CHALMERS
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Equestrian Surfaces
Connection between foundation and top layer

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

LOUISE JOHANSSON

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Cover:
A horse in gallop at a riding course with a top layer consisting of sand and fibre.

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ABSTRACT

Equestrian sport is well known worldwide. It is Sweden's second largest sport and the only Olympic sport where all competitors compete at the same terms regardless gender and age. Equestrian surfaces are a debated topic, vital for the safety of both horse and rider, and there are several different ways of how to construct an arena. Actually, two courses with the same construction can act differently depending on the used material and its properties.

A problem regarding footing is people´s lack of knowledge about the ingoing parameters. Choice of material, conditions in the ground at construction site, choice of foundation, choice of top layer, maintenance and discipline will all affect the outcome. Another problem is that the assessments almost always are subjective, which does not give a proper idea about the footing.

The purpose of performing this study was to investigate different materials and evaluate if there are any similarities between different foundations with the same top layer and vice versa.

This was done in two steps, a laboratory test and a practical test. The laboratory test was done in order to look closer at the materials and find possible deviations from the specification, this by doing a sieving and a Camsizer test. The practical tests where done by constructing test areas, at a field on a farm close to Gothenburg, with different foundations and varying top layers in the measurements. By using measurement equipment, called OBST, developed to measure equestrian surfaces the characteristics of each test area could be collected as data from which any similarities and differences could be evaluated.

In the outcome from the laboratory test a big deviation were seen, some of the materials that were ordered as the same fraction differed a lot from each other. The data from the practical test with the test areas showed that the foundation has a role in the footings properties since the areas with the same material were shown to have very varying characteristics. Moreover, the top layer does influence as well, which were seen by different values on the functional properties were the top layer of sand mixed with fibre got the highest grip meanwhile the top layer with a fraction of 0-8mm got less cushioning.

Key words: EQUESTRIAN SURFACE, HORSE, FOOTING, OBST

Ridunderlag
Sambandet mellan grundläggning och topplager

Examensarbete inom masterprogrammet Infrastructure and Environmental Engineering

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SAMMANFATTNING

Ridsport är en välkänd sport över hela världen, det är Sveriges näst största sport och den enda olympiska sporten där alla deltagare tävlar på samma villkor oavsett kön och ålder. Ridunderlag är ett debatterat ämne, med avgörande betydelse för säkerheten för både häst och ryttare, och det finns flera olika sätt för hur en bana kan konstrueras. Två banor med samma konstruktion kan faktiskt agera olika beroende på val av material och vilka egenskaper det har.

Ett problem när det gäller underlag är människors bristande kunskap om de ingående parametrarna. Val av material, förhållandena i marken på byggplatsen, val av grundläggning, val av topplager, underhåll och gren kommer alla att påverka resultatet. Ett annat problem är att bedömningarna nästan alltid är subjektiva, vilket inte ger en rättvis uppfattning om underlaget.

Syftet med att denna studie var att undersöka olika material och utvärdera om det finns några likheter mellan olika grundläggningar med samma topplager och vice versa.

Detta gjordes i två steg, genom ett laboratorietest och ett praktiskt test. Laboratorietestet gjordes för att titta närmare på olika material och hitta eventuella avvikelser från specifikationerna, detta genom siktning och ett Camsizer test. De praktiska testerna gjordes genom att konstruera provytor, på en äng på en gård nära Göteborg, med olika grundläggningar och varierande topplager vid mätningarna. Genom att använda en mätutrustning, kallad OBST, utvecklad för att mäta ridbanor kunde data om egenskaperna hos varje provyta samlas in och utifrån dessa utvärderades eventuella likheter och skillnader.

I resultatet från laboratorietestet var det tydligt att se en stor avvikelse på några av de material som beställts som samma fraktion. Data från det praktiska testet med provytorna visade att grundläggningen har en roll i underlagets egenskaper, detta kunde visas genom att områden med samma topp lager material men olika grundläggningar visade sig ha mycket varierande egenskaper. Topplagret har i sig också inflytande, vilket kunde ses genom olika resultat för de funktionella egenskaperna där det topplagret med sand blandad med fiber hade bästa grepp medan det översta lagret med en fraktion på 0-8mm hade minst dämpning.

Nyckelord: RIDUNDERLAG, HÄST, UNDERLAG, OBST

Contents

Preface

In this study tests on equestrian surfaces have been done with various common foundations and different top layers. The project went on from September 2015 to June 2016, while practical part with construction of the test areas and the measurements was carried out during May and June 2016.

The project is carried out at the Department of Civil and Environmental Engineering, DIVISION, Chalmers University of Technology, Sweden. Associate Professor Magnus Karlsteen as examiner, Associate Professor Kristina Wärmefjord and Dr Erik Hulthén as supervisors have been a great support throughout the work. The project is partly financed through *Chalmers Vänners foundation.*

I would also like to thank Lars Roepstorff and Elin Hernlund, veterinarians and researchers at SLU, for their support and helpfulness during the project. Also, for letting me borrow the OBST for the measurements at the test areas.

