratory tests. Index property tests had been carried out for MU and TY already in a past research and they revealed MU is a better clay than the currently used soil in Sri Lankan venues (Perera & Nawagamuwa, 2015). Selected samples for testing were as follows.

1. Murunkan- "Grumusol" clay sample from Murunkan, Mannar, Sri Lanka.
2. Tyronne- Sample from "Tyronne Fernando Stadium" cricket pitch Katubedda which is the same clay used by Sri Lanka Cricket Association (SLCA) for all other cricket pitches in Sri Lanka
3. Kotawehera- Sample from Kotawehera in Nikaweratiya region, Sri Lanka
4. Bangalore- Sample from a developing fast and bouncy pitch in PESIT College Bangalore, India.
5. Batticaloa A- Sample from a Clay deposit in Batticaloa, Sri Lanka which was proposed as a filling material for the clay-core of a damaged earth dam.
6. Batticaloa B- Sample from a damaged earth dam in Batticaloa, Sri Lanka
7. Batticaloa C- Typical Ant clay sample from Batticaloa, Sri Lanka

Figure 3.1 Locations of the selected samples

3.2.1 Murunkan soil sample (MU)

The Smectite type soil, which is tested along with the conventional soil which is used for pitch preparations, was collected from the Rice Research Station, Murunkan, Mannar District.

This soil is vastly known as one of the best soils for paddy cultivation, and for research purposes, Department of Agriculture has one of its rice research stations, at the location, 08° 50' 14.1" N, 80° 02' 30.1" E, at 5km post facing the Medawachchiya-Talaimannar road (A14).

First the pits were excavated within the paddy field area, and the top soil up to a depth of 300 mm was removed to avoid possible contamination from silt, gravel and surface vegetation. Then the underlying soil up to a depth of 1m was collected into bags and three pits were excavated for this purpose to make sure that the excavation does not exceed the grumusol deposits and to avoid any contamination from silts and sand particles which may not be visible to naked eye.

Figure 3.2 Excavation of pits in clay deposits

3.2.2 Clay used in the Tyrone Fernando Stadium (TY)

This soil was used as the representative of standard clay type used for local pitch preparation in Sri Lanka. The soil was brought as of 25kg bags from Mr H.S. Kaldera (Lakmali Transport, No.499, Thalangama North, Battaramulla) who is the sole supplier of clay soils for pitches maintained by Sri Lanka Cricket.

Figure 3.3 Tyronne soil

3.2.3 Kotawehera soil sample (KO)

This soil sample was collected from the Kotawehera Divisional secretariat office complex. The reason for testing this sample was due to the observations of extensive amount of cracks in the buildings indicating a possible presence of clay rich expansive soils beneath their foundations.

Figure 3.4 Cracked Buildings due to Expansive soils

Figure 3.5 Obtaining samples from Kotawehera

4 LABORATORY EXPERIMENTS AND RESULTS

A series of experiments were conducted according to appropriate guidelines such as BS 1377 and ASTM volume 04.08 for various soil samples in order to determine their index properties.

- Particle Size Distribution; Wet Sieve Analysis and Hydrometer Analysis were carried out.
- Particle size analysis for the particles 2µm-75µm was again done using a Laser particle analyser to get more accurate and reliable results.
- Atterberg's Limits test; Liquid Limit and Plastic Limit tests were done, and then Plasticity Index was calculated. Liquid limit was determined by the Casagrande's apparatus.
- Organic matter content test.

Following is the series of laboratory test done with their standards followed

Table 4.1 List of carried out laboratory tests and test standards

Test	Purpose of the test	Standards
Wet sieve analysis	To determine the distribution of particle sizes greater than 75 µm	ASTM C 117
Hydrometer test	To determine the distribution of particle sizes smaller than 75 µm	ASTM D 422
Atterberg's limits test	To determine the liquid limit, plastic limit, and the plasticity index of soils	BS 1377-1
Organic matter content test	To find organic matter percentage of clays	A5TM D 2974-87
Proctor compaction test	To determine optimum moisture content and maximum dry density of soils	BS 1377-1990-4
Specific gravity test	Specific gravity of the soil particles	BS 1377-2

4.1 Particle size distribution test

Particle size distribution shows the amount of finer particle (which are usually clay & silt) content of a soil and the soil grading. This can be determined by the sieve analysis test and the Hydrometer test. Four different methods could be used to analyse the particle size distribution. They are air dry-dry sieve, air dry -wet sieve, oven dry-dry sieve and oven dry- wet sieve. When the particles were bonded together, it will form larger size particles called colloids. Therefore, dry sieve may not provide accurate results in this situation where the required accuracy should be high in finding the clay content of these soils since the clay percentage will be one of the key factors which produce extra Pace and Bounce of a wicket (Nawagamuwa, et al., 2009). So wet sieve analysis provided better results for the particle size distribution when more clayey types of soils are concerned (See annex for the wet sieve analysis). Further extension of the grading curves was carried out with hydrometer tests conducted on samples smaller than 0.425mm.

4.1.1 Test Results of the particle size distribution test

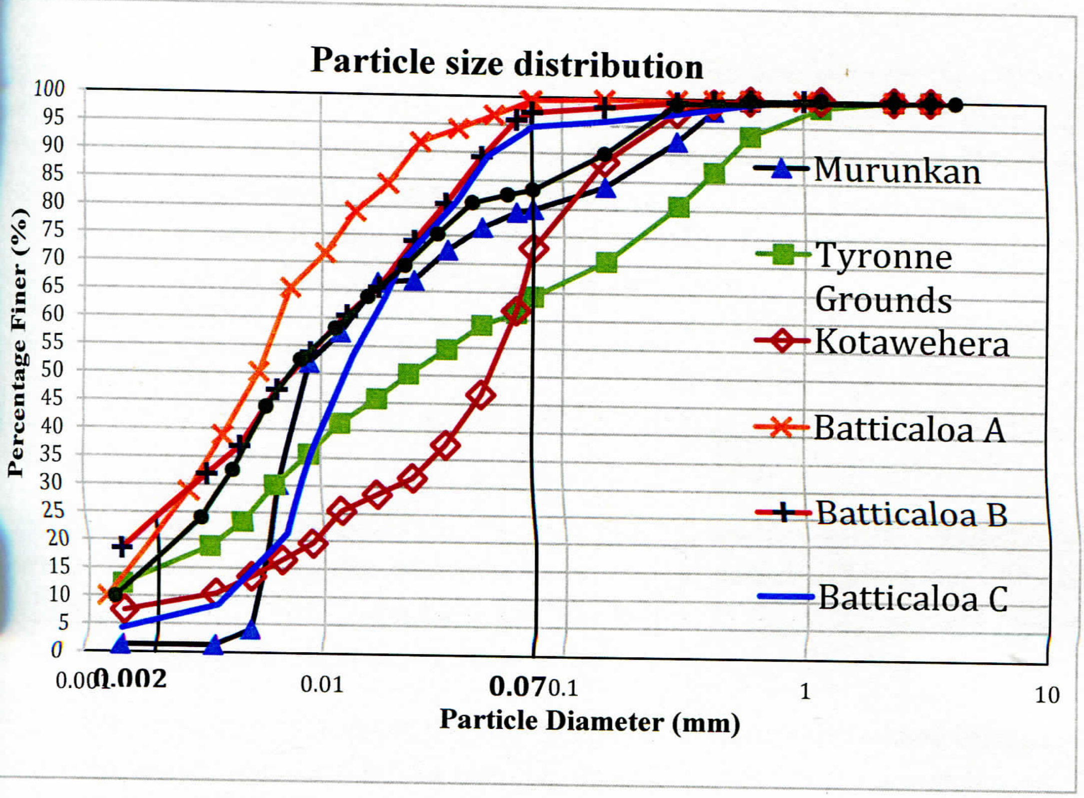


Figure 4.1 Particle size distribution test results

Following is the tabulated results obtained by Figure 4.1.

Table 4.2 Particle Size distribution results

Clay Type	% Finer than 0.075	% finer than 0.002
Tyronne (TY)	64	15
Murunkan (MU)	80	2
Kotawehera (KO)	73	8
Bangalore	83	17
Batticaloa A	99	22
Batticaloa B	97	24
Batticaloa C	95	6

4.1.2 Summary of the particle size distribution test

Except KO and TY samples other samples provided more than 80% for the clay and silt content. Moreover MU, KO and Battical a C gave below 10% for their clay content. None of the tested clays gives a higher clay percentage more than 25%. This could be due to the adopted methodology using hydrometer with a dispersing agent in addition to the separation difficulties of collided particles. Therefore further tests were carried out to find out the accurate value for the clay range.

4.2 Laser Particle Analysis (LPA)

This test was done according to ASTM B822-92 standards by using SHIN-KIGYO PRO OP2.

Since the organic matters inside the clay was binding the clay grains together, clay particles are attached together and form larger colloid particles. Therefore, the clay percentages given by the Hydrometer test was below 25 for every sample. In laser particle analysis test (Results shown in

Figure 4.5), organic matter inside the clay sample was removed by adding H2O2 and the treated sample was taken for the test. Results of the LPA test are shown below.

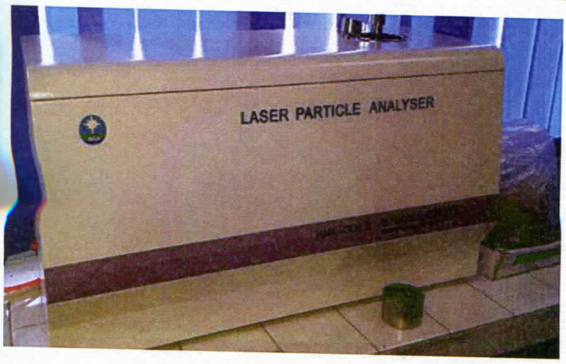


Figure 4.2 Laser Particle analyser Machine and Prepared samples

4.3 Results of Laser Particle Analysis

JL-1177 LASER PARTICLE SIZE ANALYSER Chengdu Jingxin Powder Analyse Instrument Co., Ltd. Tel: 86-28-85177668 No.19 Baimasi Street, Chengdu, P.R.China

zeroing blank powder_Preparation test save_file display_result peculiar_function Auto clean Semi-clean exit

Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)
0.020	0.000	0.000	0.389	26.676	3.805	3.289	91.835	1.570	24.36	100.000	0.000	180.5	100.000	0.000
0.035	0.001	0.001	0.444	30.292	3.616	3.759	93.526	1.691	27.84	100.000	0.000	206.2	100.000	0.000
0.050	0.021	0.021	0.500	35.187	4.896	4.296	94.533	1.006	31.82	100.000	0.000	235.7	100.000	0.000
0.060	0.136	0.114	0.580	40.531	5.344	5.000	96.317	1.784	36.36	100.000	0.000	269.3	100.000	0.000
0.069	0.488	0.352	0.663	44.913	4.381	5.610	97.808	1.491	41.56	100.000	0.000	307.8	100.000	0.000
0.078	1.039	0.552	0.757	49.965	5.052	6.411	99.337	1.529	47.49	100.000	0.000	351.8	100.000	0.000
0.089	1.892	0.852	0.866	54.661	4.696	7.327	100.000	0.663	50.00	100.000	0.000	402.0	100.000	0.000
0.102	3.164	1.273	1.000	60.356	5.695	8.373	100.000	0.000	54.27	100.000	0.000	459.4	100.000	0.000
0.117	4.610	1.445	1.130	64.979	4.623	9.569	100.000	0.000	62.02	100.000	0.000	525.0	100.000	0.000
0.134	5.441	0.832	1.292	70.404	5.425	10.00	100.000	0.000	70.88	100.000	0.000	600.0	100.000	0.000
0.153	6.135	0.694	1.476	75.150	4.746	10.94	100.000	0.000	81.00	100.000	0.000	712.6	100.000	0.000
0.174	7.008	0.873	1.687	78.913	3.763	12.50	100.000	0.000	92.57	100.000	0.000	846.3	100.000	0.000
0.200	9.509	2.501	1.928	82.794	3.880	14.28	100.000	0.000	100.0	100.000	0.000	1005	100.000	0.000
0.228	12.414	2.906	2.000	83.621	0.828	16.32	100.000	0.000	105.8	100.000	0.000	1194	100.000	0.000
0.260	15.287	2.873	2.204	85.966	2.345	18.65	100.000	0.000	120.9	100.000	0.000	1415	100.000	0.000
0.297	19.101	3.813	2.518	88.206	2.240	20.00	100.000	0.000	138.2	100.000	0.000	1684	100.000	0.000
0.340	22.871	3.770	2.878	90.266	2.059	21.32	100.000	0.000	157.9	100.000	0.000	2000	100.000	0.000

D3: 0.100µm D6: 0.149µm
D10: 0.205µm D16: 0.267µm
D25: 0.367µm D50: 0.758µm
D75: 1.470µm D84: 2.033µm
D90: 2.832µm D97: 5.280µm
D98: 5.711µm
refractive sample: 1.51 + 0.01 i
refractive medium: 1.33
V_Mean D. D[4,3]: 1.135µm
S_Mean D. D[3,2]: 0.453µm
S/V:13.259m2/cm3
Dispersant: 99
mode:Volume_freedom_1

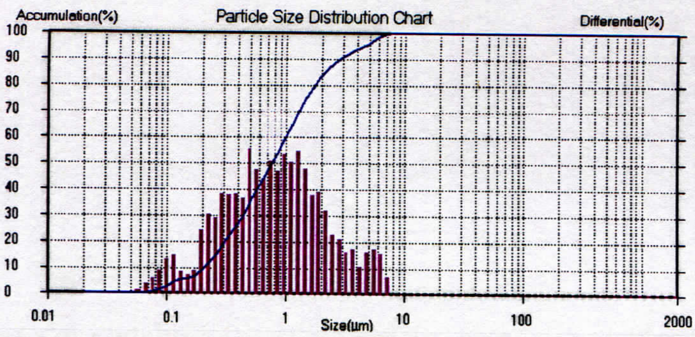


Figure 4.4 LPA test for KO

JL-1177 LASER PARTICLE SIZE ANALYSER Chengdu Jingxin Powder Analyse Instrument Co., Ltd. Tel: 86-28-85177668 No.19 Baimasi Street, Chengdu, P.R.China

zeroing blank powder_Preparation test save_file display_result peculiar_function Auto clean Semi-clean exit

Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)
0.020	0.000	0.000	0.389	25.266	3.660	3.289	89.938	1.606	24.36	100.000	0.000	180.5	100.000	0.000
0.035	0.002	0.002	0.444	28.748	3.482	3.759	91.651	1.713	27.84	100.000	0.000	206.2	100.000	0.000
0.050	0.027	0.025	0.500	33.733	4.986	4.296	92.712	1.061	31.82	100.000	0.000	235.7	100.000	0.000
0.060	0.136	0.109	0.580	39.150	5.416	5.000	94.491	1.779	36.36	100.000	0.000	269.3	100.000	0.000
0.069	0.437	0.302	0.663	43.585	4.435	5.610	95.987	1.496	41.56	100.000	0.000	307.8	100.000	0.000
0.078	0.890	0.453	0.757	48.432	4.848	6.411	97.551	1.564	47.49	100.000	0.000	351.8	100.000	0.000
0.089	1.576	0.686	0.866	52.954	4.522	7.327	98.929	1.377	50.00	100.000	0.000	402.0	100.000	0.000
0.102	2.632	1.056	1.000	58.451	5.496	8.373	99.503	0.575	54.27	100.000	0.000	459.4	100.000	0.000
0.117	3.883	1.251	1.130	63.073	4.622	9.569	100.000	0.497	62.02	100.000	0.000	525.0	100.000	0.000
0.134	4.649	0.766	1.292	68.326	5.253	10.00	100.000	0.000	70.88	100.000	0.000	600.0	100.000	0.000
0.153	5.315	0.666	1.476	73.166	4.840	10.94	100.000	0.000	81.00	100.000	0.000	712.6	100.000	0.000
0.174	6.153	0.838	1.687	77.028	3.863	12.50	100.000	0.000	92.57	100.000	0.000	846.3	100.000	0.000
0.200	8.558	2.405	1.928	80.957	3.928	14.28	100.000	0.000	100.0	100.000	0.000	1005	100.000	0.000
0.228	11.351	2.794	2.000	81.753	0.796	16.32	100.000	0.000	105.8	100.000	0.000	1194	100.000	0.000
0.260	14.114	2.763	2.204	84.008	2.255	18.65	100.000	0.000	120.9	100.000	0.000	1415	100.000	0.000
0.297	17.800	3.686	2.518	86.294	2.287	20.00	100.000	0.000	138.2	100.000	0.000	1684	100.000	0.000
0.340	21.606	3.806	2.878	88.332	2.037	21.32	100.000	0.000	157.9	100.000	0.000	2000	100.000	0.000

D3: 0.106µm D6: 0.170µm
D10: 0.214µm D16: 0.279µm
D25: 0.385µm D50: 0.795µm
D75: 1.576µm D84: 2.203µm
D90: 3.306µm D97: 6.129µm
D98: 6.709µm
refractive sample: 1.51 + 0.01 i
refractive medium: 1.33
V_Mean D. D[4,3]: 1.264µm
S_Mean D. D[3,2]: 0.478µm
S/V:12.559m2/cm3
Dispersant: 99
mode:Volume_freedom_1

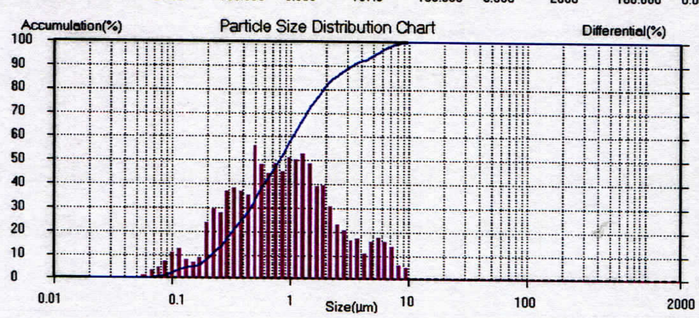


Figure 4.3 LPA test for MU

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Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)	Size (µm)	Accumulation (%)	Differ (%)
0.020	0.000	0.000	0.389	16.090	2.421	3.289	58.948	1.121	24.36	73.161	3.296	180.5	100.000	0.000
0.035	0.000	0.000	0.444	18.391	2.301	3.759	60.127	1.180	27.84	76.681	3.520	206.2	100.000	0.000
0.050	0.009	0.008	0.500	21.684	3.293	4.296	60.890	0.762	31.82	82.814	6.133	235.7	100.000	0.000
0.060	0.057	0.049	0.580	25.245	3.561	5.000	62.093	1.203	36.36	89.068	6.254	269.3	100.000	0.000
0.069	0.211	0.153	0.663	28.169	2.925	5.610	63.132	1.040	41.56	95.733	6.665	307.8	100.000	0.000
0.078	0.457	0.247	0.757	31.352	3.183	6.411	64.196	1.064	47.49	98.295	2.562	351.8	100.000	0.000
0.089	0.822	0.365	0.866	34.344	2.992	7.327	65.205	1.008	50.00	98.926	0.631	402.0	100.000	0.000
0.102	1.372	0.550	1.000	37.967	3.623	8.373	65.783	0.579	54.27	100.000	1.074	459.4	100.000	0.000
0.117	2.008	0.637	1.130	40.915	2.948	9.569	66.326	0.543	62.02	100.000	0.000	525.0	100.000	0.000
0.134	2.467	0.459	1.292	44.386	3.471	10.00	66.366	0.039	70.88	100.000	0.000	600.0	100.000	0.000
0.153	2.905	0.437	1.476	47.605	3.219	10.94	66.451	0.085	81.00	100.000	0.000	712.6	100.000	0.000
0.174	3.457	0.553	1.687	50.157	2.552	12.50	66.451	0.000	92.57	100.000	0.000	846.3	100.000	0.000
0.200	5.044	1.587	1.928	52.745	2.588	14.28	66.493	0.042	100.0	100.000	0.000	1005	100.000	0.000
0.228	6.889	1.845	2.000	53.292	0.547	16.32	67.197	0.705	105.8	100.000	0.000	1194	100.000	0.000
0.260	8.718	1.829	2.204	54.841	1.549	18.65	67.947	0.750	120.9	100.000	0.000	1415	100.000	0.000
0.297	11.149	2.431	2.518	56.434	1.593	20.00	68.920	0.973	138.2	100.000	0.000	1684	100.000	0.000
0.340	13.669	2.519	2.878	57.826	1.392	21.32	69.865	0.944	157.9	100.000	0.000	2000	100.000	0.000

D3: 0.157µm D6: 0.215µm
D10: 0.280µm D16: 0.387µm
D25: 0.574µm D50: 1.674µm
D75: 26.178µm D84: 32.739µm
D90: 37.092µm D97: 44.493µm
D98: 46.801µm
refractive sample: 1.51 + 0.01 i
refractive medium: 1.33
V_Mean D. D[4,3]: 11.046µm
S_Mean D. D[3,2]: 0.754µm
S/V:7.962m2/cm3
Dispersant: 99
mode:Volume_freedom_1

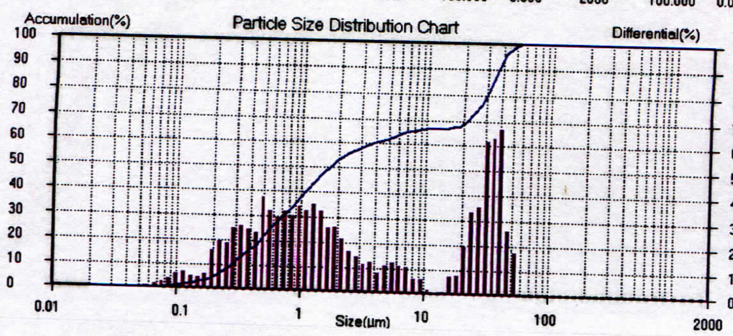

Figure 4.5 LPA test results of TY

Results obtained by the wet sieve analysis (For the particles greater than 75µm) was combined with the results of the LPA test (For the particles smaller than 75µm) as shown in the following example.

Two results from wet sieve analysis and LPA were combined and example calculation was done for the MU sample as follows.

Percentage passing from 75µm sieve was 77.21% (From wet sieve analysis). Therefore the percentage passing ("Accumulation" shown in

Figure 4.5) should be multiplied by 0.721 in order to fit the two curves at 75µm point. Following is an example done to determine the clay fraction (2µm particle size)

Percentage passing at 2µm from LPA (For MU) was 81.753%

Modified percentage passing at 2µm= $\frac{81.753 \times 77.21}{100} = 63.21\%$

Same calculation was done for each accumulation value obtained by LPA for each soil. Modified particle size distribution was shown in the following figure.

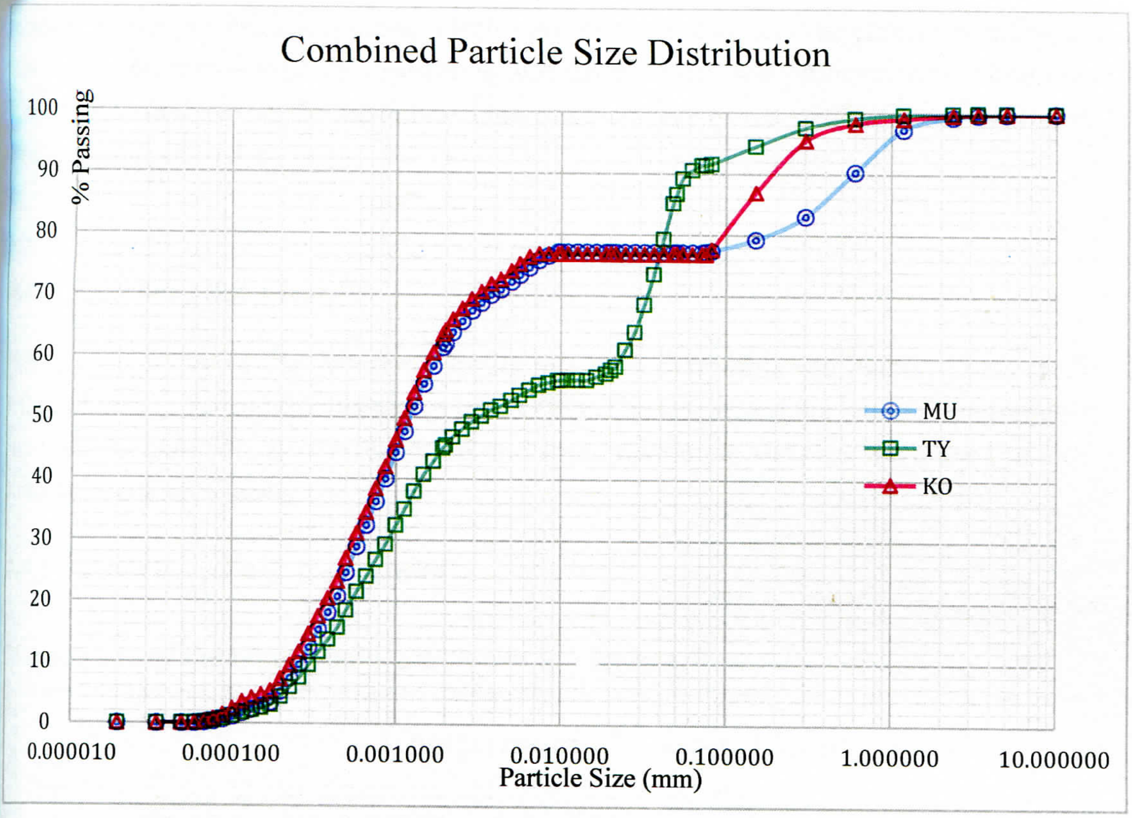

Figure 4.6 Combined particle size distribution curves

Summary of the results shown by combined particle size distribution is showed in Table 4.3.

Table 4.3 Percentage passing at the clay and silt range

Particle Size	MU	TY	KO
2 μm	62.07%	45.50%	64.25%
75 μm	77.21%	91.34%	76.83%

4.3.1 Conclusion of Laser Particle Analysis

Laser particle analysis gave a higher value for the clay fraction when compared to the conventional hydrometer test. Both MU and KO had above 60% of clay content while TY had 45.5% of clay content. Hydrometer test is based on number of assumptions where the accuracy results can be less but the LPA test can be more accurate since it is based on digital technology that utilizes diffraction patterns of a laser beam passed through any object ranging from nanometers to millimeters in size. Clearly the two alternative soils have higher clay content when compared to conventional soil which is used in current cricket pitches. High clay content may lead to proper bonding of pitch material and reduce the crumbling and deteriorating the pitch surface. Therefore the strength in between the particles of the pitch surface of MU and KO may be higher when compared to TY.

4.4 *Atterberg limit test*

Primary objective of the Atterberg limits test is to determine the Plastic Limit (PL), Liquid Limit (LL) and the Plasticity Index (PI). The test was done using Casagrende's instrument. Samples were oven dried and then powdered samples were used to find the Atterberg limit tests.

4.4.1 Atterberg limit test results

Comparison of the liquid limits are shown in 'igure 4.7

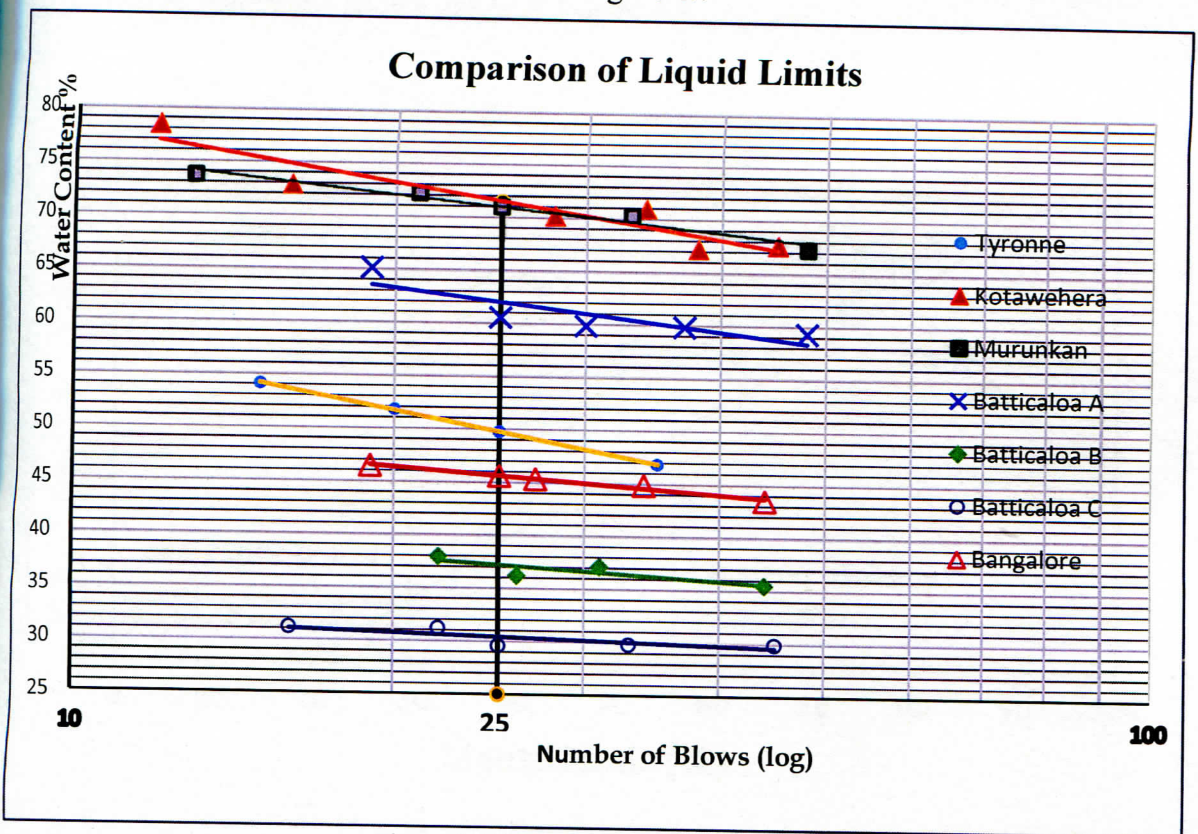

Figure 4.7 Comparison of Liquid limits

Summary of the Figure 4.7 is shown in the

Table 4.4.

Table 4.4 Atterberg Limits of the tested soils

Clay Type	LL (%)	PL (%)	PI (%)
Tyronne (TY)	49	30	19
Murunkan (MU)	74	27	47
Kotawehera (KO)	66	32	35
Bangalore (BAN)	46	19	27
Batticaloa A -B(A)	62	27	35
Batticaloa B -B(B)	37	18	19
Batticaloa C -B(C)	30	15	15

Above clay samples are marked in a soil classification (USCS) the chart according to their LL and PI values and shown below in Figure 4.8.

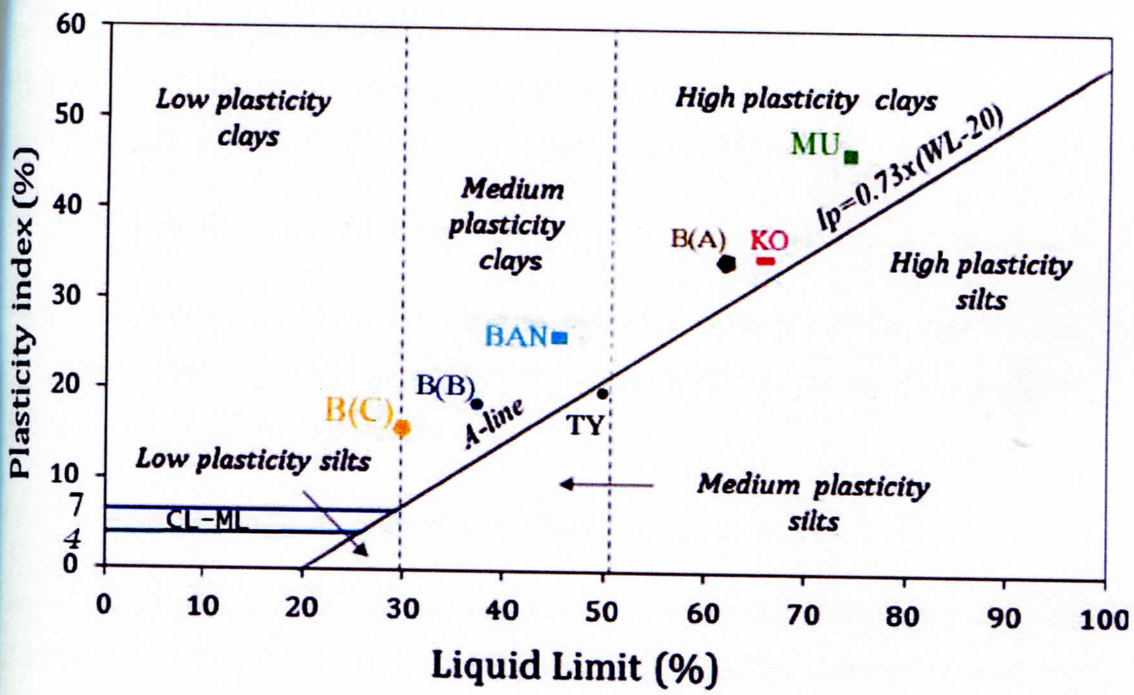

Figure 4.8 Soil Classification Chart

4.4.2 Conclusion of the Atterberg test results

Figure 4.8 gives a clear view of where the samples are located in the Unified Soil Classification System (UCSC) chart. Murunkan gives LL>70% which is an indication of a very fat clay or a High plasticity clay. Kotawehera and Batticaloa A samples give 70%>LL>50% which makes them fat clays while the rest of clays give LL<50% which makes them intermediately silty clayey soils according to the Unified Soil Classification System (USCS).

Murunkan gives PI closer to 50% which makes it an extremely plastic soil while Kotawehera and Batticaloa A sample gives PI values closer to 35% which making them high plastic clays.

4.5 Degree of Colloidal Activity

In any particular clay stratum the ratio of the Plasticity Index (PI) to the Clay Fraction (CF) (percentage by weight of particles finer than 2 microns) is approximately constant and it is defined as the "activity" of the clay. Values of activity are given for many clays and also for the more common minerals. It is shown that activity is related to the mineralogy and geological history of clays (Skempton, 1953).

Activity = Plasticity Index / Clay Fraction ....Equation 2

Number of samples are taken from a particular clay stratum and the clay fraction content (percentage by weight of particles finer than 2 microns) and the plasticity index (P1) are determined for each sample

4.5.1 Results of Degree of Colloidal Activity

Degree of Colloidal Activity was calculated twice since the clay fraction was changed after performing the LPA test instead of Hydrometer test and the summary is presented in Table 4.5 and Table 4.6.

Table 4.5 Degree of Colloidal activity with CF by Hydrometer

Clay Type	PI (%)	CF (%)	Activity
TY	19.3	15	1.3
MU	47.0	2	23.5
KO	34.7	8	4.3
Bangalore	27.0	17	1.6
Batticaloa A	34.7	22	1.6
Batticaloa B	18.9	24	0.8
Batticaloa C	15.2	6	2.5

Table 4.6 Degree of Colloida activity with CF by LPA

Clay Type	PI (%)	CF (%)	Activity
MU	47.0	62.07	0.75
TY	19.3	45.50	0.42
KO	34.7	64.25	0.54

4.5.2 Conclusion of Degree of Colloidal Activity according to the CF by Hydrometer

Murunkan is the clay, having the highest activity of 23.5 while Kotawehera shows an activity >4 and the rest of the clays show comparatively a very low activity.

Therefore Murunkan clay could be considered as a Montmorillonite clay which belongs to Smectite clay. (Skempton, 1953)

4.5.3 Conclusion of Degree of Colloidal Activity according to the CF by LPA

Highest Activity was recorded from MU out of the three tested clays. After inserting the corrected value obtained for the clay fraction by LPA, OM content was less than 1% as shown in Table 4.6. Therefore X Ray Diffraction test should be carried out for the further analysis of the clay mineralogy.

4.6 X-Ray diffraction Test (XRD)

XRD graphs were given as an output by the XRD test done by BRUKER D8 ADVANCE eco workstation.

4.6.1 Results of the XRD Test

Following are the XRD graphs drawn for three samples.

