Cricket Ball Bounce

by

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Fourth-year undergraduate project

in group D, 2011/2012

I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

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Technical Abstract

The changing characteristics of the bounce of a cricket ball over the course of a test match were researched by investigating the effects of water content and compaction of the soil, the number of loading cycles on the pitch and the number of loading cycles on the ball on the bounce of the ball.

Bounce tests were performed by dropping a cricket ball from a height of 2.4 m onto laboratory prepared pitches with different water contents and compaction and recording the impacts using high speed photogrammetry. The variation of the coefficient of restitution (CoR) with water content and compaction level was determined. It was found that the CoR is independent of the initial compaction level but increases linearly with decreasing water content until a maximum CoR of approximately 0.4 is reached at a water content of 0.12. At this condition, for pitches of all compaction levels, the CoR was found to decrease suddenly to approximately 0.3 as brittle cracking occurred.

Bounce tests were also performed on three pitches with different, but constant, water content. Each pitch was subjected to 30 bounces which represents the number of loading cycles on a small area of pitch during a five day test match. Each bounce was recorded using high speed photography and the variation of the inconsistency of the CoR with the number of loading cycles was determined. It was first found that the inconsistency of the CoR increases with decreasing water content. Secondly, it was established for pitches with water contents of 0.135 and 0.16 that the inconsistency of the CoR increases with the number of loading cycles on the pitch. For a pitch of water content 0.108 the inconsistency of the CoR was found to be independent of the number of loading cycles on the pitch since significant shrinkage had occurred and caused substantial cracking of the pitch prior to loading.

A friction sledge, similar to that devised by James *et al.* (2005), was used to find the variation of the coefficient of friction (CoF) with the water content of the pitch. The sledge was dragged across the surface at constant speed and a load cell was used to measure the force applied to the sledge. A Coulomb friction law was used to find the CoF. It was found that the CoF is linearly dependent on the water content with pitches of high water content having a high CoF. The gradient of this linear relationship is a function of the compaction of the soil, leading to a steeper gradient for pitches of low compaction.

Quasi-static force displacement tests were carried out on two cricket balls of the same brand. The balls were repeatedly loaded by an actuator to represent an average 80 over time period. Each ball was subjected to six ‘bounces’ per over, each represented by a 1 kN force, and three ‘hits’ per over, each represented by a 5 kN force. The force-displacement behaviour was measured using a load cell and an LVDT for impacts on the seam and perpendicular to the seam in order to determine how the mechanical properties of the ball vary with the number of loading cycles on the ball. Every ’10 overs’ the balls were bounce tested on concrete to find how the CoR varied with the number of loading cycles on the ball. It was found that the displacement for a given loading was much greater when loaded on the seam than perpendicular to it, in agreement with Carre *et al.* (2004). The average stiffness of the ball was found to decrease with increasing number of loading cycles. The loading regime could be split into two distinct regions with a ‘primary stiffness’ and a ‘secondary stiffness’ corresponding to two regions of constant stiffness. These distinct regions are due to compression of different layers of the ball. The CoR, when bouncing on concrete, was found to decrease linearly with number of loading cycles on the ball. There was also a linear relationship between the average stiffness of the ball and the CoR, however a more statistically significant correlation was found between the CoR and the secondary stiffness. No correlation was found between the hysteretic damping in the ball and the CoR.

Using a rigid body model derived by James *et al.* (2005), the results obtained in this project were used to find the effects of the water content, the number of loading cycles on the ball and the number of loading cycles on the pitch on the pace and height of the bounce of a cricket ball. It was found that the pace of the pitch increases with decreasing water content which agrees with the results of James *et al.* (2002). However since the horizontal component of velocity, which is dependent on the CoF, dominates the pace measurement, only very slight changes in pace were found due to the number of loading cycles on the pitch and ball. This is because the CoF was assumed to be constant with loading cycles, which could be a poor assumption and an important area for further work. It was found that the water content of the pitch had the largest effect on the height of the bounce and also that dry pitches after a high number of loading cycles gave variable bounce with the height varying by up to 22.8 %.

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1. Introduction

Cricket is the second most popular sport in the world (Fuss, 2008). Unlike most other sports; the result of the game can be greatly influenced by factors other than the player's skill, namely the aerodynamic behaviour of the cricket ball and the bounce of the cricket ball on the pitch. This report will focus on the behaviour of the cricket ball as it bounces.

Test matches last five days, with teams taking it in turns to bat for each of their two innings. Each inning normally lasts between one or two days. The Laws of Cricket ban watering of the pitch during a match, therefore, substantial drying of the playing surface usually occurs. This causes the properties of the pitch to vary greatly over the course of the match, sometimes having a significant impact on the result.

The ball is used for a minimum of 80 overs, each consisting of 6 deliveries, before being replaced by a new ball. The forces on the ball are vast, with a peak force when hit of up to 17.5kN (Cross, 2005). This again leads to greatly varying properties of the ball and therefore changing bounce during the course of a match.

Since cricket is such a popular sport, with large commercial and financial interests it is important that the behaviour of the cricket ball bounce is understood so as to allow groundsmen throughout the world to create pitches for fair, exciting matches.

1.1. Literature Review

Numerous studies have been carried out in this field looking at the properties of both the ball and the pitch. James *et al.* (2002) investigated the dynamic behaviour of cricket ball impacts by analysing data from county championship matches using high speed photography. It was found that the pace of a pitch, defined as the fraction of the ball's speed retained after impact, is inversely correlated with both the clay content and moisture content of the soil. This contradicts Baker *et al.* (1998) who found the dependence to be due to organic matter content rather than clay content.

James *et al.* (2005), again using data collected from county championship matches, found that the bounce could not be directly predicted from individual measurements of surface friction, hardness, or surface restitution. However, when a simple rigid body model was used to combine the measurements, it was found that if the surface friction and coefficient of restitution were known, then the pace of the pitch could be predicted. However the angle of the bounce was found to be dependent on deformation of the surface which was left out of the model.

McAuliffe and Gibbs (1997) found that the pace of the pitch was dependent on the grass coverage. Grass has a lubricating effect and reduces the surface friction and increases the pace of the pitch. It was also found that the age of the ball had a significant impact on the pace of the bounce. Moreover it is even suggested that the pace change during a match is largely due to the changing properties of the ball, rather than those of the pitch.

Carre *et al.* (2004) investigated the force-deflection behaviour of a cricket ball during impact with a rigid surface. It was found that greater deformation occurs during impacts landing on the seam rather than those perpendicular to it, and that only the bottom third of the ball is compressed during impact. A mass-spring-damper model was used to predict bounce for oblique impacts, returning good results for post impact speeds and spin; however the angle of the bounce could not be well modelled due to deformation of the pitch that was not included in the model. Cross (1999) also investigated the force-deflection behaviour of several different ball types however he did not include cricket balls. Quasi-static tests were compared with dynamic bounce tests, and it was found that quasi –static tests are representative of a dynamic bounce if the deflection is halved due to compression of the top and base of the ball. The total energy dissipated in a quasi-static test was found to be about 50% of the actual energy dissipated in a dynamic bounce.

Fuss (2008) carried out compression and stress relaxation tests on five different models of cricket ball. It was found that the stiffness of the ball increased with increasing deflection, and also that different balls, even of the same brand from the same manufacturer, had very inconsistent properties.

1.2. Project Aims

There are three main aims of this project:

1) To investigate the effect of the changing properties of a cricket ball on the bounce of that ball over an average 80 over duration.

2) To investigate the effects of the changing properties of a cricket pitch on cricket ball bounce.
3) To quantify the above effects into real information about how the bounce of a ball varies with different ball and pitch properties.

During a cricket match, there are three key features that lead to the changing characteristics of the bounce of a cricket ball. These are the water content and compression of the soil, the number of loading cycles on the pitch and the number of loading cycles on the ball. Each of these features will be looked at in detail in this research.

1.3. Theory

1.3.1. Hysteretic Damping (Kelly, 2012)

In real engineering materials the process of loading and unloading is irreversible due to energy dissipation within the material. Therefore force-displacement diagrams show hysteresis. The area enclosed within a force-displacement diagram for a load-unload cycle is equal to the dissipated strain energy per unit volume. This is called hysteretic damping and it is not dependent on the frequency of loading; this is the key difference to viscous damping. The energy dissipated per cycle is given by the following expression:

$$\Delta E = \pi k h X^2 \tag{1}$$

where h is the hysteretic damping coefficient, k is the stiffness and X is the amplitude of displacement.

A work-energy analysis shows that, analogous to viscous damping, a damping ratio ζ for hysteretic damping can be defined as:

$$\zeta = \frac{h}{2} \tag{2}$$

Therefore, if the area under the force-displacement diagram is known, the mechanical behaviour of the material can be found using a normal mass-spring-damper system.

2. Design of Experiments

The following sections describe the experiments conducted during the research in order to meet the aims of the project stated above.

For all experiments a "County Club 5 ½ Oz" ball was used. The ball consists of a rubber-cork composite core, surrounded by a layer of cork followed by a layer of leather. The seam is a series of stitches of a string-like material used to join two hemispheres of leather casing together.

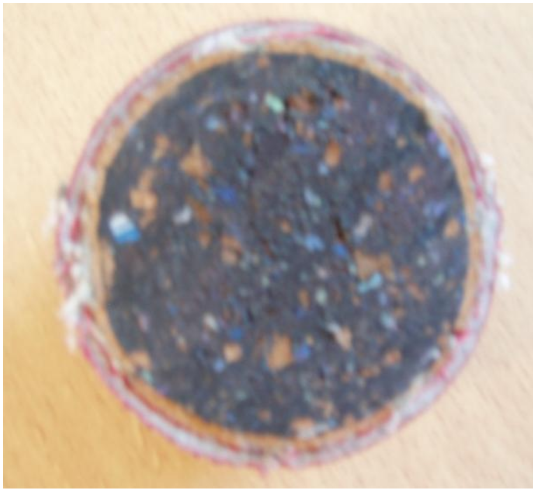
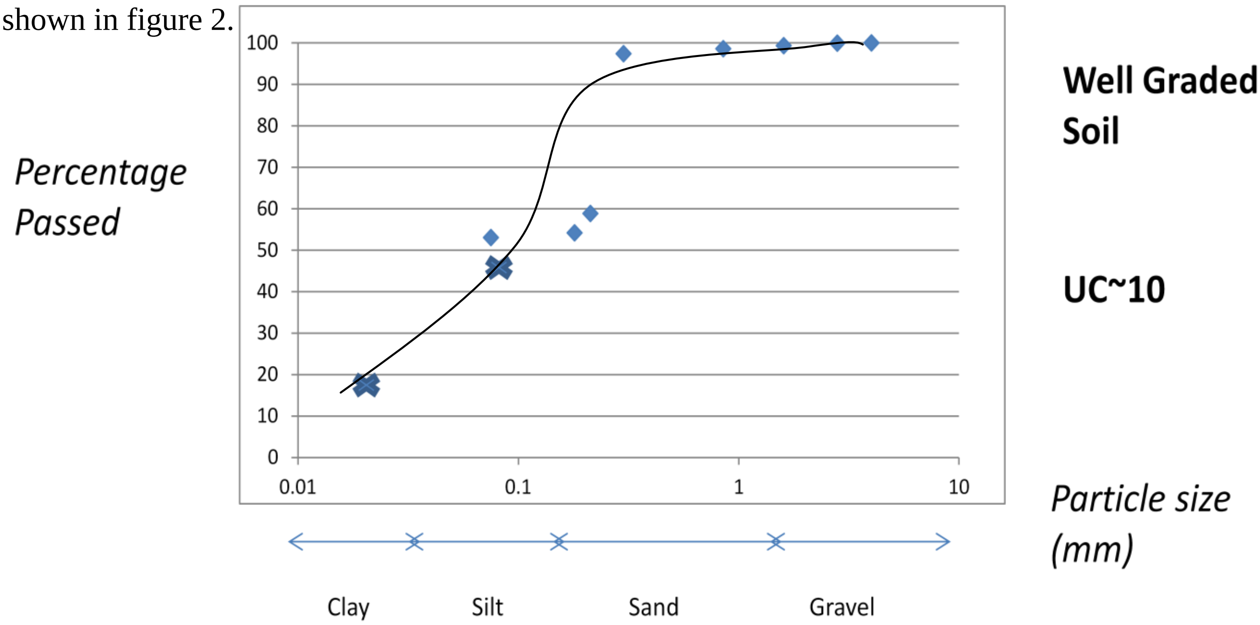


Figure 1 *Cross section of a 'County Club 5 ½ Oz' Ball*

For all soil tests, Surrey Loam was used as it is used by many cricket clubs of all standards around the UK to construct their pitches. Its particle size distribution, calculated using sieves, is shown in figure 2.



= From manufacturer's data since particles are too small for sieves.

Figure 2 *Particle size distribution of Surrey Loam*

Figure 2 shows the uniformity coefficient is 10, which shows that the soil is well graded allowing good compaction since fine particles can fit in the voids between larger particles; this is obviously good for cricket pitches as it allows a hard dense surface to be constructed.

2.1. Bounce Tests

Although this test has been carried out many times by previous research groups, research has focused on the variation of the average coefficient of restitution (CoR) with water content. The variation of inconsistency of the CoR with water content has not been considered in detail so will be investigated in this report by using a bounce test and high speed photography. The variation of the average CoR also needs to be determined for the particular soil type used in this project so it can be used as a reference figure for other results. The variation of CoR with bulk density of the soil will be found by varying the amount of compression and performing bounce tests.

Bounce tests were performed by dropping a ball from a height of 2.4 m. This achieves an impact velocity of approximately 6.8 m/s which represents the vertical impact velocity of a ball released with no initial vertical component of velocity from a bowler of average height. The exact impact velocity is slightly less than this value due to friction between the ball and the experimental apparatus shown in figure 3. A ball was dropped through a tube that was secured in place so that the top of the tube was 2.4m above the pitch.