Gothenburg June 2016

Louise Johansson

1 Introduction

Equestrian sport is exerted all over the world, it is also the second biggest sport in Sweden (Svenska Ridsportsförbundet, 2015). It the only Olympic sport where women and men, old and young are competing on the same conditions against each other (Svenska Ridsportsförbundet, 2010).

But equestrian is a very expensive and also dangerous sport (Tidningen Ridsport, 2016). The horse has its own will and since a horse is much heavier and bigger than a human, around 600kg, it gets even more dangerous. Horses can kick, bite, threw its rider off during riding but according to an inappropriate footing they can slip and fall that is dangerous due to that the rider can get the horse over him or her. There is a big lack of knowledge according to footing for riding courses that affects the safety issue, this thesis will deal with some of the areas that needs further investigation.

1.1 Background

Footing for horse arenas is a central question nowadays for the International Equestrian Federation, FEI, Federation Equestrian International. More research is done, above all in Sweden where the Swedish Agriculture University (SLU), has made several studies and has an on-going research of the topic. The Swedish Equestrian Federation demands experts in this area, experts whom they think should have knowledge about engineering, materials, horses and also entrepreneurship since they all has a large role in the final result (Svenska Ridsportsförbundet, 2015). The footing is important for the health and welfare of the horses since they can get injured depending on the surface even without falling. For example the Olympics in Athens 2004 where a disaster, since two horses got so seriously injured that they had to be put to death (Stiftelsen Hästforskning, 2015).

2014 the Swedish Equestrian Federation and SLU created the document *Equestrian Surfaces – a guide* to spread the knowledge about footing (Svenska Ridsportsförbundet, 2014). Simply it is a brief description of the topic for those who wants basic knowledge and to people who are going to build their own riding surface at home. The guide also contains tips of other articles and websites for those who wish to read and learn more.

A big problem for equestrian surfaces is the lack of knowledge about the ingoing parameters. Beyond the material properties that are further explained in Chapter 0, Section 3.1, it is necessary to take factors such as disciplines, maintenance, training schedule, type of rider and exterior of the horse into consideration since they all affect the risk of injuries on the horses (Hippson, 2008).

1.2 Aim and objectives

Based on the lack of knowledge about factors that relate to footing the aim is to find out the correlation between the different parameters in an equestrian surface after one year of research. An objective is to fill in data from the performed measurements from each combination in a table similar to *Table 1* and to be able to draw conclusions based on the analysis of the results.

Table 1 Shows which results that are wanted from the study.

Footing		Moisture	Fibre content	Surface firmness	Cushioning	Responsiveness	Grip	Uniformity
Top-layer	*Foundation*	*%*	*%*					
-	Foundation 1		-					
-	Foundation 2	-	-					
-	Foundation 3	-	-					
-	Foundation 4	-	-					
Top 1	Foundation 2	A	-					
Top 1	Foundation 3	A	-					
Top 1	Foundation 4	A	-					
Top 1	Foundation 2	B	-					
Top 1	Foundation 3	B	-					
Top 1	Foundation 4	B	-					
Top 2	Foundation 2	A	-					
Top 2	Foundation 3	A	-					
Top 2	Foundation 4	A	-					
Top 2	Foundation 2	B	-					
Top 2	Foundation 3	B	-					
Top 2	Foundation 4	B	-					
Top 3	Foundation 2	A	-					
Top 3	Foundation 3	A	-					
Top 3	Foundation 4	A	-					
Top 3	Foundation 2	B	-					
Top 3	Foundation 3	B	-					
Top 3	Foundation 4	B	-					
Top 4	Foundation 2	A	X					
Top 4	Foundation 3	A	X					
Top 4	Foundation 4	A	X					
Top 4	Foundation 2	B	X					
Top 4	Foundation 3	B	X					
Top 4	Foundation 4	B	X					

1.3 Problem description

Yet there are no guidelines at all for what type of footing is good or not good according to the horses welfare, but a lot of research is going on to set up measurable standards for footings. One problem is that the on-going research mostly is aimed to the big competitions around the world, but would need to be implemented at private riding courses as well. An amateur rider may go out on competitions now and then and hopefully ride on an appropriate footing there, but these occasions are very few compared to the ones at home with, probably, a less appropriate footing. It is not uncommon to ride on the same course everyday, and to do that on a course with a bad footing without any variation will affect the horse sooner or later. Therefore, a more user-friendly approach and knowledge have to be implemented.

So in order to fulfil the objectives for this study the following research questions are to be answered:

1. What impact does the foundation have on the characteristics of an equestrian surface?
2. How does different top layers influence the condition of the footing?
3. What differences can be seen between different spots at riding course, for example the middle and in a corner?