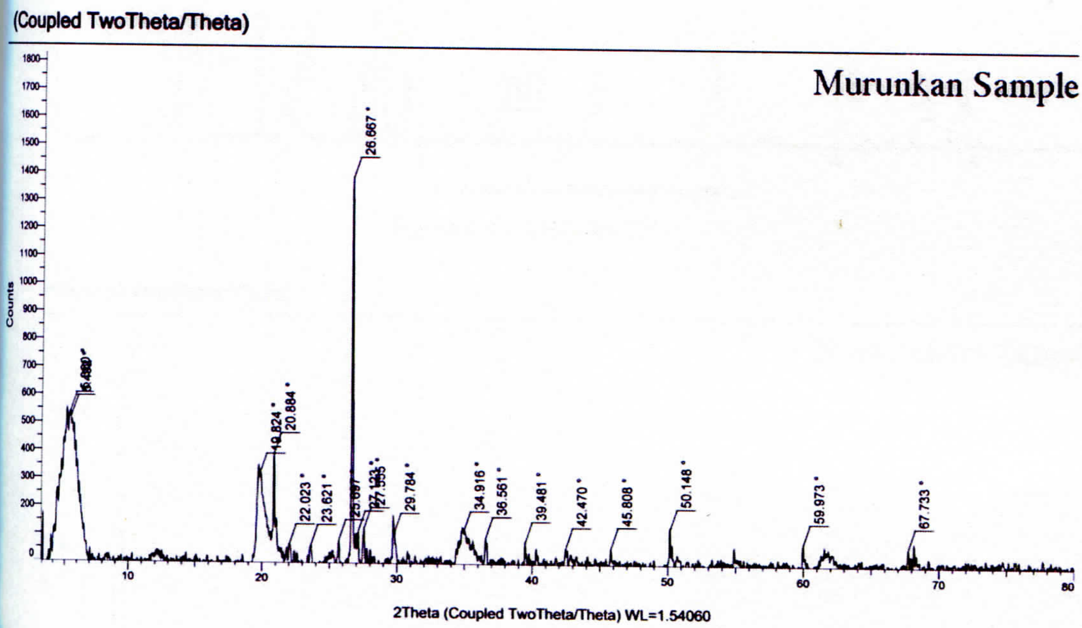

Figure 4.9 XRD for MU

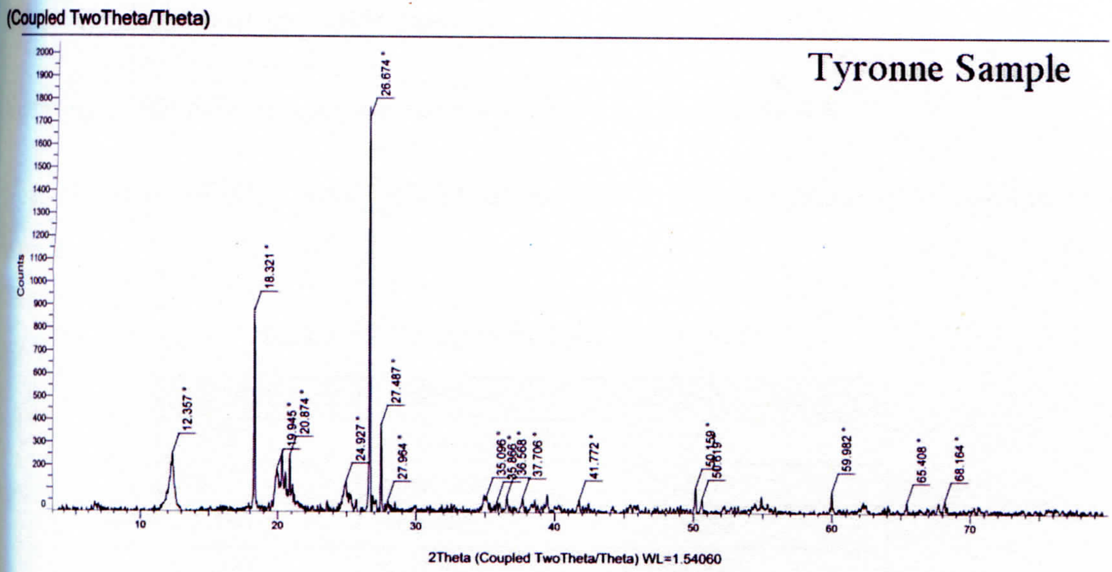

Figure 4.11 XRD for TY

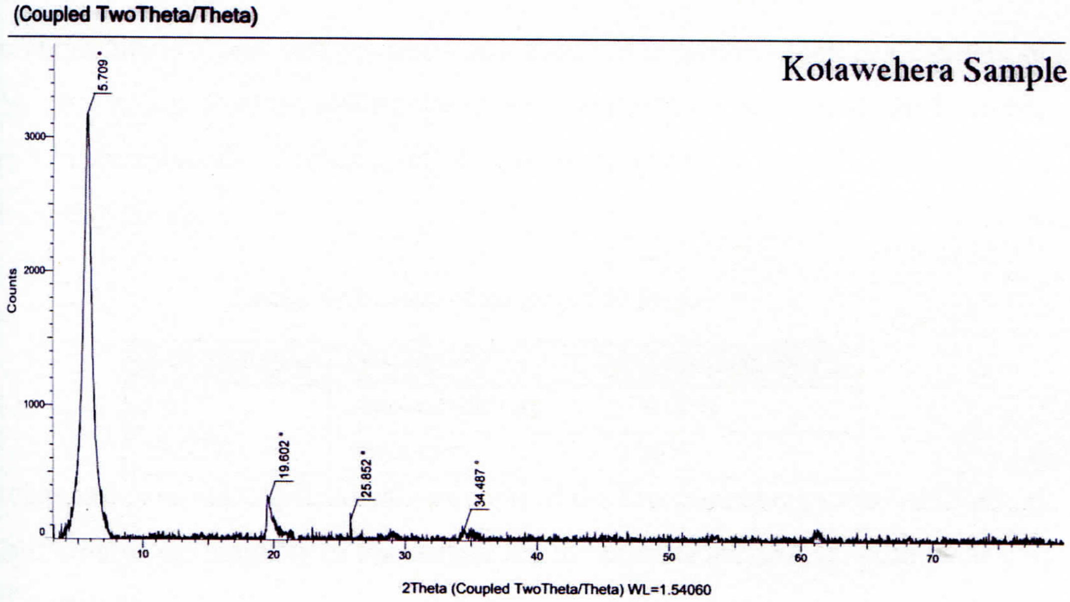

Figure 4.10 XRD for KO

4.6.2 Conclusion of the XRD Test

Summary of the XRD graphs are shown in Table 4.7 and Table 4.8.

Note – Relative intensity is the ratio of net intensity to Peak net intensity for particular sample.

Table 4.7 Summary of the XRD Test for MU

2 Theta Angle	Description	Relative intensity
5.378°	Montmorillonite	30.60%
5.627°	Notronite	27.30%
20.880°	Notronite	27.60%
26.666°	Notronite	100.00%

Montmorillonite is a very soft phyllosilicate group of minerals which is a member of the Smectite group. Besides Nontronite is the iron (III) rich member of the Smectite group of clay minerals (Anthony, et al., 2010). Majority of the MU sample is in Smectite clay group.

Table 4.8 Summary of the XRD Test for KO

2 Theta Angle	Description	Relative intensity
5.613°	Montmorillonite	100.00%
19.670°	Sauconite	9.90%

Sauconite is a complex phyllosilicate mineral of the Smectite clay group (Anthony, et al., 2010). Since the majority of the sample are in Smectite group KO could be named as a Smectite clay.

Table 4.9 Summary of the XRD Test for TY

2 Theta Angle	Description	Relative intensity
12.357°	Kaolinite	14.60%
18.321°	Triazine	50.80%
26.674°	Triazine	100%
20.874°	Quartz	14.10%
24.927 °	Kaolinite	7.40%
50.159 °	Quartz	6.4%

4.6.2 Conclusion of the XRD Test

Summary of the XRD graphs are shown in Table 4.7 and Table 4.8.

Note – Relative intensity is the ratio of net intensity to Peak net intensity for particular sample.

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20.874°	Quartz	14.10%
24.927 °	Kaolinite	7.40%
50.159 °	Quartz	6.4%

Triazine is an organic chemical compound with the formula $(HCN)_3$. Majority of the TY soil are either organic compounds, Quartz or Kaolinite clays. Hence the currently used soil for the cricket pitch preparation in SL is a Kaolinite clay with high percentage of organic compounds.

4.7 Proctor Compaction Test

Standard Proctor compaction test was carried out according to ASTM D698 standards As Murunkan and Kotawehera are tend to be promising samples for a fast and bouncy cricket pitch, Proctor compaction was conducted only for them to compare with Tyronne sample.

Test was done for 3 times for all 3 samples and the average of the Maximum dry density and the optimum moisture content values were calculated. Typical graph from each soil was selected and plotted as shown in Figure 4.12

4.7.1 Results of the proctor compaction test

Figure 4.12 was a comparison between typical graphs drawn for particular Proctor compaction tests.

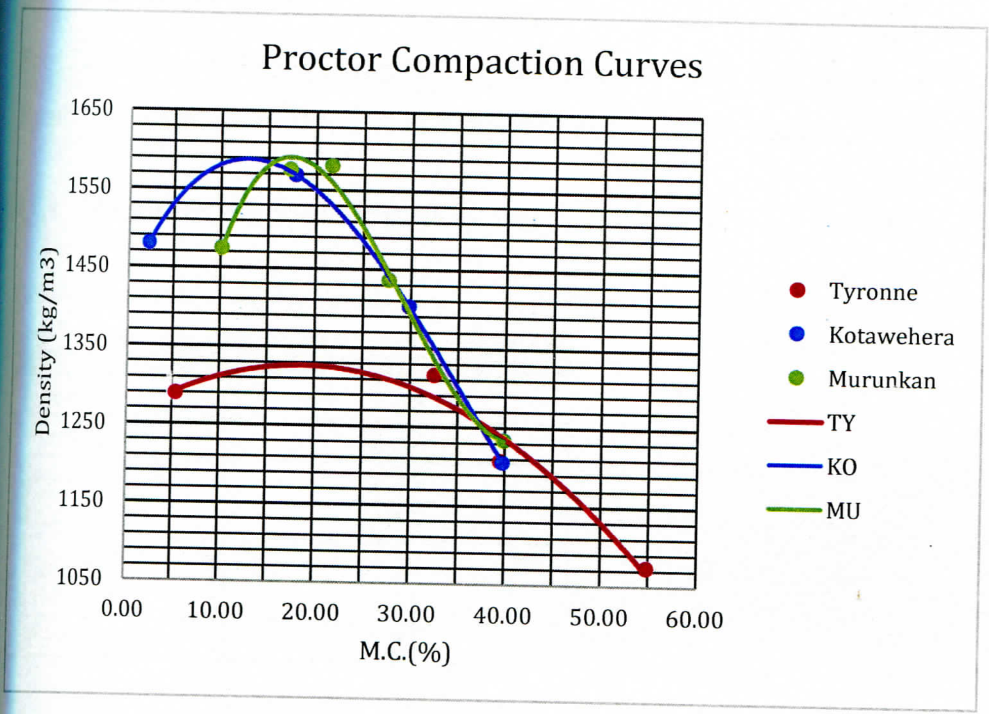


Figure 4.12 Typical graphs for Dry density vs MC%

Series of proctor compaction tests were carried out for each soil sample and the average values were summarized in Table 4.10 below.

Table 4.10 Comparison of Maximum Dry densities and Optimum Moisture Contents (OMC)

Clay Type	γd (kg/m3)	OMC (%)
Tyronne	1320	32.0
Murunkan	1581	18.3
Kotawehera	1512	17.5

4.7.2 Conclusion of the Proctor compaction results

In general, hardness, ball rebound and the "pace" of the surface increased with greater bulk density and decreased with moisture content (Baker, et al., 1998). MU gives the highest dry density of 1581 kg/m^3 while TY gives the lowest value of 1320 kg/m^3. Higher dry densities of clay would increase its compaction and strength as well as the "e" value as mentioned by (Baker, et al., 1998). Since MU and KO gives higher dry densities those soils could be well compacted until they gain higher strengths and higher ball bounce could be expected from those two clays than TY.

4.8 Specific gravity test

Specific gravity value of sample was determined according to BS 1377: part 1, Pycnometer method. Results are summarized as follows in Table 4.11.

4.8.1 Results of the Specific gravity test

Table 4.11 Specific gravity test results

Clay Type	Specific Gravity (G_s)
Tyronne	2.35
Murunkan	2.52
Kotawehera	2.41
Bangalore	2.53
Batticaloa A	2.72
Batticaloa B	2.31
Batticaloa C	2.25

4.8.2 Conclusion of the Specific gravity test

Organic particles will play a bigger role in lowering the G_s value when compared to soil particles. When organic impurities are present in a soil usually the specific gravity is decreased (Tainton, et al., 1998). Batticaloa A is having the highest G_s value of 2.72. Murunkan, Bangalore and Batticaloa A give a G_s value > 2.50 which is an indication of having lower organic impurities. Most of the samples are having G_s values lower than 2.4 which is an indication of having higher percentage of organic impurities.

4.9 Organic matter content test

Samples were initially kept at 105°C temperature and the Dry weight of the sample (DWS) was taken. Then the sample was kept at 550°C to burn the organic matter (OM) and the weight of the burnt soil /Ash (WA) was calculated using the following equation.

OM Content = (DWS-WA)/DWS --Equation (4.9)

4.9.1 Results of Organic matter content test

Three soils were tested for their Organic matter contents and the results of the test was as follows.

Table 4.12 Organic matter content results

Sample	Organic matter content
Tyrone	18.8%
Kotawehera	4.75%
Murunkan	4.98%

4.9.2 Conclusion of the Organic matter content test

Organic impurities reduces the binding strength of the pitch material (Tainton, et al., 1998). TY sample consists with higher organic impurities. As TY sample is a representative clay of other pitches also this high OM content will reduce the pace and bounce in Sri Lankan pitches (Nawagamuwa, et al., 2009).

According to ICC standards organic content should be less than 5% to categorize as a fast and bouncy wicket (Tainton, et al., 1998). Therefore, both Murunkan and Kotawehera soil is having suitable soil characteristics for a fast and bouncy pitch.

4.10 Conclusion from the laboratory test results

Seven various clays from different locations were tested as the 1st step of this research for their Particle size distribution, plastic characteristics, degree of colloidal activity, clay mineralogy, specific gravity, organic matter content and Proctor compaction values in order to select the best suitable clay for the model tests.

TY represents the currently used soil in Sri Lankan pitch preparation. As a result of having a lower finer particle percentage, lower G_s value, lower PI and having a higher organic impurities makes local pitches lower in strength and leads to crumbling and deterioration (Nawagamuwa, et al., 2009). Also the lower finer percentage causes a higher friction, hence reduces the pace of the pitch. Moreover the low dry density relates to lower ball bounce of the pitch. Also TY soil belongs to Kaolinite clay group, which generates low bounce when compared to bounce generated by Smectite clays in

AUS pitches. Therefore currently used soil is a slow pitch soil which has deviated from a fast and bouncy pitch, soil properties.

Sample from Kotawehera, Bangalore and Batticaloa sample A are having higher PI, G_s values. Therefore, those samples are performing better than the Tyronne sample in order to be a fast and bouncy pitch material.

From among all seven samples Murunkan, Kotawehera and Batticaloa A were tended to be promising samples for a fast and bouncy cricket pitch.

Bangalore sample has a higher G_s and comparatively a high PI which is a good indication of being a fast pitch material.

Batticaloa sample A has a higher G_s, higher PI and comparatively a high clay content. In contrast the sample has spread over a concise area. Therefore sample is insufficient for cricket pitch construction.

Kotawehera sample has a higher LL, PI and γd value and lower OM content. Therefore KO will have a high binding strength and it will lead to a higher ball bounce. Also lower sand content will reduce the friction in between ball and clay. Therefore it will generate greater pace. Since the "Test" cricket ball is red in colour International Cricket Council (ICC) prefers to use less reddish clay material for the top surface of a cricket pitch. Kotawehera soil is brownish in colour. Therefore it will not ideally match with ICC standards (Tainton, et al., 1998).

Murunkan sample gives the highest LL, PI from among all tested clays which make it extremely plastic clay. As a result of having a lower OM content Murunkan clay may have a higher binding strength. Having a high maximum dry density of 1581 kg/m3 is an indication of a good soil for fast and bouncy pitch preparation (Baker, et al., 1998). Moreover, Murunkan clay is a highly active clay according to colloidal activity results by hydrometer and the results are further proved by XRD test. Therefore, it can be concluded that Murunkan clay is a Montmorillonite clay which belongs to Smectite clay group. This is the same clay type with respect to minerology used in Australia for pitch preparation. Therefore, Murunkan is the most suitable local clay out of the available information for the development of fast and bouncy pitches.

5 LABORATORY MODEL STUDIES

5.1 Introduction

After selecting the appropriate clays to continue the research by doing laboratory studies, the next step was to conduct friction test and bounce test on the prepared laboratory models. These laboratory models represented the top layer of 150mm of actual cricket pitches made by different clayey soils with different surface grass conditions. Results from the bounce and the friction tests on each model were analysed to select the best clay to construct actual pitch models and carry out pace and bounce test in the actual field conditions. Objective of these tests is to find the coefficient of restitution (e) and coefficient of friction (μ) for each model

5.2 Prepar tion of samples for the laboratory model

In order to conduct the model tests, soil samples were compacted and prepared in a 150mm×150mm×150mm standard concrete cubic mould. The best two soils (MU and KO) selected from the soil tests along with the conventional clay used in SL cricket pitch preparation (TY) were selected to continue with further model tests. Moreover, the three selected samples were tested varying the grass conditions with and without grass. Three moulds contained with compacted clay only while grass was planted inside the other three moulds from the 1st layer of bottom most ant clay and the procedure is explained below.

- Step 01 – Six concrete moulds of size 150mm x 150mm x 150mm were selected and cleaned.
- Step 02 – All six moulds were filled with loosened ant clay of 50mm. Then the soil was compacted up to 30mm by CBR compacting machine by applying 445kPa on the surface for 2 minutes in order to give approximately similar amount of energy by typical roller passes on a typical pitch. Main purposes of the ant clay layer is to act as a fertilizing medium for the grass as well as to represent immediate base layer next to the clay layer of a cricket pitch.
- Step 03 - In order to plant grass, 25mm x25mm grid was drawn at the

5.3.1.4 Friction test results and conclusion

Variation of μ is presented according to the soil type and the respected tested date. In addition, in a given day for one sample friction value is also determined according to the tested ball type (eg.: new ball or 30 over played ball etc.) TY, MU, KO stands for Tyronne sample, Murunkan sample and Kotawehera sample and surface is without grass type condition. In addition to that +GR means that sample is having the grass layer on top. A summary of the Friction test is shown in Table 5.1

Table 5.1 Results of the Coefficient of friction

Soil Type	Ball type	μ value				
		D1	D2	D3	D4	D5
TY	New Ball	0.377	0.422	0.461	0.483	0.505
	30 overs	0.445	0.465	0.432	0.474	0.516
	60 overs	0.488	0.493	0.469	0.500	0.531
MU	New Ball	0.480	0.453	0.390	0.375	0.391
	30 overs	0.490	0.468	0.425	0.432	0.416
	60 overs	0.501	0.483	0.435	0.480	0.441
KO	New Ball	0.501	0.408	0.309	0.325	0.309
	30 overs	0.490	0.450	0.347	0.350	0.327
	60 overs	0.501	0.491	0.378	0.369	0.352
TY+GR	New Ball	0.350	0.429	0.362	0.406	0.380
	30 overs	0.484	0.461	0.400	0.433	0.396
	60 overs	0.474	0.507	0.412	0.457	0.449
MU+GR	New Ball	0.456	0.469	0.441	0.415	0.395
	30 overs	0.485	0.486	0.459	0.432	0.414
	60 overs	0.487	0.494	0.470	0.442	0.419
KO+GR	New Ball	0.451	0.436	0.294	0.356	0.417
	30 overs	0.455	0.484	0.338	0.392	0.447
	60 overs	0.471	0.535	0.427	0.451	0.476

r! Not a valid bookmark self-reference. shows the surface MC% of each sample ch day.

Table 5.2 MC% of the top surface of the samples on each day

	Day 1	Day 2	Day 3	Day 4	Day 5
TY	21.28	20.69	21.28	20.41	16.31
KO	18.74	18.52	18.74	19.79	20.06
MU	13.25	12.29	12.18	11.90	10.46
TY+GR	27.26	27.94	27.26	27.67	22.89
KO+GR	21.62	20.67	21.62	20.52	18.15
MU+ GR	14.90	15.06	14.90	12.49	16.63

ical representation of the MC% variation is showed in following figures (Figure nd Figure 5.17) separately for Grass/ without Grass conditions.

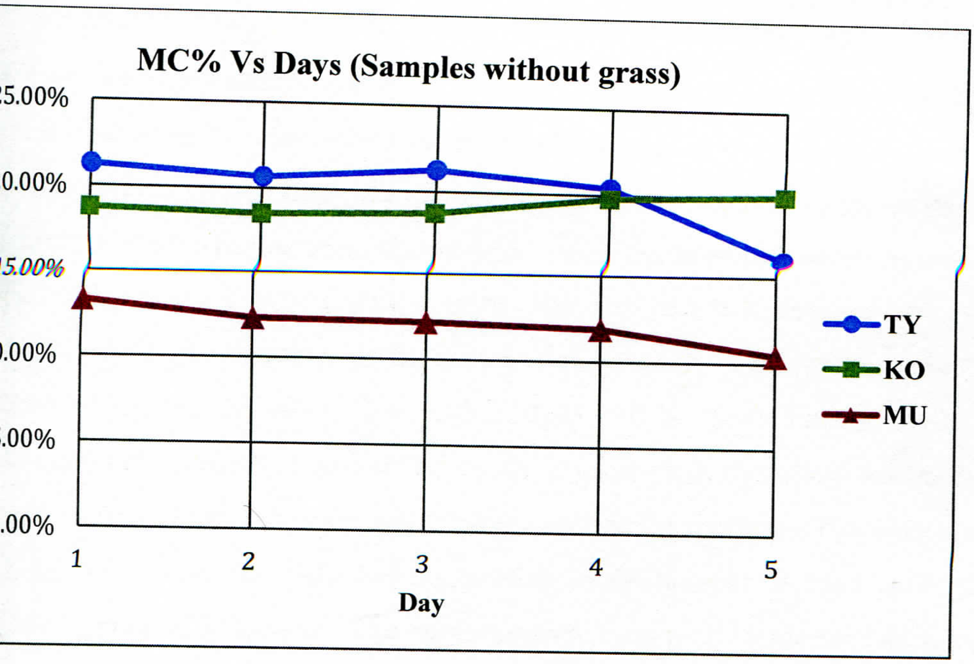


Figure 5.16 Samples without grass model tests between MC% and no of Days

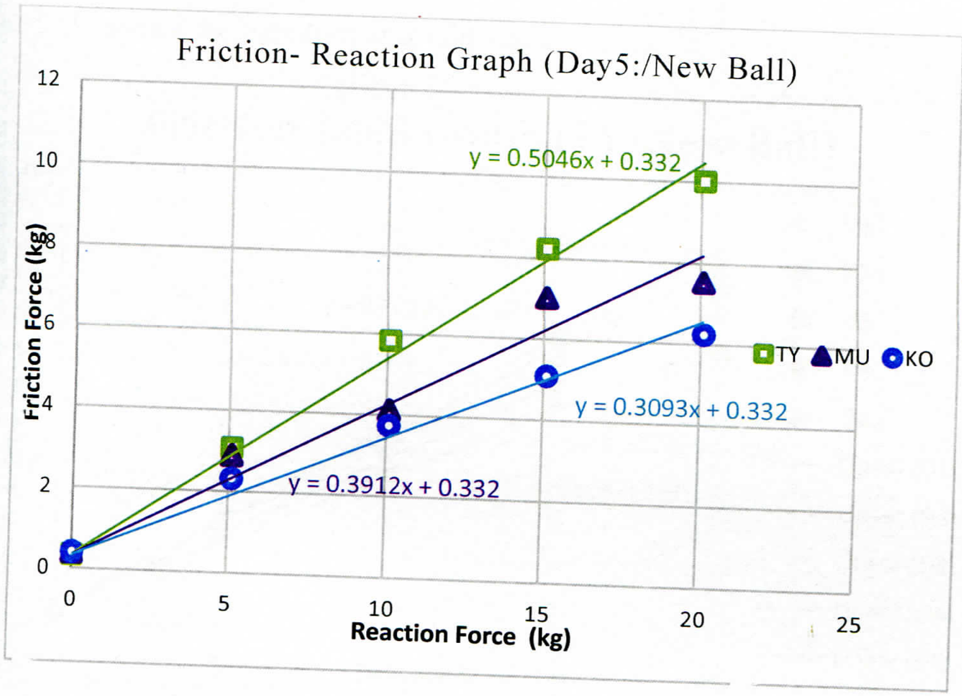


Figure 5.18 Typical Friction force - Reaction force graph for Day5, New ball

Graphs were drawn varying the ball type, grass conditions at the top surface and the clay type. Most of them showed that TY soil was having higher friction when compared to KO and MU soils. That may be due to the higher sand content inherited by TY when compared to other two. Higher sand content generates higher friction of a cricket wicket while making it slow and low (James, et al., 2005).

Therefore, MU and KO can be considered possible fast and bouncy pitch materials when compared to presently used soil for cricket pitch preparation in Sri Lanka.

Figure 5.19 shows the variation of μ with days

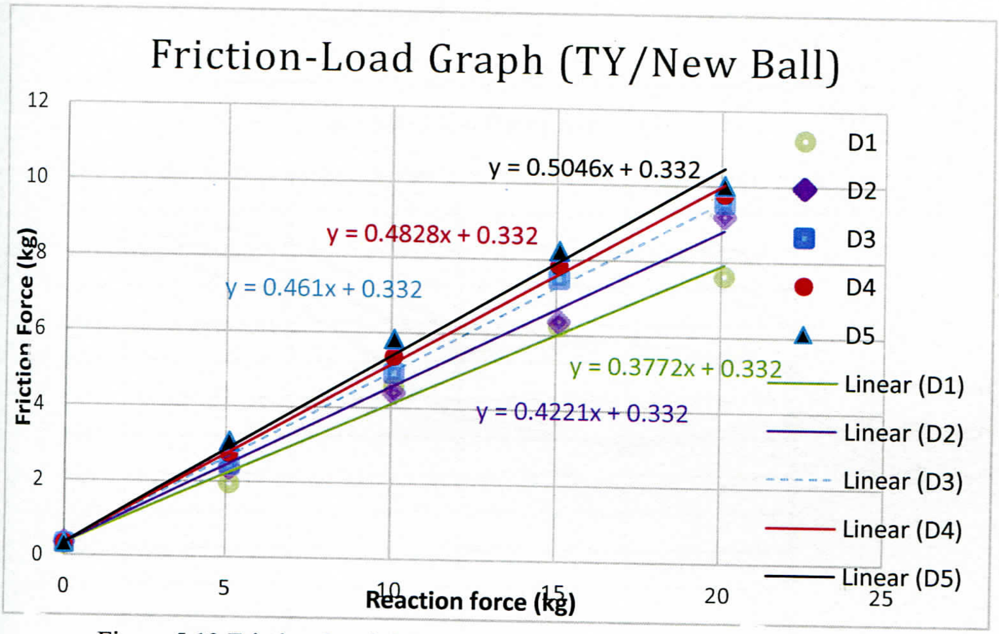


Figure 5.19 Friction-Load Graphs comparison with days (TY, New Ball)

Each day (D1, D2 are the day numbers shown in Figure 5.19) showed an increasing value for μ. The surface friction between the ball and the pitch is one of the key three factors affecting the cricket ball rebound. (James, et al., 2005). Obviously the coefficient of friction increases with number of days after final pitch preparation since the surface water content decreases with time. During a five day test cricket match not a single drop of water is added to the pitch after the final pitch preparation day before commencing the match (Shannon, 2010). Therefore, the pitch gets dried with time, hence the μ value increases and the pitch becomes slow and rather spin friendly with the time.

Since μ has strong negative correlation with velocity ratio and μ has strong positive correlation with top spin gained, high level of friction would cause the ball to spin more during impact and allow to gain top spin (Carré, et al., 1999). This research was done neglecting the tear and wear conditions caused by the players. Therefore, the μ values can be increased more due to the deterioration caused by the players during the real playing condition of a match.

Figure 5.20 shows the variation of the friction values with number of days at MU mould according to the ball type tested.

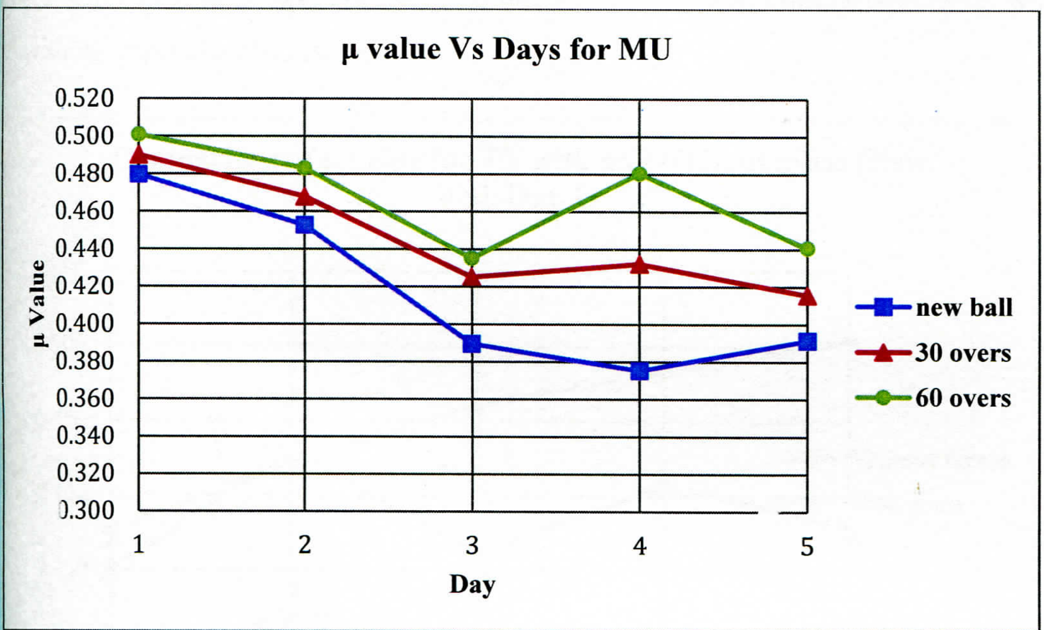


Figure 5.20 μ value Vs Days for MU

Figure 5.20 shows that the surface friction between ball condition (new ball, 30 overs used ball and 60 overs used ball) is increasing with the usage since the ball gets rough with time. MU is a soil of a high clay content and soils with high clay content (smaller particles) have lower hydraulic permeability than a sandy soil with relatively larger particles with more voids. Water trapped inside clay with high clay content cannot drain outside easily since the high clay content creates impermeable layer. While the pressure was applied on each day before starting the practical, trapped moisture was able to drain outside the soil making the surface of wet clay (Terzaghi, et al., 1996). Surface water combines with clay particles and makes a micro slurry surface on top which causes less friction. Moreover, the Lab models were kept inside the laboratory and the test was done on each morning before the samples get dry by the sunlight. Therefore, the surface moisture was not evaporated at the time when the friction test was done. The respective μ values decreased with the time. Therefore, a test should be carried out outside in the normal playing environment with real conditions of a cricket match.

Figure 5.21 produces a graphical comparison of μ values for TY with and without grass. The results were taken from the test done by new ball on day 1. Similar variation of the μ values could be achieved for MU and KO in the same comparison using with and without grass conditions.

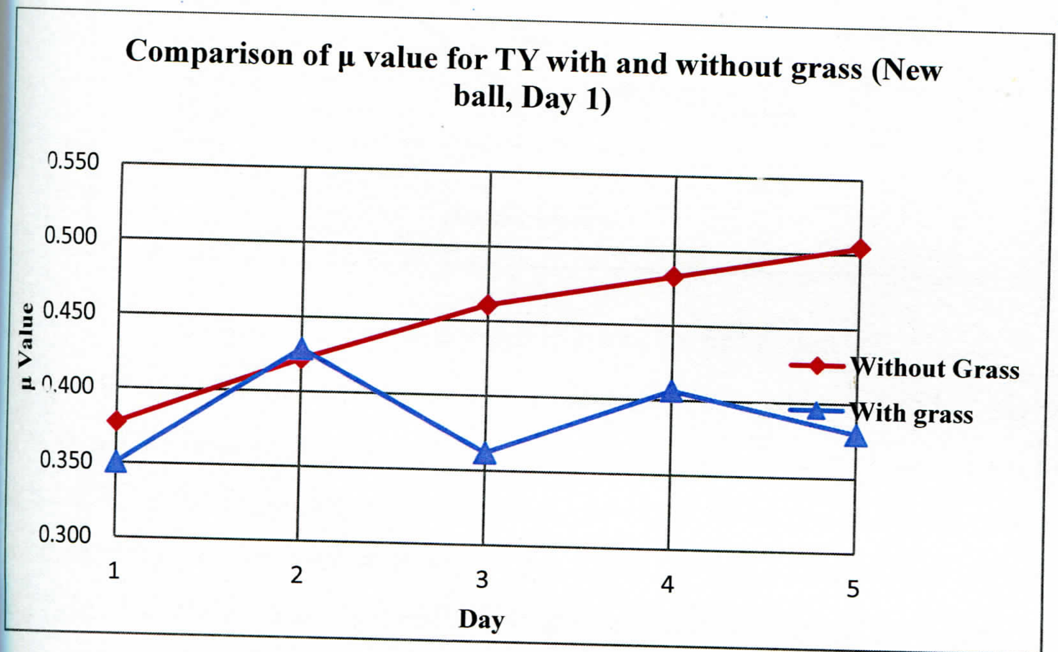


Figure 5.21 Comparison of μ value for TY with and without grass (New ball, Day 1)

Figure 5.21 shows that the coefficient of friction value for samples with surface grass was lower than samples without surface grass on each day. Therefore it can be concluded that the grass reduces the frictional resistance in between ball and cricket pitch soil. Due to the less frictional force acting on the ball, pitches with high grass content are faster than pitches with little surface grass (McAuliffe & Hannan, 2001).

Since there was a considerable fluctuation in μ values on different soil types during tested days, a better comparison can be obtained in between the conventional clay used in SL pitch preparation and other two soils. Sample calculation for MU can be done as follows.

% change of μ w.r.t TY= $\frac{\mu\ of\ MU - \mu\ of\ TY}{\mu\ of\ TY} \times 100\%$ --------------------Equation (5.3.3)

Following Figure 5.22 shows % change of μ w.r.t. TY for MU and KO.

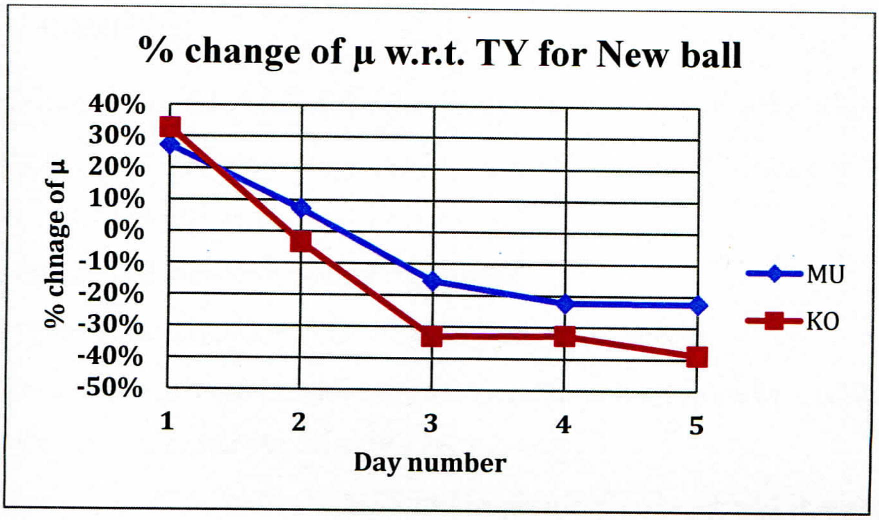


Figure 5.22 Percentage change of μ w.r.t. TY for New ball

After the 2nd day MU and KO shows less μ value than TY. MU and KO had higher MC% than TY (Figure 5.16,Figure 5.17). High moisture at the beginning caused for less μ for TY at the beginning since water has a lubricant effect on soil which reduces the surface friction. However with the μ value of MU and KO reduces than TY after the 2nd day. KO shows less frictional resistance than MU after the 1st day. Therefore MU and KO show positive results than currently used pitch material in SL.

5.3.2 Bounce test for the laboratory model

5.3.2.1 Introduction

Bounce test was carried out to determine the coefficient of restitution (e) between the cricket ball and the soil samples. Since the objective was to find the clay type which gives the highest ball bounce, seam less hockey ball which was having the same weight (156g) of the standard cricket ball was used to reduce the uneven ball bounce due to seam - surface impact. Ball was dropped from 2m height above the top clay surface of the model. HD camera was used to record the ball bounce and the clear rebound height was taken by analyzing the video output by Adobe Premier pro software. Test was carried out for five days for each model.

5.3.2.2 Methodology

- The same cubic sample used for the friction test was used for the bounce test.
- Sample mould was kept horizontally on a rigid concrete surface in front of a clear white background.
- Surveying staff was kept behind the model.
- HD camera was placed exactly 3.5m in front of the model.
- 2m height was marked on the staff measured from the top surface of the sample and a plastic ring was placed at the 2m marking.
- Bottom edge of the ball was held at the plastic ring level and it was dropped through the ring.
- About 20 perfect ball bounces were recorded neglecting the uneven ball bounces due to cracks.
- Rebound height reading up to the top surface of the ball was obtained by analyzing the video output.
- Corrected rebound heights were calculated by reducing the ball diameter and sample height from the observed measurement.