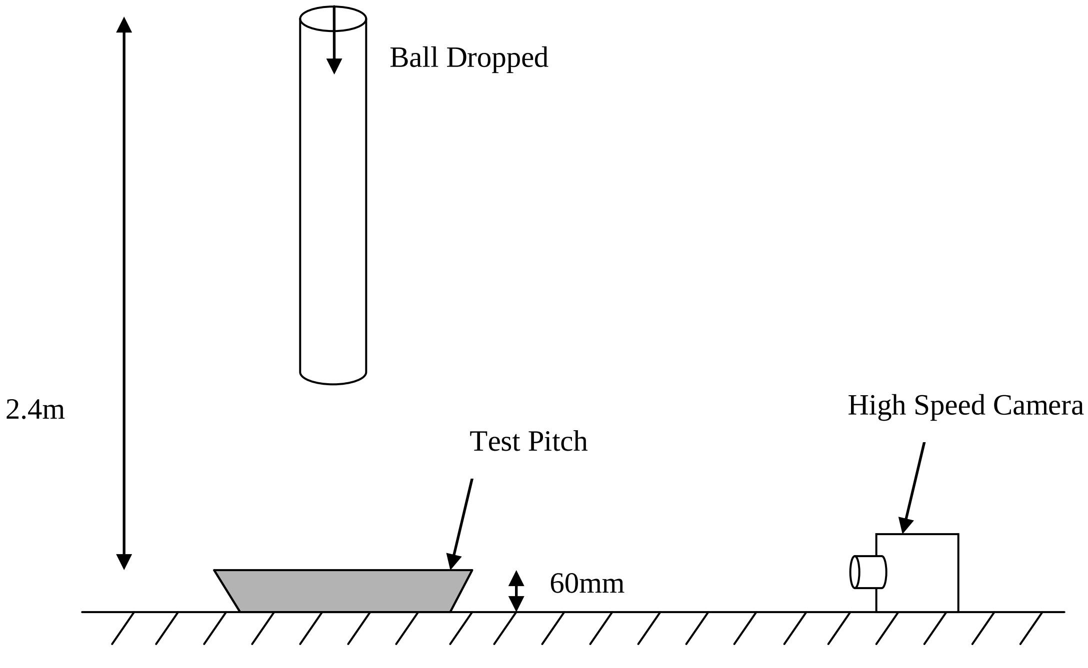


Figure 3 *Bounce tests experimental setup*

A high speed camera is used to record the impact and the images can be analysed to calculate the CoR.

All bounce tests were carried out on small samples of pitch made up in the laboratory. The samples were 170 mm x 270 mm x 60 mm. Adams *et al.* (2004) recommended that the topsoil layer be thicker than 150 mm. This is not the case for the 'test pitches', however, using Boussinesq's linear elastic stress equation (equation 3) it can be shown that the stress change is negligible at the base of the 'test pitches' so the experimental setup is valid:

$$\sigma_v = q\left[1 - \left(\frac{1}{1+(a/z)^2}\right)^{\frac{3}{2}}\right] \tag{3}$$

The radius of contact *a*, is dependent on the conditions of the pitch – for wet pitches *a*~1.5 cm, for dry pitches *a*~0.5 cm.

Water content	**High (0.2)**	**Low (0.12)**
Impact radius, *a* (cm)	1.5	0.5
Stress at base (% of applied stress)	8.7	1.0

Table 1 . *Boussinesq's linear elastic stress equation results*

Table 1 shows that the stress change at the base of the test pitches is negligible compared to the contact stress, therefore the experimental setup is a valid approximation to reality.

A proctor compaction test was carried out to determine the optimum water content of the Surrey Loam. The results are shown in figure 4.

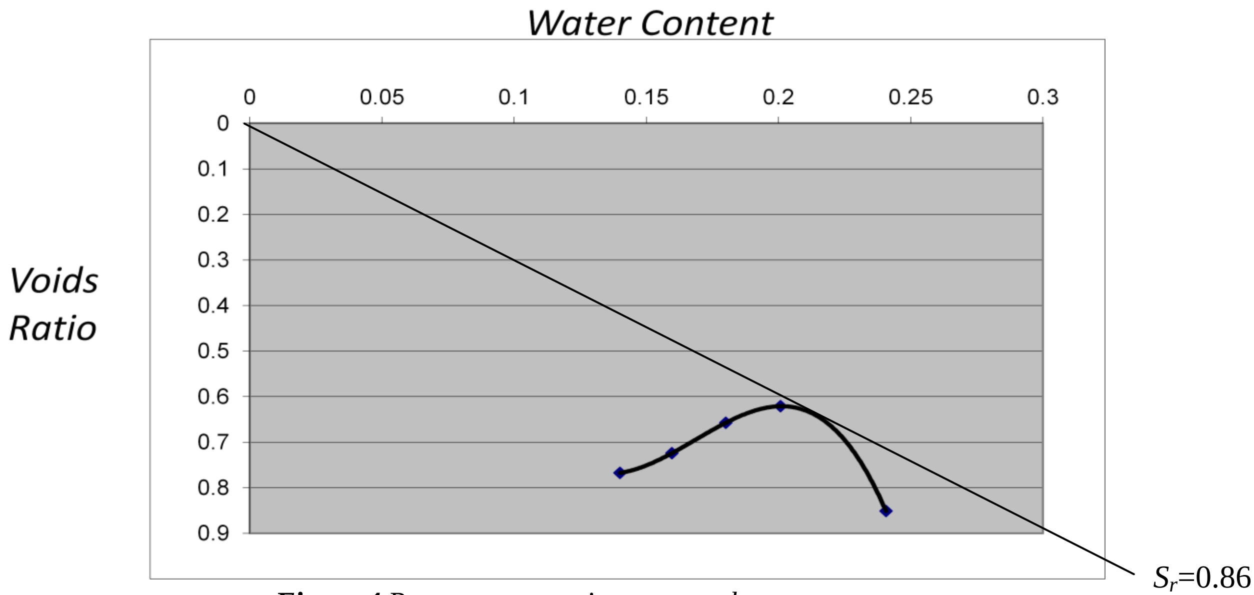


Figure 4 *Proctor compaction test results*

Figure 4 shows that the maximum compaction occurs at a water content of 20% and a saturation ratio of 0.86.

2.1.1. Variation of average CoR with water content

Three ‘test pitches’ each having a saturation ratio of 0.86 were constructed at ‘low’, ‘average’ and ‘high’ compaction. The voids ratio for each pitch is shown in table 2.

	High Compaction	**Average Compaction**	**Low Compaction**
Voids ratio	0.46	0.53	0.61
Initial water content	0.15	0.175	0.2

Table 2. *Initial conditions of test pitches*

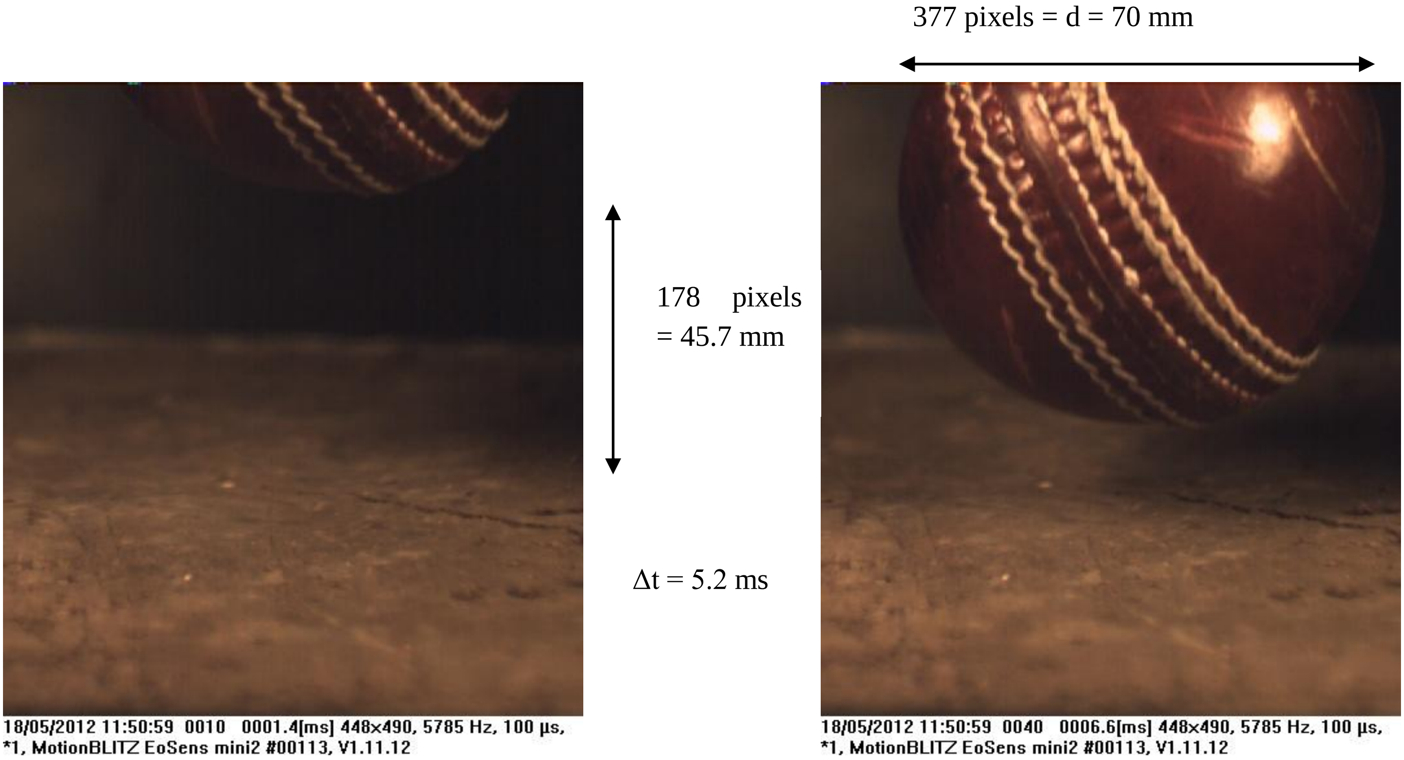
Each pitch was then allowed to dry out and the CoR was measured at regular intervals. At each interval 3 bounce tests were performed and an average CoR was calculated.

The CoR is calculated by analysing images of the ball before, during and after the bounce as shown in figure 5. First the initial and rebound speeds of the ball are calculated by calculating how many pixels the ball had travelled in a given time. The errors in this process are shown below:

Image time: +/- 0.05 ms

Pixel number: +/- 2 pixels

The number of pixels the ball travelled is of the order 200 pixels and the time taken is of the order 10 ms before the bounce and 15 ms after the bounce. Therefore the percentage error in the calculated initial velocity is 1.1% and that of the final velocity is 1%. Therefore the percentage error of all coefficient of restitution measurements is approximately 1.5%.



Therefore $V_{in} = \frac{45.7}{7.4} = 6.2\ m/s$

Figure 5 *Example calculation for initial velocity*

2.1.2. Effects of water content and number of loading cycles on the inconsistency of the coefficient of restitution

Over the course of a test match the ball bounces on the pitch approximately 2700 times. The results from the bounce tests explained above show that the average force exerted on a pitch during a bounce is of the order of 1 kN. Three test pitches with voids ratio of 0.53 (average compaction) were constructed with water contents of 0.108, 0.135 and 0.16.

The ‘pitch map’ data shown in figure 6, from Hawkeye (a ball tracking device used in professional cricket), shows the number of bounces in a specific location bowled by England player Tim Bresnan, a normal seam bowler, during a test match against Australia in 2010.

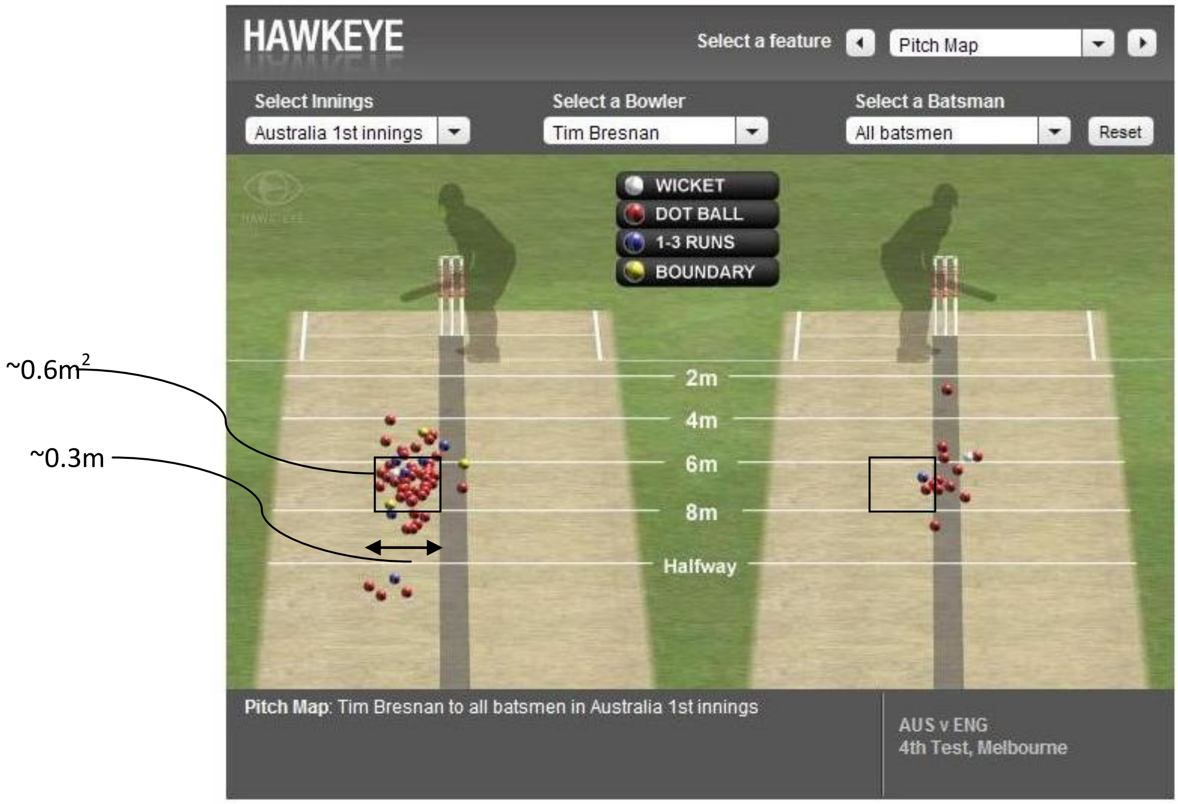


Figure 6 *Pitch map for a seam bowler, Hawkeye as cited in A Cricketing View (2010).*

This shows that 40 out of a total of 67 balls bowled (60%) to both left and right handed batsmen bounced within a 0.6 m^2 area. Therefore, if this is assumed to be valid for an entire test match, 810 impacts will occur within that 0.6 m^2.

Each 'test pitch' has a total area of 0.046 m^2; however the area suitable for bounce tests is only the centre of the pitch with an area of 0.017 m^2. This section of the pitch will be repeatedly loaded to represent a test match by bouncing a new ball 30 times at random locations over the loading area. Each bounce was photographed using high speed photography and the CoR was measured. The variation of the inconsistency of CoR with loading cycles was found for pitches of different water content, and the changes to the surface of the pitch were observed visually.

2.2. Surface friction tests

James *et al.* (2005) found that if the surface friction and coefficient of restitution were known, the pace of the pitch could be determined using a simple rigid body model. Therefore, similarly for the bounce tests, three 'test pitches' were constructed at a saturation ratio of 0.86 with the voids ratios and initial water contents shown in table 2.

A friction sledge, similar to that devised by James *et al.* (2005), was used to measure the variation of the coefficient of friction of the pitch surface with water content of the pitch. The experimental apparatus is shown in figure 7.