1.4 Delimitations

The delimitations for this report are set to investigate equestrian surfaces on permanent courses outdoors, in Swedish climate, for show jumping. For eventual calculations, due to be able to set up laboratory tests, a horse with a weight of 600kg will be used.

Regarding the test areas, a limitation is that the outer parameters such as temperature and the exact same moisture content will not be possible to regulate in this thesis. Surface runoff or drainage capacity for the test areas will not be taken into consideration according to the lack of time during the measurements. Neither will the existing ground conditions at site.

1.5 Methodology

In order to answer the research questions a more detailed overview of the topic is needed. Therefore, the project started with a literature study including looking at actual research, reports and their results to analyse and see what information can be collected and used for this study. Most of the reports and documents from the literature study are used as references in the report. Furthermore, some study visits, specific case studies and meetings also took place, with various people in the equestrian world such as experts in this specific area and people with big influence in the sport, since all input are good for a useful result. More information about the case study and study visit that gave a lot of experience and useful information are found in Chapter 4.

Next step in the project was to collect sand samples and analyse them through two different laboratory tests, a sieving analysis and an analysis with laboratory equipment called Camsizer. In Chapter 3, Section 3.1 the material properties and how to measure them are explained in detail, and Chapter 5 contains a further explanation of how the analyses for this specific project was prepared and performed together with the results.

The main part in this project was be to build test areas where different foundations, described in Chapter 6 especially in Section 6.1, were to be tested. One of the areas will be tested with four different top layers in order to see the differences of footing characteristics with the same foundation but different top layer. Description of the tested top layer is found in Section 6.2. Measurement equipment that is used for the measurements of the footing characteristics is the OBST that is more detailed described in Chapter 2, Section 2.2. The idea was to measure each test area at 5 different spots, on in each corner with one drop and one in the middle of the area with 3 drops, and to collect the data and evaluate using the software MatLab. All the measurements from the different sports should be evaluated as one to minimize the risk for errors depending on the construction and to get a valid mean value.

Based on both the literature study where common foundations were investigated and the laboratory test where the top layer sands were analysed the materials for the test areas were chosen. The results from the measurements at the test areas were compared and evaluated based on knowledge from previous parts in the project.

1.6 Outline of report

This report is divided into 7 chapters. After the introduction, Chapter 2 contains information about the existing research and its outcomes so far.

Chapter 3 provides general information about Equestrian Surfaces. It covers materials and their properties, construction types and maintenance.

During the project some possibilities to do study visits and case studies were given. In Chapter 4 two of them, considered as the most rewarding, are explained.

In Chapter 5 the laboratory measurements are described in different sub-chapters. The obtained results are also presented here.

Chapter 6 describes the test areas that were built for the practical measurements. The different foundations that were constructed as well as the different top layers used for the measurements are described in detail here. Also, the results obtained from the measurements are presented.

Finally, the conclusions are drawn in Chapter 7 along with suggestions of possible improvements and further investigations.

2 Existing research

As equestrians have put more interest in the topic a higher demand on footing has occurred, especially on competitions, which contributes to a increasing demand of more research.

FEI did in 2014, after four years of research, publish the biggest document so far on equestrian surfaces called *The Equine Surfaces White Paper* (FEI, 2014). The study covers all seven equestrian disciplines with the aim to look at which effect the footing has on the horses' health. The document was created in a collaboration consisting of eight experts on footing. The goal with the study is to make it possible for riders, trainers, course designers and arena builders to be able to provide a suitable footing for both competition and training. The document will be updated as more research has been done and valid input for the study is created.

In Sweden the University of Agriculture, SLU, has the leading role in this research with Lars Roepstorff, veterinarian and professor in functional anatomy of domestic animals, and Elin Hernlund, veterinarian and PhD student on equestrian surfaces, in the lead. Together with a lot of experts in the area such as veterinarians, engineers, trainers and researches from different countries, SLU and the Swedish Equestrian Federation has developed a publication called *Equestrian Surfaces – A guide* (Svenska Ridsportsförbundet, 2014). As the document got available and spread between equestrian people FEI got interested and did a translation of the guide to English to be available for equestrian all over the world (FEI, 2016).

Measurements with a force plate covered by sand in the landing area after a fence, have shown that the peak load that is created in the landing phase of a horse jumping a 1m fence is approximately 1.5 times the bodyweight of the horse on the forelimb (Meershoek, Roepstorff, Schamhardt, Johnston, & Bobbert, 2001). Which means if a horse on 600kg jumps a 1m fence the load on the foreleg can be as much as 900kg. According to the large weights the forces on the horse increase, which entails that the footing needs to be good to prevent injuries on both horse and rider.