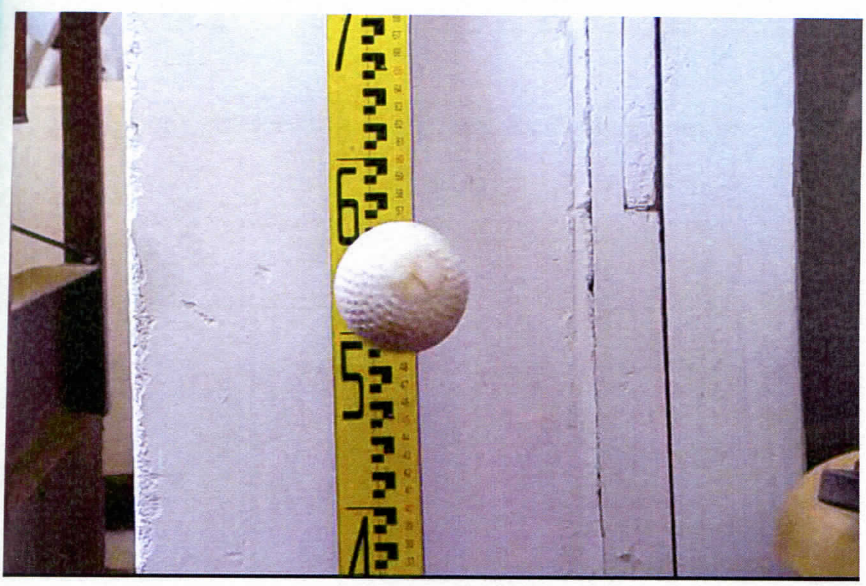


Figure 5.23 Image of the ball at its maximum rebound height (MU day 3)

5.3.2.3 Calculations

Figure 5.24 shows the schematic view of the bounce test.

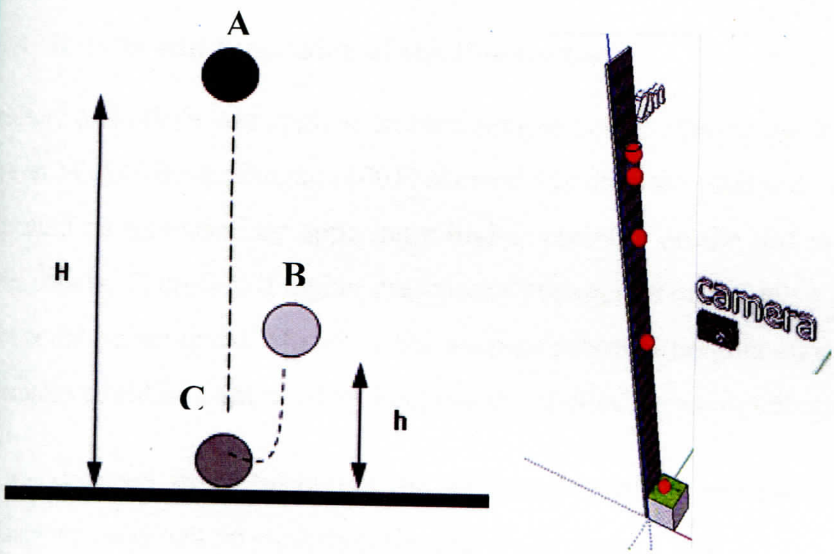


Figure 5.24 Bounce test apparatus

Coefficient of restitution (e)

$e = \frac{Vout}{Vin}$ --Equation (5.3.4)

Mechanical Energy conservation equation; for A and C points

$(K.E + P.E)_A = (K.E + P.E)_C$

$mgH = \frac{1}{2} mV_{in}^2$ --Equation (5.3.5)

;For C and B points

$(K.E + P.E)_C = (K.E + P.E)_B$

$\frac{1}{2} mV_{out}^2 = mgh$ --Equation (5.3.6)

From 5.34 and 5.3.6

$$\frac{V_{out}^2}{V_{in}^2} = \frac{h}{H}$$

$\therefore e = \sqrt{\frac{h}{H}}$; Where h is the rebound height, H is 2.0m.-------------------Equation (5.3.7)

5.3.2.4 Results and conclusion of the Bounce test

A pressure of 444kPa was applied on each sample before starting the tests on each day. However McAuliffe & Hannan (2001) showed that the peak rebound height for a given pitch could be increased by applying a higher pressure on the turf wickets by using heavier rollers. Therefore if higher pressures were applied on models a greater rebound height could be achieved. However the average rebound heights ad e value given by six samples could be compared by keeping the applied pressure unbiased.

Ball was dropped from 2m height on the sample surface and the average rebound heights were recorded on each day. Results are given in Table 5.3.

Table 5.3 Average rebound heights in cm

Average Rebound Heights (cm)					
	Day 1	Day 2	Day 3	Day 4	Day 5
TY	59.24	56.22	58.42	58.26	57.92
KO	47.12	52.31	59.60	59.46	60.26
MU	37.78	57.12	58.18	64.50	63.94
TY+GR	22.30	34.92	42.20	51.93	55.05
KO+GR	20.04	28.12	39.72	45.31	54.26
MU+GR	24.74	33.73	45.72	58.28	59.80

Average rebound height for all samples was plotted against days as shown in Figure 5.25

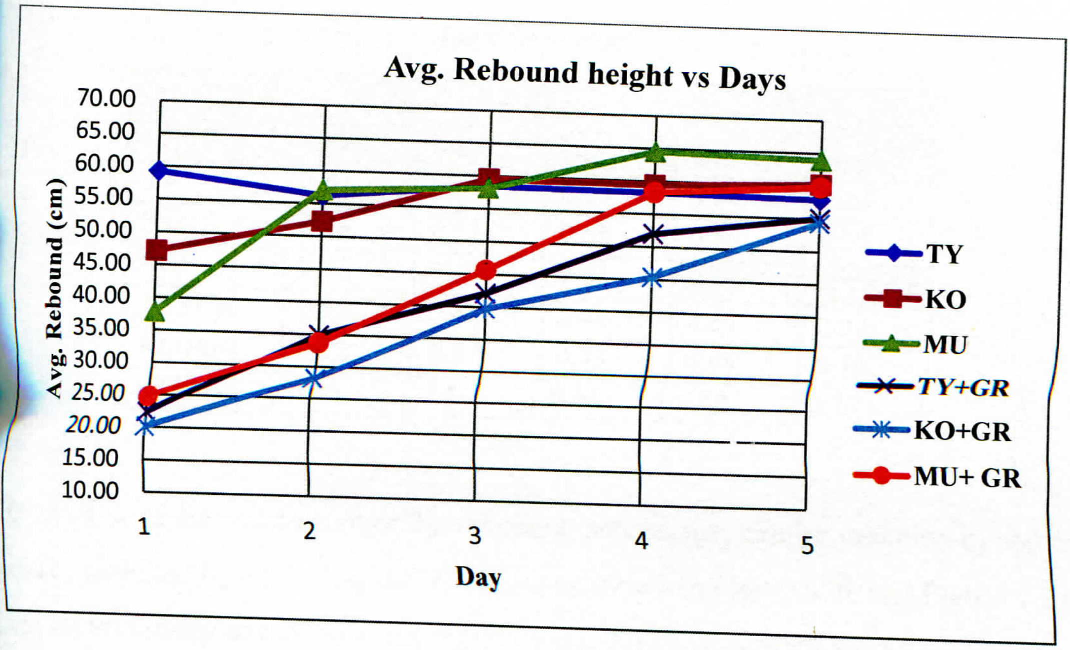


Figure 5.25 Avg. Rebound height vs Days

Average rebounce heights of all the samples increased with time. MU showed the highest Average rebounce height from among all samples in Day 4 and 5. KO and MU+GR gave the next highest average rebound heights. KO+GR was rapidly increasing its rebounce value with time. The highest value was shown by TY at the beginning but it remained merely a constant with time. Average rebounce heights given by MU, KO, MU+GR and TY+GR were increasing at the beginning and the gradients of the graphs becomes low in Day 4 and 5 which implies that the samples were closer to achieve their maximum average rebounce heights for the given particular applied pressure of 444.5 kPa.

However each and every sample without grass showed a higher average rebound height than the samples prepared by the same soil with grass in every day.

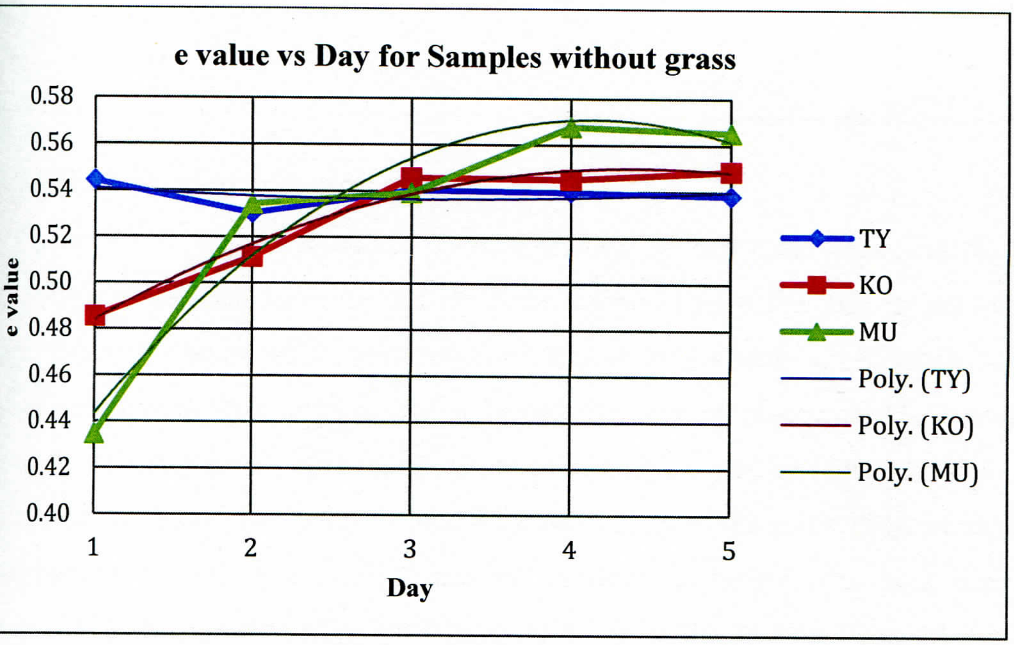
According to the result given by Table 5.3 the e value was calculated using equation 3.3.7 and tabulated in Table 5.4.

Table 5.4 e values

"e" value					
	Day 1	Day 2	Day 3	Day 4	Day 5
TY	0.54	0.53	0.54	0.54	0.54
KO	0.49	0.51	0.55	0.55	0.55
MU	0.43	0.53	0.54	0.57	0.57
TY+GR	0.33	0.42	0.46	0.51	0.52
KO+GR	0.32	0.37	0.45	0.48	0.52
MU+ GR	0.35	0.41	0.48	0.54	0.55

Since e value is the square root of the rebounce percentage, similar variation as above ould be obtained by analyzing the 'e' values as shown in Figure 5.26 and Figure 5.27. amples with/without having surface grass were shown separately for the convenience f analyzing.

ariation of "e" values with number of days for samples without grass is shown in gure 5.26



re 5.26 e value vs Day for Samples without grass

Figure 5.26 trend lines shows the rate of increase in e values of each sample. TY d line was having a gradient closer to zero which says there is no increase in e value with time. In contrast a positive gradient was indicated at the beginning by the other two samples. Although both MU and KO had positive gradients in their trend lines, MU had a higher gradient than KO in the beginning part. That result implied that MU was increasing its e value rapidly with time than KO. But in Day 4 and 5 the rapid increasing became low in both KO and MU which implied that both samples were reaching for their peak e values for that particular applied pressure.

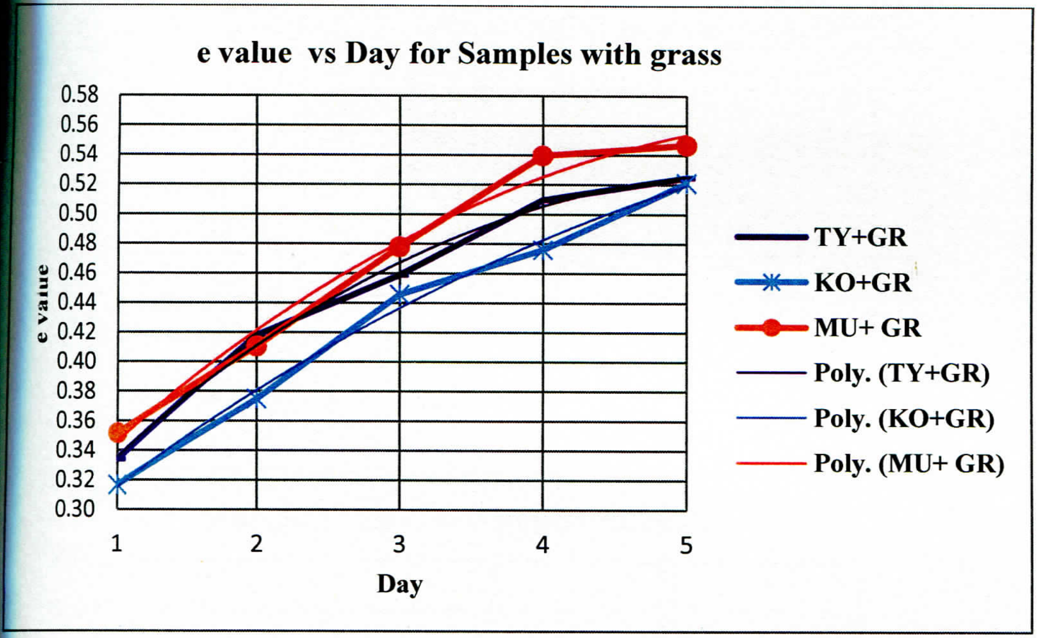


Figure 5.27 e value vs Day for Samples with grass

All the samples with grass showed a positive gradient in their trend lines over the five tested days. Grass can take out the moisture trapped inside the mid layers of the impermeable clay layer. MC% of the mid and bottom layers could not be taken during this tests because the top surfaces where the ball impact took place could be damaged due to the disturbance. But the moisture in the mid layers will be reduced due to the photo synthesis process of grass. Hence the bulk density of the soil will be increased. As shown by Baker, et al., (1998) the ball rebound increased with bulk density. However higher rebounce may have been achieved if the test was carried out for several days for the samples with grass since there is a significant gradient in their tend lines in the last tested day as shown in Figure 5.27

MC% of the samples was different throughout the tests for laboratory models since the starting point was their optimum MC%. In order to remove the effect of the influence of MC%, a normalized 'e' value was obtained by dividing the 'e' value with MC%. Results are tabulated in Table 5.5.

Table 5.5 "e" value Normalized by M.C

"e" value Normalized by M.C					
	Day 1	Day 2	Day 3	Day 4	Day 5
TY	2.557	2.563	2.539	2.645	3.300
KO	2.590	2.761	2.913	2.756	2.737
MU	3.280	4.348	4.426	4.771	5.403
TY+GR	1.225	1.496	1.683	1.842	2.292
KO+GR	1.464	1.814	2.062	2.320	2.869
MU+ GR	2.360	2.726	3.208	4.321	3.288

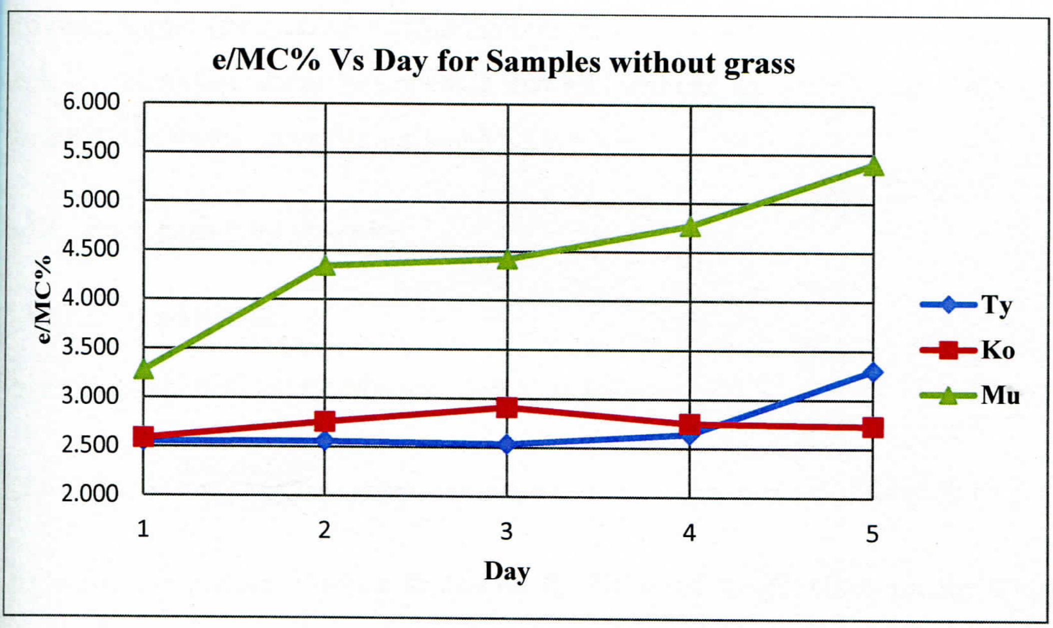


Figure 5.28 Normalized 'e' Vs number of Days for Samples without grass

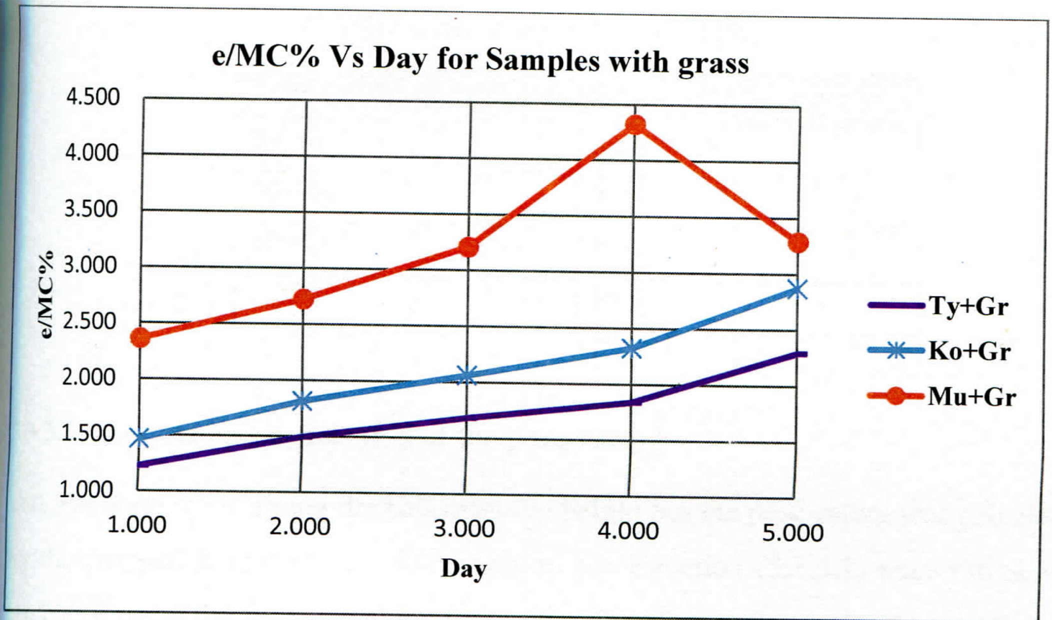


Figure 5.29 Normalized "e" Vs Day for Samples with grass

Samples with/without having surface grass are shown separately in Figure 5.28 and Figure 5.29 respectively for the convenience of analyzing. MU and MU+GR samples showed a higher normalized e value than the rest of the samples in their categories in each day. Therefore, it can be conclude that MU soil can generate higher bounce than the rest of the tested clays for a given MC%.

5.3.3 Pace rating by murphy

5.3.3.1 Introduction

Pace rating was defined by Murphy (1985) as follows

$$\text{Pace rating} = \frac{Bounce(cm)}{Friction} \text{--Equation (5.3.3.1)}$$

In the above Equation, Bounce stands for the Rebound height taken for the dropped height of 4m and the Friction stands for the Friction coefficient (μ value). Pace rating chart given by Murphy is showed in Table 5.6 below.

Table 5.6 Pace rating by Murphy (1985)

Pace Rating	Pace
0 - 50	Very Slow
50-100	Slow
100-300	Easy
> 300	Fast

5.3.3.2 Results and conclusion of the pace rating

Test was done by dropping the ball from 2m height but the pace rating was calculated for the dropped height of 4m. According to the Equation (5.3.3.1) pace rating was calculated using the above equation for the six laboratory soil samples. Converting the values into 4m dropped height was done keeping the same Potential energy reduction percentage for the tests done from 2m dropped height. Pace rating was calculated for the three ball types (New, 30 overs used and 60 overs used) which represent each session of an inning and shown in the Table 5.7, Table 5.8 and Table 5.9 below.

Table 5.7 Pace rating for new ball

Soil type	Pace rating for new ball				
	D1	**D2**	**D3**	**D4**	**D5**
TY	**Fast**	Easy	Easy	Easy	Easy
KO	Easy	Easy	**Fast**	**Fast**	**Fast**
MU	Easy	Easy	Easy	**Fast**	**Fast**
TY+GR	Easy	Easy	Easy	Easy	Easy
KO+GR	Slow	Easy	Easy	Easy	Easy
MU+ GR	Easy	Easy	Easy	Easy	**Fast**

Table 5.7 shows the Pace rating done for the New ball. For the New ball TY soil had a Fast pace rating on the 1st day but then it was easy paced. KO became a Fast after the 2nd day and it was continued till the last day. MU and MU+GR pitches became fast after the 3rd day and 5th day respectively.

Table 5.8 Pace rating for 30 overs used ball

Soil type	**Pace rating for 30 overs used ball**				
	D1	**D2**	**D3**	**D4**	**D5**
TY	Easy	Easy	Easy	Easy	Easy
KO	Easy	Easy	**Fast**	**Fast**	**Fast**
MU	Easy	Easy	Easy	Easy	**Fast**
TY+GR	Slow	Easy	Easy	Easy	Easy
KO+GR	Slow	Easy	Easy	Easy	Easy
MU+ GR	Easy	Easy	Easy	Easy	Easy

Table 5.8 shows the pace rating done for the 30 overs used ball which represents the 2nd session of a test cricket inning. KO and MU became fast after the 2rd and 4th days respectively.

Table 5.9 Pace rating 60 overs used ball

Soil type	**Pace rating 60 overs used ball**				
	D1	**D2**	**D3**	**D4**	**D5**
TY	Easy	Easy	Easy	Easy	Easy
KO	Easy	Easy	**Fast**	**Fast**	**Fast**
MU	Easy	Easy	Easy	Easy	Easy
TY+GR	Slow	Easy	Easy	Easy	Easy
KO+GR	Slow	Easy	Easy	Easy	Easy
MU+ GR	Easy	Easy	Easy	Easy	Easy

Table 5.9 shows the pace rating done for the 60 overs used ball which represents the 3rd session of a test cricket inning. Only KO became fast after the 3rd day.

From the above tables KO and MU can be identified as "Fast" rated pitches while TY was "Fast" only on the starting day.

6 TESTS FOR THE ACTUAL FIELD CONDITIONS

After conducting the laboratory studies for the models as the 1st stage of the research, Pace test and Bounce tests were carried out for the sample pitches made at University of Moratuwa cricket grounds as the 2nd stage of the research.

6.1 Preparation of soils

Three soils were basically used to prepare the model pitches inside the grounds. MU, TY and a mixed sample of MU and TY (1:1 by weight) are the three different soils used for the 2nd stage of the research. Moreover ant clay was used as the foundation material to support the clayey top most layer of 125 mm. Preparation of each samples are described as follows.

6.1.1 Murunkan sample

Although the soil was collected from its' natural deposits during the dry season, considerable amount of moisture was present in clayey soil. This may be due to the lesser depth to the ground water table or due to the very low permeability of the grumusol clayey soil. Hence the soil was first exposed to air drying in bulk quantity. After air drying the soil was then crushed using a vibratory rammer and then sieved using the 19mm sieve to ensure that no larger portions of the soil will be present during the compaction of the soil filling during the pitch construction.

Figure 6.1 Crushing and sieving Murunkan soil

6.1.2 Tyronne Sample

Unlike the Murunkan sample, TY soil was received as crushed and dried state and had been prepared specially for cricket pitches. Therefore no any further preparation was needed.

6.1.3 Ant Clay sample

Underneath both soil types, a compacted ant clay layer was laid as an impermeable layer separating the gravel layers and the well compacted clayey soil layer. Ant clay was also air dried and crushed like the Murunkan sample.

6.2 Preparation of the pitch area at the university grounds.

For testing purposes, 2m x 2m area was prepared using the Murunkan (MU) and Tyronne soils (TY).

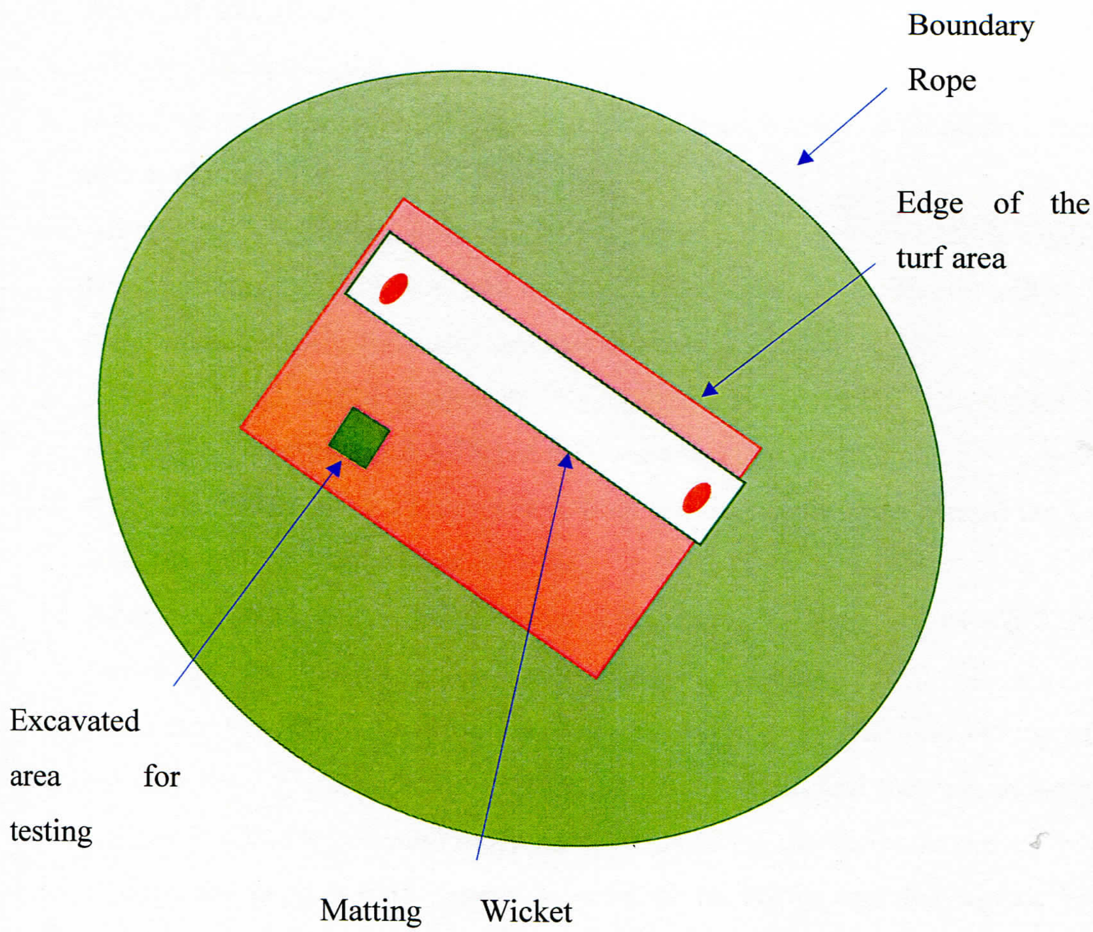


Figure 6.2 Location of the testing area in the university grounds (Not to a scale)

6.2.1 Procedure

1. Location for the relaying of clay layers was identified within the pitch area.
2. Existing soil layers were removed up to a maximum thickness of 150mm (Figure 6.6 and Figure 6.7).
3. A water spray was sprinkled into the pit, and then ant clay was laid for a compacted thickness of 30mm using a vibratory rammer. (Figure 6.5)
4. Holes were driven into the compacted ant clay layer with a grid spacing of 25mm in both x and y directions and grass was planted in each hole. Four plants were inserted into the same hole to ensure at least one plant will grow up and will maintain the necessary grass density. (Figure 6.4)
5. Two soils were dumped into the two adjacent pits influencing minimum disturbance to the grass plants. The grass plants were covered with 18mm pvc conduit pipes of 100mm length to stop them being bent down and drowned under the soil. (Figure 6.3)
6. Soil was filled up to the existing ground level and slight compaction was given.
7. Water was sprinkled and the grass was left to be grown up. Fertilizer B11 was also applied.
8. After about 3 ½ months, grass cover was sufficiently overtopped the top soil, hence another soil layer was laid on top of the existing layer. Newly laid soil was levelled equally and water was sprinkled. (Figure 6.5)
9. After another 3 weeks, grass cover was grown up sufficiently, then the hand operated light roller (550kg, Figure 6.8) was used for compaction.
10. After the settlement was taken place, final refilling of soil was carried out to level the surface with the ground level.
11. After compacting using the light roller, 3 ton machine roller (SAKAI SW 350) was used for compaction as the heavy roller. (Figure 6.9)
12. Core samples were taken from the compacted clayey layers up to the top of ant clay layer to quantify the existing moisture content and that values were compared with the optimum moisture contents of the two different soils.
13. Finally, the pitch was tested for pace by throw downs and for bounce by allowing the free fall and then measuring the rebound height.

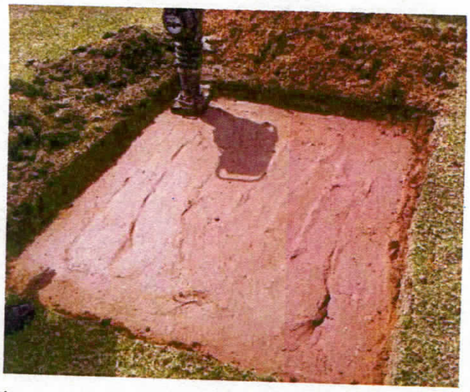
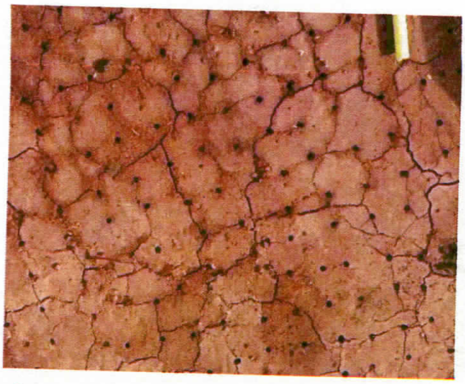



Figure 6.4 Compacted ant clay layer and holes driven in


Figure 6.3 Grass placed within pipes and placing in the pitch


Figure 6.5 Watering and laying of soil again

Figure 6.7 Existing clay layer thickness

Figure 6.6 Excavated pit for the pitch model

Figure 6.9 Machine roller compaction

Figure 6.8 Light roller/ hand roller

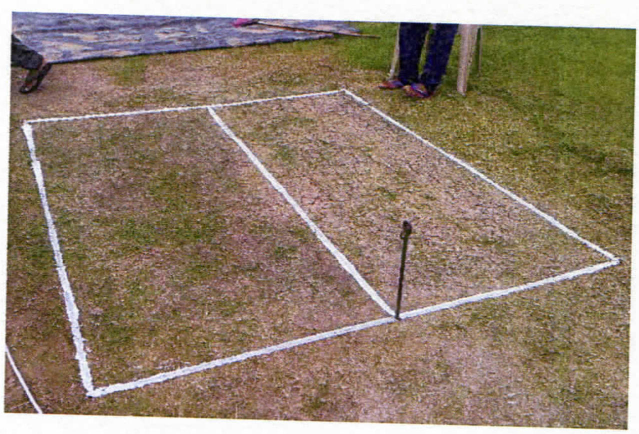


Figure 6.10 Prepared model pitch for testing

6.2.2 Ant-clay Layer

Ant clay acts as a nutrient base for the grass cultivation. At the same time, it reduces the seepage of water into the topmost clay layer through the underlying soil strata with the low permeability due to considerable presence of ant clay. In this research, ant clay was borrowed from an ant-hill located within the university of Moratuwa premises. It had a very low moisture initially and after one day of air drying, it was crushed using a vibratory rammer and then placed in the prepared pit and compacted using the same machinery. During the compaction, water was added whenever it seemed to be necessary. The compacted thickness of the ant clay was 25mm.

A core cutter test was carried out to find the in-situ dry density and the moisture content.

6.2.3 Core cutter test for Ant clay layer

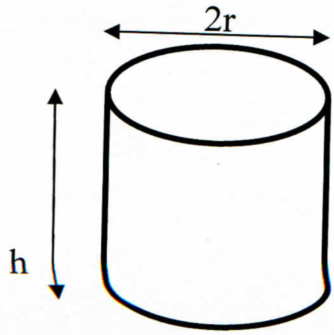
$$Initial\ sample\ weight + core\ \ (w_1) \quad = 306g$$

$$oven\ dried\ sample\ weight + core\ (w_2) = 264g$$

$$Weight\ of\ core\ \ (w_3) \quad = 84g$$

Figure 6.11: Core cutter test

Core Cutter dimensions



$r = 25.98mm$

$h = 52.46mm$

Figure 6.12: Core cutter dimensions

$$dry\ soil\ weight(Excluding\ core\ weight) = w_2 - w_3 = 264 - 84g = 180g$$

$$Moisture\ content = \frac{Mw}{Ms} = \frac{w_1 - w_2}{w_2 - w_3} = \frac{306 - 264g}{180g} = 23.33\%$$

$$Bulk\ density\ of\ compacted\ ant\ clay\ layer = \frac{w_1 - w_3}{volume\ of\ core}$$

$$= \frac{(306 - 84) \times 10^{-3} kg}{\pi \times 25.98^2 \times 52.46 \times 10^{-9}\ m^3}$$

$$= 1996\ kg/m^3$$

$$Dry\ density\ of\ the\ compacted\ ant\ clay\ layer = \frac{Bulk\ density}{(1 + w)}$$

$$= \frac{1996\ kgm^{-3}}{(1 + 0.233)}$$

$$= 1618.8\ kgm^{-3}$$

6.2.4 Compaction energy given to the ant clay layer by vibratory rammer

Model of the vibratory rammer: Wacker BS 60-2i

Type of engine : *2 stroke gasoline engine*

Operating weight : 66kg

Power output : 1.8 kW @ 4400 rpm

Assume Weight drop height (average lift of the rammer plate above ground elevation) is to be 0.2m.

According to BSI technical draft, for a rammer with an operating weight of 65kg. That value is extrapolated for the 66kg used Wacker.

For 0.1m drop height,

Energy output per strike = 15.59J per blow (modified for the 66kg rammer weight)

Wacker was used for **60 minutes** consists of 30mm of compacted thickness.

Max percussion rate: 700 per minute

Assume the operating percussion rate is to be 240 per minute (6 blows per second)

Operating percussion rate: 360 per minute.

Energy given to the soil by the vibratory rammer = 360 x 50 x 15.59 J = 280.62 kJ

(For a soil volume of 2m x 2m x 0.03m)

$$Energy\ given\ by\ the\ rammer\ per\ soil = \frac{280.62\ kJ}{0.12\ m^3} = 2338.5\ kJ/m^3$$

6.2.5 Compaction of the cricket pitch

Compaction is undoubtedly the most important stage of construction or maintenance of a cricket pitch. A satisfactory amount of compaction relative to the need, means a preferable turf wicket construction. Higher compaction energy input ensures the clay layers will get higher densities with packed soil particles. It aids the ball to loss lesser energy during an impact with the turf, hence paving the way for a faster rebound velocity or higher bounce after the impact.

During the pitch construction, several equipment and machinery were used at different stages. They are stated below.

1. Vibratory rammer (**Make**:Whacker-neuson **Model:** BS 60-2i**Total Weight**: 66kg)
2. Walk-behind roller (**Make:** Tacom **Model :** TMR 65KD : **Total Weight:** 660kg)
3. Machine vibratory roller (**Make:** SAKAI **Model :**SW 350 **Total Weight :** 2750kg)
4. Hand operated non-vibratory light roller (**Total Weight:** 566kg)
5. Hand operated non-vibratory heavy roller (**Total Weight:** 1412kg)

6.2.6 Compaction Methodology

First stage

1. First of all, compaction was given by the light roller (hand operated) via 20 passes for each soil. Then after an hour, another set of 20 passes were given to each soil.
2. After two days (24th November), machine roller compaction was done using SAKAI SW 350 roller. The operating total weight of the roller was 2750kg. First 16 roller passes were applied. Then the pitch was left to dry for about 10 minutes. Then after a little spray of water, another 16 roller passes were applied to each soil. Again, after letting half an hour to dry, another 16 roller passes were applied and to make the surface even, another 6 roller passes were applied.
3. Then the pitch was covered at about 4pm in the afternoon.

4. 20 passes were given to each soil on 25th , 28th November using the light hand operated roller.
5. The testing procedure was started on 29th November and before testing on first day, a tiny spray of water was applied and then after 10 minutes, light roller was used for compaction for 20 passes. White line markings were drawn on the boundary of the pitch area to be clearly visible during videography.
6. Then on each day of testing, light roller was used for 20 passes prior to the commencement of testing for pace and bounce. During the testing procedure, water was not added.
7. On 7th December, the testing for the first stage was finished due to the unfavourable cracking widths on the pitch which violates the standard playing conditions and also the bounce results had shown a peak value and then a slight depreciation.