Figure 7 *Experimental setup for surface friction tests*

The friction sledge was dragged over the pitch at constant speed and a load cell was used to measure the force, F, applied to the sledge. A simple Coulomb friction law was assumed:

$$F = \mu N \tag{4}$$

where μ is the coefficient of friction (CoF) and N is the force normal to the loading direction.

It was important to ensure that the force applied to the load cell was perpendicular to the cell as it very sensitive to bending moments. The balls were rotated after each test, because significant wear of the surface occurred.

The friction coefficient was taken as the average value from the course of the test. The tolerance of the load cell is +/- 0.5%, as given on the load cell's data sheet. This tolerance has been used to calculate the experimental accuracy which is very low so has been neglected.

2.3. Quasi-static force-displacement tests

In a cricket match, a ball experiences a high load each time it bounces on the pitch and each time it is hit by a bat. A bounce occurs on average 6 times per over, and the ball is hit by a bat on average 3 times per over. Quasi-static force-displacement tests have been carried out on two different cricket balls of the same brand to find how the behaviour of the ball varies with the number of loading cycles. The bounce tests explained above found that the average force on a ball during a bounce is of the order of 1 kN, and when hit by a bat the average force is 8.8 kN (Cross, 2005).

Two balls were cyclically loaded using a pneumatic actuator at positions equidistant around the circumference of the ball. The maximum load that could be applied by the actuator was 5 kN, therefore a 5 kN force was used to represent a ‘hit’, and 1 kN was used for a ‘bounce’. For every ‘10 overs of loading’, 12 different positions on the ball, 4 on the seam and 8 not on the seam, were subjected to 5 ‘bounces’ and 2 or 3 ‘hits’.

Every ‘10 overs of loading’ the force-displacement behaviour was measured using a load cell and an LVDT and was recorded using DasyLab. The ball was ‘bounce tested’ every 10 overs using the technique described in section 2.1.. The balls were bounce tested on concrete so as to remove the effects of the pitch variability. The CoR was measured for impacts on the seam and perpendicular to the seam.

The force-deflection behaviour has been used to calculate the variation of stiffness and damping with loading cycles. Results were obtained for impacts on the seam, and for impacts perpendicular to the seam.

The tolerances of the load cell and LVDT are again very small so the experimental errors in this experiment are negligible.

3. Results and Discussion

3.1. Bounce Tests

3.1.1. Variation of average CoR with water content

Three 'test pitches' were constructed at a saturation ratio of 0.86. This represents optimum compaction as was found for a Proctor Compaction Test. The pitches were of different water content, as shown in table 2. The pitches were allowed to dry out and were tested using the method described in section 2.1.1. in order to calculate the variation of CoR with water content and compaction level. The results are shown in figure 8.

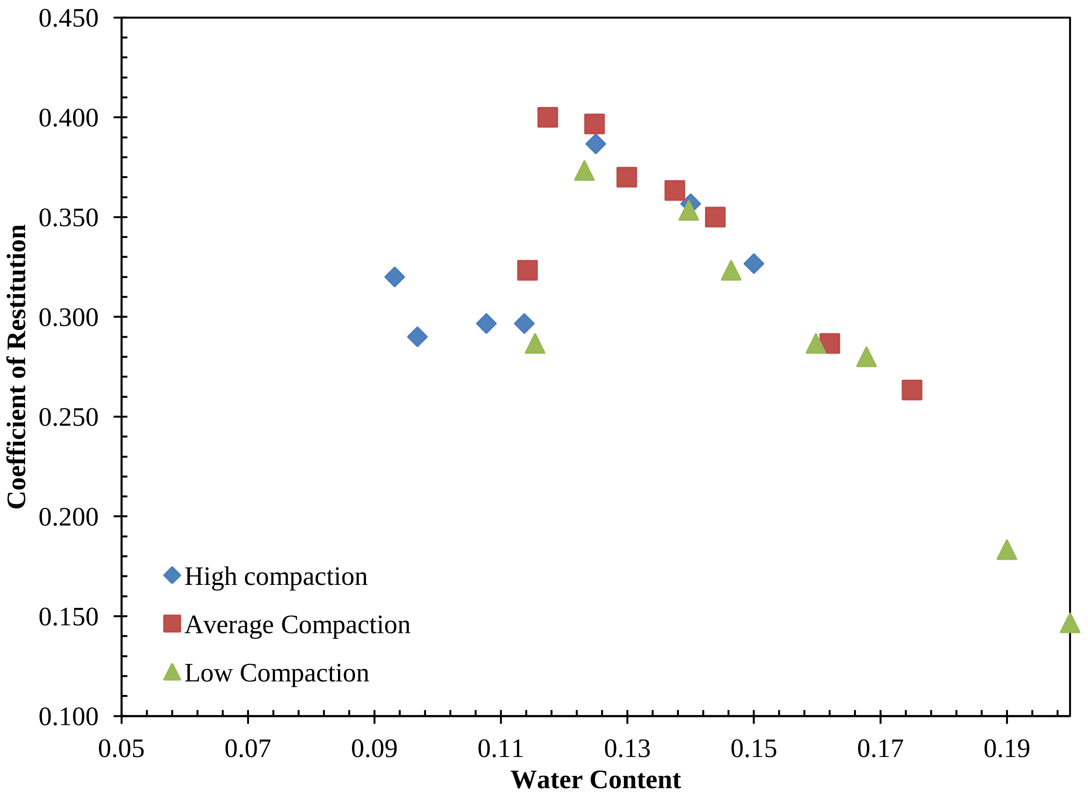


Figure 8 *Variation of CoR with water content and compression*

Figure 8 shows firstly that the bounce is independent of the compaction level. This is surprising since one could think that increasing the compaction would increase the peak friction angle between soil particles and therefore increase the strength leading to a higher CoR. However, the decreasing water content of the soil leads to increasing pore suction between particles. This increases the effective stresses between particles, which causes shrinkage and effectively increases the compaction of the soil. This effect is larger for the low compaction pitch with a high initial water content; therefore, although the initial compaction level of the pitches are different, drying of the soil has the effect of compacting all the pitches to the same level. This leads to the graph above where the CoR is solely dependent on the current water content of the soil.

The CoR of all three samples initially increases with decreasing water content. This is because the curvature of the menisci between particles increases with decreasing water content, increasing the pore suction and hence increasing the effective stress. This increases the strength of the soil, but also makes it more brittle. The CoR for all samples reaches a maximum at a water content of approximately 0.115 before suddenly decreasing. This is because the brittle characteristic of the soil, and shrinkage, create enough cracks in the soil that much of the energy of the ball is dissipated in plastic deformation of the soil. At low water contents the pitch is cracked into distinct 'plates'. When the ball bounces on a 'plate', the high speed photography shows movement of solely the 'plate' the ball has impacted on. This leads to opening and closing of cracks dissipating much energy hence causing a low CoR. Also, as found later in the report, at low water contents the inconsistency of the CoR is high because each 'plate' has different characteristics.

3.1.2. Repeated Loading of the Pitch

Three ‘test pitches’ with voids ratios of 0.53 and water contents of 0.108, 0.135 and 0.16 were subjected to repeated loading through repeated bounces of a new ball. The CoR was measured using the same method as described in section 2.1. to find the variation of CoR with number of loading cycles. The results are shown in the figure 9.

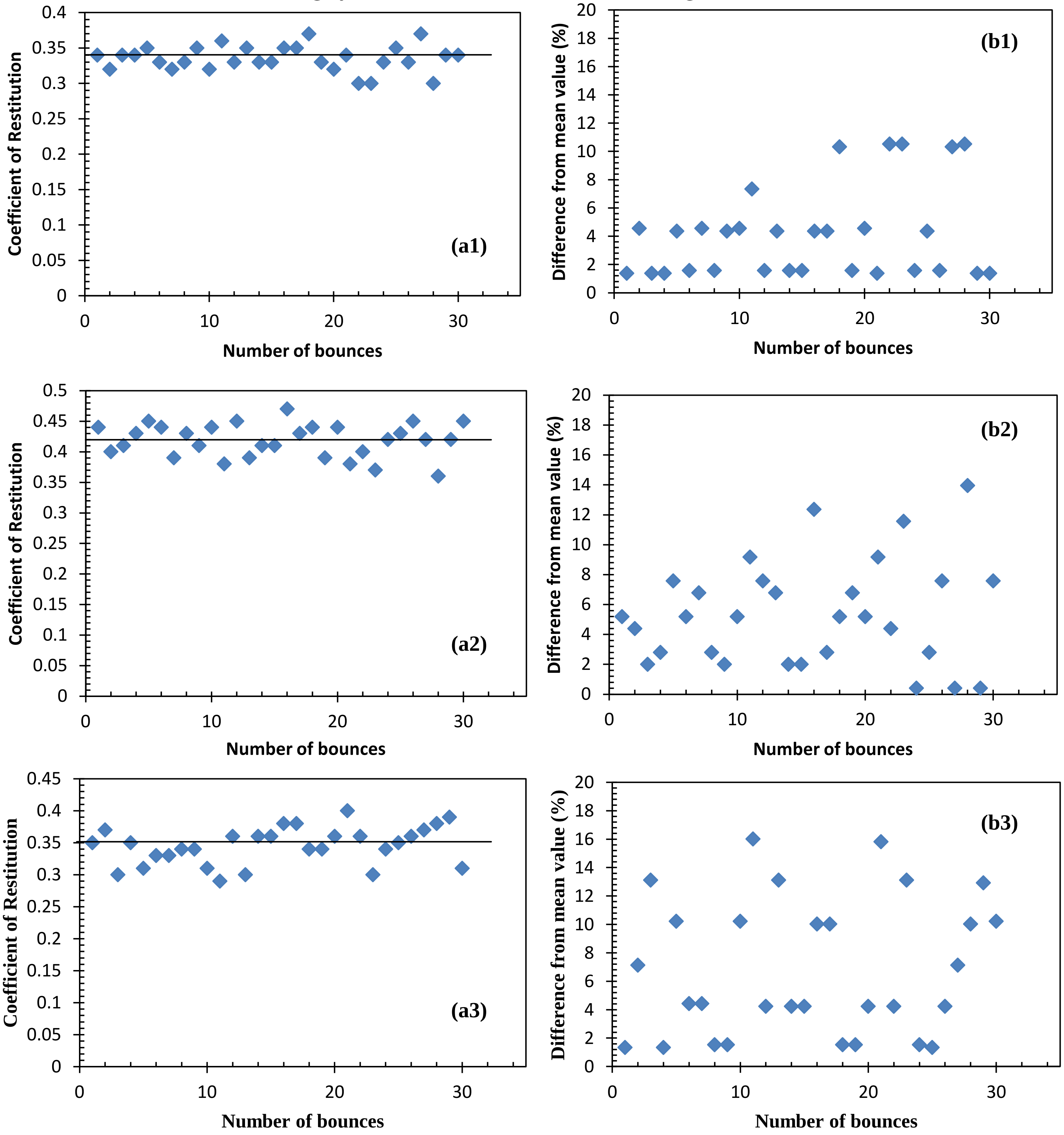


*Figure 9 **(a)** CoR vs. Number of bounces, **(b)** Difference from mean value vs. Number of bounces for 1) w=0.16, 2) w=0.135, 3) w=0.108*

The images below show how the surface of the pitches change with number of loading cycles:

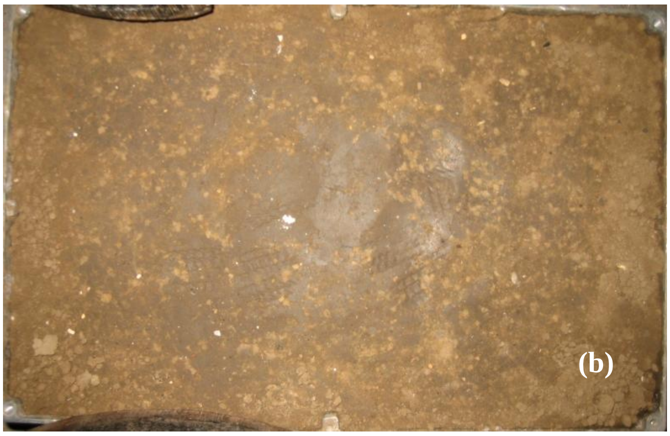


Figure 10 *Pitch surface after* ***(a)*** *0 bounces,* ***(b)*** *15 bounces,* ***(c)*** *30 bounces. Water content -0.16*

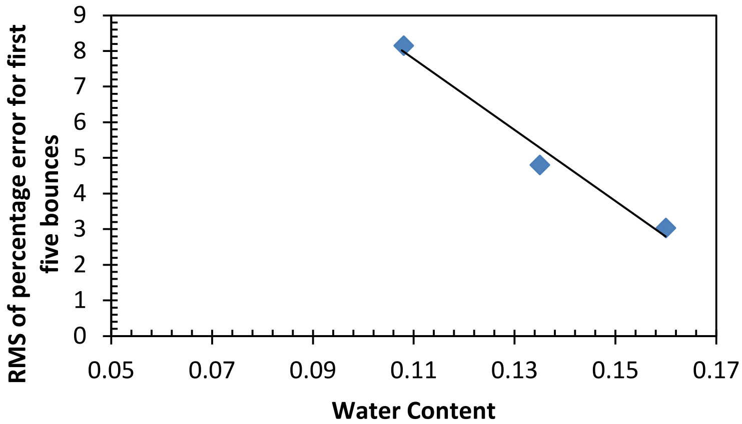
Figure 11 *Pitch surface after* ***(a)*** *0 bounces,* ***(b)*** *15 bounces,* ***(c)*** *30 bounces. Water content – 0.135*

Figure 12 *Pitch surface after 30 bounces. Water content – 0.108*

Figure 9 shows that the inconsistency of the CoR is dependent on both the water content and the number of loading cycles of the pitch. The photos in figures 10, 11 and 12 show that the amount of cracking of the pitch is dependent on the both the water content and the number of loading cycles of the pitch.

As the water content of the pitch decreases, the inconsistency of the CoR increases independently of number of loading cycles. This is because all pitches have been first constructed at the optimum water content for compression and then allowed to dry out. This leads to shrinkage causing cracks within the pitch, both on the surface and hidden within the soil. This cracking can be seen in the photos in figures 10, 11 and 12. It can be seen that for the pitch at optimum water content, 0.16, where no shrinkage has occurred, there is no cracking before loading, while for the pitch with water content of 0.135, shrinkage has occurred and there is slight cracking of the surface before any loading. Unfortunately there is no image of the pitch with water content 0.108 before loading, however significant cracking was observed.

To find the dependence of the inconsistency of the CoR on the water content, the root mean squared error was found for the first 5 bounces on each pitch. This minimised the effect of the number of loading cycles on the inconsistency. The relationship is shown in figure 13. For the pitch of approximately optimum water content, there are very few cracks, so for the first 5 loading cycles the inconsistency of the CoR is low, with an RMS value of 3.0%. For the pitch with water content 0.135, which shows some shrinkage and cracking, the inconsistency is slightly higher, with an RMS value of 4.8%. For the dry pitch, with water content 0.108, which showed substantial shrinkage and cracking, the inconsistency is large, with an RMS value of 8.1%. This shows that the amount of cracking of the pitch contributes to the variation of the bounce. Cracking of the surface splits the pitch into many ‘plates’. When a ball bounces on a ‘plate’, significant plastic deformation occurs with the ‘plate’ moving relative to other ‘plates’. This leads to cracks closing or opening. Each plate has different properties, and the same ‘plate’ has different properties if it is in a different position relative to the other ‘plates’ so the properties of a ‘plate’ vary after a bounce. Equation (3) shows that the depth of soil stressed by an impact is of the order of 60 mm, whereas the plan area is approximately four times the contact area (~ 4 mm^2). Therefore, the behaviour of the bounce is characterised by local properties. This means a different amount of plastic deformation occurs for each bounce leading to an inconsistent CoR.



r	*p*	*n*
-0.988	0.085	3

Figure 13 *RMS error in CoR of first 5 loading cycles vs. water content.*

For pitches of water content 0.135 and 0.16, the variation of the CoR increased with increasing number of loading cycles as shown in figure 14. This is because, as shown in figures 10 and 11, the loading of the pitch causes further cracking. This is because the pitches are below optimum water content and hence are brittle. Therefore loading the pitches leads to cracks. For the pitch with water content 0.108, no change was seen in the variation of CoR with number of loading cycles. This is because so much shrinkage had occurred prior to loading that the pitch was already extensively cracked so loading had no further effect.

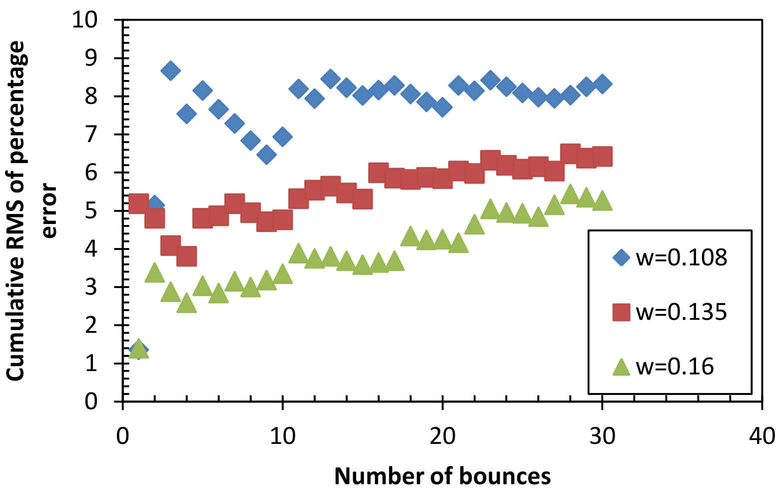


Figure 14 *Cumulative RMS error in CoR with number of bounces for pitches of different water contents.*

The results show that both factors, namely number of loading cycles and water content of the soil, play a significant role in the variation of inconsistency of the CoR. Both factors are important and their impact on the real pace and bounce of a cricket pitch will be investigated later in the report.

3.2. Surface Friction Tests

Three test pitches of voids ratio 0.86, and initial moisture content of 0.156, 0.178 and 0.185 were tested using a friction sledge to determine the surface friction coefficient. The pitches were tested as the water content decreased. The results are shown in figure 15. Error bars are not shown because the experimental error is negligible.

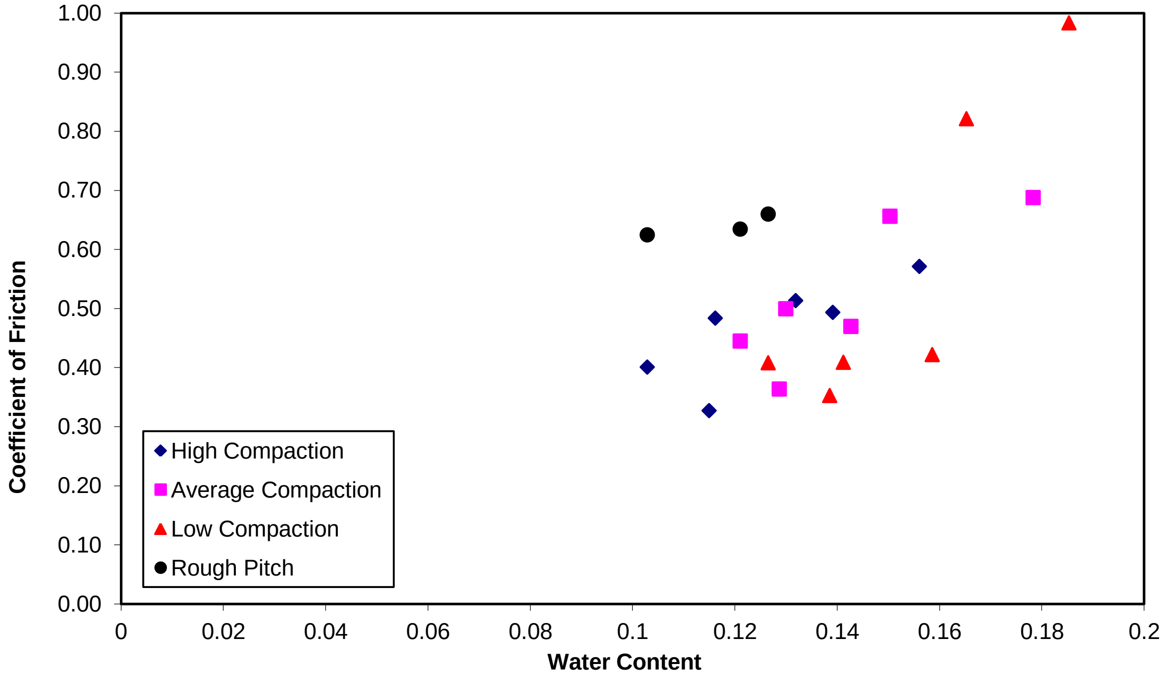


Figure 15 *CoF vs. Water content*

Ignoring the 'rough pitch' data points, a linear correlation can be observed for each of the three pitches. Table 3 shows the Pearson's Correlation Coefficient, (*r*), the statistical significance, (*p*), and the number data points, (*n*), for each of the three 'pitches'.

Compaction	***r***	***p***	***n***
High	0.795	0.06	6
Average	0.847	0.017	6
Low	0.877	<0.01	6

Table 3. *Statistical significance of linear correlations in figure 15.*

Table 3 shows that the linear correlations are statistically significant, especially for the pitches of average and low compaction. The gradient of the correlation decreases with increasing compaction, so decreasing the water content has less effect on more compacted pitches. Therefore, unlike for the bounce tests where the CoR was found to be independent of the compaction, the compaction level is important. This is because the CoF is a measure of only the surface properties of the soil, whereas the CoR is a measure of the bulk properties of the soil. The CoF is proportional to the force required for a cricket ball to slide across the surface. Therefore if a pitch deforms more under loading, the CoF will be higher as a higher force is needed to 'plough' the ball through the soil. For pitches of low compaction, the shrinkage of soil when the water content reduces increases the compaction as explained earlier. Therefore the strength of the soil increases with decreasing water content since there is both more friction and higher suction between particles. This means that the amount of deformation decreases quickly with decreasing water content, so the CoF also reduces quickly. However the increase in strength for a more compact pitch is less since the shrinkage is lower; therefore the gradient of the linear relationship between water content and CoF decreases with increasing compaction.

The tests have shown that the CoF decreases with decreasing water content of the soil; however this has only considered the properties of the soil when the surface has had no usage. During a match, the surface becomes worn and rough due to repeated bounces of the ball and because of players running on the pitch. The effect of roughness was investigated briefly and it was found to increase the CoF of the surface significantly, as shown in figure 15.

Grass has not been included in this experiment, although it plays an important role in determining the CoF. McAuliffe and Gibbs (1997) found that the level of grass coverage of a pitch determines the pace of the bounce. A further investigation is required to find the coupled relationship between grass coverage and water content on the CoF.

3.3. Quasi-Static Force Displacement Tests

Two balls were subjected to quasi-static loading as explained in section 2.3. To make the quasi-static tests representative of dynamic loading, the measured deflections were halved since the ball is being compressed at its top and its base (Cross, 1999). The force-displacement behaviour for the two balls during a ‘bounce’ is shown in figures 16 and 17 for impacts perpendicular to the seam and impacts on the seam.

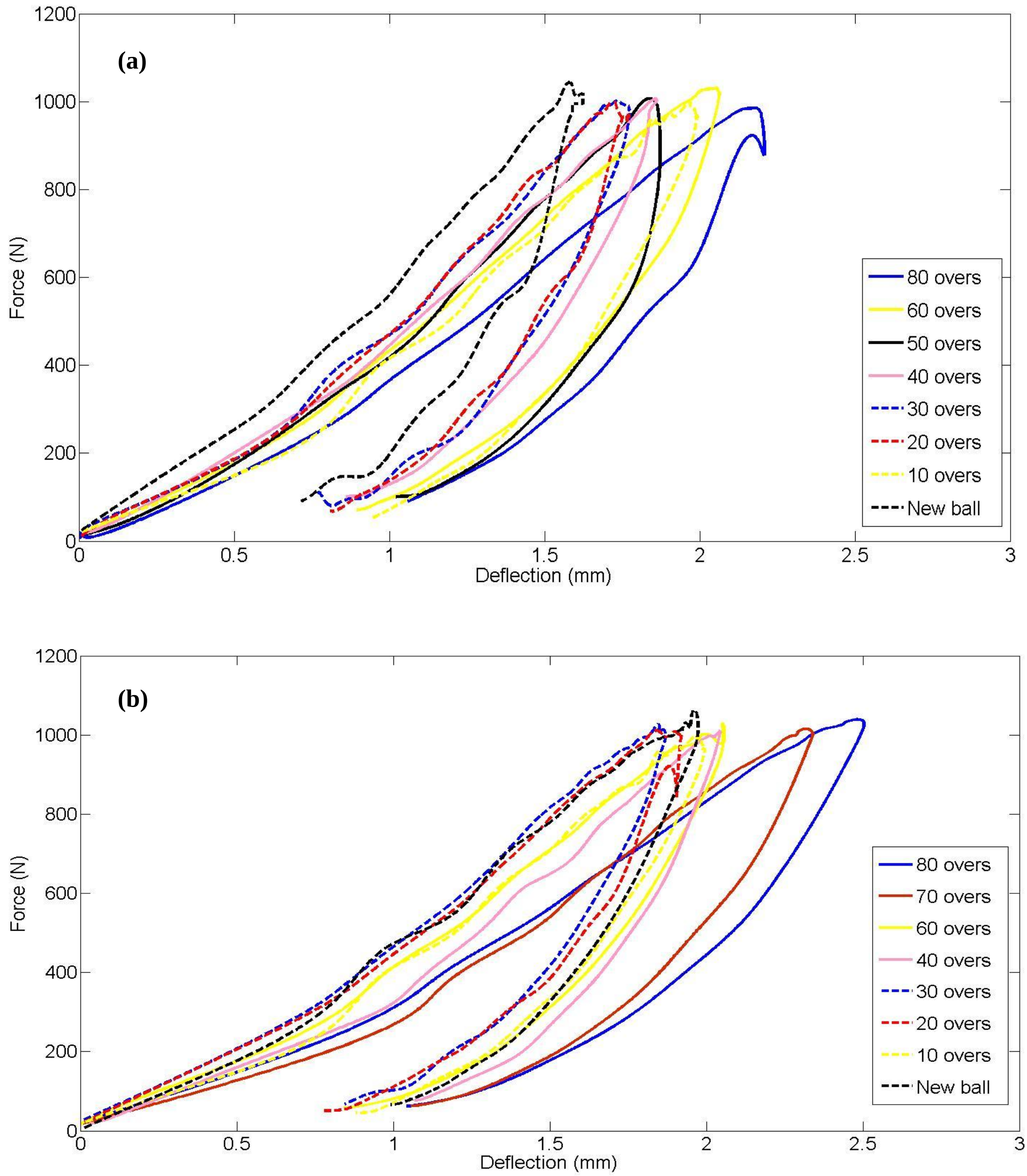


Figure 16 *Force-deflection curves for ball 1 -* ***(a)*** *Impact perpendicular to seam* ***(b)*** *impact on seam*

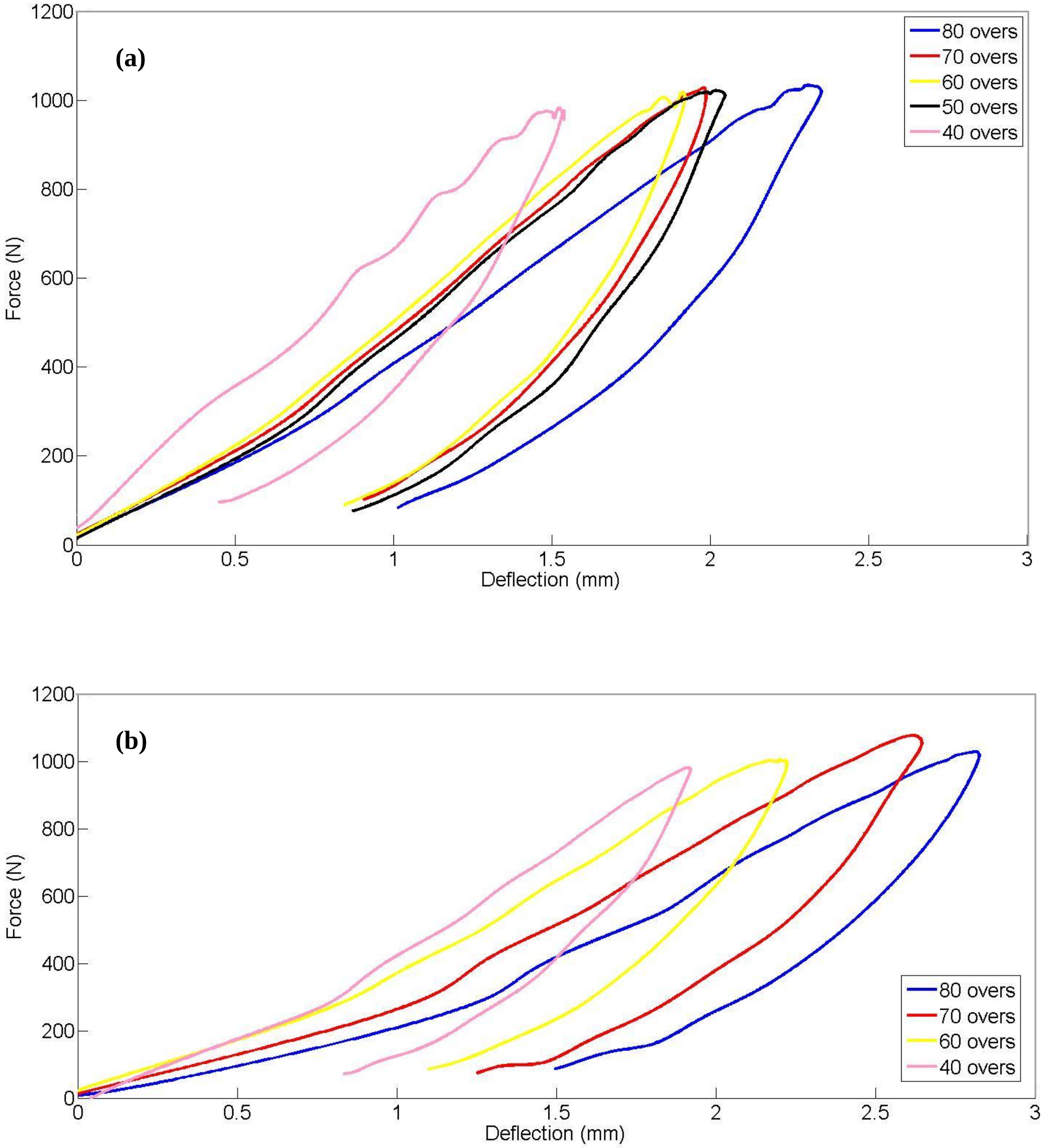


Figure 17 *Force-deflection curves for ball 2 -* ***(a)*** *Impact perpendicular to seam* ***(b)*** *impact on seam*