6.2.7 Re-laying of Murunkan soil

Due to the prevailing high moisture conditions inside the Murunkan clay layer, the bounce test results were deviated largely when compared to results from the model tests. In contrast, Tyronne soil had an increasing trend in terms of bounce and after a peak, the rebound heights started to decline while cracks propagate within the pitch violating playing conditions. Therefore, the testing for Tyronne soil was finished and Murunkan soil layer was proposed to be re-laid after loosening the compacted layer. The pitch area which belongs to Murunkan soil was divided into two, and one half was filled with Murunkan soil and the remaining half was filled with a mixture of Murunkan and Tyronne soil with a weight to weight ratio of 1:1

Figure 6.13 Mixing of two soils

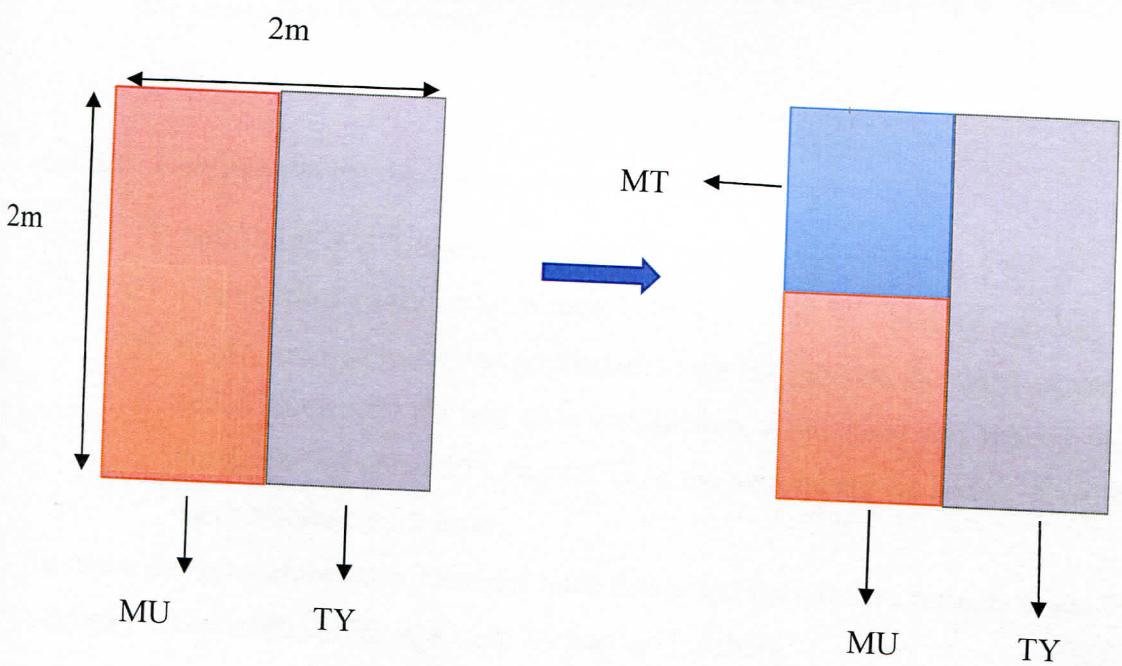


Figure 6.14 Arrangement of compacted soil within the pit in two stages (Stage 1 on left and stage 2 on right)

6.2.7.1 Procedure of relaying of soil

1. Murunkan clay soil was loosened and the soil was left to air dry.
2. Air dried soil was mixed with Tyronne soil with weight ratio of 1:1.
3. Both Murunkan and Murunkan + Tyronne mixture was re-laid with compacted layer thicknesses of one inch. Five layers were compacted in each type of two soils.
4. Layer wise compaction was done using a vibratory rammer. After reaching the ground level during filling, final surface finishing was done using hand operated non-vibratory heavy roller and vibratory double drum roller.
5. White line markings were drawn like in the first stage of testing at the edges of the newly filled pitch area.

6.2.7.2 Compaction Methodology of second stage

1) Soil filling and compacting was done in five layers of one inch thick.
2) Compaction was done by Wacker (Neusan BS 60-2i vibratory rammer).
3) First a spray of water was applied on to the ant clay and then the first layer was added. Soon after the first layer compaction, water spray was applied and then left to dry for about 15 minutes. Then the next layer was added. This process was continued for 5 layers.

To make the top surface even, hand operated heavy and light rollers were used and finally vibratory walk-behind roller was used for surface finishing.

6.3 Compaction of the model pitch

1. Compaction of the pitch preparation stage one

Table 6.1 Energy by each roller

Day	roller	No. of passes	Energy (KJ/m3)	Cumulative energy (KJ/m3)
22/11/2016	L/H	40	1456.5	1456.5
24/11/2016	H/M	56	9303.4	10760.0
25,28/11/2016	L/H	40	1456.5	12216.4

Table 6.2 Daily cumulative compaction energy input per each soil during testing in Stage 1

Testing day	Tested soil	Day	roller	No.of passes	Energy (KJ/m3)	Cumulative Energy (KJ/m3)
1	TY	29/11/2016	L/H	20	728.2	12944.6
2	MU&TY	30/11/2016	L/H	20	728.2	13672.9
3	MU&TY	01/12/2016	L/H	20	728.2	14401.1
4	MU&TY	02/12/2016	L/H	20	728.2	15129.4
5	TY	07/12/2016	L/H	20	728.2	15857.6
6	TY	08/12/2016	L/H	20	728.2	16585.9

2. Compaction during relaying of soil before second stage of testing

Table 6.3 Energy by vibratory rammer (VR)

Type of	Date	Duration	Percussion rate	Energy (KJ/m3)
Machine		(Minutes)	(per min.)	
VR	23/12/2016	50	360	2338.5

Table 6.4 Energy by rollers

Date	Roller	No. of passes	Energy (KJ/m3)	Cumulative E (KJ/m3)
23/12/2016	WBR	125	8256.2	10594.7
24,30/12/2016	H/H	80	4917.8	15512.5
30/12/2016	L/H	60	2184.7	17697.3

Table 6.5 Daily compaction energy input during testing period of second stage

Testing day	Tested soil	Date	Roller	No. of passes	Energy (KJ/m3)	Cumulative E (KJ/m3)
7	MU&MT	02/01/2017	L/H	20	728.2	18425.5
8	MU&MT	03/01/2017	L/H	20	728.2	19153.7
9	MU&MT	04/01/2017	L/H	20	728.2	19882.0
10	MU&MT	05/01/2017	L/H	20	728.2	20610.2
11	MU&MT	06/01/2017	L/H	20	728.2	21338.5
12	MU&MT	09/01/2017	L/H	20	728.2	22066.7
13	MU&MT	10/01/2017	L/H	20	728.2	22795.0
14	MU&MT	11/01/2017	L/H	20	728.2	23523.2

6.4 Summary of the applied energy on the pitch

- Energy was applied on the pitch as follows.

Table 6.6 Energy was applied on the pitch

Applied Energy (in kJ)			
Day	TY	MU	MT
1	12944.64	12944.64	-
2	13672.89	13672.89	-
3	14401.13	14401.13	-
4	15129.38	15129.38	-
5	15857.62	15857.62	-
6	16585.87	16585.87	-
11	-	18425.50	18425.50
12	-	19153.74	19153.74
13	-	19881.99	19881.99
14	-	20610.23	20610.23
15	-	21338.48	21338.48
16	-	22066.72	22066.72
17	-	22794.97	22794.97
18	-	23523.21	23523.21

In stage one & two pace tests were done for TY & MU, MU & MT respectively. In those two stages two different energies were applied on the pitch.

E_1- Initial Energy applied on 1st day, E_2- Total energy Applied on next day, Δ AE% - Percentage change in applied energy

$$\Delta AE\% = \frac{(E2-E1)}{E1} \times 100\%$$ --Equation 6.4

6.5 Variation of the Moisture content

Moisture of the top 1/3 of the clay layer (50mm) was varied as follows

Table 6.7 Variation of the MC% (Top 50mm)

Moisture content %			
Day	TY	MU	MT
1	25.53%	22.94%	-
2	21.50%	21.52%	-
3	21.25%	21.50%	-
4	20.54%	17.67%	-
5	20.11%	15.96%	-
6	20.08%	10.20%	-
11	-	23.08%	23.55%
12	-	24.71%	24.42%
13	-	26.33%	25.28%
14	-	19.8 %	20.07%
15	-	19.89%	16.93%
16	-	16.17%	9.58%
17	-	8.62%	9.30%
18	-	5.26%	6.15%

Each and every day 3 samples from top middle and bottom of the clay layer was taken and the wet weight of the samples were measured (W_w). Then the samples were oven dried for 24 hours and the dry weight was measured (Wd). Moisture content (MC %) was calculated as follows.

$$MC\ \% = \frac{(Ww - Wd)}{Wd} \times 100\%$$ ---Equation 6.5

Bounce and pace data was normalized by MC% and Δ AE% to remove the effect of different conditions caused by the variation of applied energy and MC%

6.6 Testing of the pitch

After compaction, the pitch area was demarcated with white lines to separate the area with different soil types.

First stage

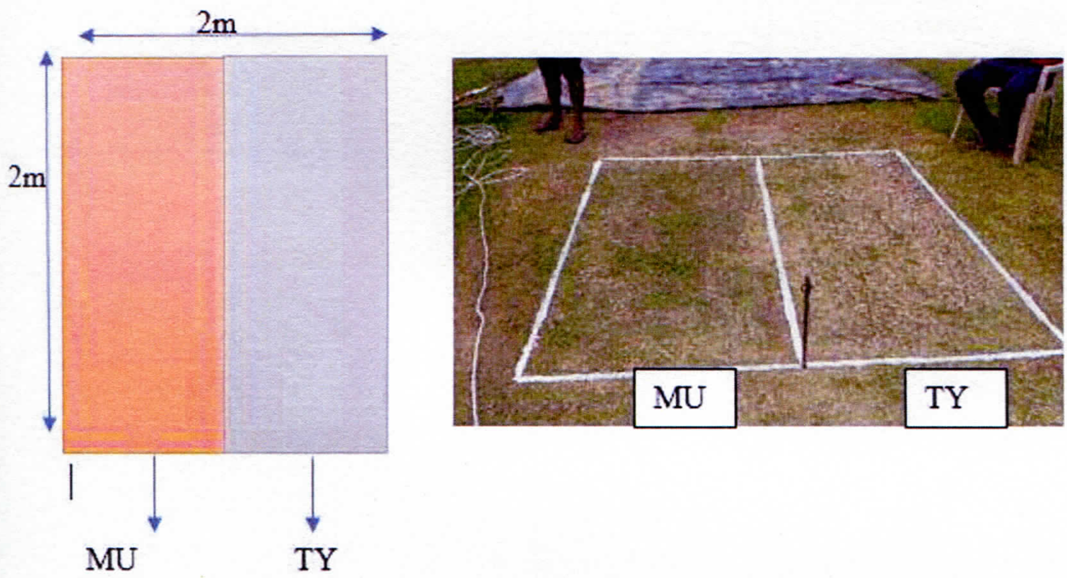


Figure 6.15 Model pitch during first stage of testing for MU and TY

Second Stage

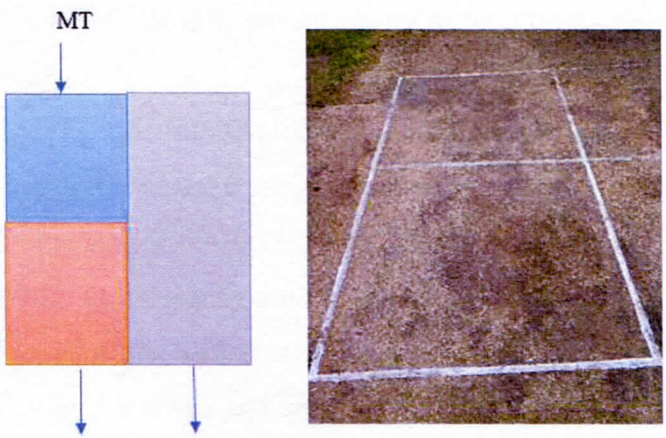


Figure 6.16 Model pitch during second stage of testing for MU and MT

White lines were drawn in the boundaries of the newly compacted pitch area and the leather ball impacts were kept within the white line boundaries.

6.7 Pace test

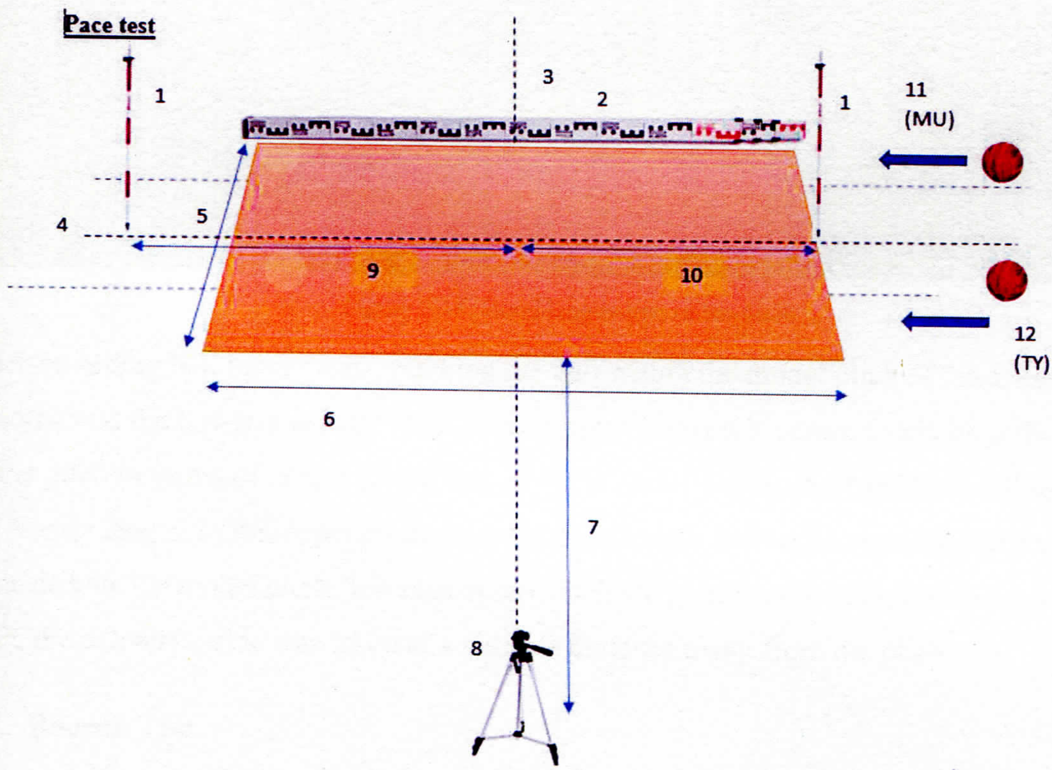


Figure 6.17 Arrangement of camera for the testing procedure

LEGEND

1. Poles (To identify the incoming and outgoing heights of the delivery at known points
2. Staff (To identify the location of the impact between the turf and leather ball
3. Center line of the testing area along x axis
4. Center line of the testing area along y axis
5. Width of the testing area (2210mm)
6. Length of the testing area (2380mm)
7. Distance between the line no.5 and the location of the tripod (along x axis)
8. Tripod mounted with an Apple® I phone 6S mobile phone
9. Distance to the pole (within outgoing trajectory) from the center of the pitch (2m)

10. Distance to the pole (within incoming trajectory) from the center of the pitch (1.25m)
11. Ball trajectory of MU
12. Ball trajectory of TY

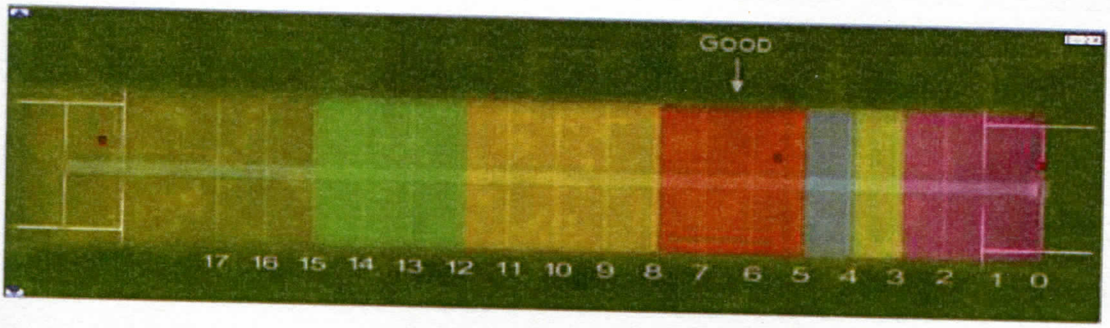


Figure 6.18: Good length area of the pitch

When recording ball movements, pitching the ball within the model pitch of 2m x 2m was essential and the bowlers usually have several options when it comes to pitching the ball on the pitch in terms of length of the delivery. i.e. good length, short pitched, full length and Yorker length. In this experiment, only the good length deliveries were recorded which coincide with the model pitch. To consistently pitch the good length balls within the model pitch, the delivery stride was taken at a suitable distance away from the pitch.

6.8 Bounce Test

As shown in Figure 7.1 the staff was held vertically and the ball was dropped from the 2m level (bottom of the ball at 2m mark) and the rebound motion was recorded by the I phone mounted on the tripod. The tripod was kept in the same location as the above diagram. The free fall height was reduced to 2m unlike in the experiment by James et al., (2004) to reduce any effects from viscous force. Therefore, the release height of the ball was maintained at 2m. The bottom of the ball was kept to 2m near the staff when releasing and the rebound elevation was measured up to the bottom of the ball because the centre of the ball (centre of gravity) was not a clearly visible and readily recognizable in video footages. The ball was kept as closer as possible to the staff to overcome any possible parallax errors in videos.

6.9 Measurement of crack density

Surface cracking of the compacted clayey soil in natural turf pitches is an inherent quality and it adds variations to the behaviour of the cricket ball within different phases of an international test match. Sometimes surface cracks influence the ball to change its trajectory in an unpredictable way which causes difficulties for batsman and thereby effecting dismissals.

Cracking of the pitch was quantitatively measured during this experiment using image processing methods. Digital photographs were taken on each day of testing and a square of 300x300mm was photographed with clear boundaries and the images were analysed using MATLAB software to calculate the percentage pixel density which shows cracks. It should be noted that these results cannot be used as absolute values of crack density of soils as the numerical values depend on the parameters defined in the MATLAB code, but can be used for comparison purposes within this experiment as the above mentioned parameters are constant for all three soils.

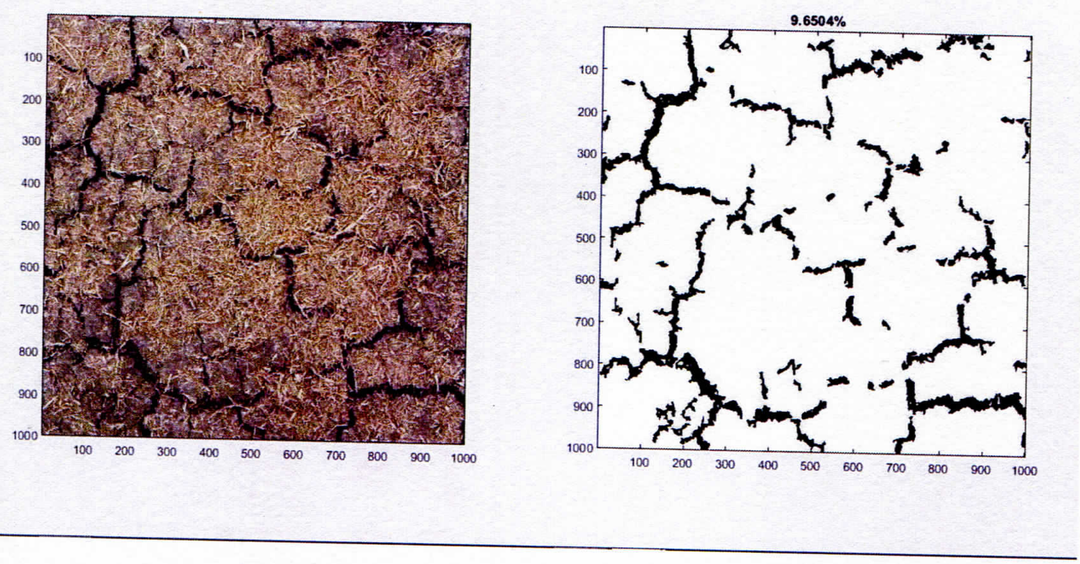


Figure 6.19: Image analysis results of a digital photograph which covers 300x300mm of the prepared

When the pitch is dried continuously, the surface tends to powder and crumble making the surface roughens. This allows the ball to grip when it pitches and so it will turn. To avoid the pitch from being over-dried, water sprinkling was done whenever needed during the testing procedure.

7 CALCULATIONS, RESULTS AND DISCUSSION

7.1 Bounce Test

After the model pitch was prepared at the grounds in university of Moratuwa according to the standards, preliminary tests were started for the cricket pitch. Bounce test was carried out for each day for several soils/soil combinations. Previously discussed methodology was adopted here as a field bounce test. In this case both hockey ball and test cricket ball was used for the test. Ball was dropped from 2m height in front of a continuously recording video camera and the rebound height was taken from the video analysis.

7.2 Video recording for the pitch model

7.2.1 Video analysis for the Bounce test

The video output from the iPhone 6s was analyzed by Adobe® Premier Pro software package. Video was imported into source monitor interface of the software and time line was changed into audio time units in order to display the time units in millisecond terms. Then the timeline was stretched for fine adjustments. After that the video was resumed and paused at its maximum rebound height while the best fit frame was selected by doing the fine adjustment for the timeline. Then the zoom level was adjusted to 200 get a clear view of the height measurement. The height was taken up to the bottom level of the ball from

Figure 7.1 Bounce test at he model pitch

the ground. All rebound heights were recorded in an excel sheet and the best 20 rebound heights were selected for the data analysis.

7.2.1.1 Data Analysis

Video footages recoded at the field were imported to Adobe Premier pro software. Data analysis was done by Adobe Premier Pro software. In the bounce test capturing the peak rebound height was the main objective. The cursor could be moved within four millisecond time intervals and the precision level was more than enough to fulfill the requirement.

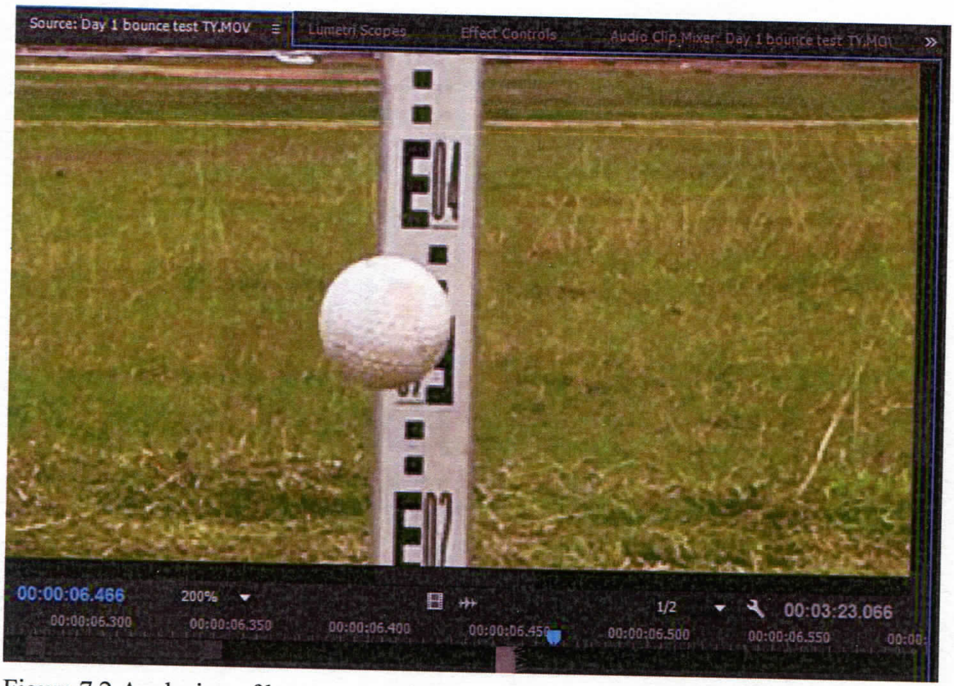


Figure 7.2 Analysing of bounce test videos using Adobe Premier Software

All rebound heights were taken to an excel sheets and the following calculations were done for the best 20 bounces neglecting the uneven bounce due to cracks or seam-pitch interaction. Average, standard deviation and the maximum reading was taken for each day and soil types. (All data sheets were included in annex)

Dropped height was 2m measured from the pitch level up to the bottom of the ball at rest for both laboratory model (LM) and the Pitch model (PM).

For the LM the test was done using only hockey ball and for the PM the bounce test was done using both Test cricket ball and Hockey ball.

Moisture content (MC) and the applied energy for soil was varied from each day. For further analysis the e value was divided by the MC and Percentage change in applied energy (Δ AE %) in order to eliminate the effect of different MC% and Applied Energy values.

Rebound percentage and Co-efficient of restitution ("e" value) was calculated as follows.

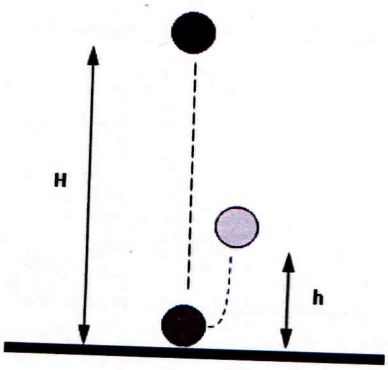


Figure 7.3 Bounce test

$$\text{Rebound percentage} = \frac{\text{Rebound Height (h)}}{\text{Dropped height (H)}}$$

$$e = \sqrt{\frac{h}{H}} \quad \text{------------------------------ (Equation 8.1)}$$

7.2.2 Calculations for the parallax error

Since the line of sight of the camera is not perfectly under the bottom edge of the ball parallax error could be happen. Although the gap between the staff and the ball was maintained very narrow to minimize the parallax error.

As shown in the Figure 7.4 (all measurements are in cm), error that could be happen when measuring the rebound height was taken as δ, maximum rebound height for 1% percentage error was Y, camera height was 55cm and ball radius was 3.5cm.

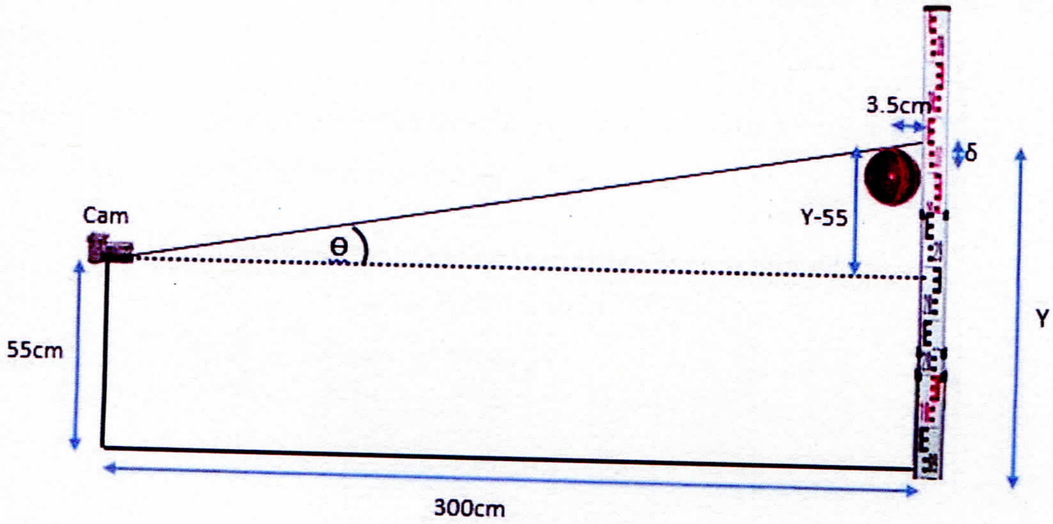


Figure 7.4 Parallax error calculation for Bounce test

$$\tan\theta = \frac{\delta}{3.5} = \frac{Y-55}{303.5}$$

$$\text{Percentage Error} = \frac{\delta}{y} \times 100\% < 1\%$$

By solving above equation, we have,

$\therefore$ Y < 414 cm.

Therefore, the maximum rebound height should be over 414cm to exceed the 1% error limit. All the rebound height measurements were below 85cm. Therefore, the reading taken directly from the camera could be used for further calculations.

7.2.1 Results and Analysis of the bounce test for the Pitch model

The bounce test was first done for both MU and TY soils. After six days, large cracks opened up in TY making the surface unfit to play. At the same time MU showed less bounce due to high moisture content sustained throughout the testing period.

Then the bounce test was restarted after loosening and compacting again of the soil. Then MU was tested along with MT. Rebound height of MU was more than that of MT after few days. In the analysis of results, maximum and average rebound heights vs days of testing were plotted after normalizing with moisture content and energy given in daily compaction.

Bounce test for the pitch model was done in two stages. In the 1st stage MU and TY was compared. Optimum MC% was maintained at the 1st stage.

Table 7.1 Average Ball bounce of the Hockey ball for Pitch Model

Hockey ball			
Average Bounce (cm)			
Day	TY	MU	MT
1	45.30	19.50	-
2	49.60	19.05	-
3	46.75	29.10	-
4	55.0	39.30	-
5	58.21	41.95	-
6	57.53	48.10	-
11	-	32.55	21.38
12	-	43.15	22.70
13	-	41.30	21.63
14	-	56.6	43.3
15	-	64.0	47.1
16	-	61.0	49.9
17	-	65.8	48.7
18	-	60.8	44.8

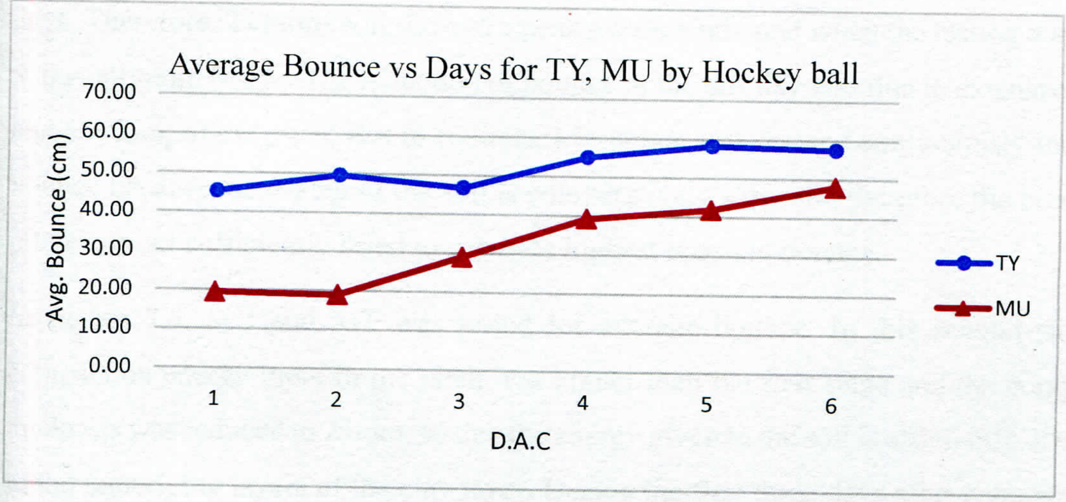


Figure 7.5 Avg. Bounce Vs Days of TY, MU for HB

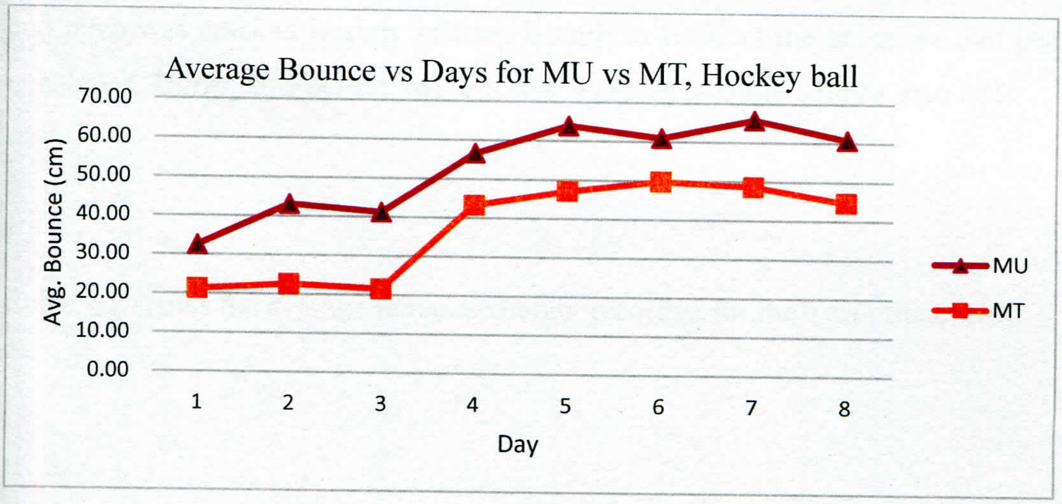


Figure 7.6 Avg. Bounce Vs Days of MU, MT for HB

In Figure 7.5, average bounce is plotted against the days after compaction for MU and TY for the hockey ball. The pitch was sprinkled in the first day and was allowed to dry in the following days. Before commencing the pace and bounce tests, model pitch was watered to have the optimum moisture content of both soils. (i.e. optimum MC% of Murunkan and Tyronne are 19% and 30% respectively.) Tyronne soil showed a steady increase in average bounce for five days and then in the sixth day, the bounce was decreased. At the same period, Murunkan soil had an increasing average bounce for all six days a within those six days. Therefore, Tyronne soil showed a peak average rebound when the testing was started at the optimum MC%. The reduction of bounce in the last day was due to extensive drying and cracking of the pitch. But in contrast, Murunkan soil showed continuously increasing bounce because the drying of the soil is comparatively slow and therefore the crust of the pitch was not sufficiently dried to generate highest possible bounce.

In Figure 7.6, MU and MT was tested for average bounce. In this second stage, the compaction energy input to the pitch was higher than the first stage and the compact lift thickness was reduced to 25mm, so that the energy given to the soil is efficiently distributed to the underlying layers of the clay layer. During the first three days after compaction the pitch was watered and therefore, average bounce does not increase as expected. Then, after third day onwards, the pitch was allowed to dry and the average rebound height was improved considerably and eight days after ompaction, the average bounce was reduced and pitch was cracked heavily making it unfit to conduct the game, so that testing was concluded. During this period, MU showed a higher average bounce than MT.

Table 7.2 shows the average rebounce height recorded for the Test cricket ball.

Table 7.2 Average rebound values of the Test cricket ball for PM

Average Bounce (cm)			
Day	TY	MU	MT
1	46.10	21.65	-
2	40.80	21.55	-
3	38.8	24.95	-
4	42.20	40.25	-
5	63.35	41.90	-
6	62.55	44.65	-
11	-	36.83	22.35

12	-	44.10	20.85
13	-	40.23	25.55
14	-	59.9	39.1
15	-	62.8	44.5
16	-	67.7	47.3
17	-	73.3	53.1
18	-	71.4	48.0

Figure 7.7 and Figure 7.8 show the variation of rebound heights in each day for three pitches.

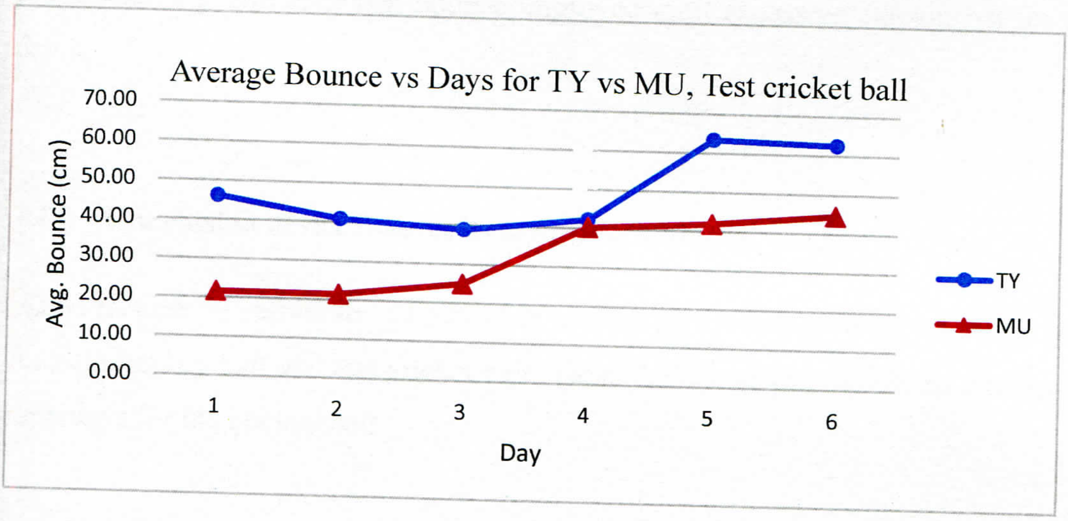


Figure 7.7 Average Bounce vs Days for TY vs MU with high MC%, Test cricket ball

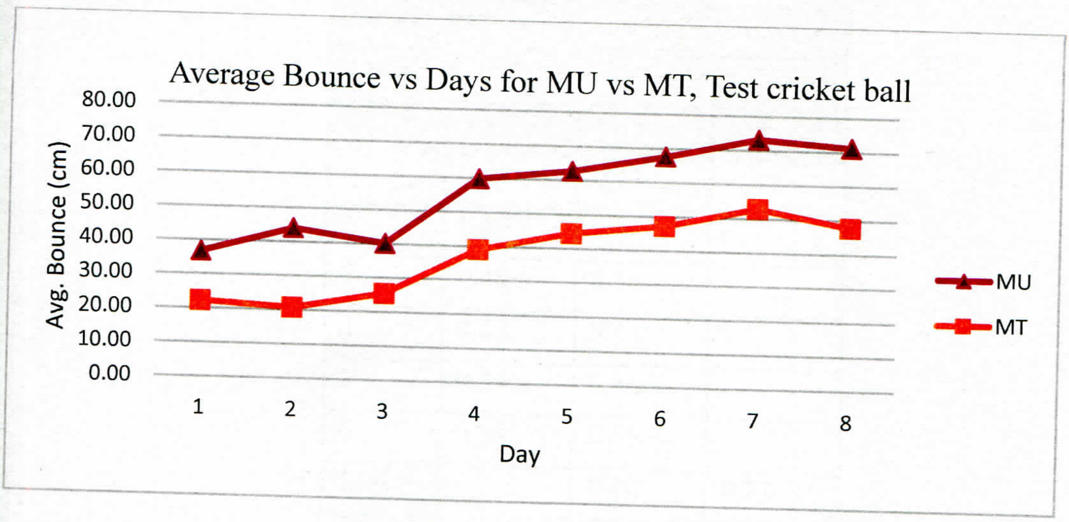


Figure 7.8 Average Bounce vs Days for MU vs MT, Test cricket ball

In Figure 7.7 and Figure 7.8, average bounce test results are plotted for the test cricket ball. In the Figure 7.7, there was a continuous improvement on average bounce for MU while TY shows a peak average bounce on the 5th day and then decrease with the drying and cracking of the pitch. The rebound values were lower for MU than TY for the test cricket ball as well. In Figure 7.8, Average bounce results were plotted for MU and MT for test cricket ball. In these results, MU has a higher average bounce than MT throughout the period. In the first two days after compaction, rebound height increase was very small due to the watering, and after that bounce improved until excessive cracking of the pitch on day 8.