Figures 16 and 17 show that the the deflection of the ball is larger when loaded on the seam, than when loaded perpendicular to the seam. The maximum deflection for a new ball loaded on the seam was 1.9 mm whereas that for loading perpendicular to the seam was 1.5 mm. This agrees with the results obtained by Carre *et al.* (2004). This disparity is due to the presence of the seam. When the ball is loaded the ball compresses in the direction of loading at the point of the load. However, due to Poisson's ratio effects, the ball must elongate in the direction perpendicular to loading elsewhere in the ball. The seam can be thought of as a loop of fabric encircling the ball with a high stiffness. The circumference of the 'loop' cannot easily be increased. Therefore when loading is perpendicular to the seam, the elongation perpendicular to loading is restricted by the seam so the elongation is reduced. Therefore the deflection in the direction of loading must also be reduced. When loaded on the seam there is nothing restricting the elongation so the deflection is higher. This is shown in figure 18.

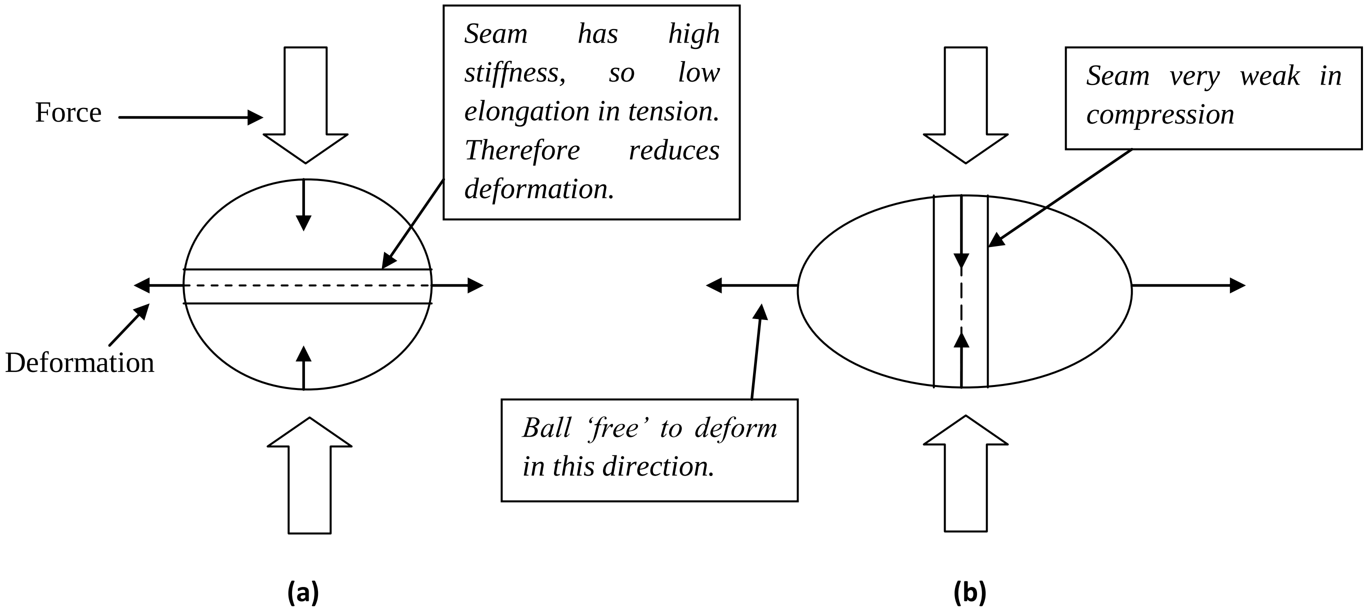
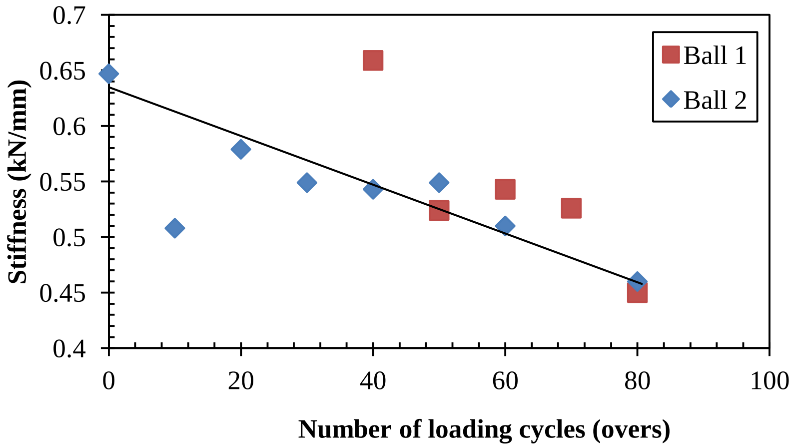


Figure 18 *Deflection for a cricket ball loaded **(a)** perpendicular to seam **(b)** on seam*

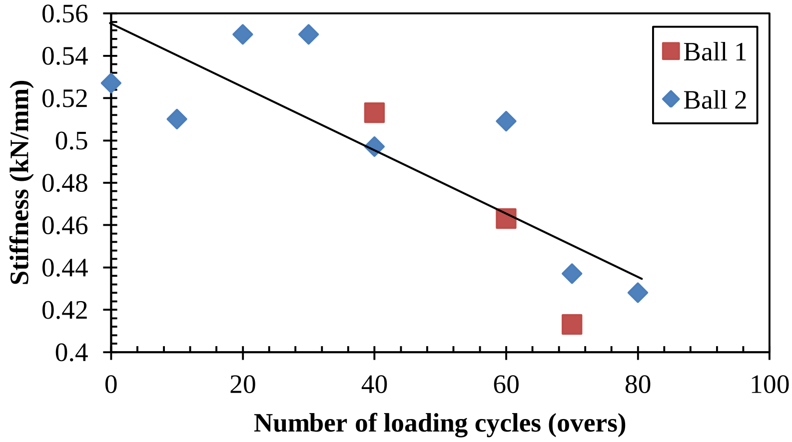
It is also apparent that a cricket ball is not constructed from a linear-elastic material. The loading curves show that the stiffness of the ball increases with deformation as stated by Fuss (2008). However, for the loading regime, two distinct linear stiffness regions are apparent; a 'primary stiffness' for approximately the first 0.75 mm of deformation followed by a higher 'secondary stiffness' for the remainder of the loading regime. For each of these regimes the stiffness is approximately constant. These two different regimes occur because the initial deformation occurs in the leather and cork layers of the ball, but, when the deformation is higher, the rubber-cork core is also deformed which has a higher stiffness than the outer layers. This leads to a 'secondary stiffness' higher than the 'primary stiffness'.

Figures 16 and 17 also show a trend of increasing deformation with number of loading cycles for a given force. Figures 19 and 20 show how the average stiffness over the loading cycle varies with number of loading cycles.



r	*p*	*n*
-0.831	<0.01	11

Figure 19 *Average stiffness vs. number of loading cycles – loading perpendicular to seam.*



r	*p*	*n*
-0.659	0.0203	13

Figure 20 *Average stiffness vs. number of loading cycles – loading on the seam.*

Figures 19 and 20 both show a strong negative correlation between average stiffness and number of loading cycles for both loading orientations. The correlation is significant since $p<0.05$ for both orientations. The reduction in stiffness with loading cycles is due to permanent deformation and damage to the ball caused by loading. On dissecting the ball, cracking is visible in the leather casing of the ball and the cork layer; however there is no visible damage to the rubber-cork composite core, as shown in figure 21.

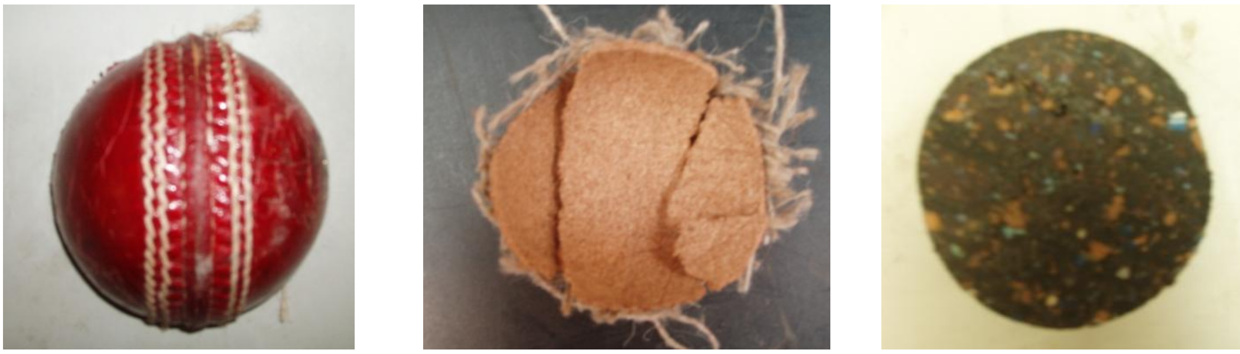


Figure *21 Damage to ball after 80 'overs' of loading*

This suggests that the changing properties are due to solely the changing properties of the outer layers of the ball. When the ball is new, the leather and cork casing are relatively stiff however the stiffness decreases with loading cycles due to cracking. The primary stiffness can be seen to decrease with loading cycles in figures 16 and 17. This also means that the rubber-cork composite core is less restrained and so can deform more easily leading to a lower 'secondary stiffness' as shown in figure 22. Therefore the average stiffness also decreases with loading cycles.

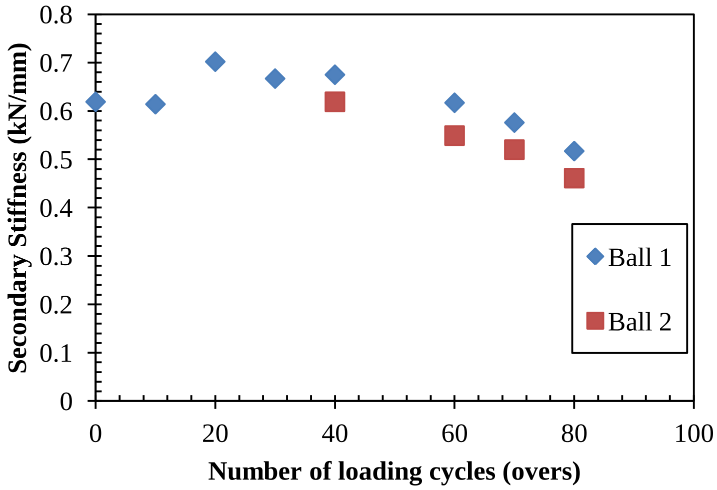
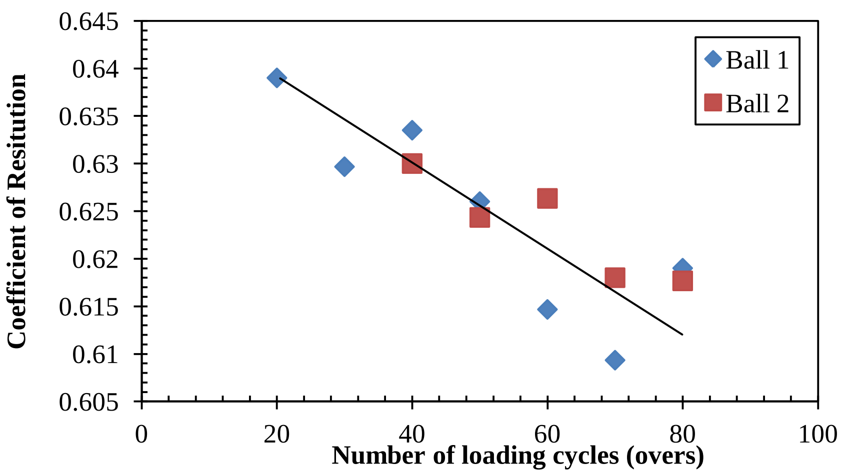


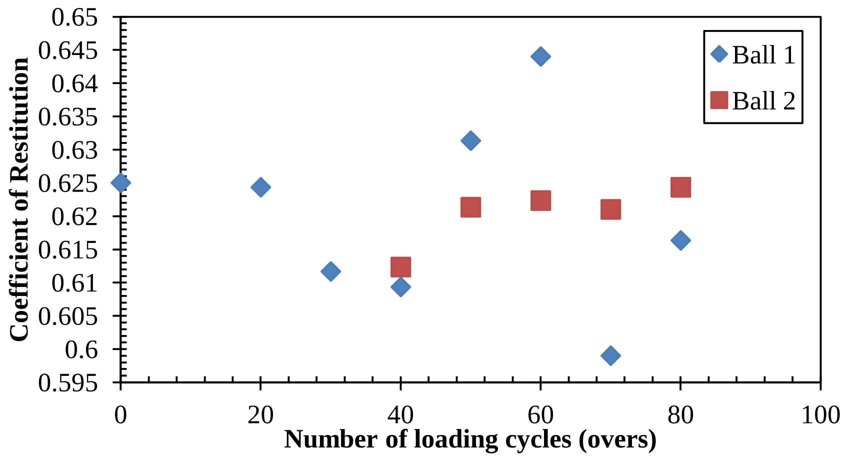
Figure 22 *Secondary stiffness vs. number of loading cycles on ball*

To find how the CoR varies with number of loading cycles, bounce tests were performed on the balls every '10 overs of loading' using the method described in section 2.1. The results are shown in figures 23 and 24.



r	***p***	***n***
-0.883	<0.01	13

Figure 23 *CoR vs. number of loading cycles – loading perpendicular to seam.*

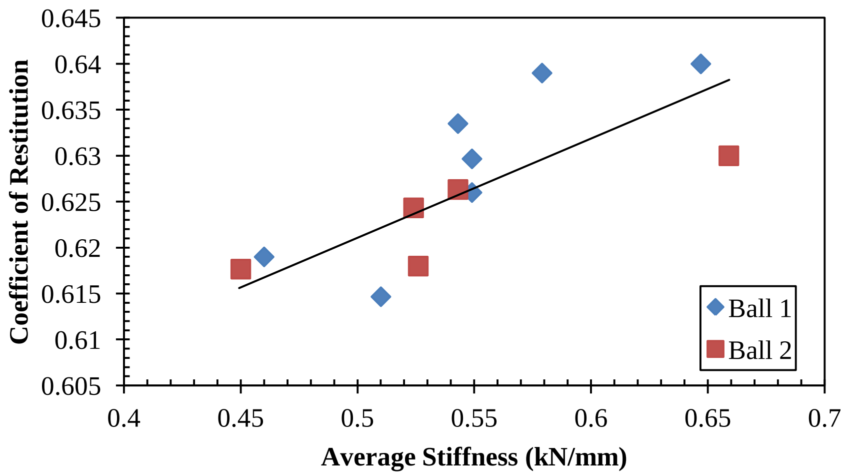


r	*p*	*n*
-0.046	n.s.	13

Figure 24 *CoR vs. number of loading cycles – loading on the seam.*

Figure 23 shows that there is a strong correlation with $p<0.01$ between the CoR and the number of loading cycles when bounced perpendicular to the seam. However figure 24 shows that when loaded on the seam, no correlation is apparent. This could be due to localised damage occurring on the seam when loaded causing inhomogeneous properties around the seam. Therefore when the ball is bounced tested the CoR is dependent on the exact location of the impact on the seam relative to the location of the loading tests.

The two correlations found above between average stiffness and number of loading cycles and CoR and number of loading cycles perpendicular to the seam, suggest a relationship between the average stiffness of the ball and the CoR for ball bounces perpendicular to the seam. This relationship is shown in figure 25.

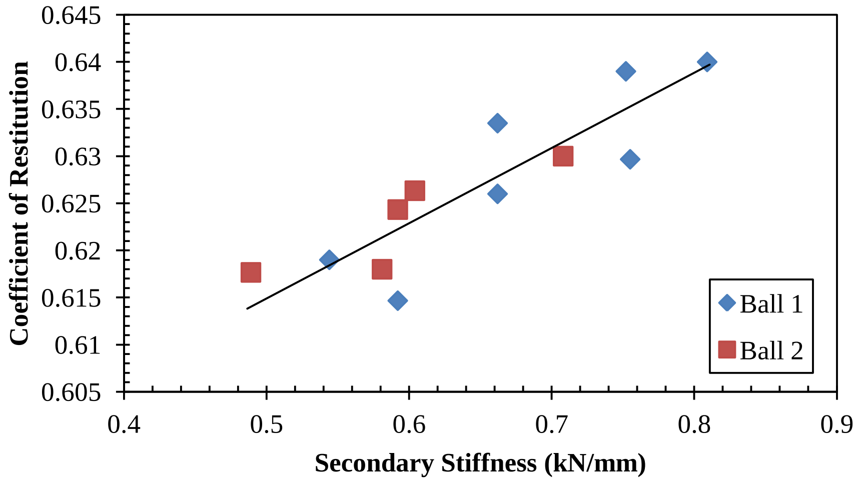


r	*p*	*n*
0.752	<0.01	12

Figure 25 *Average stiffness vs. CoR – loading perpendicular to the seam.*

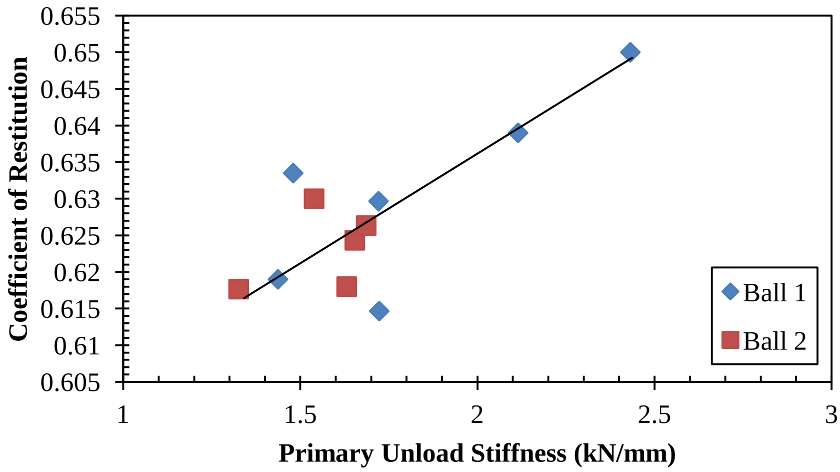
The correlation is statistically significant with $p<0.01$. This means that the average stiffness of a cricket ball, which can be easily measured, can be used to predict the bounce of the ball.

Although the average stiffness provides a good correlation to the CoR, further work was carried out to investigate whether the ‘secondary stiffness’ or the ‘primary unload stiffness’, defined as the average stiffness during unload for the first 0.5 mm of unloading, gave a better correlation. The reason for the work was that it was thought that these two stiffnesses are what the ball ‘experiences’ at the very end of its deceleration and very start of its acceleration so may play an important role in determining the behaviour of the bounce. The correlations are shown in figures 26 and 27 for impacts perpendicular to the seam.



r	*p*	*n*
0.874	<0.01	12

Figure 26 *Secondary stiffness vs. CoR – loading perpendicular to the seam.*



r	*p*	*n*
0.777	<0.01	11

Figure 27 *Primary unload stiffness vs. CoR – loading perpendicular to the seam.*

Figures 26 and 27 show that both the ‘secondary stiffness’ and ‘primary unload stiffness’ give statistically significant correlations with CoR. Both give more statistically significant correlations than the average stiffness, with the secondary stiffness correlation being substantially more significant than the primary unload stiffness correlation.

The second mechanical property that can be obtained from the force-deflection plots is the energy dissipated through hysteretic damping. This is calculated by finding the area under the force-deflection curve. In order to make the quasi-static tests representative of a dynamic bounce, the energy dissipated per cycle, ΔE, must be doubled (Cross, 1997). Using equation (1) the hysteretic damping coefficient, h, can be calculated. Figures 28 and 29 show how h varies with number of loading cycles for impacts on the seam and perpendicular to the seam.

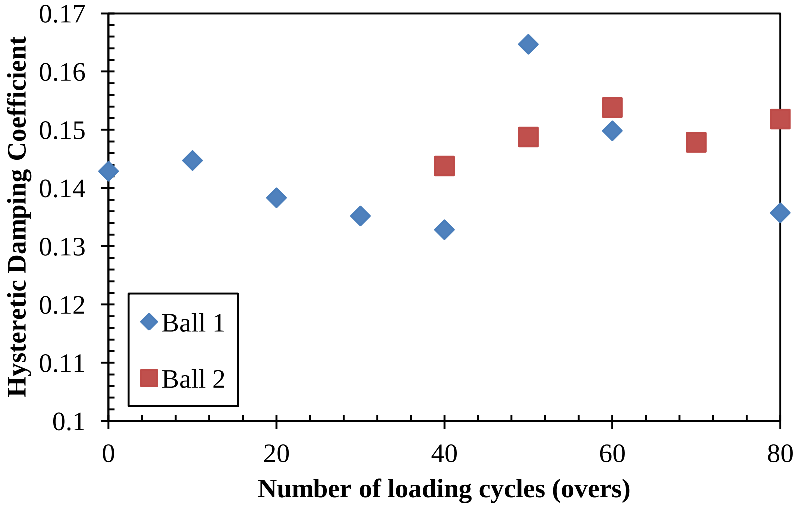


Figure 28 *Hysteretic damping coefficient vs. number of loading cycles – loading perpendicular to the seam.*

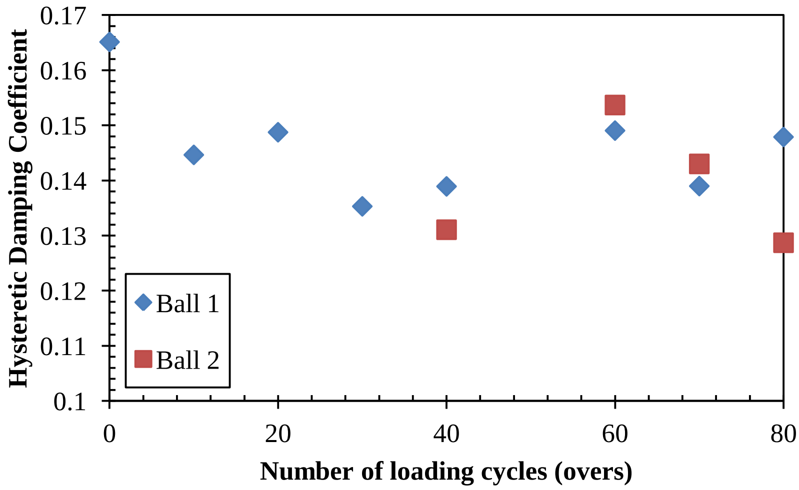


Figure 29 *Hysteretic damping coefficient vs. number of loading cycles – loading on to the seam.*

Figures 28 and 29 show no correlation between the hysteretic damping coefficient and the number of loading cycles. It appears that the damping is independent of the number of loading cycles.

Carre *et al.* (2004) proved that a Hertzian mass-spring-damper model can be used to model the force-deflection behaviour of a cricket ball. The authors found that the best results occurred when the damping coefficient varied with contact area of the bounce. Further work could involve creating a similar model, but with the damping coefficient as a function of the hysteretic damping coefficient, not the contact area. The equation of motion is shown below:

$$F_y = ky^a + c\dot{y} \tag{5}$$

If *c* is allowed to vary with hysteretic damping coefficient, *h*:

$$c = ph \tag{6}$$

where p and a are constants.

This would then enable the CoR to be modelled using both the damping coefficient and the stiffness of the ball.

4. Interpretation

This section of the report focuses on how the results explained earlier affect the actual bounce of a ball during a cricket match.

James *et al.* (2005) found that a rigid body model can be used to predict the rebound dynamics given the surface restitution and friction. Although the model does not allow for deformation of the pitch or ball so is inherently inaccurate, it has been found to accurately predict the rebound speed and therefore the pace of the bounce as shown in figure 30.

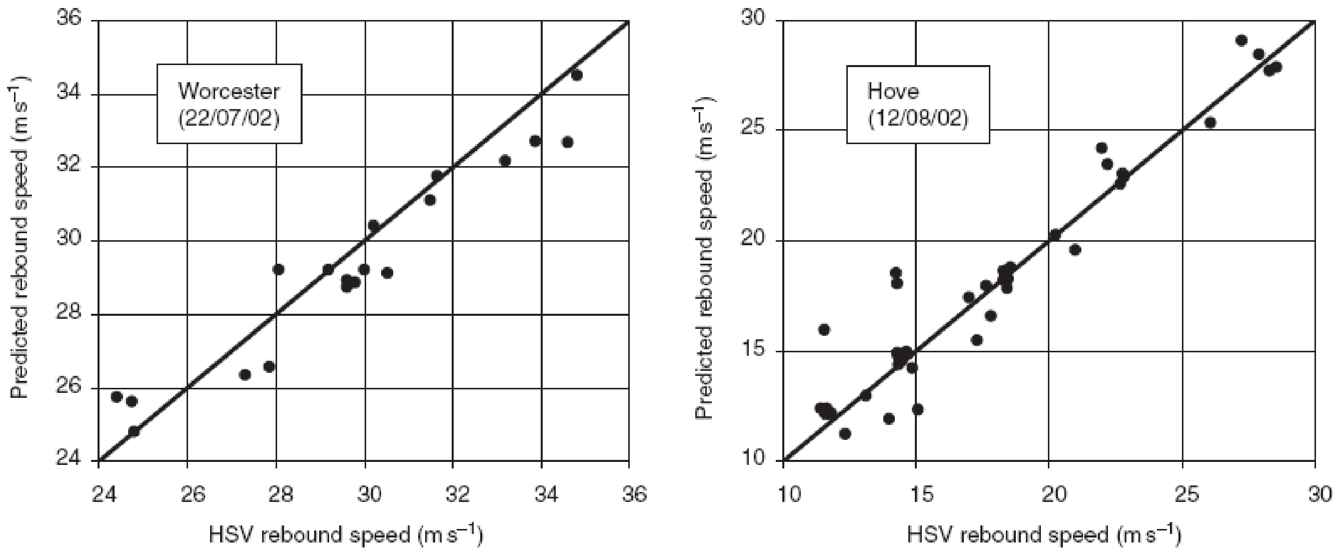


Figure 30 *Comparison between high speed video rebound speed from matches and the predicted speed from a rigid body model, James et al. (2005)*

However the model was found to poorly predict the rebound angle – it always underestimates the angle. This is because the model does not take deformation into account. Deformation of the pitch has the effect of kicking the ball up at a steeper angle than a rigid body. Despite this the model provides a method of investigating how changes to the ball and pitch affect the pace of the bounce. It can also be used to provide trends of how the rebound angle would vary. Adams *et al.* (2004) surveyed professional cricket umpires and found the most important parameter is the pace of the bounce, so the model is very useful.

The derivation of the model is shown in the appendix. However the key equations are shown below:

$$V_{x\,out} = V_{x\,in} - \mu V_{y\,in}(1 + e) \tag{7}$$

$$V_{y\,out} = eV_{y\,in} \tag{8}$$

$$\omega_{out} = \frac{5\mu V_{y\,in}}{2R}(1+e) - \omega_{in} \tag{9}$$

where e is the coefficient of restitution, μ is the coefficient of friction and R is the radius of the ball.

For each of the following parameters, the effect the parameter has on the pace of the bounce has been evaluated for a pitch of 'average compaction'-voids ratio 0.53:

1) Water content of pitch
2) Number of loading cycles on pitch
3) Number of loading cycles of ball

The effects have been evaluated for an 'average seam bowler' as defined by James *et al.* (2005). The delivery arrives at the pitch with a speed of 36 m/s at an angle of 12.5^0 to the horizontal. Therefore the vertical and horizontal components of the velocity of the ball are shown in table 4.

$V_{x\,in}$	$V_{y\,in}$
35.15 m/s	7.80 m/s

Table 4. *Initial dynamics of an average seam delivery*

4.1. Water Content of Pitch

The water content of the pitch has been found to affect both the CoF and the CoR. The relationships between water content and CoR and water content and CoF have been modelled by using the linear relationships found in this report. These are shown in figure 31.