7.2.2 Conclusion of the Bounce Test for Pitch Model

In this section, the results and variations of coefficient of restitution (e) values are presented for both hockey ball and test cricket ball. Table 7.3 shows the calculated average e value with days for the hockey ball.

Table 7.3 Average e value for Hockey ball

Hockey ball			
e value			
Day	TY	MU	MT
1	0.48	0.31	-
2	0.50	0.31	-
3	0.48	0.38	-
4	0.52	0.44	-
5	0.54	0.46	-
6	0.54	0.49	-
11	-	0.40	0.33
12	-	0.46	0.34
13	-	0.45	0.33

14	-	0.53	0.47
15	-	0.57	0.49
16	-	0.55	0.50
17	-	0.57	0.49
18	-	0.55	0.47

Figure 7.9, Figure 7.10 and Figure 7.11 show the variation of the avg. e value with days or the hockey ball.

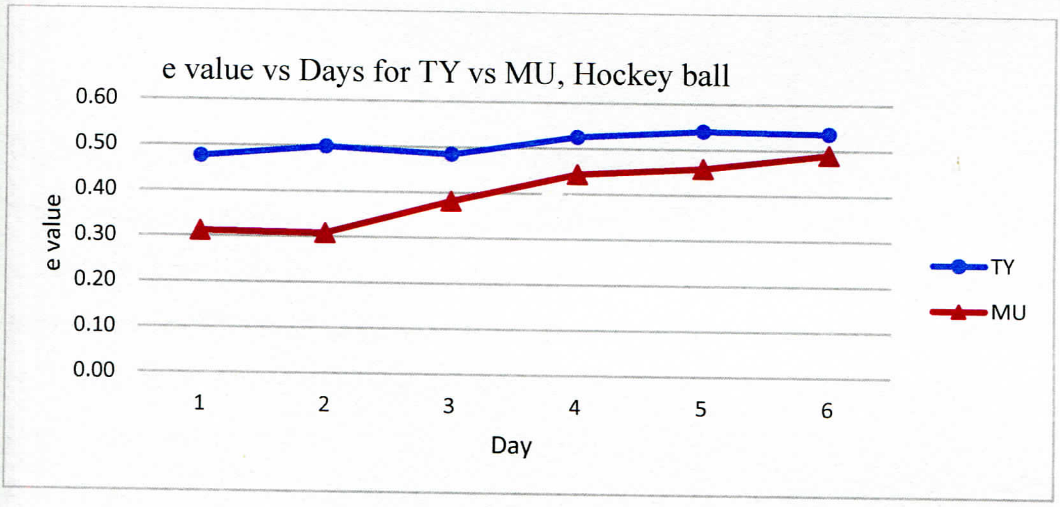


Figure 7.9 e value vs days for TY and MU (high MC%) for hockey ball

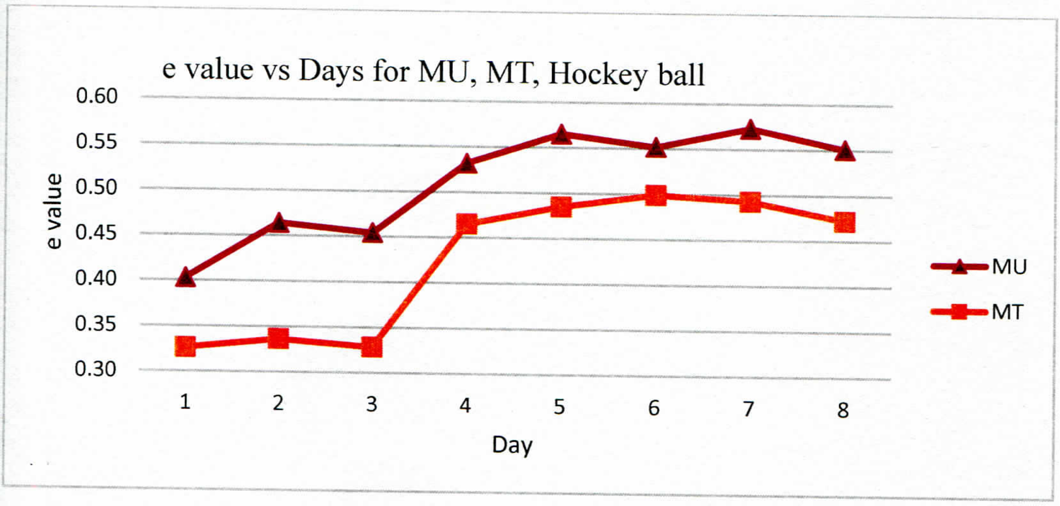


Figure 7.10 e value vs days for MU and MT for hockey ball

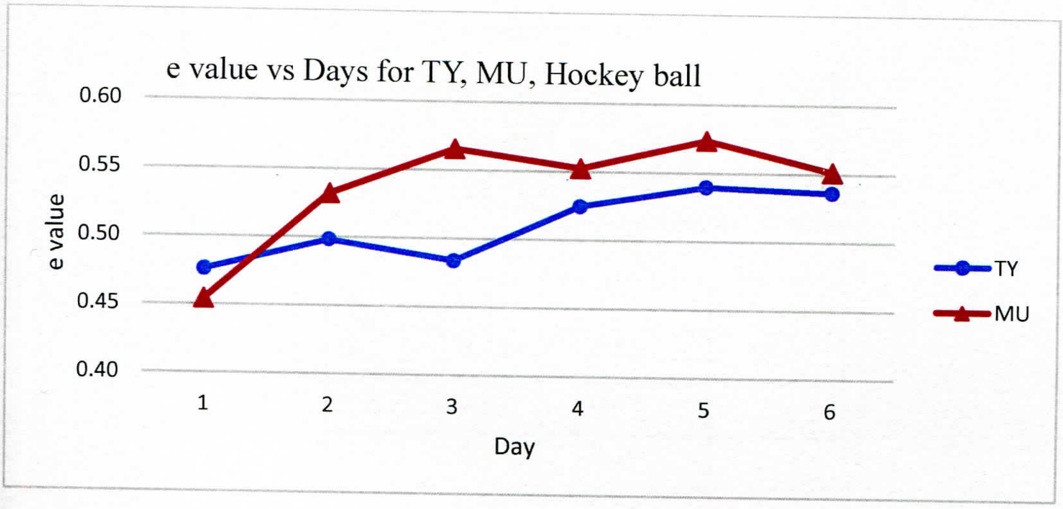


Figure 7.11 e value vs days for TY and MU for hockey ball

The e value vs days after compaction for hockey ball between MU and TY, MU and MT shows the same variation as the average bounce graphs. In the final graph, e value vs days are plotted for TY (first stage) and MU (first six days of second stage) in the same chart. MU with high compaction energy input has a higher e value than TY with a lower compaction energy input.

Table 7.4 Avg e value for Test cricket ball

Test cricket ball			
Average e value			
Day	TY	MU	MT
1	0.54	0.35	-
2	0.48	0.35	-
3	0.48	0.39	-
4	0.56	0.49	-
5	0.59	0.50	-
6	0.58	0.52	-
11	-	0.48	0.38
12	-	0.50	0.37
13	-	0.49	0.39
14	-	0.58	0.50
15	-	0.59	0.52
16	-	0.60	0.51
17	-	0.63	0.57
18	-	0.62	0.54

Figure 7.12, Figure 7.13 and Figure 7.14 show the variation of average e values calculated for each pitch, tested on each day.

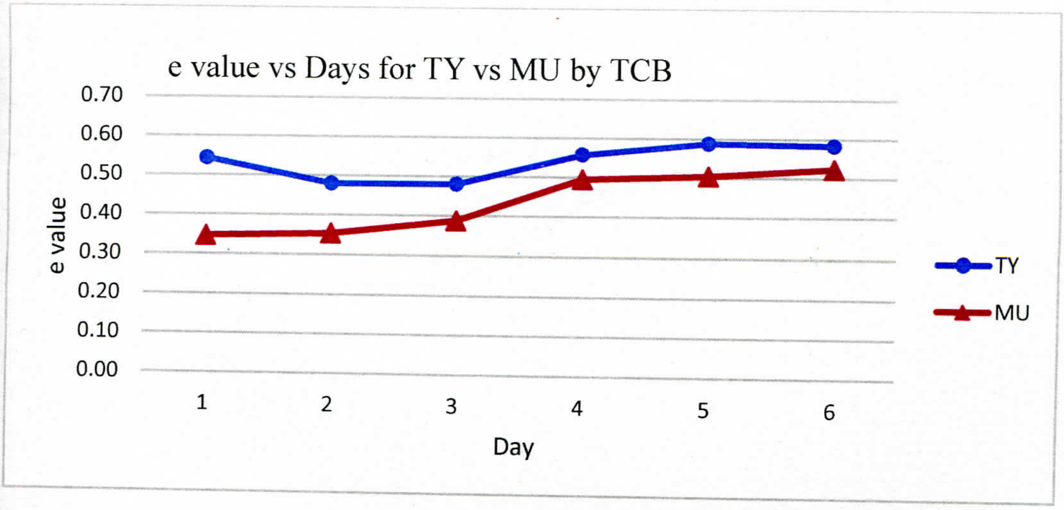


Figure 7.12 e value vs days for MU (High MC%) and TY for test cricket ball

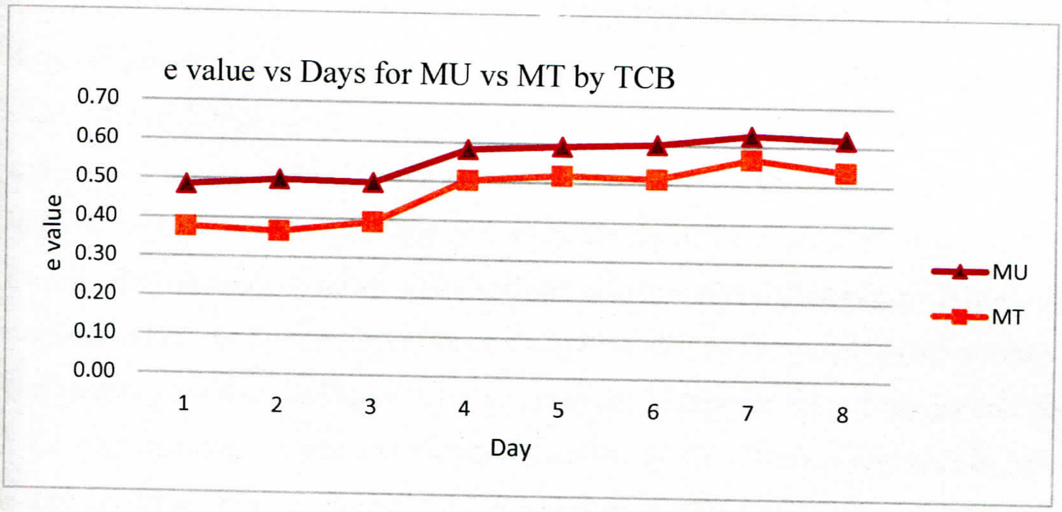


Figure 7.13 e value vs days for MU,MT for the test cricket ball

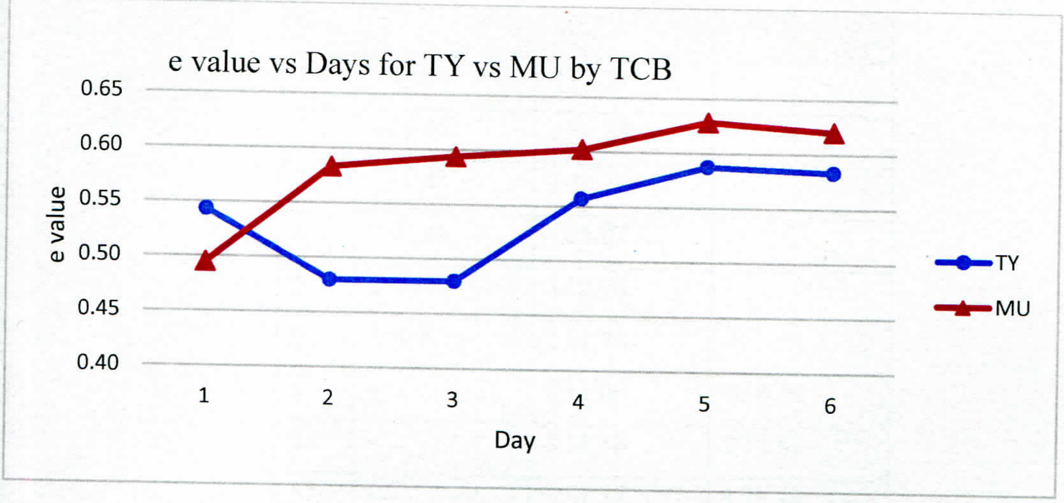


Figure 7.14: e value vs Days for TY and MU for the test cricket ball

The e value vs days after compaction graphs for test cricket ball between MU and TY, MU and MT shows the same variation as the average bounce graphs. In Figure 7.14, e value vs days are plotted for TY (first stage) and MU (first six days of second stage) in the same chart. MU with high compaction energy input has a higher e value than TY with a lower compaction energy input. The reason due to lower e value (rebound height) in MU in first stage is the high moisture content prevailed during that period. Due to the high moisture content, the soil tends to shrink and swell and also the compaction energy is not sufficiently distributed into the bottom layers since the rollers slip on the moist clayey surface without compressing the soil. In Figure 7.14, e values are higher for MU of the second stage than TY of the first stage. Optimum moisture content of TY (30%) is higher than MU (19%), but in the drying process the swelling and shrinkage effect of TY is very less compared to MU therefore, soil layers get compacted well with higher moisture contents. (Puppala, et al., 2013)

During the two stages, different amounts of energy were applied to the pitch. In the above graphs, average rebound height was plotted after normalizing by percentage change in applied compaction energy (%Δ AE)

Table 7.5 Average Bounce / % change in applied energy for HB of PM

Hockey ball
Average Bounce / % change in Applied energy (cm)

Day	TY	MU	MT
1	759.91	327.12	-
2	416.02	159.78	-
3	261.41	162.72	-
4	230.66	164.82	-
5	195.30	140.74	-
6	160.83	134.48	-
11	-	791.00	519.44
12	-	524.30	275.82
13	-	334.55	175.17
14	-	344.05	263.12
15	-	310.81	229.04
16	-	247.16	202.06
17	-	228.52	169.15
18	-	184.77	135.94

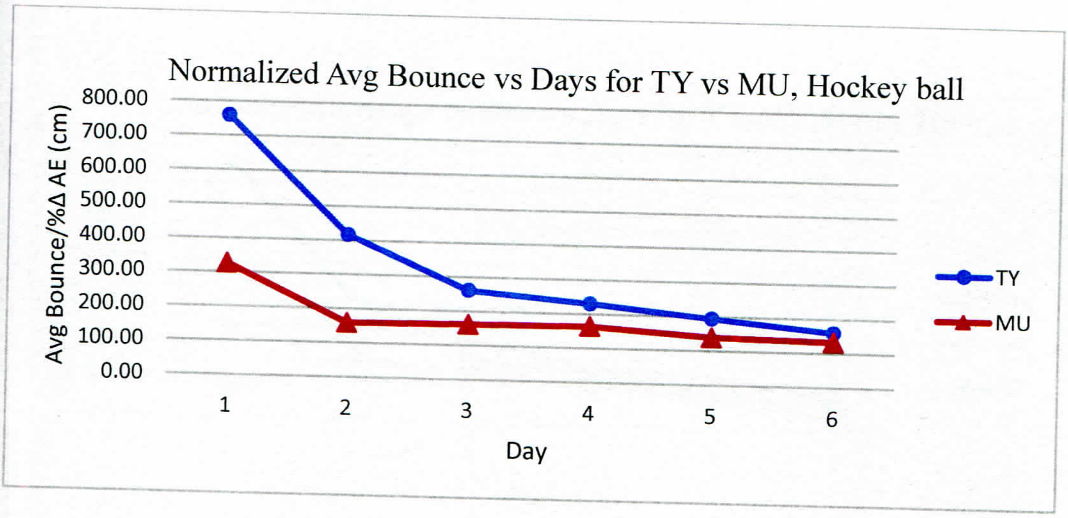


Figure 7.15 Avg. bounce normalized with applied compaction energy vs days for MU(high MC%) ,TY - Hockey ball

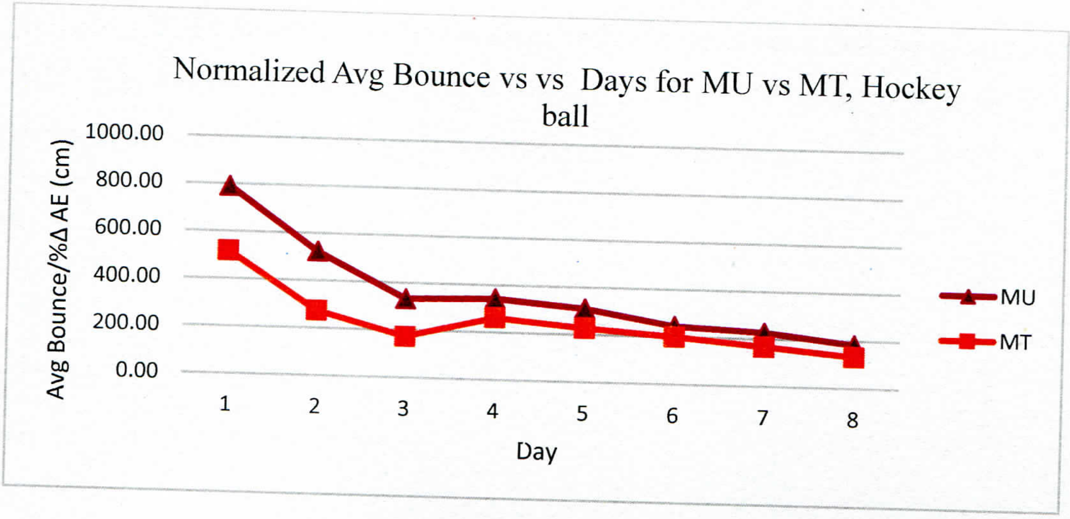


Figure 7.16:Avg. bounce normalized with applied compaction energy vs days for MU, MT -Hockey ball

During the first six days TY had a higher average rebound height than MU and during the second stage MU improved than MT. Fo comparison purposes, TY of first stage is plotted with MT and MU from third day onwards after compaction. The reason for omitting the first three days' results of MU and MT is sprinkling of the pitch during those two days.

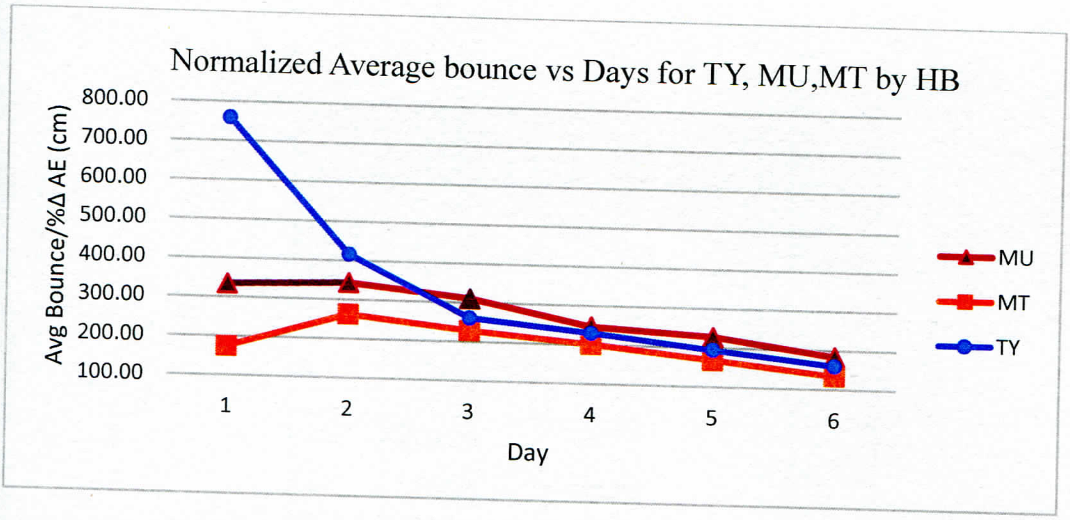


Figure 7.17:Avg. bounce normalized with applied compaction energy vs days for TY, MU,TY-Hockey ball

In Figure 7.17, TY has a higher average rebound height during the first two days because the applied energy during first stage was relatively less than the compaction given to MU and MT during the second stage. But after that the applied energy for MU is high so that the avg. bounce divided by daily increase in applied energy ratio is highest for MU than

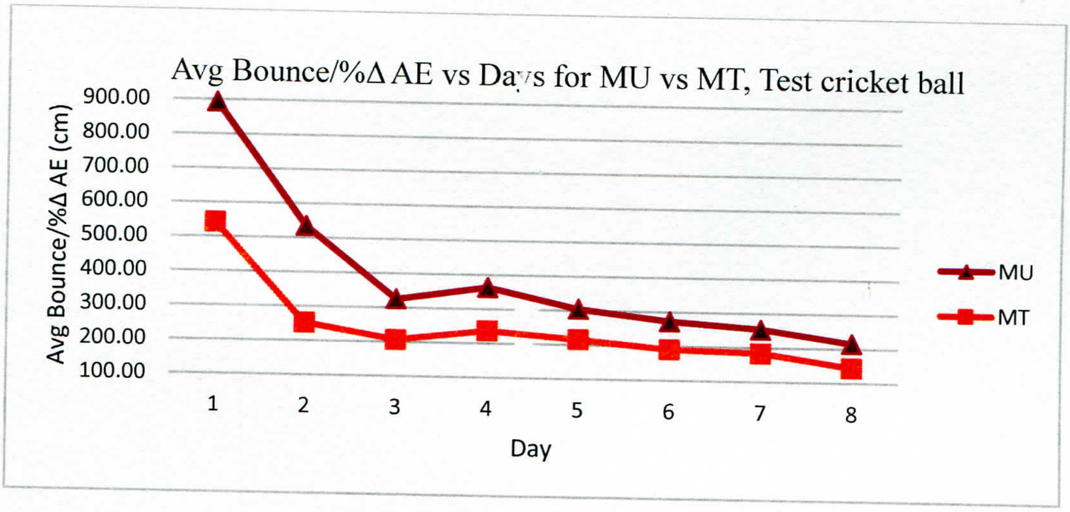
MT and TY. TY has the next best normalized average bounce and the mixture of TY and MU (MT) has the lowest normalized average bounce. All the three soils show a gradual decrease in normalized average bounce towards 5th,6th days.

Table 7.6 Average Bounce / % change in applied energy for TCB of PM

Test cricket ball			
Average Bounce / % change in Applied energy (cm)			
Day	TY	MU	MT
1	773.33	363.18	-
2	342.21	180.75	-
3	216.96	139.51	-
4	176.98	168.80	-
5	212.54	140.58	-
6	174.88	124.83	-
11	-	894.89	543.13
12	-	535.84	253.34
13	-	325.84	206.97
14	-	363.72	237.58

15	-	305.22	216.40
16	-	274.20	191.75
17	-	254.56	184.17
18	-	216.89	145.88

Figure 7.18:Avg. bounce normalized with applied compaction energy vs days for MU, TY-Test cricket ball



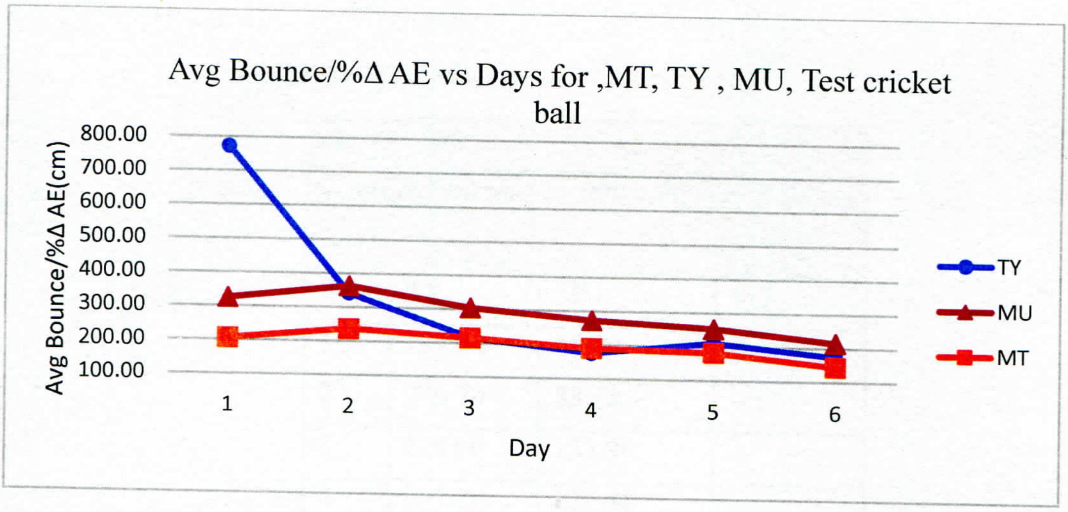


Figure 7.19:Avg. bounce normalized by applied compaction energy vs days for MT, MU,TY-Test cricket ball

Via the Figure 7.18 and Figure 7.19 for test cricket ball also, it can be noted that variation of average bounce is very similar to the variations in hockey ball. MU has had the highest average bounce (normalized by percentage change in applied energy) after the second day of testing.

Table 7.7 Average Bounce / MC% for HB

Hockey ball			
Average Bounce / Moisture content (MC %) (cm)			
Day	TY	MU	MT
1	177.44	85.00	-
2	230.70	88.52	-
3	220.00	135.35	-
4	267.77	222.41	-
5	289.46	262.84	-
6	286.48	471.57	-
11	-	141.03	90.76
12	-	174.63	92.96
13	-	156.86	85.54

14	-	284.87	215.80
15	-	321.52	278.35
16	-	377.40	520.76
17	-	763.63	523.92
18	-	1156.37	727.64

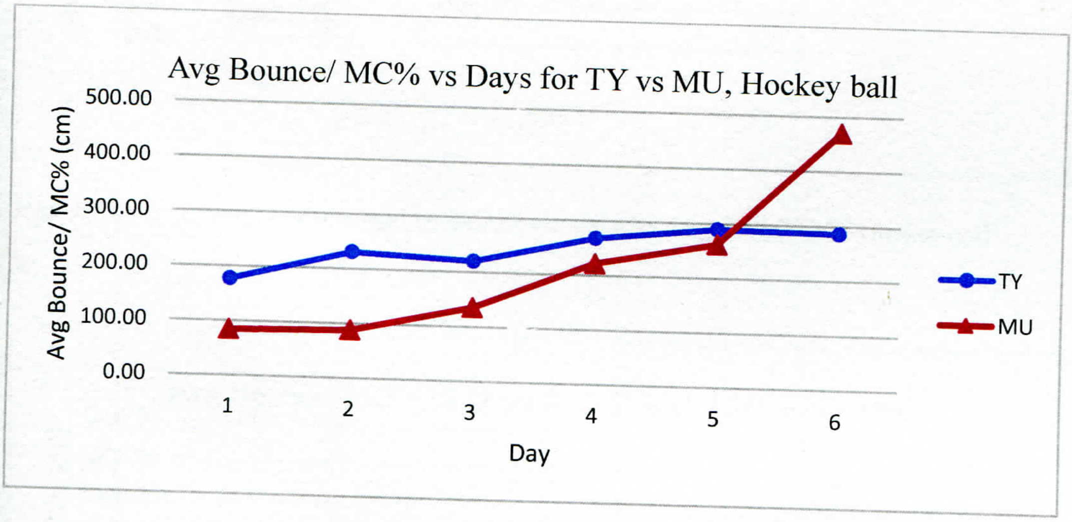


Figure 7.20 Avg. bounce normalized by moisture content vs days for MU (high MC%),TY-Hockey ball

Figure 7.20 shows the average rebound heights modified with the top surface moisture content vs days of testing for the hockey ball. In the first 3-4 days, TY had a higher normalized average bounce even maintaining a higher moisture content while MU showed a lesser value even sustaining a lower moisture content. But after day 5, MU soil has improved drastically over TY which maintained a steady variation over that period. The reason for this improvement is the decrease in moisture content of MU at the crust of the pitch which induced more rebound height. Therefore the normalized value increases due to both factors which cause steep increase in the graph.

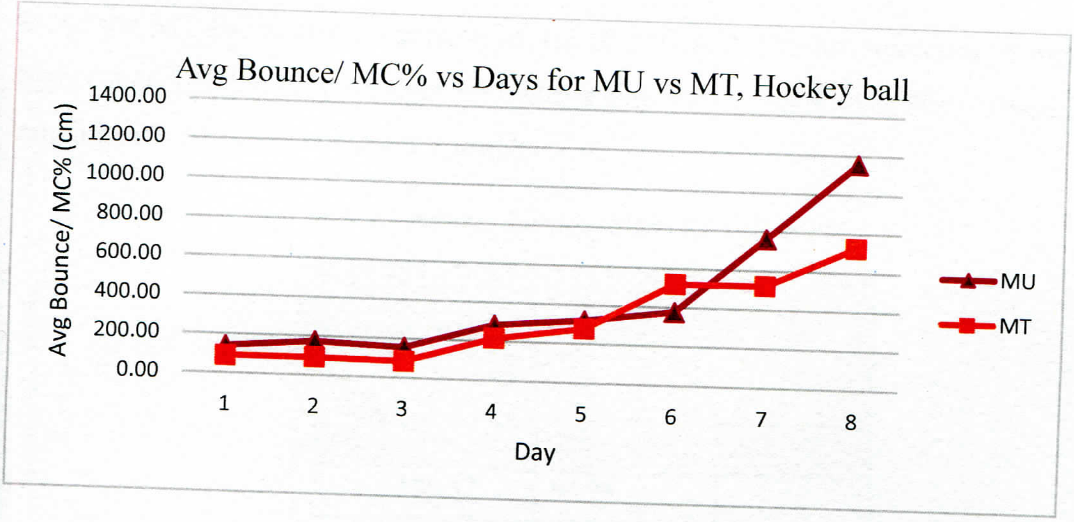


Figure 7.21 Avg. bounce normalized by moisture content vs days for MU,MT-Hockey ball

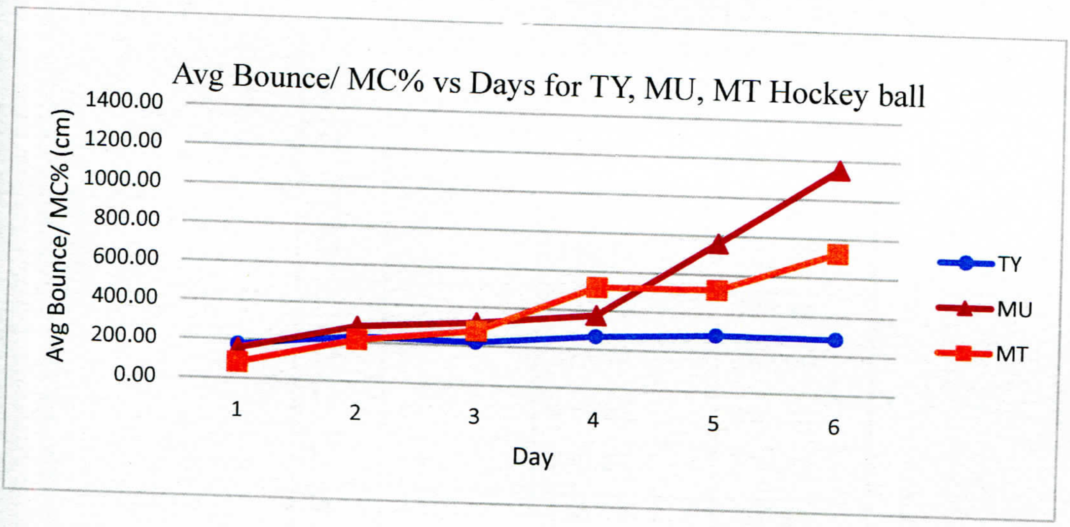


Figure 7.22 Avg. bounce normalized by moisture content vs days for MU,MT-Hockey ball

The steep increase of the normalized average bounce in MU can be identified in the Figure 7.21 and Figure 7.22 as well. The average bounce increased during those days while the moisture content also dropped simultaneously. The testing was concluded after day 6 of the above graph due to extensive cracking and drying of the model pitch surface.

TY has the lowest average bounce (normalized with m/c) for most of the days of testing due to its' high moisture content and the capability of retaining more water than MU.

When the pitch starts to dry more and more, the bounce is improved in MU, but during that period, the soil is vulnerable for cracking as well.

Since the MT has a mix proportion of 1:1 of MU and TY, the retention of moisture is higher than TY, but is lower than MU with a clay content as high as 80%. Therefore, MT graph lies in between Mu and TY graphs.

Table 7.8 Average Bounce / MC% for TCB of PM

Test cricket ball			
Average Bounce / Moisture content (MC %) (cm)			
Day	TY	MU	MT
1	180.57	94.38	-
2	189.77	100.14	-
3	182.59	116.05	-
4	205.45	227.79	-
5	315.02	262.53	-
6	311.50	437.75	-
11	-	159.55	94.90
12	-	178.47	85.38
13	-	152.77	101.07
14	-	301.15	194.84
15	-	315.74	262.99
16	-	418.68	494.18
17	-	850.64	570.43
18	-	1357.41	780.89

Following graph was drawn by the data from the Table 7.8

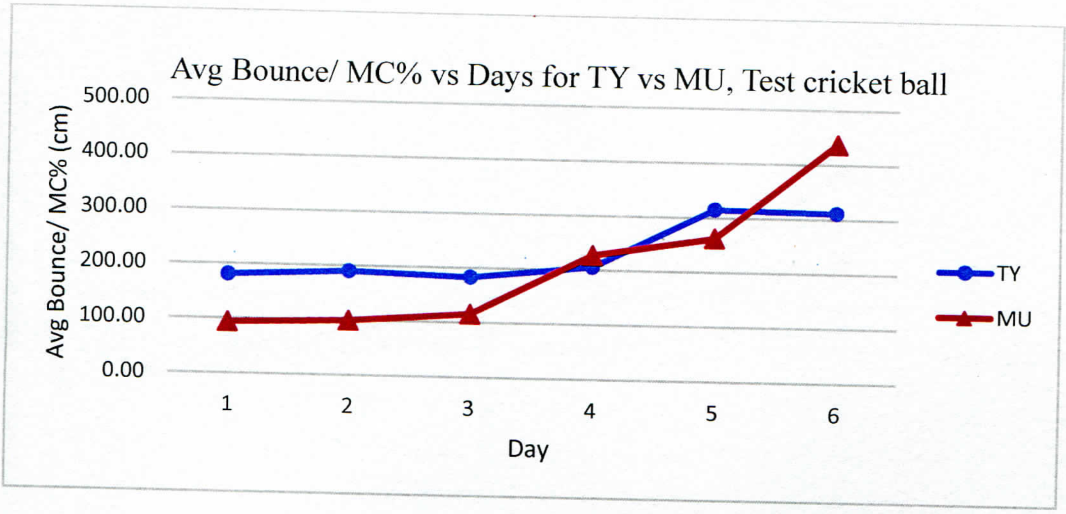


Figure 7.23 Avg. bounce normalized by moisture content vs days for MU, TY-Test cricket ball

Results for the test cricket ball have some similar variations when compared to average bounce results for the hockey ball. T ′ soil produces more average rebound height than MU up to day3 and then the results are almost similar for day 4. After day 4, TY has a higher bounce and in the final day of testing, MU passes the average bounce value of TY on that day.

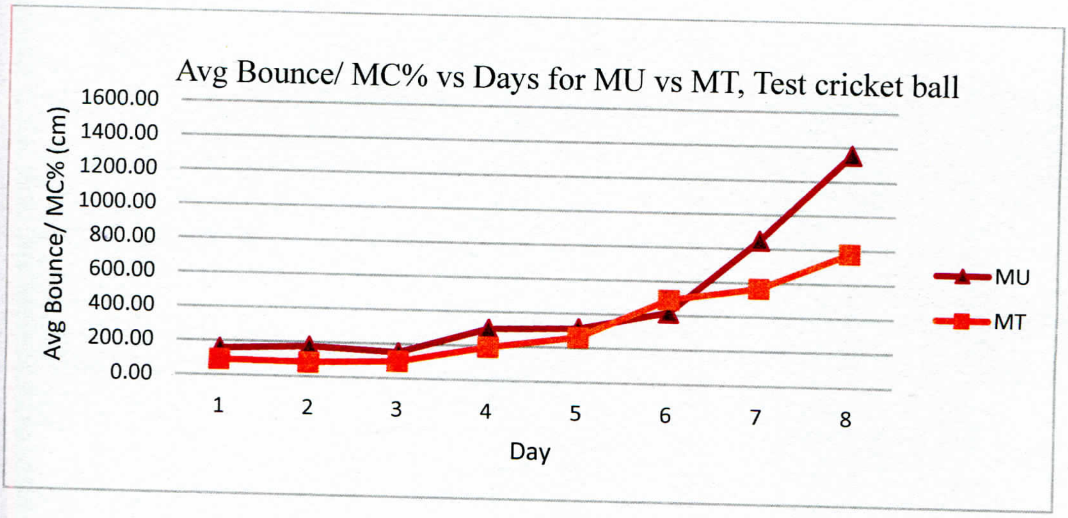


Figure 7.24 Avg. bounce normalized by moisture content vs days for MU,MT-Test cricket ball

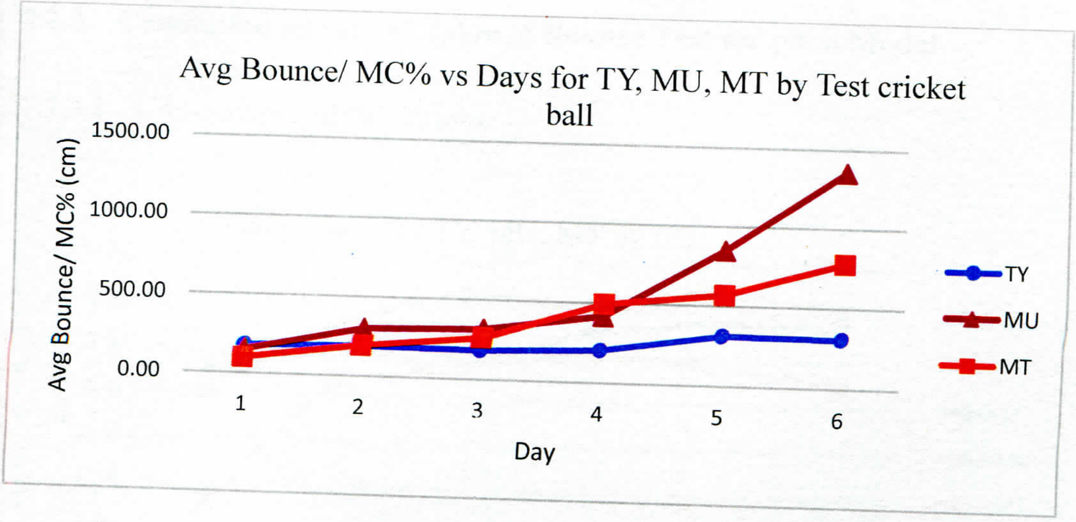


Figure 7.25 Avg. bounce normalized by moisture content vs days for MT, MU, TY-Test cricket ball

Figure 7.25, is plotted with the test data of TY (first stage) and MU, MT (second stage-after final sprinkling of water) for the test cricket ball. Results were very similar to respective graphs for the hockey ball. MU had higher rebound heights in reduced moisture conditions while MT and TY had lower average rebound heights.

7.2.3 Conclusion on the "e" value of Bounce Test for pitch Model

7.2.3.1 Comparison of "e" values

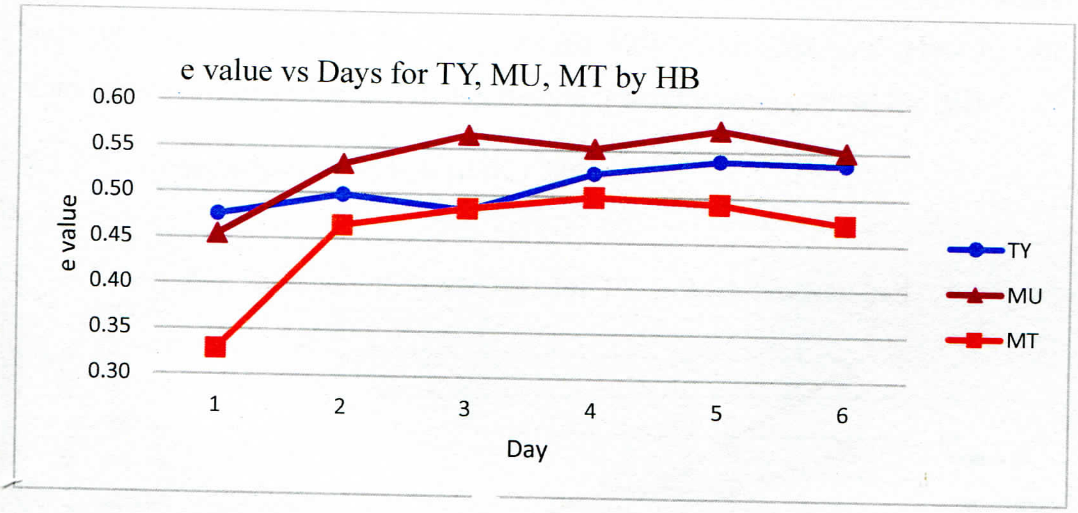


Figure 7.26 e value vs days for TY,MU,MT- hockey ball

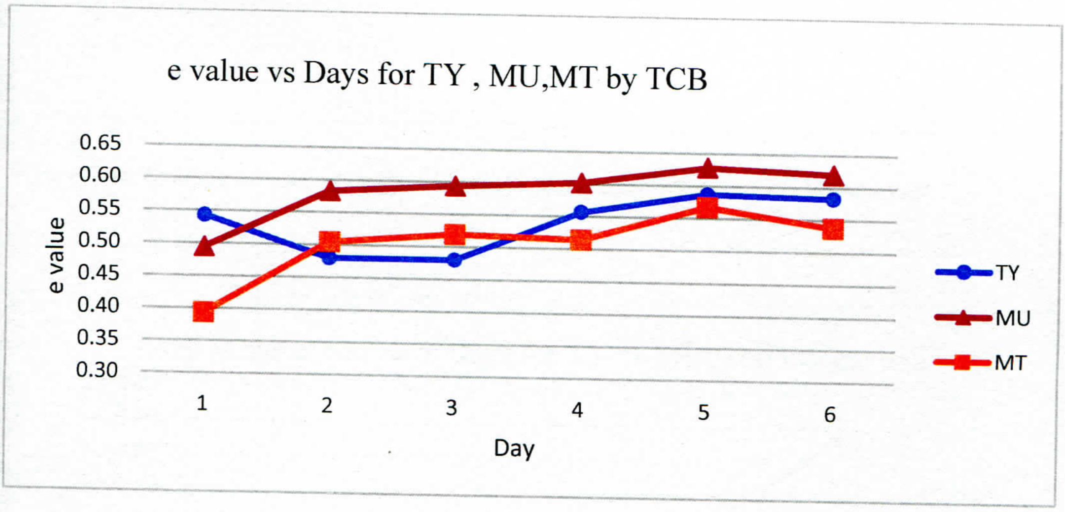


Figure 7.27 e value vs days for TY,MU,MT- Test cricket ball

Figure 7.26 and Figure 7.27 show the variation of coefficient of restitution (e) vs days after compaction for all three soil types and the two graphs represent values for both hockey ball and test cricket ball respectively. For both test cricket ball and hockey ball, MU has the highest e value from day 2 onwards among the three soils that were tested via the model pitch. MT and TY has very closer variation between them throughout the period.

When comparing the two graphs, it can be noted that the e values for the three soils vary in the same pattern for both test cricket ball and hockey ball. Therefore, using hockey ball to investigate the bounce of a cricket pitch can be justified when the effect of seam should be eliminated which is a part of the test cricket ball. The seam of the cricket ball produces more bounce when it is contacted with the pitch in bounce test. Therefore, hockey ball not only allows to simulate the test cricket ball conditions, but also it can recreate homogeneous surface contact by not having a seam woven around the ball.

7.2.3.2 Comparison of Rebound % / MC

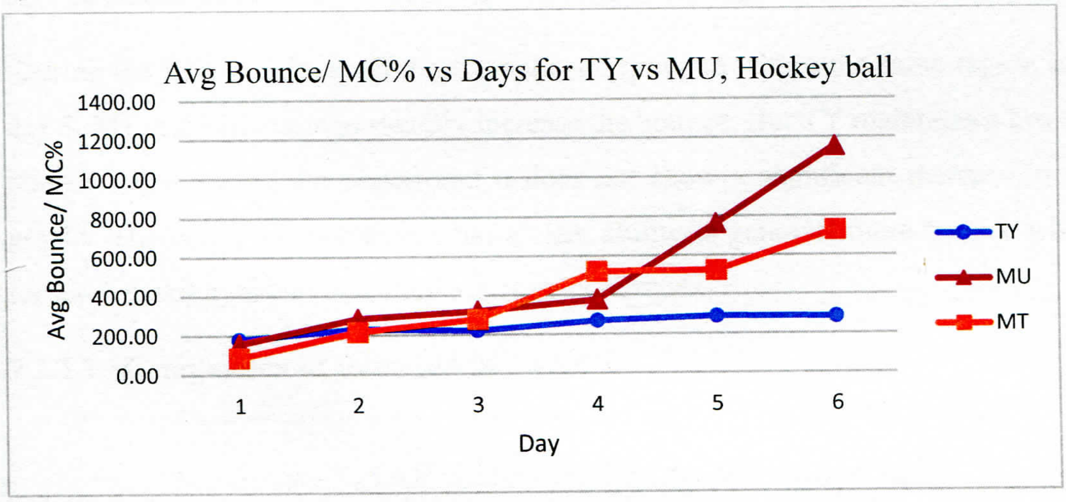


Figure 7.28 Average bounce normalized by m/c vs days for TY,MU,MT- hockey ball

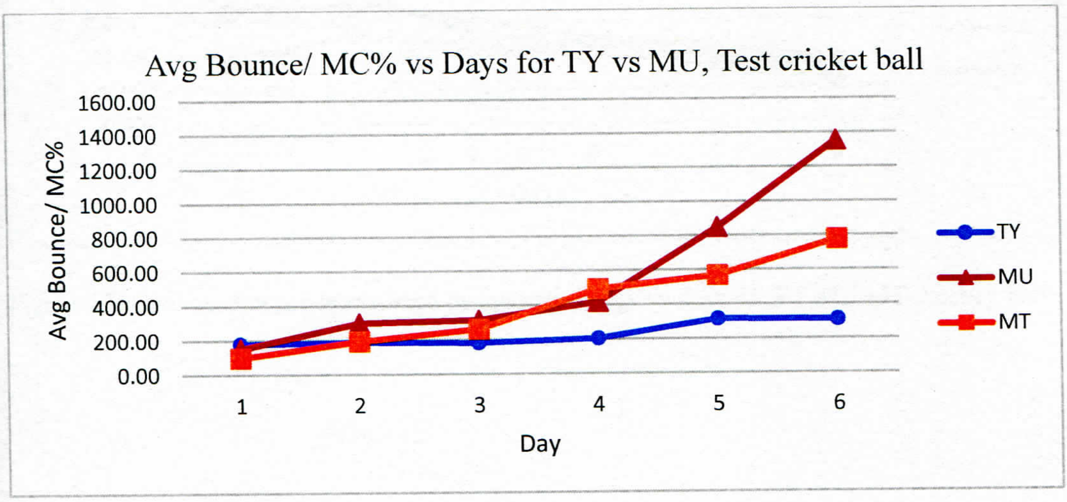


Figure 7.29 Average bounce normalized by m/c vs days for TY, MU, MT- test cricket ball

When comparing Figure 7.28 and Figure 7.29, both test cricket ball and hockey ball provides similar variation for all three soils. Due to very low moisture conditions, MU shows improvement in average bounce data normalized with m/c. But during those days of testing (Day 5, 6) the crust of the pitch (topmost layer) dried up to moisture contents about 9% - 10% while TY had a moisture content of about 15% during the same period. Therefore, average bounce results normalized with the moisture content exaggerate the bounce results obtained during the last two days of testing.

During the first two days, all three graphs are grouped within the same region and after day 3, MT and MU starts to steadily increase the bounce. But TY maintains a low average bounce value during the period and it does not show a significant increase in the two graphs. Therefore, Murunkan soil has a clear ability to generate more bounce when used for pitch making under controlled n oisture conditions.

7.2.3.3 Comparison of Rebound % / ΔAE%

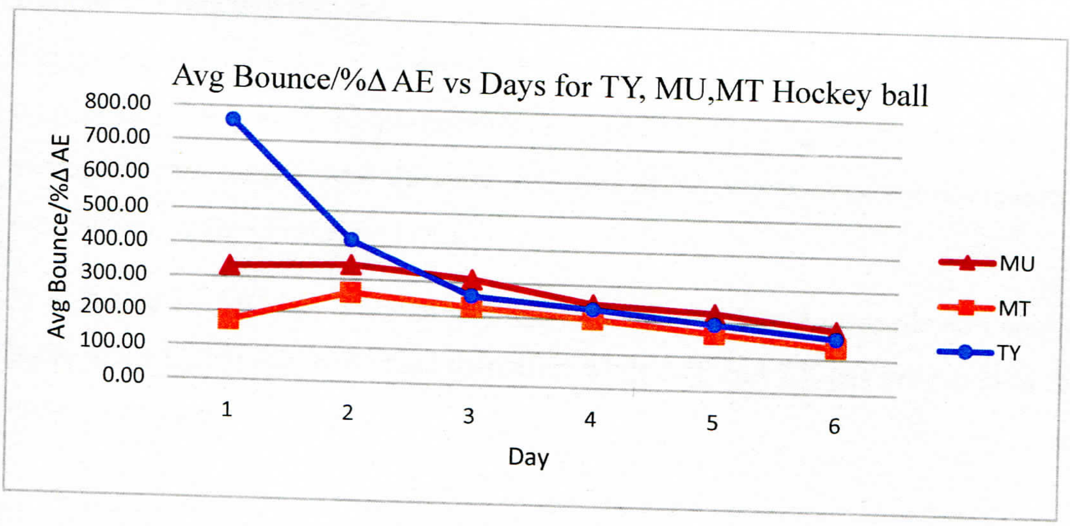


Figure 7.30 Average bounce normalized by applied energy vs days for TY,MU,MT- hockey ball

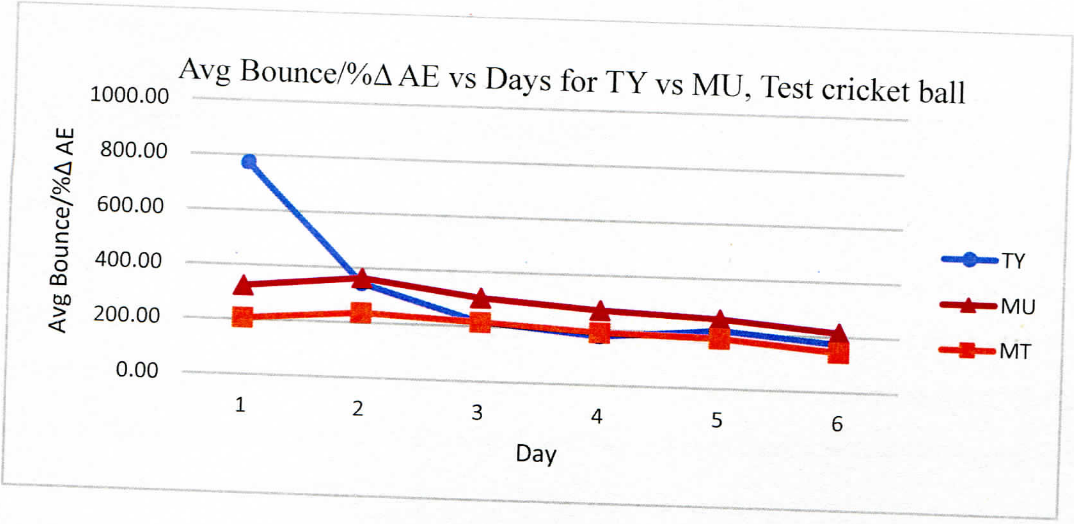


Figure 7.31 Average bounce normalized by applied energy vs days for TY, MU, MT - Test cricket ball

Figure 7.30 and Figure 7.31 show the variation of average bounce normalized by percentage increase in daily compaction for all three soils. TY soil has a higher bounce index value on the first day because in the first stage the energy given during the compaction was less than the second stage where MU and MT soils were compacted with a higher compaction energy. After day 2 onwards, only the light roller was used with same number of roller passes for all the soils on each day of testing. Therefore, the normalized average bounce results show the same variation as the raw average bounce results (before normalizing with compaction energy).

In both graphs, MU has a higher average bounce after day 3 onwards and continuously maintains a higher rebound value thereafter while MT and TY has very similar results in terms of bounce.

7.3 Pace test

7.3.1 High Speed Video (HSV) recording

iPhone 6s was used for video recording. The SLO-MO (Slow motion) feature of the phone records a video in 240fps which cannot be achieved by a DSLR camera. Since approximately there is a one frame in each 4 milliseconds the quality of the video recording was up to high standards and also the error in time measuring was minimum. Camera was kept at the same point as the bounce test and the camera range was set to cover the whole range in between two poles.

Figure 7.32 iPhone 6s used in the field tests

7.3.2 Video analysis for the Pace test

Camera was set at the camera point (Figure 6.17) and SLO-MO mode was activated 3 seconds before releasing the 1st ball. Signal was given by the cameraman and the baller started to ball until three good deliveries were captured from a particular soil section and a particular ball. Video was continuously recorded throughout about 50 ball passes per day. A new ball, 30 overs used ball and a 60 overs used ball was used for pace test in different ball conditions. Balls trajectories which were aligned with the center line of a particular soil were taken for the calculations neglecting the bad ball bounces due to major crack openings.

Then the video was imported to Adobe Premier Pro software for further analysis.

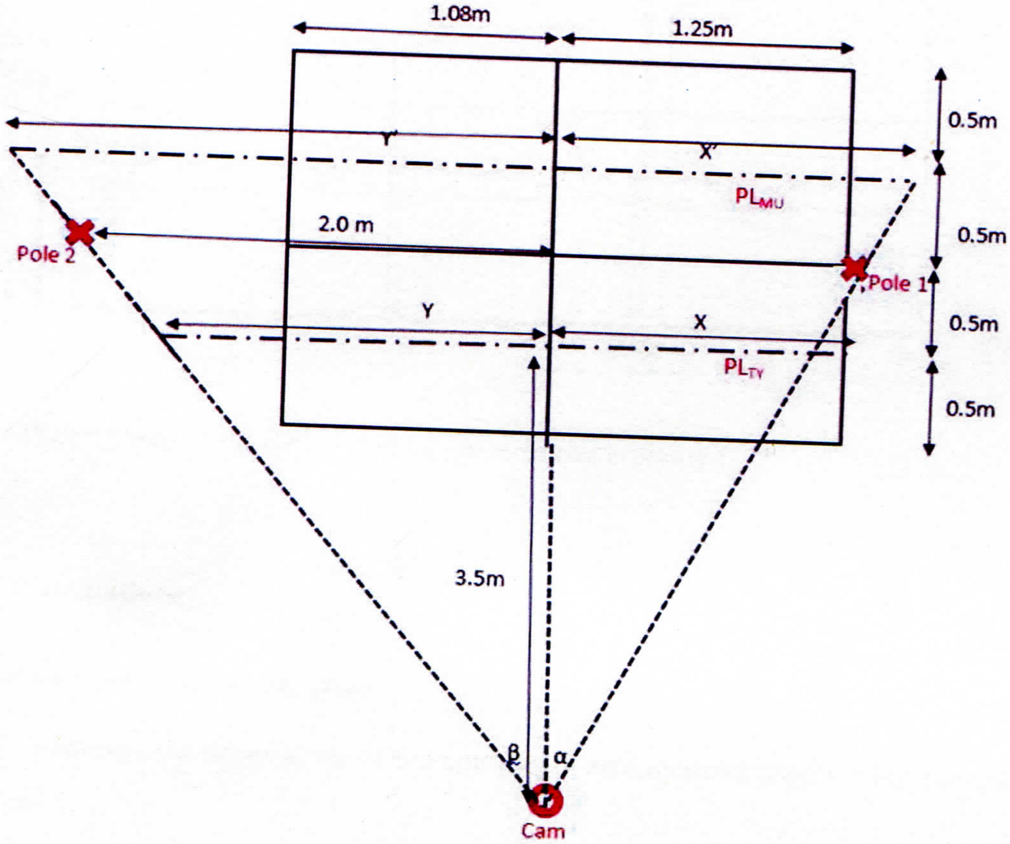


Figure 7.33 Corrections for the horizontal distance measurements in pace test

7.3.3 Videography for pace test

Ball movement starting from the pole at the bowlers' end to the ground and from the ground to passing the pole at wicket keepers' end was continuously recorded by Apple iPhone 6s. Camera was kept 3.5m from the ball pitching line of TY soil and at a height of 55cm from the ground level. Over 25 deliveries were recorded for a one soil section per one day. The deliveries with high deviations in trajectory was neglected which happened due to cracks and due to the seam-pitch interaction.

One person bowled the deliveries and it was ensured that the ball is pitched in the middle area of the model pitch during deliveries.

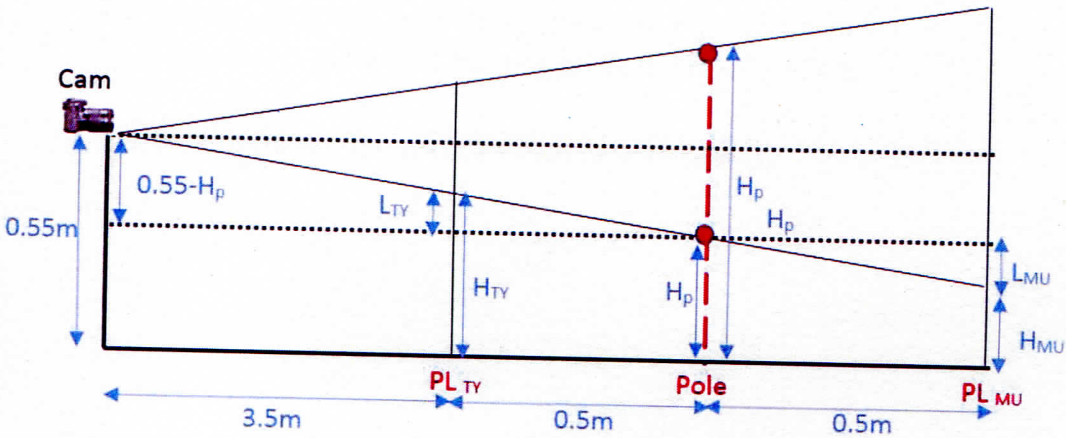


Figure 7.35 Corrections for the vertical distance measurements in pace test

7.3.4 Calculations

7.3.4.1 Calculations for the pace

Figure 7.34 shows the dimensions of the equipment arrangement used for the calculations for the pace.

Following steps were followed for the calculations.

- Corrections for the horizontal distance measurements

Ball pitching line and poles were not in the same vertical plane. Therefore following corrections were done in **horizontal distance measurements**.

$$tan\alpha = \frac{X}{3.5} = \frac{1.25}{4} = \frac{X'}{4.5}$$

$$tan\beta = \frac{Y}{3.5} = \frac{2.00}{4} = \frac{Y'}{4.5}$$

$$\therefore X = 1.094\ m, X' = 1.406\ m, Y = 1.750\ m, Y' = 2.250\ m$$

$X + Y = 2.844\, m\,,\ X' + Y' = 3.656\, m$

Total corrected length between two poles in PL_{TY}=2.844m
Total corrected length between two poles in PL_{MU}=3.656m

- Corrections for the **vertical distance measurements**

$$\frac{0.55 - Hp}{4} = \frac{LTY}{0.5} \Rightarrow LTY = \frac{55 - Hp}{8}$$

$$H_{TY} = LTY + Hp = \frac{0.55+7Hp}{8}$$

$$\frac{0.55 - Hp}{4} = \frac{LMU}{0.5} \Rightarrow LMU = \frac{55 - Hp}{8}$$

$$H_{MU} = Hp - LMU = \frac{9Hp-0.55}{8}$$

Error was caused due to the pole and the ball pitching lines were not in the same plane. Therefore corrections were made for all vertical ball bounces indicated by the pole

1. Time in milliseconds was recorded from the timeline when the ball passed two poles and at the pitching spot (T_{In}, T_p, and T_{Out}). Then the time taken by the ball to travel pre-bounce distance and post-bounce distances were calculated as $T_1 = T_p - T_{In}$ and $T_2 = T_{Out} - T_p$ respectively.
2. Pitching spot was measured using a virtual ruler keeping the zooming as 150% and the pitching distance was calculated using the ratio method as following.

Example for the MU Day 1, 60 overs used ball, 1st ball

T_{In} = 436.508 ms, T_p = 436.562 ms, T_{Out} = 437.754 ms

$T_1 = T_p - T_{In}$ = 54 ms, $T_2 = T_{Out} - T_p$ = 192 ms

Distance measured from the X=0 line	=	5mm
Distance from X=0 axis to positive end	=	67mm
Pitching distance from X=0 line	=	$\frac{1250}{67} \times 5 = 97.66mm$
Pre-bounce distance (D_{In})	=	1250-98 = 1152 mm

Post-bounce distance (D_{Out}) = 98+2000 = 2098 mm

3. Pre-bounce horizontal velocity and post-bounce horizontal velocity was calculated as follows

Pre-bounce horizontal velocity (Vx_{in}) = $\frac{\text{D In}}{\text{T 1}} = \frac{1.152m}{0.054s} = 21.33ms^{-1}$

Post-bounce velocity (Vx_{out}) = $\frac{\text{D Out}}{\text{T 2}} = \frac{2.098m}{0.192s} = 10.93ms^{-1}$

4. Pre-bounce vertical velocity and post-bounce vertical velocity was calculated as follows

Vertical heights of the ball measured from the 1st and 2nd poles were taken as H_{in} and

H_{out} respectively.

H_{in} = 392 mm, H_{out} =820 mm

Pre-bounce vertical velocity (Vy_{in}) = $\frac{H\,in}{T1} + \frac{g \times T1}{2}$ = 7.27 ms^{-1}

Pre-bounce vertical velocity (Vy_{out}) = $\frac{H\,out}{T2} + \frac{g \times T2}{2}$ = 4.28 ms^{-1}

5. Pre-bounce kinetic energy (KE_{in}), potential energy (PE_{in}) and post bounce kinetic energy (KE_{out}), potential energy (PE_{out}) was calculated as follows.("m" was the mass of the cricket ball, 156g)

$KE_{in} = \frac{1}{2} \times m \times (Vx\,in^2 + Vy\,in^2)$ = 49.91 J

$KE_{out} = \frac{1}{2} \times m \times (Vx\,out^2 + Vy\,out^2)$ = 13.09 J

$PE_{in} = m \times g \times Hin$ = 0.60 J

$KE_{out} = m \times g \times Hout$ = 1.26 J

6. Total pre-bounce energy (TE_{in}) and post-bounce energy (TE_{out}) was calculated and the difference was the reduction of total energy due to ball impact.

$TE_{in} = KE_{in} + PE_{in}$ = 50.51 J

$TE_{out} = KE_{out} + KE_{out}$ = 14.35 J

7. Percentage reduction of total energy was calculated as follows.

$$\text{T.E red \%} = \frac{(\text{TEin} - \text{TEout})}{\text{TEin}} \times 100\% = 71.59\%$$

Percentage change in horizontal velocity was calculated in the above mentioned manner

7.3.5 Use of different conditions of cricket balls

In this experiment, three balls with three distinct conditions were used for testing of incoming and outgoing pace of deliveries.

Ball 1 : Brand new ball (2 balls for each three days)

Ball 2 : Slightly lacquer removed knocked gently (Representing 30 over old ball)

Ball 3 : Lacquer removed and knocked (Representing 60 over old ball)

Two brand new balls were used for each three days of testing as the ball lost its' shine when knocked onto the pitch continuously. Lacquer removal was done by an experienced coach to replicate the 30 & 60 over conditions of the ball. In the official games, during lost ball situations, umpires tend to select a used cricket ball from the collection of balls kept by them. If the balls do not match with the over played by the lost ball, umpiring officials can artificially change the condition of the ball by removing lacquer as mentioned above.

7.3.6 Results

7.3.6.1 Percentage energy reduction of each pitch (ER%)

After the impact between the ball and the pitch surface the energy of the ball be reduced mainly due to the friction. Therefore the velocity of the ball as well as the rebound height will be decreased according to the conditions of the pitch. The pitch which have the lower value for the ER% will be selected as a good soil for fast and bouncy cricket pitch development.

7.3.6.1.1 Data analysis for the new ball

In stage one the pace test was done for MU and TY only. ER% for the TY and Mu will be shown in Figure 7.36

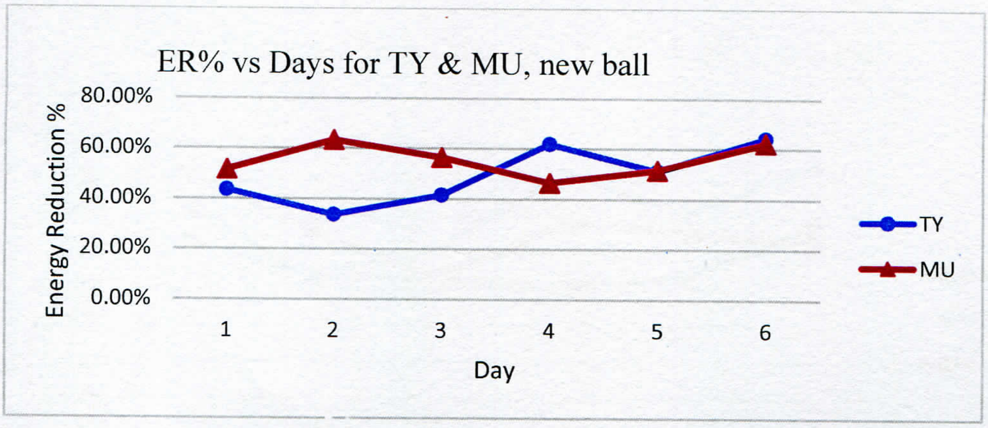


Figure 7.36 Energy reduction percentage for TY &MU, new ball

In stage two the tests were done for MU and MT pitches and the results are shown in Figure 7.37

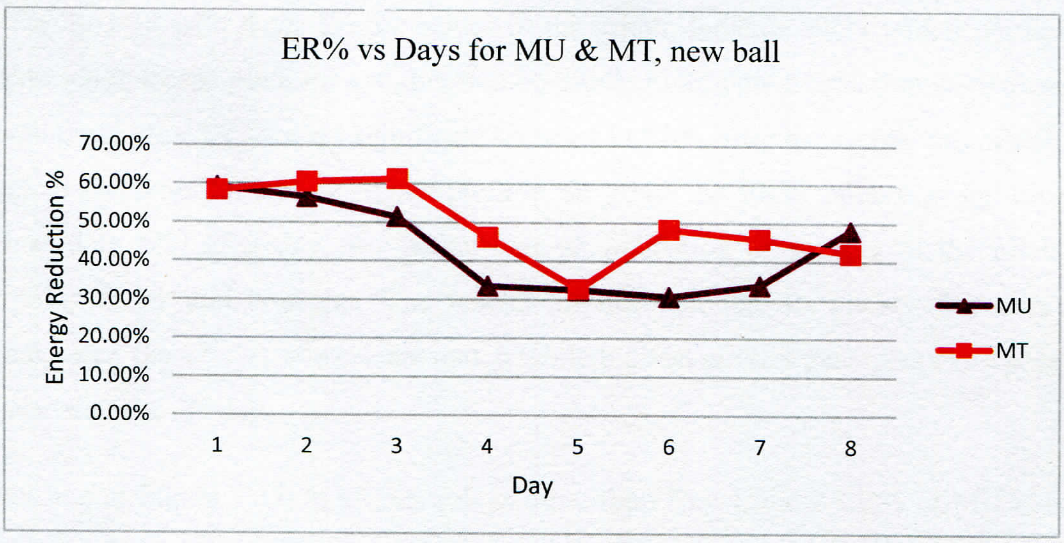


Figure 7.37 Energy reduction percentage for MT &MU, new ball

Figure 7.38 was drawn combining the results given by both stages.

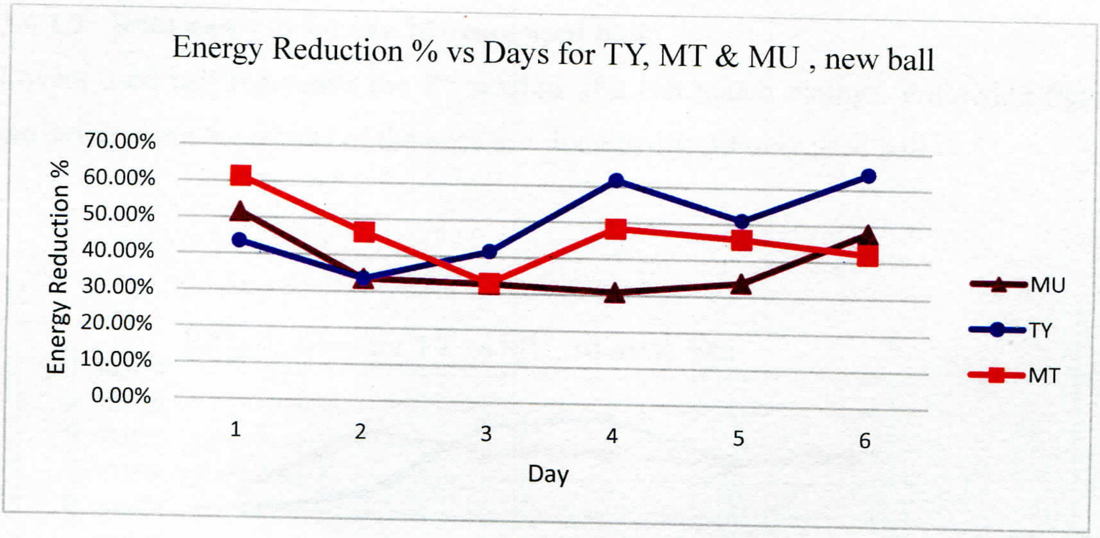


Figure 7.38 Energy reduction percentage for TY, MT &MU, new ball

Variation of the percentage reduction of the total mechanical energy (ER%) was shown in the Figure 7.36 with days. Lower values in the graph, indicate ER% which implies the support given by the pitch for a higher ball bounce is high. Few fluctuation were observed in both graphs but TY showed significant increase in ER% after the second day which was a typical indication of a slow cricket pitch in SL while the ER% value was significantly decreased in MU after day two which was an indication of settling of the pitch and becoming faster and bouncier. The results implies that the SL pitches becomes spin friendly after the 2nd day of a cricket match while the fast pitches generates extra pace and bounce after the 2nd day.

According to Figure 7.37, in all other days other than Day 1 and 8 ER% of MU is lower than MT which implies that model pitch made out of MU:TY=50:50 dissipates more energy at the point of impact than unmixed MU.

Different amount of energy amounts were given in two stages of pitch preparation. However, according to Figure 7.38, ER% of 6 days of TY was compared with last 6 days of MU and TY where the pitch was allowed to dry continuously (no sprinkling). Result shows that MU is ER% is lower than two other soils in most of the days which clearly indicates the higher potential of MU of being a Fast pitch soil.

7.3.6.1.2 Data analysis for the 30 overs used ball

30 overs used ball represents the 2nd session of a test match innings. Following figures were drawn from the results of the pace test done by the 30 over used ball.