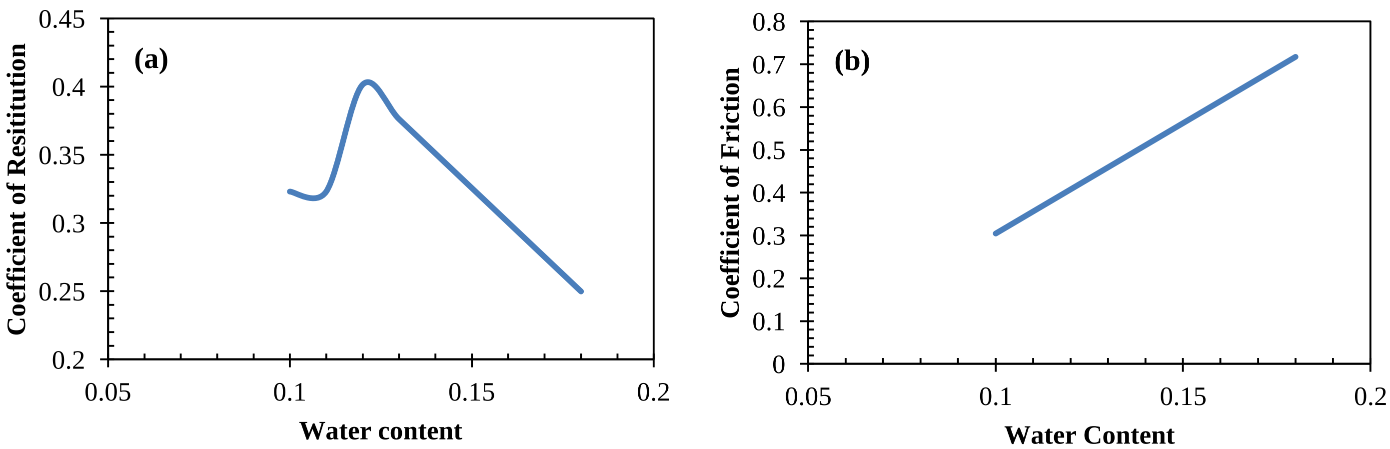


Figure 31 *(a) Modelled water content vs. CoR, (b) vs CoF*

Using these models, the relationship between the pace of the pitch and the water content can be found using equations (7) and (8). This is shown in figure 32.

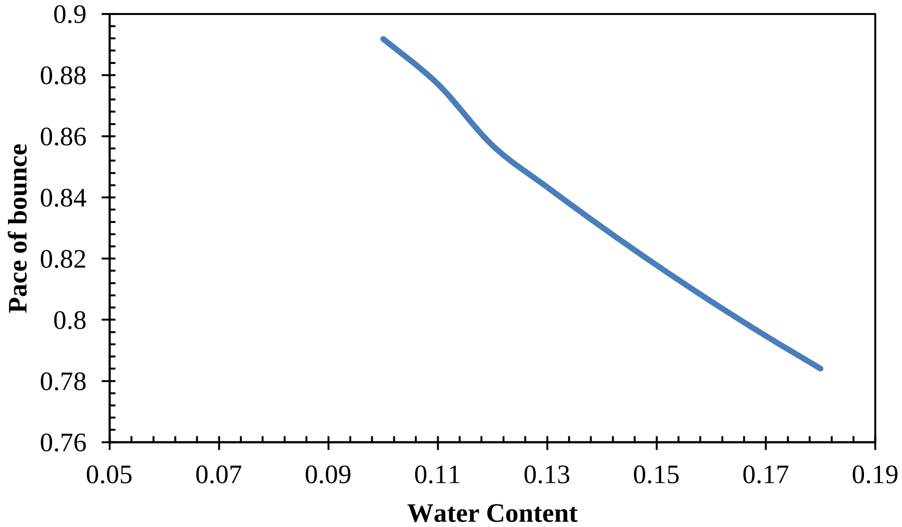


Figure 32 *Pace vs. water content*

Figure 32 shows that the pace of the pitch increases with decreasing water content despite the fact that the CoR decreases substantially at a water content of approximately 0.11. This shows that the decreasing CoF with water content dominates the effect of water content on the pace of the pitch. This is because the decreasing CoF increases the horizontal component of rebound velocity, and since this is much larger than the vertical rebound velocity it is the dominating property. Therefore over the course of a match, as the water content decreases, the pace of the pitch would be expected to increase. This correlation agrees with the results from James *et al.* (2002) although they predict the pace to be slightly higher.

As explained in section 3.2. the model used for water content vs. CoF is very simple. It took neither the effects of grass or usage of the pitch into account. Grass reduces the CoF (McAuliffe and Gibbs, 1997) and usage increases it through roughening the surface. Therefore over the course of a match three effects - the water content decreasing, the wear of the pitch increasing and the amount of amount of grass decreasing - may create a relationship for CoF against time that is far more complex than that given here. The CoF may be lower when these effects are considered which would account for the lower pace results calculated in this report. This is an area that requires further work.

An important aspect of the bounce is the height of the ball as it reaches the batsman. Although the model does not predict the rebound angle accurately, it can be used to show the generic trend of how the height of the ball as it reaches the batsman varies with water content. Figure 6 shows that the average seam bowler delivery bounces approximately 5 m in front of the batsman. Therefore using the initial ball dynamics shown in table 4, and assuming no drag force on the ball, the relationship between the height of the bounce and water content can be found using equations 10 and 11. This is shown in figure 33.

$$t = \frac{5}{V_{x\ out}} \tag{10}$$

$$H = V_{y\ out}t - 0.5gt^2 \tag{11}$$

where t is the time taken for the ball to reach the batsman after bouncing, and H is the height of the bounce at the batsman.

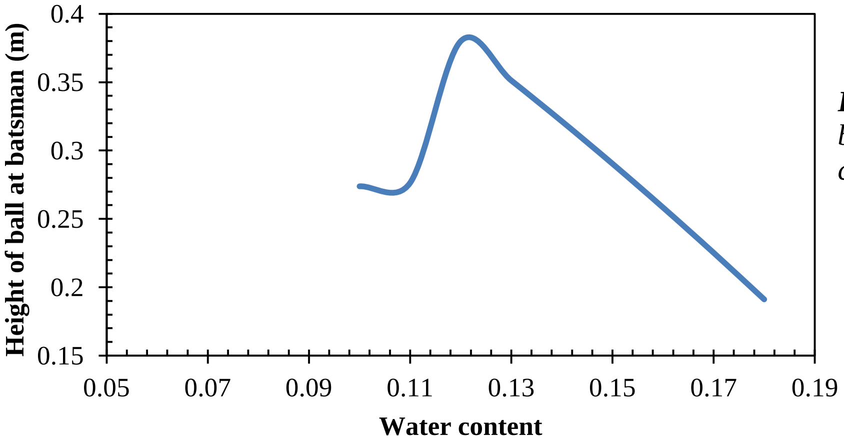


Figure 33 *Variation of height of ball at batsman with water content for a normal seam bowler*

As explained above, figure 33 does not show an accurate prediction of the bounce of the ball, as it is dependent on the deformation of the pitch. However it can be used to show a trend which can then be compared with the effects of different parameters.

4.2. Number of loading cycles on pitch

Both the number of loading cycles the pitch has experienced and the water content of the soil affect the inconsistency of the CoR. No work has been carried out to examine whether the CoF is dependent on the number of loading cycles so it will be assumed to be only dependent on water content. This is an area that requires further work.

Again using equations (7) and (8) the RMS error in the pace of the bounce can be calculated. As before, since the horizontal component of velocity dominates the pace measurement, and the CoF is assumed constant, the inconsistency of the pace is very small as shown for the pitch of water content 0.135 in figure 34.

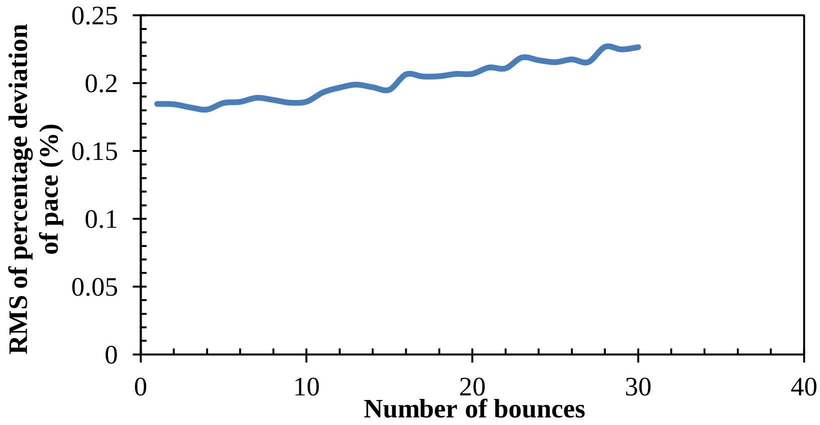


Figure 34 *RMS deviation of pace vs. Number of bounces for a pitch of water content 0.135*

However, the inconsistency of bounce in the vertical direction is found to be substantial. The rigid body model and equations (10) and (11) predict the trend shown in figure 35 for the variation of the RMS error in the deviation of the height of the bounce with number of loading cycles.

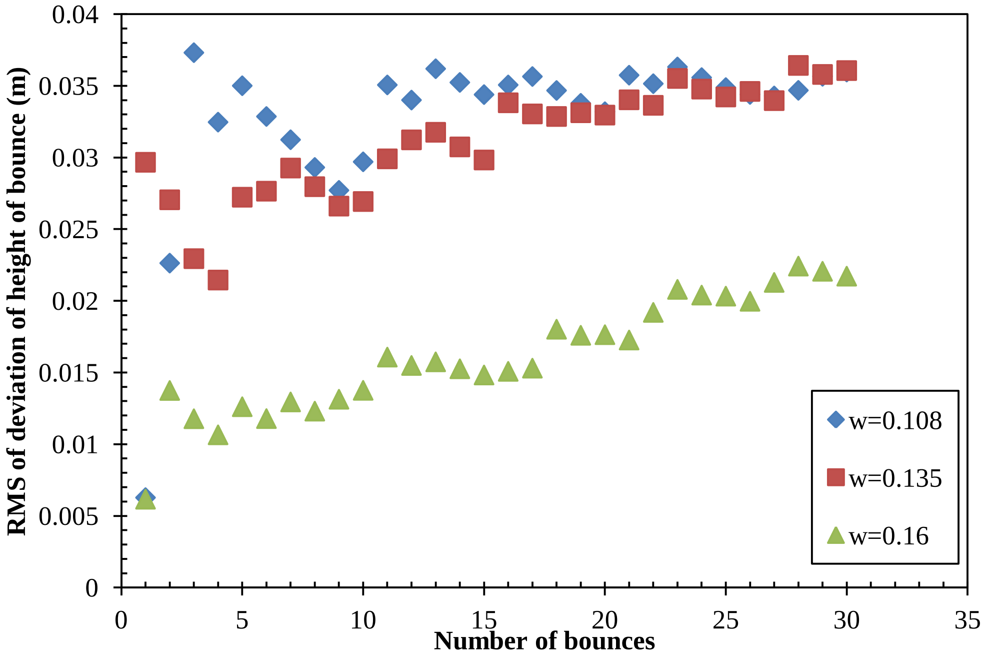


Figure 35 *RMS deviation of height of bounce at batsman vs. Number of bounces for pitches of varying water content.*

Figure 35 shows that the inconsistency of the height of the bounce is greater for pitches of both lower water content and higher number of loading cycles. This is because of cracking as explained in section 3.1. The model returns an RMS error value of the order of 3cm for a pitch of low water content. Whilst this is interesting, what is important for a batsman is what the maximum inconsistency of the bounce will be. The distribution of the CoR is likely to be

Gaussian, so having only examined 30 bounces experimentally, the extreme values of the Gaussian distribution are not known. Despite this, the measured extreme values should be close enough to the extremes to give an insight into the variation of the maximum inconsistency of the bounce with water content over the period of a match (30 bounces). Table 5 shows the maximum percentage variation in height of the bounce for the three pitches.

Water Content	**Maximum variation of height of bounce (%)**
0.16	15.0
0.135	17.2
0.108	22.8

Table 5. *Maximum percentage variation of height of bounce*

Therefore, although the model has been found to not accurately predict the angle of the bounce, table 5 shows that with decreasing water content the vertical bounce of the ball becomes increasingly inconsistent. This will lead to the ball reaching the batsman at varying heights causing him many difficulties. This is what is found in reality; variable bounce is a common feature of cricket pitches on days 4 or 5 of a test match.

4.3. Number of loading cycles on ball

The best correlation between loading cycles and CoR was found by using the measured 'secondary stiffness' of the ball. Therefore this will be used to find how the pace of the pitch varies with mechanical properties of the ball. Figure 36 shows the linear correlation found in this report between the 'secondary stiffness' and the CoR, and between the number of loading cycles and CoR. The results measured experimentally were for bounces on concrete, therefore to find how the CoR would vary on a real cricket pitch of average compaction and water content 0.12 the same relationship has been used.

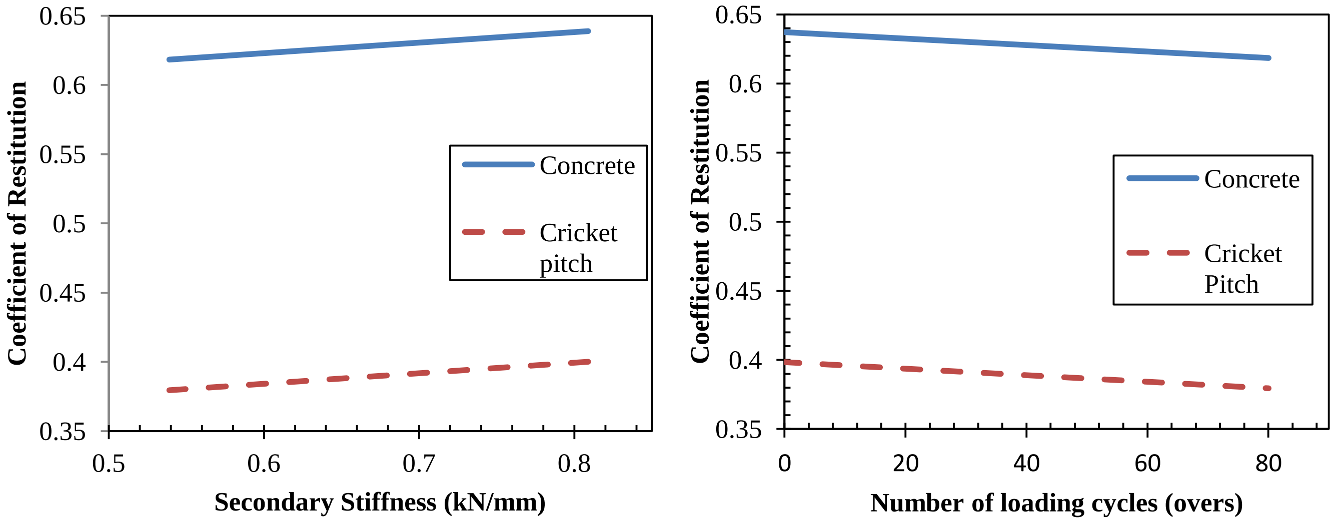


Figure 36 *Modelled relationships of CoR vs. Secondary stiffness and CoR vs. Number of loading cycles on ball*

Therefore, the pace of the pitch can be calculated given the secondary stiffness, which is easily measured, or given the age of the ball using the rigid body model as before. The variation of pace with secondary stiffness and age is shown in figure 37.