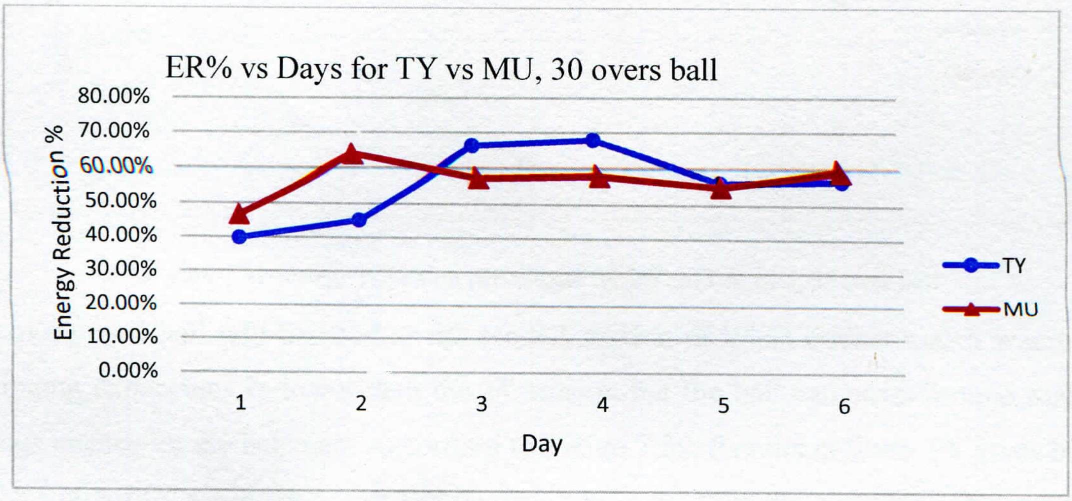


Figure 7.39 Energy reduction percentage for TY &MU , 30 over ball

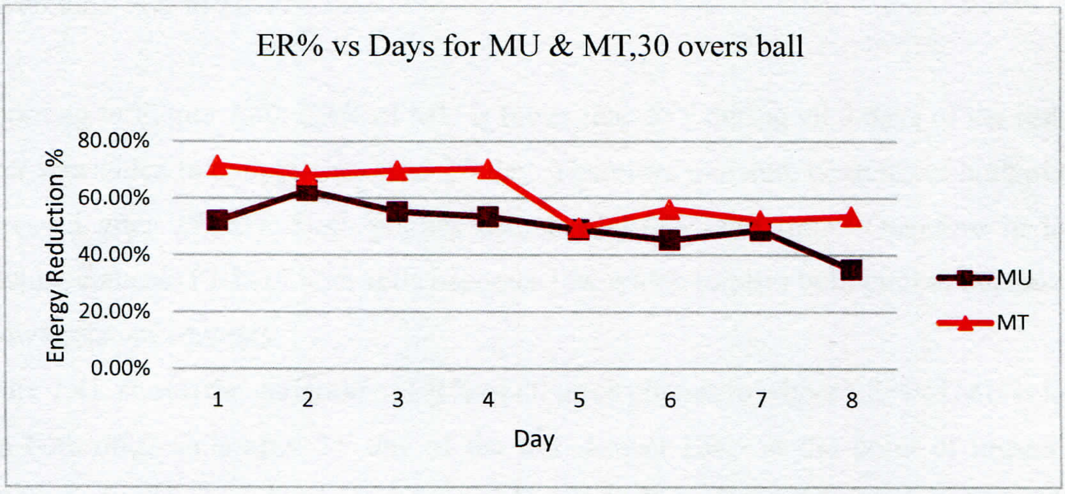


Figure 7.40 Energy reduction percentage for MT & MU, 30 over ball

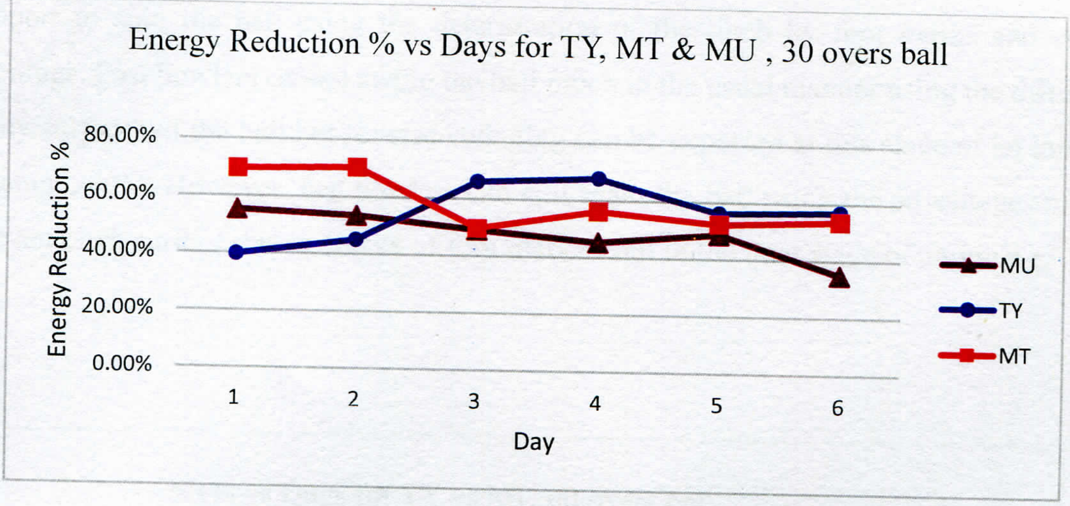


Figure 7.41 Energy reduction percentage for TY, MT & MU, 30 over ball

30 overs used ball will be used at the second session of a test cricket match where the swinging expectancy is lower than the 1st session but the ball can seam around making things uneasy for the batsmen. According to Figure 7.39, Results indicate TY gives better pitch support for a fast bowler in 1st two days and in the final day than MU. But in 3rd, 4th and 5th days MU pitches becomes faster than TY. Again, the results show that MU pitches settle in half way through of a game and then generate extra pace and bounce than the conventional soil in SL.

According to Figure 7.40, ER% of MU is lower than MT during all 8 days of the test. No water was added to both pitches after 2nd day. Therefore moisture contents of both pitches decreased after 2nd day. Both pitches decreased ER% with time. Therefore in lower moisture contents ER% of both soils becomes low which implies both pitches become fast in low moisture contents.

Figure 7.41, shows the variation of ER% of all three pitches in where ER% of MU is lower than both other soils after 2nd day of the test. Lower ER% at the point of impact can generate more pace and bounce of a particular pitch. Therefore MU pitch has the potential to generate higher pace and bounce according to the results

7.3.6.1.3 Data analysis for the 60 overs used ball

60 over used ball is used in the third session of an inning where the ball surface is damaged up to significant amount. In this period of time the spin bowlers gets the maximum pitch

support to spin the ball using the deterioration of the pitch by foot marks and crack openings. Fast bowlers cannot swing the ball much in the usual manner using the different shiny surfaces of the ball but reverse swinging can be expected at this stage of an inning. (Mehta, 2005). However, fast bowlers can still seam the ball using the advantages of the uneven pitch surface due to cracks of foot marks even in the later stage of an inning.

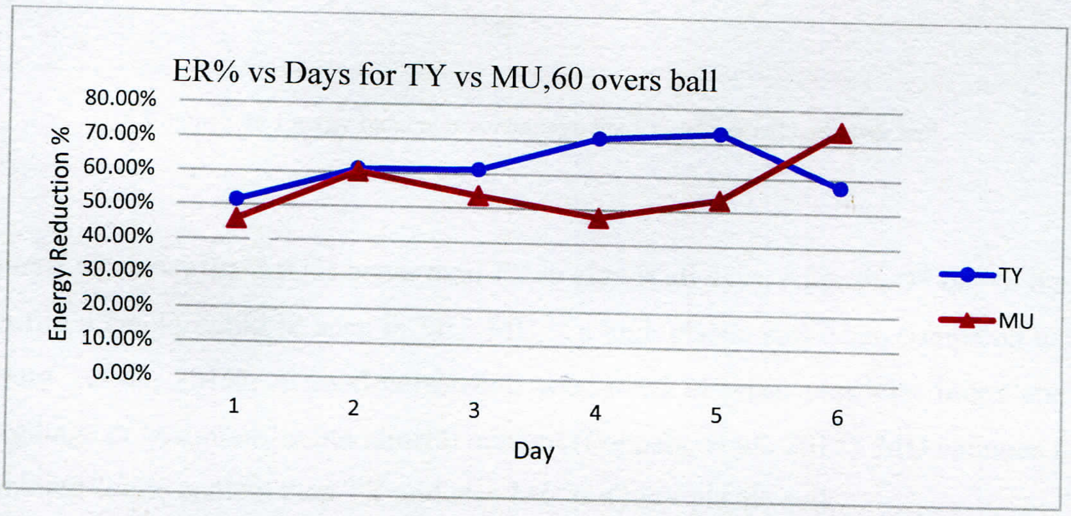


Figure 7.42 Energy reduction percentage for TY & MU, 60 over ball

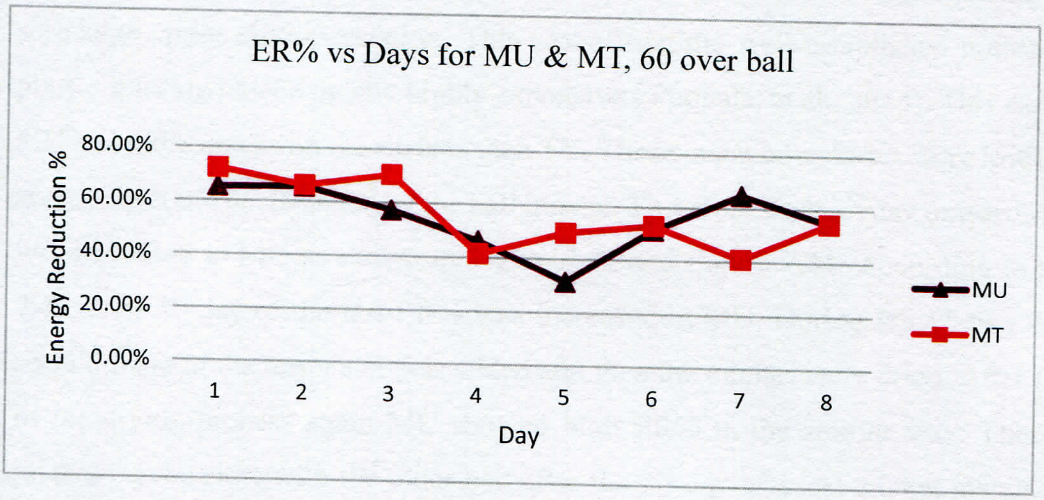


Figure 7.43 Energy reduction percentage for MT & MU, 60 over ball

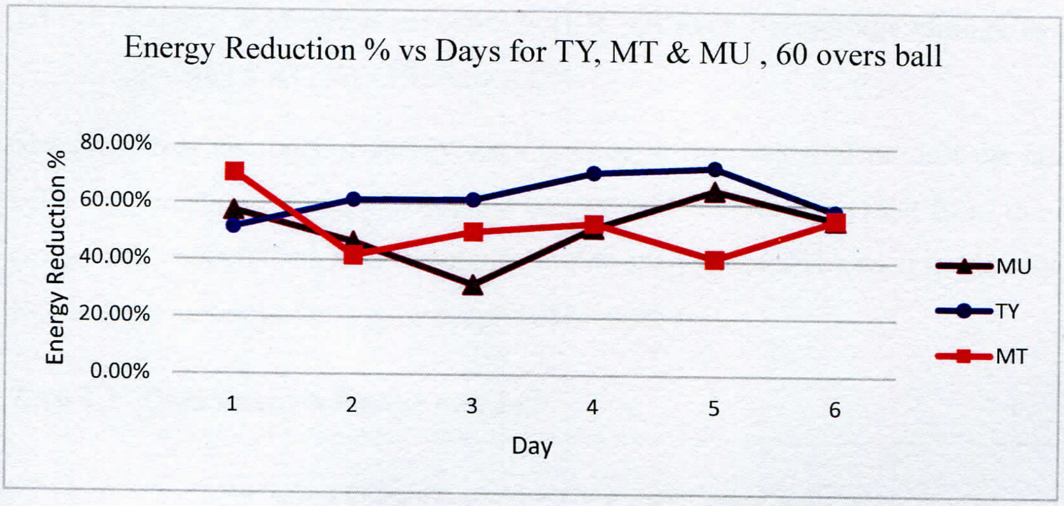


Figure 7.44 Energy reduction percentage for TY, MT & MU, 60 over ball

Figure 7.42 shows that MU is better than TY in almost all days. After the 4th day of the test significant cracks could be seen in MU. MU is a high plastic soil when compared to TY. (Perera , et al., 2016). A good correlation was noted between plasticity index and the percentage of Montmorillonite mineral content (Puppala, et al., 2014). MU contains more Montmorillonite content than TY and also MU is a high plastic soil.

Soils with high plasticity properties experienced large volume changes during swell and shrinkage strain characterization. This reconfirms the well-established notion that high plastic soils are indeed mostly highly expansive (Puppala, et al., 2013). This explains why MU had more cracks on the surface than TY. These crack boundaries were low in strength and easily could be damaged by the ball impact. Therefore from 3rd day onwards high ER% was increased in MU as shown in Figure 7.42 and Figure 7.44. According to the Figure 7.43, after 5th day of the test ER% was increased in MU. During the 1st two days of the second stage of the test water was added and then the pitches were dried. After the 3rd day of the drying process again MU showed high ER% in the similar way. Therefore MU pitches can be slow with the older ball after the 3rd day of a test cricket match. But if we maintain the MC% on the 3rd day (20%) at the beginning the MU pitches can be faster from the day one onwards.

7.3.6.2 Energy Reduction percentage (ER %) over Percentage change in Applied energy (Δ AE %) - ER%/Δ AE%

Since different amounts of energy were applied in two stages of the test the normalized ER% by percentage change in applied energy will remove the effect from the different energy amounts on the ER%. Results from this analysis could be used to identify the best clay if same amount of energy was applied on each soil.

7.3.6.2.1 Data analysis for the new ball

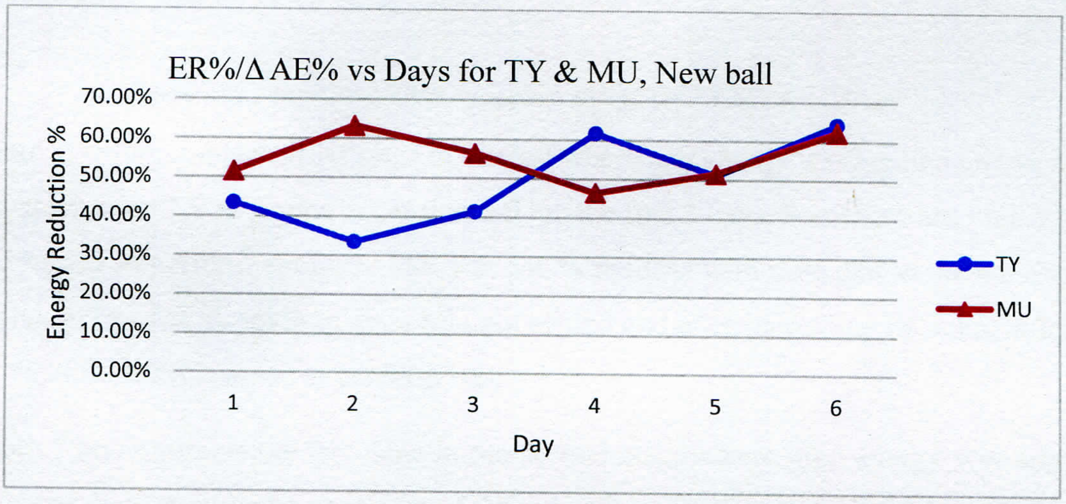


Figure 7.45 Normalized ER% by applied energy for TY & MU (high MC%) , new ball

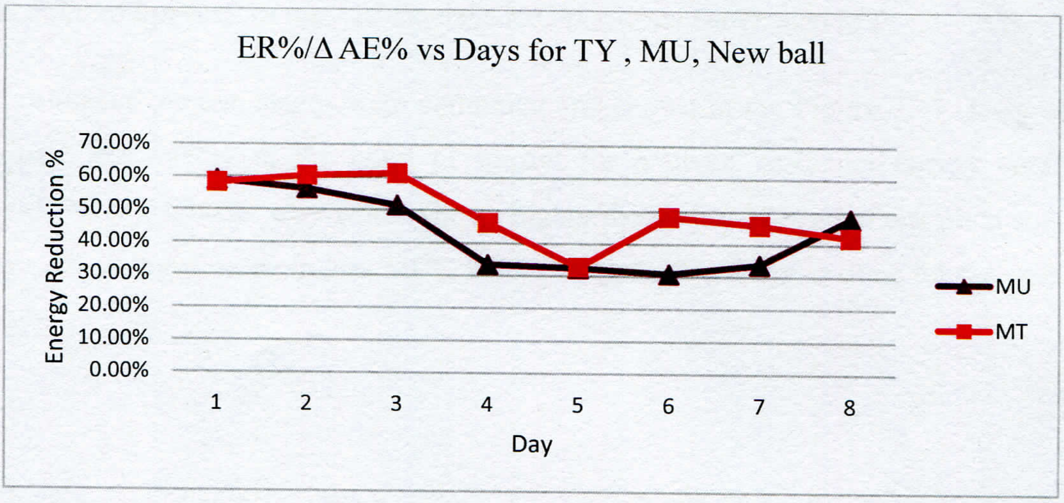


Figure 7.46 Normalized ER% by applied energy for MT & MU, new ball

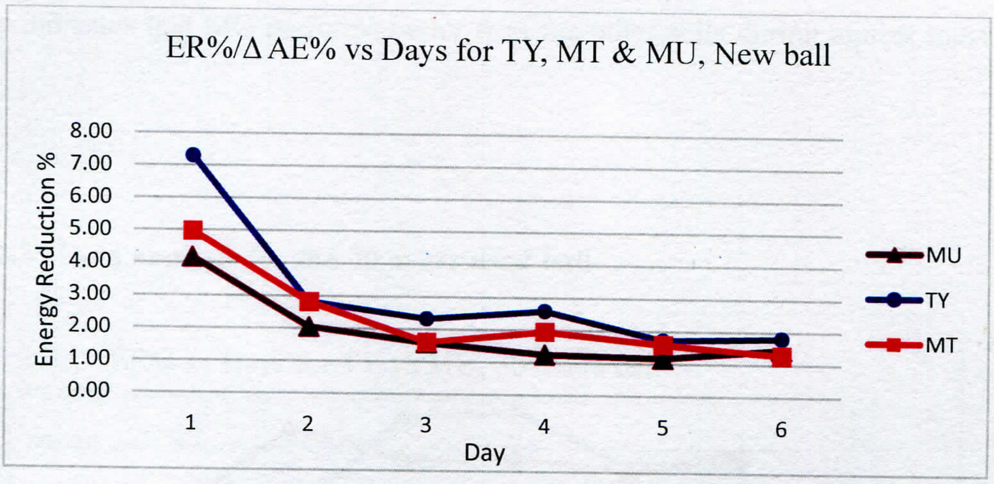


Figure 7.47 Normalized ER% by applied energy for TY,MT & MU, new ball

Figure 7.45 represents the first stage of the test where less energy was applied on two soils. In that situation TY performs better than MU in the first 3 days. Somehow after the 4th day MU started to perform similarly like TY. MC% reduces with time due to the continuous drying. In less MC% environments MU got settled and after increasing its strength in this dry conditions MU started to perform well.

Figure 7.46 represents the test done at the second stage where high energy was applied. However same energy was applied on MU and MT during that stage. After the 3rd day the pitch was kept to dry without adding water. After the 3rd day both soils may have increased their strength in low MC% and started to perform well, reducing the energy dissipation at their point of impacts. In most of the days MU performs better than MT.

The results of the two stages were combined and shown in the Figure 7.47. Soils which dissipate less energy at the point of impact for a given particular energy could be considered as the better clay which shows higher the ability of being a fast pitch soil. All three soils perform better in less MC% environments. This analysis done for the new ball clearly indicates that MU performs better than the other soils during almost most all the days.

7.3.6.2.2 Data analysis for the 30 overs used ball

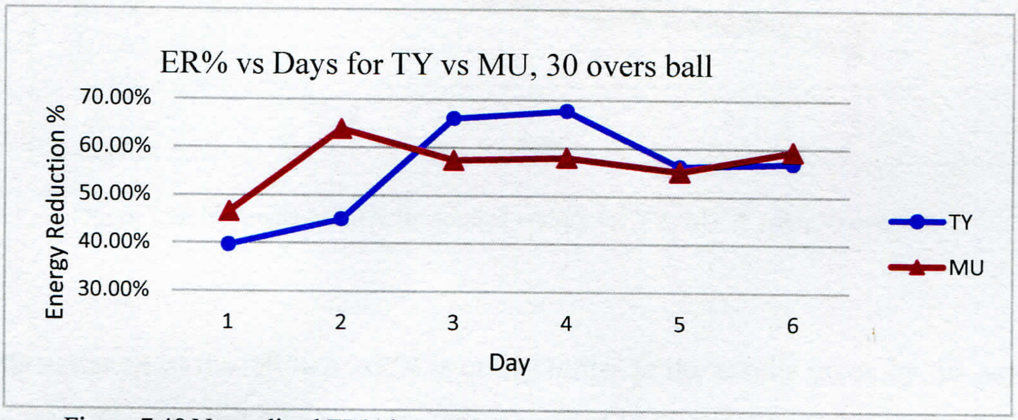


Figure 7.48 Normalized ER% by applied energy for TY & MU (high MC%) , 30 over ball

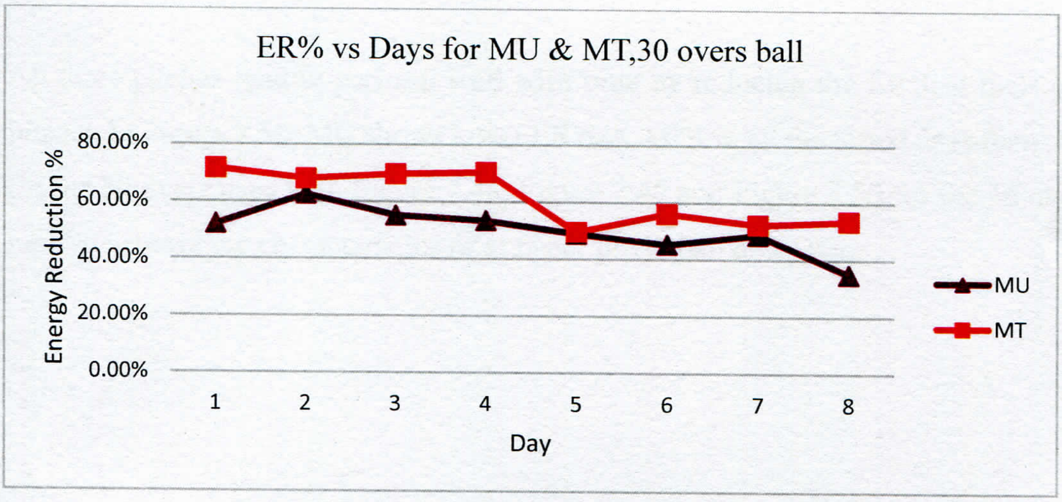


Figure 7.49 Normalized ER% by applied energy for MT & MU, 30 over ball

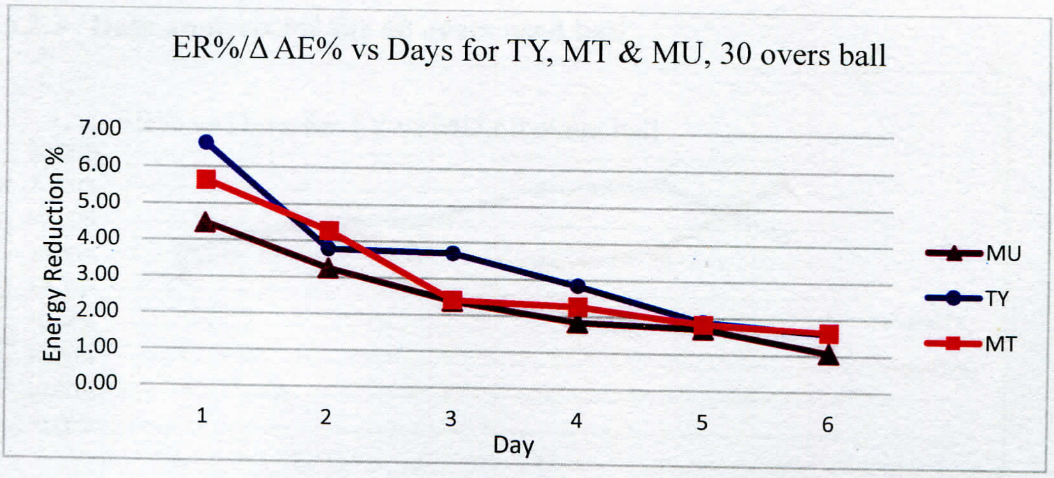


Figure 7.50 Normalized ER% by applied energy for TY, MT & MU, 30 over ball

This variation of the ER%/Δ AE% is quite similar to the results given by the new ball. In Figure 7.48, after the 3rd day no water was added to the pitches and kept for drying. Both soils reduce their ER% in low MC% values but MU performs better than MT during all days.

All three pitches tend to perform well with time by reducing the ER% at their points of impact. In Figure 7.50, MU shows lower ER%/Δ AE% in all the tested days than other two for the 30 overs used ball. Figure 7.48, Figure 7.49 and Figure 7.50 for the 30 overs used ball MU shows the characteristics of at faster pitch than other two.

7.3.6.2.3 Data analysis for the 60 overs used ball

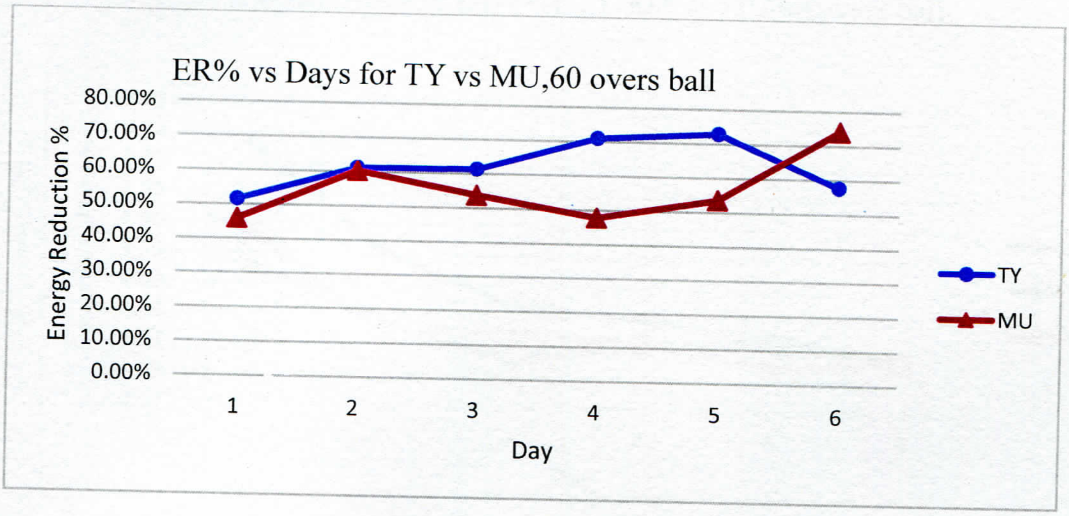


Figure 7.51 Normalized ER% by applied energy for TY & MU, 60 over ball

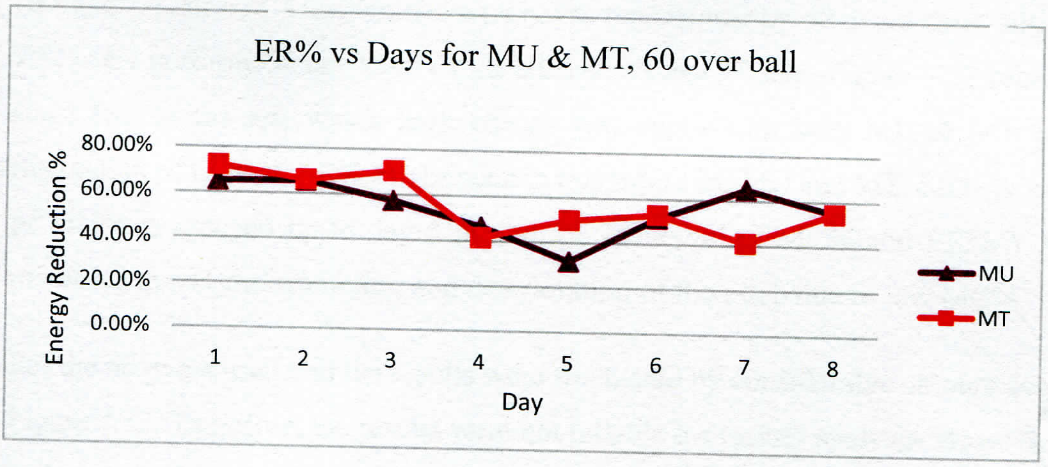


Figure 7.52 Normalized ER% by applied energy for MT & MU, 60 over ball

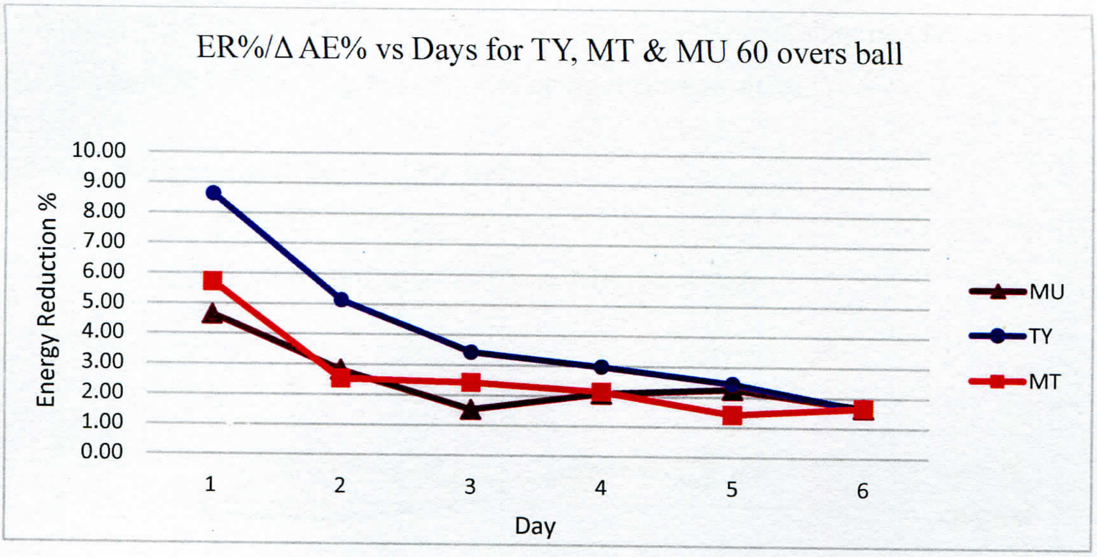


Figure 7.53 Normalized ER% by applied energy for TY, MT & MU, 60 over ball

At the 3rd session of a test innings which was represented by 60 overs used ball, in Figure 7.51, MU performs better than TY in all days except 6th day. Figure 7.52 represents the stage two of the test where high energy was applied on both MU & MT pitches. A fluctuation of ER%/Δ AE% can be seen in this figure for MU and MT. ER%/Δ AE% value of MU was reduced up to day 5 due to the reduction of MC% and ER%/Δ AE% was increased due to the crumbling and deterioration of the pitch due to low MC%.

For the 60 overs used ball the results were fluctuated by considerable amount according to Figure 7.53. Therefore, the results were not reliable for further analysis. However all three soils seem to be decreasing ER%/Δ AE% value with time which implies all soils get faster in a low MC% values rather than high MC% at the beginning.

7.3.6.3 Energy Reduction percentage (ER %) over Moisture content – (ER% / MC%)

This data analysis removes the effect of having different moisture contents in different soils over the energy dissipation at the impact point since the normalized ER% was taken by dividing the ER% by MC%. Through this analysis the best clay or clay combination could be identified neglecting the effect of using different MC%.

7.3.6.3.1 Data analysis for the new ball

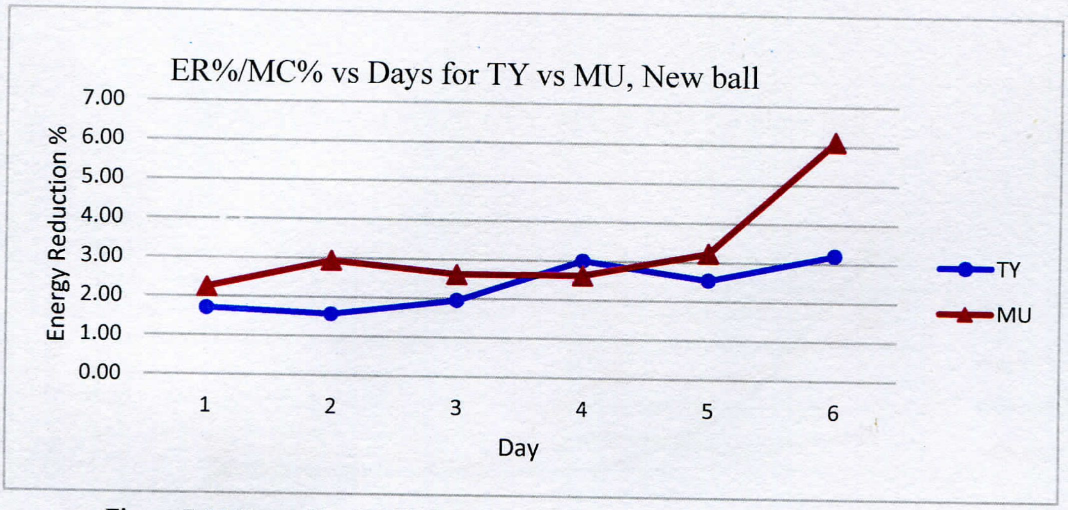


Figure 7.55 Normalized ER% by MC% for TY and MU(high MC%) , new ball

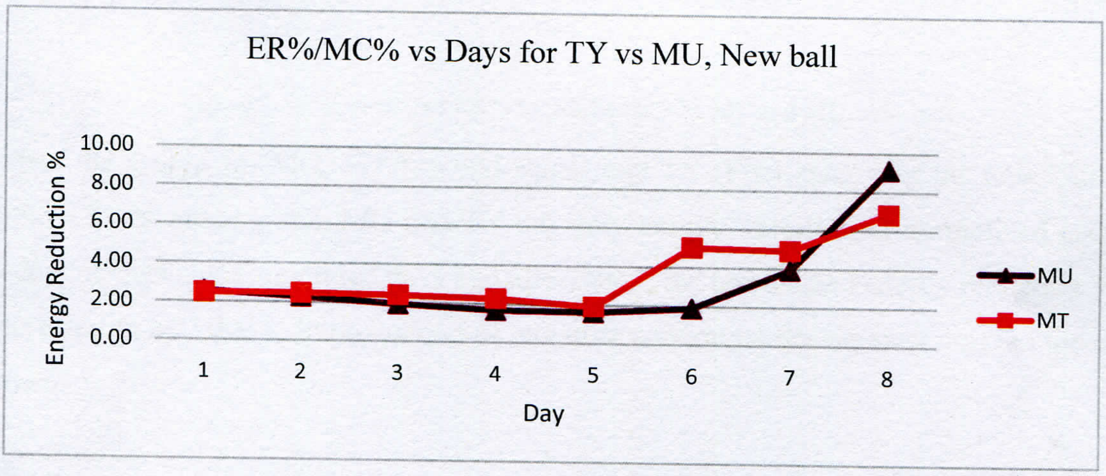


Figure 7.54 Normalized ER% by MC% for MT and MU, new ball

In Figure 7.55, during the first three and last two days, normalized ER% of TY is lower than that of MU. Before the first day of testing, both soils were watered in order to achieve optimum moisture content. The optimum moisture content is higher for TY (31%) than the OMC for MU (19%). Hence the energy reduction normalized (divided) with MC is higher for MU than TY.

In Figure 7.54, normalized energy reduction is considerably lower on Day 6 for MU because the moisture content is higher for MU especially in that day. In the other days, the normalized energy reduction is slightly less for MU except in Day 8.

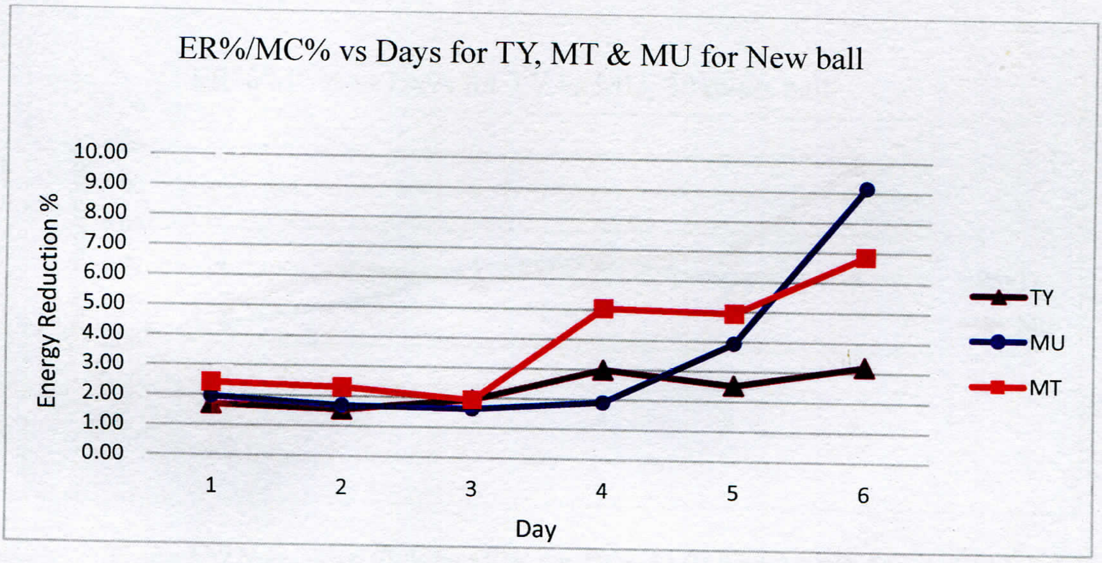


Figure 7.56: Normalized ER% by MC% for TY, MT and MU, new ball

When the graphs for MU, MT (second stage) and TY (First stage) for the new ball are plotted in the same graph, MU and TY has very similar variation in normalized energy reduction during the first three days and after day 5, the normalized energy reduction % is increased in MU due to the reduction of moisture content on the topmost crust of the clay layer.

7.3.6.3.2 Data analysis for the 30 overs used ball

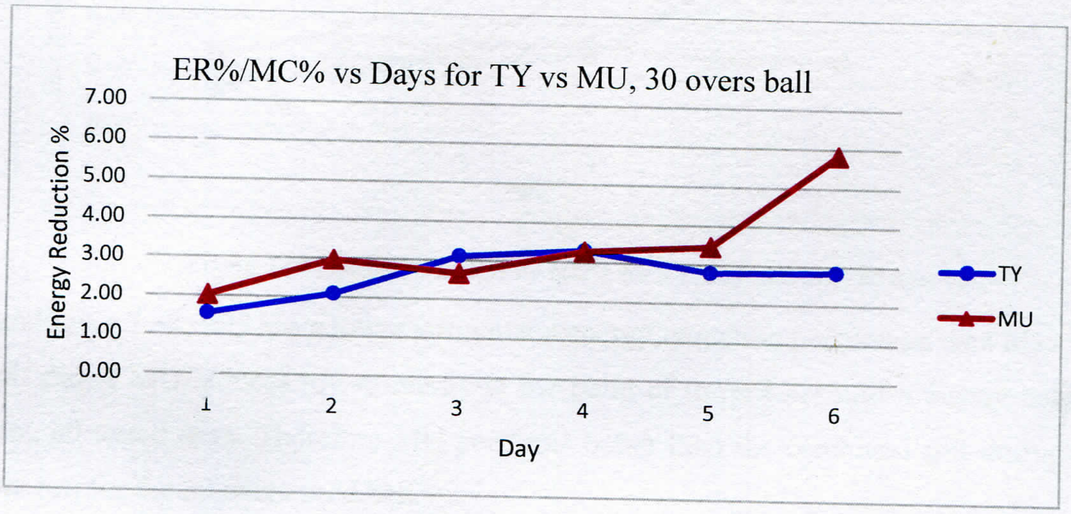


Figure 7.57 Normalized ER% by MC% for TY and MU (high MC%), 30 over ball

In Figure 7.57 of normalized energy reduction for 30 over cricket ball, the variation is very similar to the graph of new ball. The normalized energy reduction percentage is lower for TY than MU for all days except day 3, due to the high moisture content of the top soil layer.

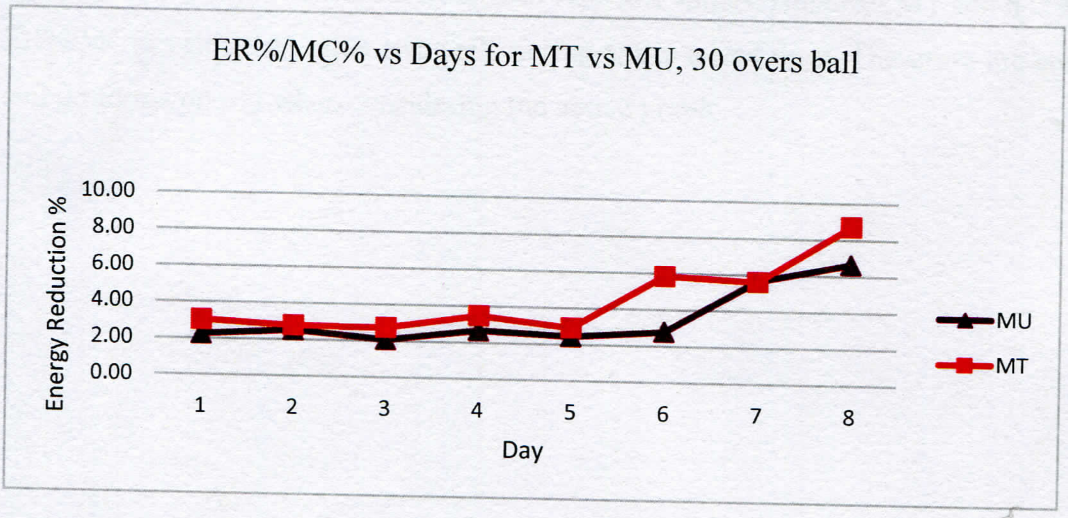


Figure 7.58 Normalized ER% by MC% for MT and MU, 30 over ball

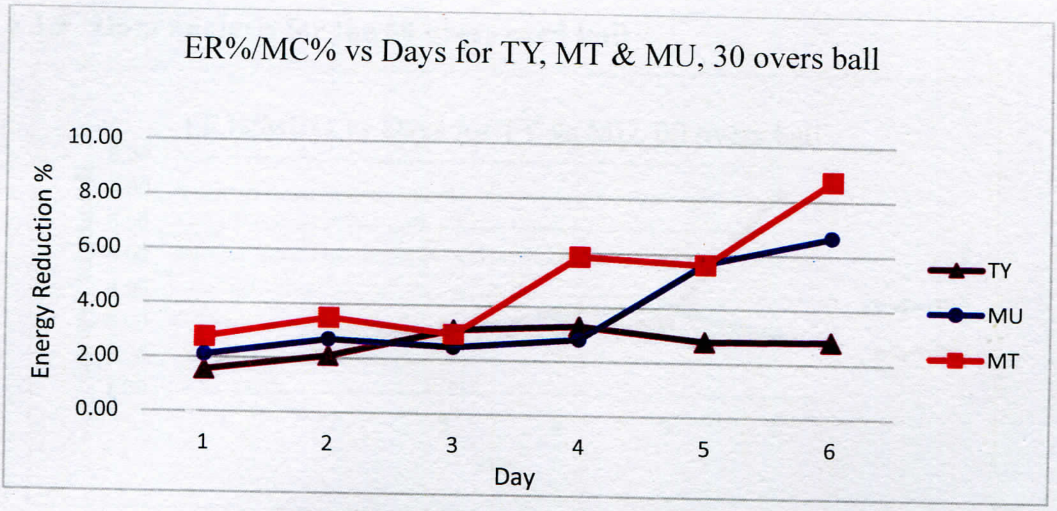


Figure 7.59 Normalized ER% by MC% for TY, MT and MU, 30 over ball

From Figure 7.58, MU has a lower normalized energy reduction percentage than MT. The result shows MU reduces lower energy at the point of impact per unit moisture content during all tested days. Therefore MU performs better than the combined soil during the entire test for the 30 overs used ball.

In the Figure 7.59, Variation of energy reduction percentage for all three soils was plotted in one graph for the 30 over old ball. MU has the lowest energy reduction percentage (normalized) on day 3 and 4. In other days, TY has the lowest normalized energy reduction percentage. In the last two days, normalized ER value is rapidly increased due to the reduction of moisture content of MU up to very low values. However MT soil had a higher ER%/MC% value than other two soils during entire tested days. Therefore the combined soil performs poorly when considering the above graph.

7.3.6.3.3 Data analysis for the 60 overs used ball

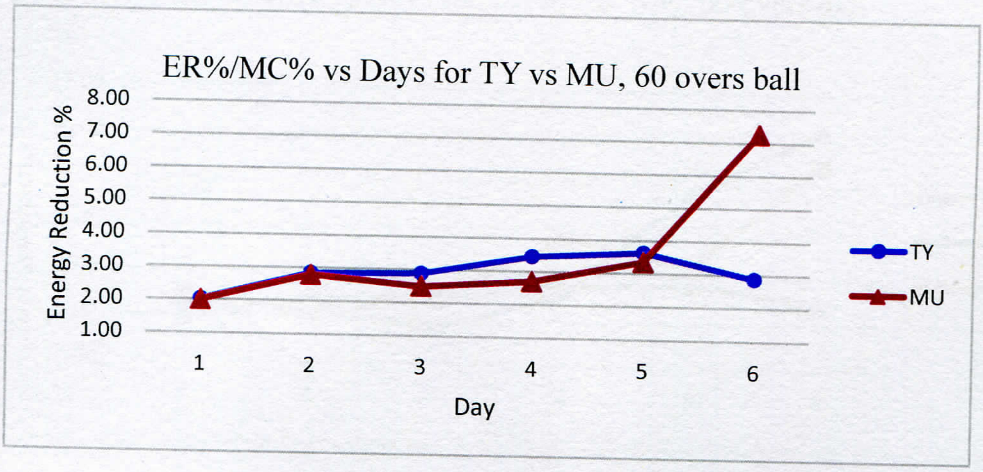


Figure 7.60 Normalized ER% by MC% for TY and MU (high MC%), 60 over ball

For the 60 over ball graphs, shown in Figure 7.60 the normalized ER % is slightly lower for MU for the first five days and in the final day, it has increased beyond the TY value.

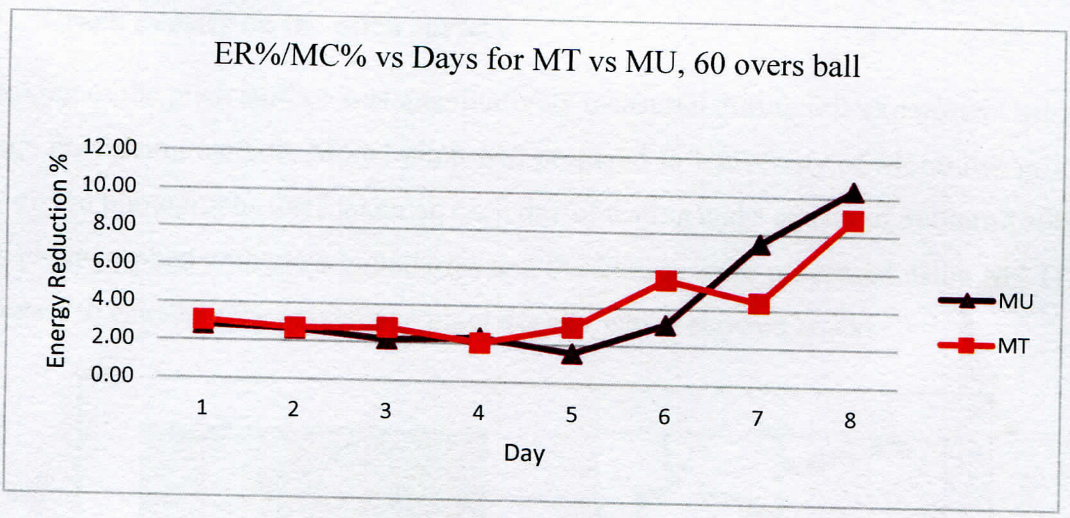


Figure 7.61: Normalized ER% by MC% for MT and MU, 60 over ball

For the variation of ER% between MT and MU graph of 60 over ball shown in Figure 7.61, both soils have highs and lows of ER% during the days of testing with no any visible pattern.

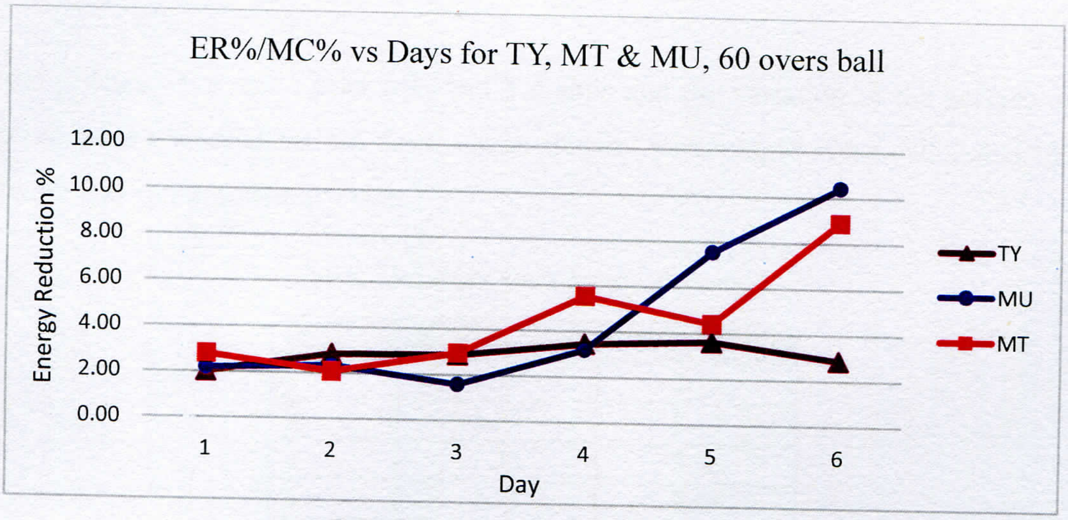


Figure 7.62: Normalized ER% by MC% for TY, MT and MU, 60 over ball

Figure 7.62, shows the variation of normalized energy reduction percentage variation of all three soils for the 60 over ball. The graph for 60 over ball does not show any significant pattern in variations like in new ball and 30 over ball graphs.

7.4 Crack density on the pitch surface

Cracking of the pitch surface was quantitatively measured during this experiment using an image processing method. Model pitch was prepared in University of Moratuwa grounds and digital photographs were taken on each day of testing and a square of 300mmX300mm was photographed with clear boundaries and the images were processed using MATLAB software to calculate the percentage pixel density which showed cracks.

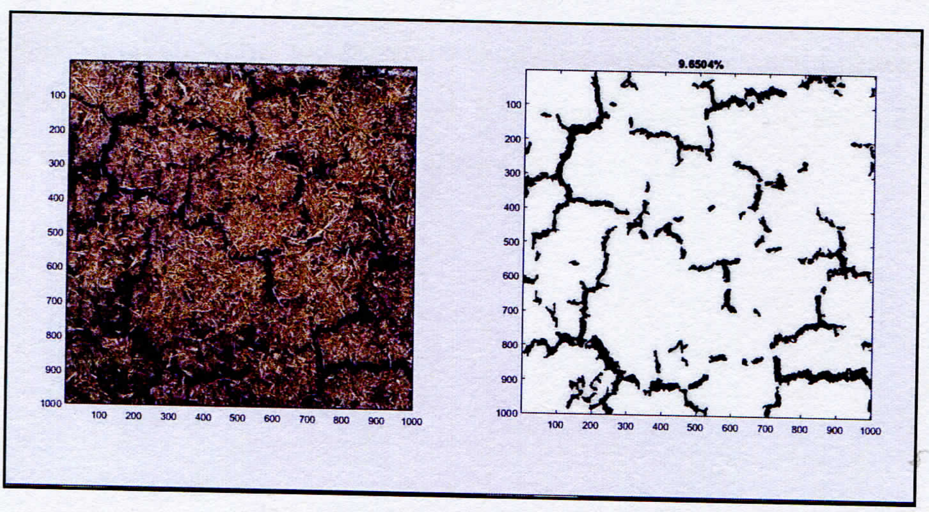


Figure 7.63 Actual image of the pitch and image analysis results by MATLAB software

Model pitches were made from MU and TY soils and the variation of the surface crack patterns were observed for six days. Crack density percentages were calculated by the software and summarized in Table 7.9.

Table 7.9 Surface crack density percentage

Day	MU%	TY%
1	2.79	3.13
2	5.35	3.14
3	7.45	3.94
4	8.75	4.35
5	8.71	5.05
6	8.13	9.63

Crack density depends on the clay mineralogy and MC%. Smectite is a type of an expansive clay which tends to excessively shrink in low moisture environments. Hence it shows a significant cracking when subjected to drying conditions. (Herath, 1973)

Soils with high plasticity properties experienced large volume changes during swell and shrinkage strain characterizations studies. This reconfirms the well-established notion that high plastic soils are indeed mostly highly expansive. (Puppala, et al., 2013).

7.4.1 Surface crack density analysis

Crack density variation on the top surface was photographed daily and images processed by MATLAB software was further analysed. Variation of crack density percentages of the first 5 days were plotted against days and shown in Figure 7.65.

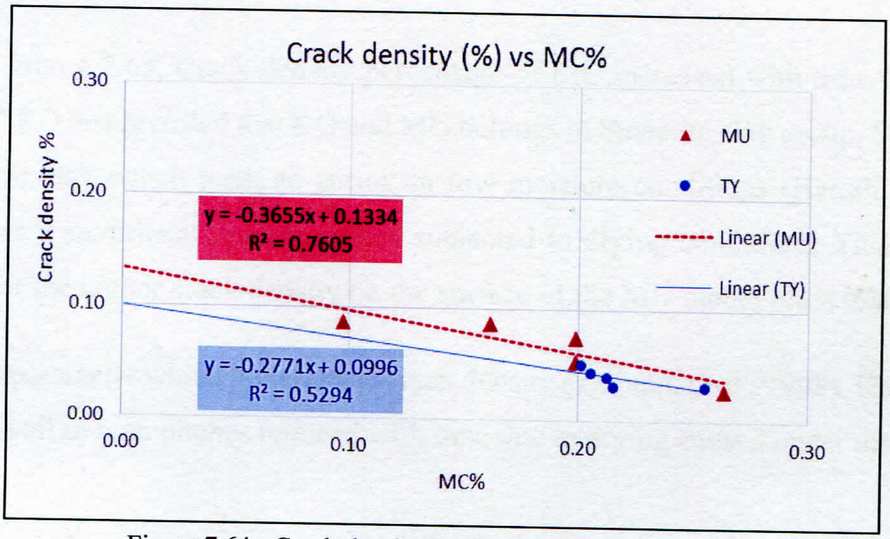


Figure 7.64 - Crack density% vs MC%

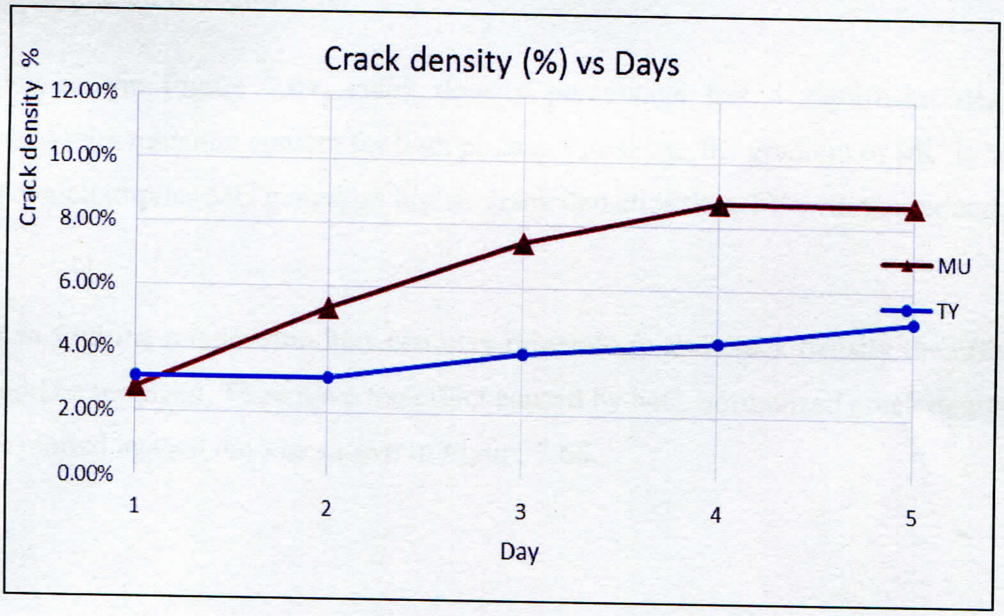


Figure 7.65 Crack density percentage vs days

According to Figure 7.65, Crack density percentage of MU increased with time than the value of TY. XRD test revealed that KO and MU belongs to Smectite clay group. Smectite is an expansive clay which tends to shrink in low moisture conditions (Herath, 1973). Hence it shows a significant cracking when subjected to drying conditions. This would have caused for the higher crack density on the surface of the MU model pitch than TY.

MC is another parameter which governs the crack density (Tainton, et al., 1998). However, MC of the top soil in both pitches reduced with time due to drying caused under direct sun light.

In order to find the relationship between crack density and MC% both parameters of MU and TY was plotted in Figure 7.64.

According to the Figure 7.64, crack density percentage has a significant negative relationship with moisture content for both pitches. However, the gradient of MU is higher than TY which implies MU generates higher crack densities than TY with the reduction of MC.

In order to find the relationship between clay mineralogy and crack density the effect of MC should be removed. To remove the effect caused by MC, normalized crack density by MC was plotted against days as shown in Figure 7.66.

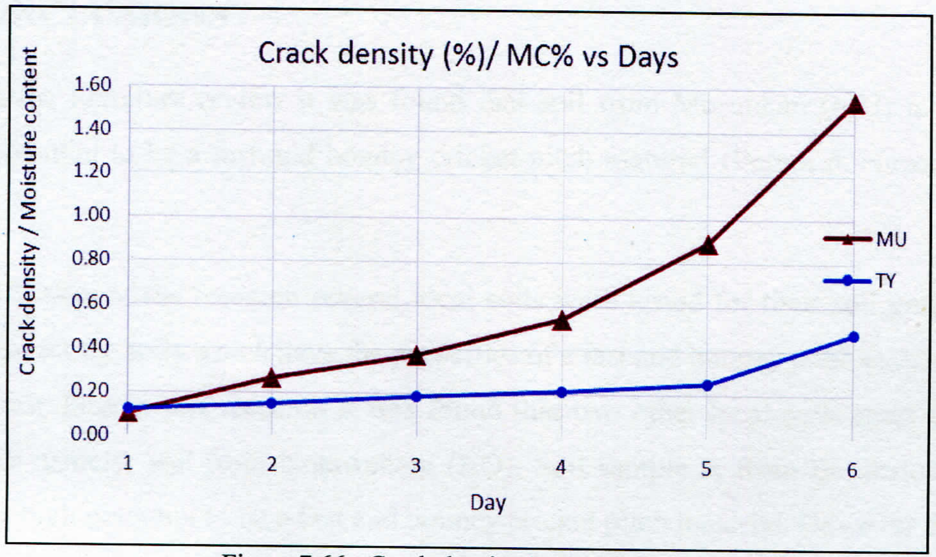


Figure 7.66 - Crack density (%)/ MC% vs Days

According to Figure 7.66, Crack density % / MC% values of MU was higher than for TY after the 2nd day of the test. Therefore crack density has a significant correlation with the clay mineralogy. This implies that MU which belongs to Smectite clay group is highly expansive clay and it matches with the characteristics of fast and bouncy pitches in Western Australian Cricket Association grounds (Nawagamuwa, et al., 2009).

8 CONCLUSIONS

Through the literature review it was found that soil from Murunkan (MU) is having a higher potential to be a fast and bouncy cricket pitch material (Perera & Nawagamuwa, 2015).

As the 1st stage of the research several local soils were tested for their soil properties in order to select the soils which have the properties of a fast and bouncy pitch material. From the soil test done in this research it was found that two other local soils apart from MU which are namely, soil from Kotawehera (KO), Soil sample A from Batticaloa (B (A)) showed a high potential to be a fast and bouncy cricket pitch material. However due to the brownish colour of the KO and the limitation of the source spread of B(A), MU was selected as the most promising local soil for the development of Fast and bouncy cricket pitches. In contrast the currently used soil in SL cricket pitch preparation, Tyronne soil (TY) showed the reasons for being slow and low cricket pitch material. Therefore MU, KO and TY was selected to continue the research further.

As the 2nd stage of the research, bounce test and friction test were carried out for the laboratory samples prepared by afore-mentioned three soils and the pace rating was calculated by the results of Bounce and Friction tests. Six samples were prepared by varying the top surface grass condition (with grass or without grass) and the clay type (MU, KO and TY).

Friction coefficient (μ value) was increased with the usage of the ball. Therefore the pace will be decreased with time as well as the pitch will be spin friendly with the higher friction. μ value of TY increased with the days after the last water sprinkled day. In contrast the μ value of KO and MU decreased with time due to the moisture uplift after the pressure application on each day. Comparatively TY gave the higher μ value when compared to MU and KO. μ value of KO was the lowest from among the three tested samples.

Bounce test was carried out to determine the coefficient of restitution value (e value) of each sample and e value was normalized by Moisture content (MC %) to remove the effect of MC% on e value. Highest rebound height was recorded from MU as 64.5cm (e value=

0.57) on the day 4 of the bounce test at a MC% of 32.25%. KO was the second having a rebound height of 60.26cm (Rebound%=30.13%, e value=0.55) on day 5 of the test at a MC% of 20%. Average rebound height of TY was recorded as 59.24cm (Rebound % =29.6%, e value=0.54) on Day 1 of the test at a MC% of 21.28%. e value of MU and KO was increased with time while TY had a near constant e value throughout the time. Also the samples without grass had a higher e value than the samples made from the same soil with grass on each day. MU gave the highest normalized e value by MC% from among each tested soil samples.

MU and KO gave lower μ values and higher e values when compared to TY. According to the pace rating by Murphy (1985) MU and KO were within the range of fast rating after some days and they continued the fast rating throughout the last day while TY was fast only on the 1^{st} day. Therefore MU and KO were selected as the local soils to be used for the Development of Fast and bouncy cricket pitches.

As the 3^{rd} stage of the this research, a new local clayey soil type (Murunkan) was tested in a model pitch constructed at the University of Moratuwa grounds to investigate the possibility of preparing a fast and bouncy cricket pitch using local soils after successful laboratory tests. For comparison purposes, Tyronne soil was also used separately in the model pitch as it is the conventional pitch making soil currently used in Sri Lanka. A mixture of above soils in w/w ratio of 1:1 was used as the third soil type which was tested at the model pitch. Bounce and pace tests were carried out using standard test cricket balls and via the high speed (slow motion) videos, the results described in chapter 4, were obtained.

The e value results for the MU soil during second stage are higher than that of TY soil results in first stage. TY has a maximum coefficient of restitution of nearly 0.58 while MU has a maximum value in the range of 0.6 to 0.62. And the average bounce normalized by the applied energy is higher for MU than TY for all days except for the day 1. The average bounce variation normalized by MC% does not provide one soil which significantly has a higher average bounce than the rest of soils. From the results of the average bounce and e values from the pace test, MU has the capability of producing more pace and bounce off deliveries than TY, which is the conventional pitch making soil in Sri Lanka.

The energy reduction percentage graphs for new ball and 30 over old ball has shown that MU has the lowest energy reduction percentage than TY, and also it had taken 1-2 days for MU to become the lowest energy dissipating soil among other soils. 60 over ball graph didn't show a clear variation in terms of a lowest energy reduction curve. In the graphs of Energy reduction percentage normalized by applied energy, MU has the lowest energy reduction percentage in all brand new, 30 over and 60 over ball graphs except for the last two days of testing of 60 over ball graph. The energy reduction graphs normalized by MC% has no pattern in variation and hence do not show a soil with lowest energy reduction percentage.

From the pace test results, MU soil has the lowest energy dissipation during impacts between the ball and the soil layer, therefore MU has the lowest reduction in mechanical energy (both kinetic and potential) during impacts. Therefore, it can be concluded that cricket ball retains a higher percentage of energy when the pitch is made out of MU soil than conventional TY soil.

"Fast" pitches are quite commonly become "bouncy" pitches. (Nawagamuwa, et al., 2009) Murunkan (MU) soil has improved the bounce of the pitch tested via the bounce test and at the same time, it has reduced the total mechanical energy lost during an impact of a delivery. Therefore, Murunkan soil, as a locally available soil, has the potential to be used for the preparation of fast and bouncy pitches in Sri Lankan context.

According to the results of crack density percentage variation MU displayed its highly expansive nature than TY, which is an indication of Smectite clay. Moreover Crack density percentage showed a significant negative relationship with Moisture content for both soils. Effect of MC% was removed by normalising the crack density percentage by MC% and plotted against the day. Results showed that Crack density percentage depends on the clay mineralogy where Smectite clay showed higher surface crack densities than Kaolinite clay.

8.1 Guidelines for making fast and bouncy pitches

- Smectite clay deposits which can be found near "*Yoda wewa*" is ideal for the development of fast and bouncy pitches.
- Clay content should be above 60%.
- Organic matter content should be below 5%.
- For the maximum pace and bounce the Moisture content should be about 9% for MU and 20% for TY
- Friction coefficient should be less than 0.375 and 0.377 for MU and TY respectively.
- 4000kg roller should be used for compacting MU soil at least once before starting the season at a moisture content value of 20%.
- Wacke can be used for better compaction but the surface wi be uneven. After applying the Wacker, 4000kg roller can be used to even the pitch.
- Currently used two grass types "*Blue*" and "*Running*" can be used to limit the crack openings and generate extra pace by reducing the friction of the top surface.

8.2 Limitations of the research and recommendations for further studies

8.2.1 For the laboratory models studies

- Optimum moisture contents of the samples were used at the beginning of the bounce tests. Higher rebound heights were observed in low MC% values.
- MC% variation could not be smoothly controlled and varied in the laboratory model or in actual field conditions. MC% was controlled by the natural environmental processes such as sunlight and humidity.
- MC% was not checked below 25mm depth from the surface in the laboratory tests. Surface of the laboratory model should be horizontal and smooth in order to conduct the bounce and friction tests. Therefore taking samples from the mid depths for the MC% calculation could not be done without damaging the surfaces.

Nondestructive method should be used to determine the MC% at mid depth in such cases.

- Laboratory model was developed inside a standard concrete mould made out of steel. Hence boundary conditions given to the laboratory model was different from the actual conditions.
- Environmental conditions inside the laboratory during the bounce and friction test was vastly different in from the actual field conditions.
- Pressure application on the laboratory models was done by compressing them using CBR machine or AMSLER machine as a static load application but in actual field conditions dynamic load application was done by using machine rollers by the curators.

8.2.2 For the actual field tests

- Effects of the tear, wear conditions during an actual cricket match due to cricket boots and the ball impacts was not simulated during this research.
- This research on accrual field conditions can be further expanded to investigate the effect of top grass on pace and bounce of each soil. Grass was planted inside the clay but before the grass leaves spreads on the surface the tests were begun due to the weather conditions and time limitation. Only the cut leaves were spreaded on the surface to make temporary grass surface.
- Since the model pitch was newly constructed and tested soon after compacting of soil, the possibility of using Murunkan soil in long term conditions (i.e. maintenance, water sprinkling, continuous need of compaction etc.) should be studied.
- Further studies of surface cracking of the Murunkan soil can be investigated with comparing other clayey soils and applicability of Murunkan soil in pitches in terms of surface crack density can be studied according ICC rules and regulations on playing conditions.
- Pace and bounce tests were carried out during a one particular time for a day. Therefore the variation of pace during three main sessions of a test cricket match was not studied. Therefore further studies should be carried out to find the variation

of the pace in Morning session (1st 30 overs), 2nd session after lunch (30-60 overs) and session after tea (60-90 overs).

- In this research, the largest compaction roller used was a 3 tonne machine roller. Since the new soil type is prone to high shrinkage and swelling due to changes in MC%, larger machinery should be used to compact newly laid Murunkan clay layers effectively. However in SL cricket pitch preparation pressure application by using a 4000kg roller was a common step after laying the top most clay. 4000kg roller will not be used in every season but should have been used at least once in a life time of a pitch (Fernando, 2016). But in the history of University of Moratuwa ground preparation it was not sure whether they have used 4000kg roller or not. However 4000kg roller was not used in the sample pitch preparation process.
- Deliveries by a single fast bowler was used in the Pace test. But in actual case different bowlers having different releasing points will be used. The effect on the ball by the pitch can be different from one delivery to another. Study of pace and bounce on different deliveries made by bowlers with different actions can be implemented in the future studies based on this research.
- In the pace test, video analysis and the calculations were done for average of five balls (maximum) due to the difficulty of pitching the ball in the same line and length maintaining a constant pace in each delivery. However a balling machine in which standard cricket balls are being used could be adopted to have more deliveries at the desired line and length and obtain more accurate average values in the pace tests.
- Rotational kinetic energy was considered as negligible when compared to the linear kinetic energy and potential energy. Therefore it was not taken in to account in the energy calculations. However a rotational movement of the ball could be observed after the impact.
- Finite element analysis can be carried out in order to find the stress distribution at the ball impact.

9 Bibliography

Puppala, A. J., Manosuthikij, T. & Chittoori, B. . C. S., 2013. Swell and shrinkage characterizations of unsaturated expansive clays. *Engineering Geology,* Volume 164, pp. 187-194.

Anthony, J. W., Bideaux, R. A., Bladh, K. W. & Nichols, M. C., 2010. *Handbook of Mineralogy.* [Online]
Available at: http://www.handbookofmineralogy.org/
[Accessed June 2016].

Baker, S. W. et al., 1998. The effect of soil type and profile construction on the performance of cricket pitches. II. Playing quality during the first season of use. *Journal of turfgrass science,* Volume 74, pp. 9-23.

Burrows, A., ed., 2013. Filtration + Seperation. *Elsevier Ltd.*

Carré, M. J., Baker, S. W., Newell, A. J. & Haake, S. J., 1999. The dynamic behaviour of cricket balls during impact. *Sports Engineering,* Volume 2, pp. 145-160.

Carré, M. J., Baker, S. W., Newell, A. J. & Haake, S. J., 1999. The dynamic behaviour of cricket balls during impact and variations due to grass and soil type. *Sport Engineering,* Volume 2, pp. 145-160.

Challenger, I., 1986. *Cricket and cricket wickets-A discussion of the two.* Christchurch,New Zealand: Lincoln College.

Crawley, G. M., 2001. Particle sizing online. *Powder Metallurgy,* 44(4), p. 304.

Fernando, P., 2016. *Cricket pitch preparation at the Tyronne Fernando Stadium* [Interview] (23rd January 2016).

Herath, J., 1973. Industrial clays of Sri Lanka;geology,minerology,and appraisal for ceramics and other industries. *Economic Bulletin, Geological survey,Sri Lanka,* Volume No.1, pp. 1-113.

James , D., Carré, M. & Haake, S., 2004. The playing performance of county cricket pitches. *Sports Engineering,* Volume 7, pp. 1-14.

James, D., Carré, M. & Haake, S., 2005. Predicting the playing character of cricket pitches. *Sports Engineering,* Volume 8, p. 193–207.

James, D., MacDonald, D. C. & Hart, J., 2012. The effect of atmospheric conditions on the swing of a cricket. *Procedia Engineering,* Volume 34, p. 188 – 193.

James, I. T. & Shipton, P., 2012. Quantifying compaction under rollers using marker tracing image analysis. *Soil & Tillage Research,* Volume 120, pp. 40-49.

McAuliffe, K. W. & Hannan, B. K., 2001. Effects of root zone construction and preparation methods on cricket pitch performance. *International Turfgrass Society Research Journal,* Volume 9, pp. 553-558.

Mehta, R. D. 2005. An overview of cricket ball swing. *Sports Engin ering,* pp. 181-192.

Moore, D. M. & Reynolds, R. C., 1997. X-ray Diffraction and the Identification and Analysis of Clay Minerals.

Murphy, J., 1985. *Cricket pitch playability in N.Z..* s.l., The Third N.Z. Sports Turf Conference.

Nawagamuwa, U., Senanayake , A., Silva , S. & Sanjeewa, D., 2009. Improvement of local soils in order to make "fast & bouncy" cricket. *Engineer,Institution of Engineers, Sri Lanka,* Volume 42(4), pp. 46-55.

Nawagamuwa, U., Senanayake, A., Silva, S. & Sanjeewa, D., 2009. Improvement of local soils in order to make "fast & bouncy" cricket. *Engineer,Institution of Engineers, Sri Lanka,* october, Volume 42(4), pp. 46-55.

Perera , W., Nawagamuwa , U. & Wijerathna, H., 2016. *Study on properties of locallyavailable clays to be used in fast and bouncy cricket pitches.* s.l., Institute of Engineers' Sri Lanka.

Perera, W., Nawagamuwa, U. & Wijerathna, H., 2015. Study on properties of locally available clays to be used in fast and bouncy cricket pitches. *110th Annual Sessions of IESL-Transactions,2016,* pp. 19-25.

Perera, W. S. U. & Nawagamuwa, U. P., 2015. *Identification of Local soil for developement Cricket pitches.* s.l., Department of Civil Engineering, University of Moratuwa.

Puppala, A. . J., Manosuthikij, T. & Chittoori, B. . C., 2014. Swell and shrinkage strain prediction models for expansive clays. *Engineering Geology,* Volume 168, pp. 1-8.

Rathnayake, N. et al., 2005. Anthropogenic impacts recorded in the sediments of Lunawa, a small tropical estuary, Sri Lanka. *Environmental Geology,* 48(2), pp. 139-148.

Shannon, J., 2010. *Basic Guide to Turf Cricket Pitch Preparation.* s.l.:VCA.

Shipton, P., James, I. & Vickers, A., 2006. The Mechanical Behaviour of Cricket Soils During preparation by rolling. *The Engineering of Sport,* Volume 1, pp. 229-234.

Shipton, P. M., 2008. *Optimization of cricket pitch rolling,Doctorate Thesis,* Cranfield,UK: Cranfield University.

Skempton, A. W., 1953. *The Colloidal Activity of Clays.* Zurich, s.n., pp. 57-61.

Sobana, A., Mapa, R. & Gowthamy, P., 2014. Characterization Of Grumusols In Mannar District In Sri Lanka and their applicability to Agriculture. *Proceedings of the Peradeniya University,* p. 527.

Sobana, A., Mapa, R. & Gowthamy, P., 2014. CHRACTARIZATION OF GRUMUSOLS IN MANNAR DISTRICT IN SRI LANKA AND THEIR APPLICABILITY TO AGRICULTURE. *Proceedings of the Peradeniya University,* p. 527.

Tainton, N. et al., 1998. *Principles and practice of pitch preparation.* [Online] Available at: http://static.espncricinfo.com/db/ABOUT_CRICKET/PITCHES/PREP_OF_PITCHES.ht

ml
[Accessed 2 June 2016].

Terzaghi, K., Peck, R. B. & Mesri, G., 1996. In: *Soil Mechanics in Engineering Practice.* 3 ed. s.l.:Wiley - Interscience.

Wang, J. & Yang, Z., 2016. Axial friction response of full-scale pipes in soft clays. *Applied Ocean Research,* Volume 59, pp. 10-23.