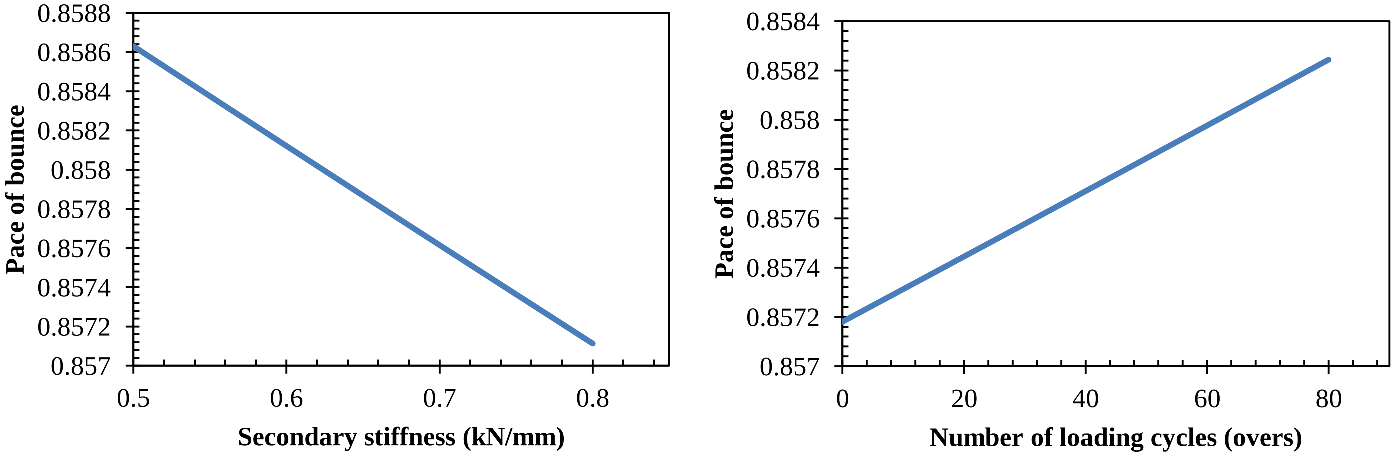


Figure 37 *Pace vs. Secondary stiffness and Pace vs. Number of loading cycles on ball*

The model predicts that the pace of the bounce will increase as the ball gets older. This is because although the decreasing CoR with age decreases the vertical rebound velocity, it increases the horizontal component of velocity. The horizontal component is larger than the vertical component, therefore this increase dominates the change in pace. This is not what would be expected, as in reality the pace of the bounce decreases with age of the ball. The discrepancy in the results found in this report could be because the variation of CoF of the ball with number of loading cycles was assumed to be constant. It could increase with increasing loading cycles as it will become rough, and therefore the horizontal rebound velocity would be decreased, hence causing the pace of the bounce to decrease with the number of loading cycles. This is an area that requires further work.

The results do however predict a trend of the height of the bounce of the ball at the batsman decreasing with the number of loading cycles as is expected. Using the average impact dynamics shown in table 4, the variation of the height of the ball as it reaches the batsman is shown in figure 38, again assuming no drag on the ball and using equations (10) and (11).

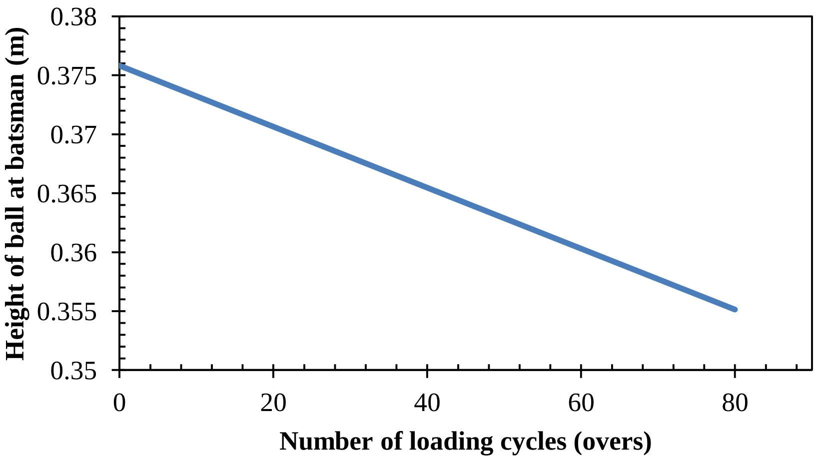


Figure 38 *RMS deviation of height of bounce at batsman vs. Number of loading cycles on ball*

Therefore it can be seen that the effect of the changing properties of the ball only leads to a small change in height of the bounce.

5. Further Work

An in depth analysis of how variables other than the water content affect the CoF will enable far better modelling of the pace of the bounce to be carried out. The effects of grass, wear of the pitch and the number of loading cycles on the pitch should be investigated. Over the course of a cricket match it would be expected that the amount of grass coverage would decrease, whilst the wear and amount of loading of the surface will increase.

A Hertzian mass-spring-damper model could be derived for a cricket ball, similar to that found by Carre *et al.* (2004), that incorporates both the stiffness of the ball and the hysteretic damping. This should give an excellent correlation between the mechanical properties of the ball and the CoR.

The effect of deformation of the pitch and ball could be investigated so as to improve the rigid body model derived by James *et al.* (2005). Deformation of the pitch steepens the bounce of the ball, as the ball is effectively bouncing off an upslope. With this improvement to the model, the vertical height of the bounce could be accurately predicted.

There are several different types of cricket ball that are available. Fuss (2008) found that the properties of different types of ball are very different. Research could be carried out to find how the properties of balls of different construction methods vary with number of loading cycles. Figure 39 shows some of the different type of ball available.

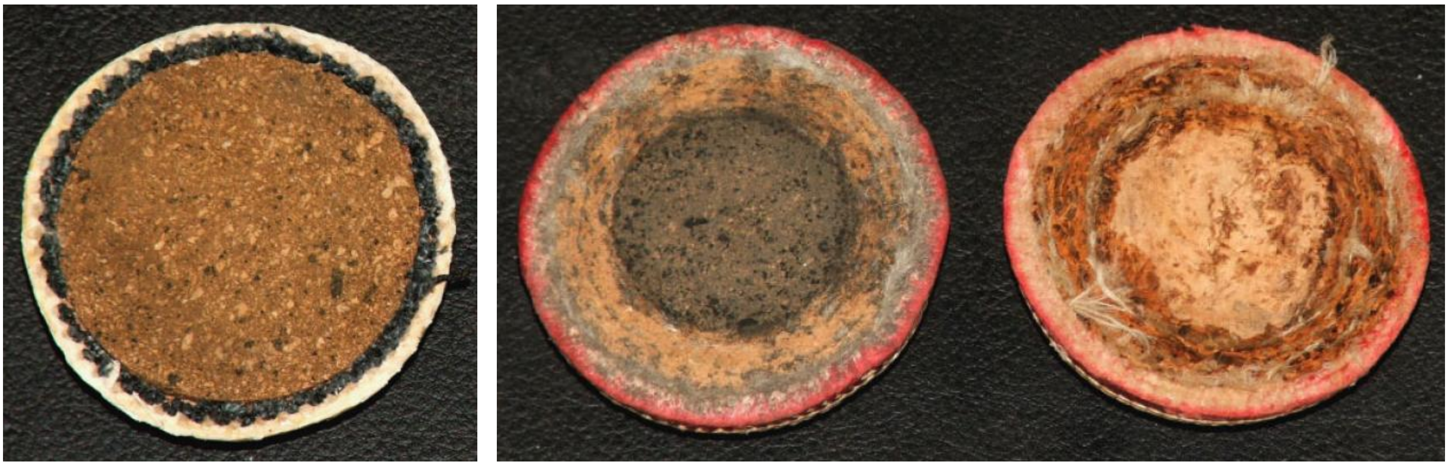


Figure 39 *Cross sections of different types of cricket ball (a) rubber-cork composite core, (b) rubber core, (c) Cork Core*

6. Conclusions

The experimental assessments of sample pitches, constructed in the laboratory, have yielded some important results. The CoR of a pitch has been shown to be independent of the compactive effort, and to increase linearly with decreasing water content until a maximum CoR of 0.4 is reached at a water content of approximately 0.12. At this condition the CoR, for pitches of all compaction levels, was found to decrease suddenly to approximately 0.3 as brittle cracking occurred.

The variability of the CoR has been found to increase with decreasing water content, and with increasing number of loading cycles. Both these factors correspond to increased cracking of the pitch.

Friction sledge measurements have found the CoF of a pitch to be linearly dependent on water content. The gradient of this linear relationship is a function of the compaction of the soil leading to a steeper gradient for pitches of low compaction.

A cricket ball was found to deflect further when loaded on the seam than perpendicular to the seam. The average stiffness of the ball was found to decrease with increasing number of loading cycles experienced by the ball. The loading regime could be split into two distinct regions with a 'primary stiffness' and a 'secondary stiffness' corresponding to two regions of constant stiffness. These distinct regions are due to compression of different layers of the ball. The CoR, when bouncing on concrete, was found to decrease linearly with number of loading cycles on the ball. There was also a linear relationship between the average stiffness of the ball and the CoR, however a more statistically significant correlation was found between the CoR and the secondary stiffness. No correlation was found between the hysteretic damping in the ball and the CoR.

A rigid body model from James *et al.* (2005) was used to interpret how the results affected the actual bounce of a ball. It was found that the pace of the pitch increases with decreasing water content, however since the horizontal component of velocity, which is dependent on the CoF, dominates the pace measurement, only very slight changes in pace were found due to the number of loading cycles on the pitch and ball. This is because the CoF was assumed to be constant with loading cycles, which could be a poor assumption and an important area for further work.

The rigid body model, although not predicting accurate rebound angles, was used to find trends on how the height of the bounce varies with changing ball and pitch properties. It was again found that the water content of the pitch had the largest effect; however it was found that dry pitches after a high number of loading cycles gave variable bounce with the height varying by up to 22.8 %.

7. Acknowledgements

The author would like to thank his supervisor Dr S. Haigh for all his guidance throughout the project and all the technicians at the Schofield Centre, University of Cambridge who aided in setting up the experiments.

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Appendix

A. Nomenclature

a	Radius of contact	m
c	Damping coefficient	Ns/m
CoF	Coefficient of friction	-
CoR	Coefficient of resitution	-
E	Material Strain Energy	J
H	Height of bounce at batsman	m
e	Coefficient of restitution	
h	Hysteretic damping coefficient	Ns/m
k	Stiffness	kN/mm
n	Number of data points	-
p	Statistical significance	-
R	Radius of ball	m
r	Pearson's correlation coefficient	-
t	Time for ball to reach batsman after bounce	
w	Water content of soil	-
$V_{x\ in}$	Initial horizontal speed of ball	m/s
$V_{y\ in}$	Initial vertical speed of ball	m/s
ζ	Damping ratio	-
μ	Coefficient of friction	-

B. Risk assessment retrospective analysis

The main risk encountered within this project was that of working in a workshop around machinery. Therefore normal workshop safety rules were abided by:

1) No work was carried out outside of workshop opening hours therefore all work was carried out under the supervision of technicians.
2) Appropriate clothing was worn at all times including long trousers and appropriate footwear

Another hazard that was encountered was when using the actuator during the quasi-static force-displacement tests. There was a risk that the ball could be asymmetrically loaded thus causing the ball to 'fire' out of the machine. Therefore a guard was constructed and used at all times.

The risk assessment at the start of the project did not include the risks associated with the actuator. This is because the experimental procedures were not sufficiently planned to appreciate all the risks involved. If starting the project again the risk assessment would be carried out after completing a thorough experimental plan for the year.

C. Derivation of rigid body model (James *et al.* 2005)

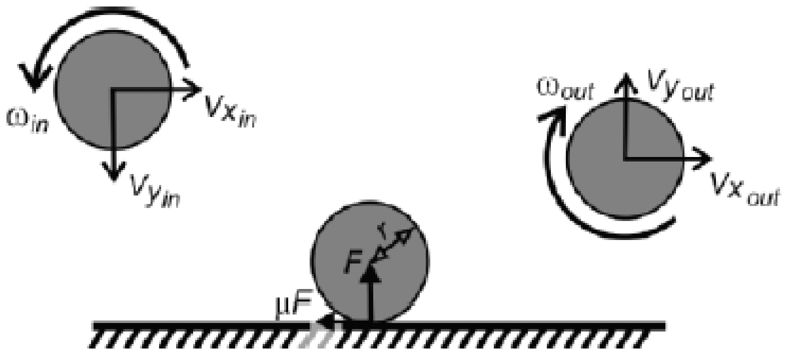

Figure 40 *A schematic of the rigid body model, James et al. (2005)*

Two possible impact scenarios are possible. Firstly the ball can slide across the surface, or secondly it could roll. It has been shown by James (2004) that a cricket ball will always slide across the surface for a delivery from an average seam bowler. The governing equations are as follows:

$$-\int \mu F dt = m(V_{x\,out} - V_{x\,in}) \tag{A1}$$

$$\int F dt = m(V_{y\,out} + V_{y\,in}) \tag{A2}$$

$$\int \mu F r dt = \int T dt = I(\omega_{out} + \omega_{in}) = mk^2\,(\omega_{out} + \omega_{in}) \tag{A3}$$

Also where e is the CoR,

$$V_{y\,out} = eV_{y\,in} \tag{A4}$$

Therefore equations A1, A2, A3, A4 give:

$$(V_{x\,out} - V_{x\,in}) = -\mu\left(V_{y\,out} + V_{y\,in}\right) = -\mu V_{y\,in}(1+e) \tag{A5}$$

$$(\omega_{out} - \omega_{in}) = \frac{\mu r \int F dt}{mk^2} = \frac{\mu r m(V_{y\,out} + V_{y\,in})}{mk^2} \tag{A6}$$

However for a solid sphere:

$$k^2 = \frac{2}{5}R^2 \tag{A7}$$

Therefore:

$$(\omega_{out} - \omega_{in}) = \frac{5\mu V_{y\,in}(1+e)}{2R} \tag{A8}$$

Therefore the rebound dynamics for a sliding impact are given by:

$$V_{x\,out} = V_{x\,in} - \mu V_{y\,in}(1+e) \tag{7}$$

$$V_{y\,out} = eV_{y\,in} \tag{8}$$

$$\omega_{out} = \frac{5\mu V_{y\,in}}{2R}\quad(1+e) - \omega_{in} \tag{9}$$