Another example of existing research is a study, done at SLU, where the forces in the landing phase were mimicked. This was done by attaching an accelerometer on a drop hammer were the data from the measurements were compared to riders' own experiences of 5 different competitions in Sweden (Tollig, 2011). This study is similar to the development of the measurement equipment called the OBST, which is further described in Section 2.2.

2.1 Functional properties

To be able to define a footing, 5 functional properties have been set up: surface firmness, cushioning, responsiveness, grip and uniformity (Roepstorff, 2015). It is common to discuss a footing by its material, but to be able to compare different equestrian surfaces it is the functional properties that should be discussed (Hästsverige, 2013).

Based on the explanation in the publication *Equestrian Surface – a guide* (Svenska Ridsportsförbundet, 2014) the functional properties will one by one be explained below. However, it is important to have in mind that what a human is experiencing does not always correspond to the horses since there is a huge difference in weight, and the horse will therefore feel differences deeper down in the construction than humans.

Surface firmness
The top layer is the first to get in contact with the hoof when it hits the ground, therefore the firmness in the top layer is important according to how big the impact will be on the horse. A way to look at it visually is to see how much the hoof is allowed to move forward and downwards in the top layer.

Cushioning
It is the footings' ability to absorb the forces from the horse to decrease the stress on the horses' legs. A material with an elastic deformation is good to use, since it compacts under the hoof but returns to its initial form thereafter.

Responsiveness
Another type of cushioning is the responsiveness, the elasticity, and is the ability of a footing to reproduce energy to the horse in the push off. It is about the natural elasticity of the footing and its responsiveness when loaded.

Grip
Measuring grip, which is friction, means to look at how much the hoof moves in the footing in horizontal direction. All layers in the construction have a friction effect and in the landing phase it is the friction in the top layer that is essential since it determines how much the hoof is allowed to move horizontal in the footing. The other crucial friction effect is the friction between the layers that has to keep the materials together to not cause a slippery surface when the horse pushes off or turns in the footing.

Uniformity
A surface can be even and flat to the eye but still have different characteristics at different spots, with uniformity means how much the function varies over places on the same arena. When the variations are big it is harder for the horse to handle, the risk for injuries increases.

2.2 Orono Biomechanical Surface Tester

In order to be able to mimic the situation where a surface gets loaded by a horse at gallop the measurement equipment called Orono Biomechanical Surface Tester, abbreviated as OBST, has been developed (Biologically Applied Engineering, 2015). It mimics the most critical phase where the hoof gets in contact with the ground and loaded by the whole horse weight, in this moment the highest loads are applied to the soil.

The system was developed by three Americans and presented in the report *System development for in-situ characterization of thoroughbred horse racing track surfaces* (Peterson, McIlwraith, & Reiser, 2008). To develop a useful system it was decided to mount it on a mobile platform that made it easy to move at arenas and between arenas with big geographical distance to be able to collect sampling data from different arenas around the world. There are nowadays four such devices in the world, two in the United Stated one in the United Kingdom and one in Sweden at SLU (Biologically Applied Engineering, 2015).

The measurement equipment consists of a metal hoof that is connected to a mass that is released from a steel frame with a two-axis drop tower, see *Figure 1*. It is dropped from a specific angle, so that the hoof hits and impacts the soil as if it were during an actual gait of a horse. On the two-axis drop tower the force is generated by gravitation where the mass, with a total of 30 kg for the moving apparatus, creates a force by accelerating towards the ground and provides energy of 540 Joules to the soil at impact. That impact is equivalent to the energy of the horse and the part of the horse weight that are estimated to be transferred to the hoof in that phase (Biologically Applied Engineering, 2015).

a – synthetic horse hoof
b – two axis drop tower
c – metal spring
d – industrial damper
e – three axis accelerometer
f – string potentiometer
g – load cell

Figure 1 Picture of the OBST in Sweden.

To be able to measure the vertical load and acceleration, a sliding of the hoof when it has contact with the surface is allowed by two non-orthogonal axes of motion (Peterson, McIlwraith, & Reiser, 2008). Also, a second set of rails are attached to the sliding part as a part of the mass and moves down, this second axis is then preloaded by a gas spring and only moves once the hoof is in contact with the soil and because of the difference in angle between first and second axis the hoof is forced to move forward as it impacts the soil and the preloaded axis is compressed (Peterson, McIlwraith, & Reiser, 2008).

There is also a three-axis accelerometer attached to the stiff mass above the hoof. This makes it possible to record a total of five data channels during each test. The two measured functional properties, shear and impact force, are then correlated to the performance of and risk of injury for the horse. (Biologically Applied Engineering, 2015).

This device was originally developed for racing track surfaces, but has been adapted to measure show jumping courses by mimic the biomechanics of the forelimb in the landing phase. To do that some changes have been made to the equipment from the original design, these changes are presented in *Table 2* (Hernlund, 2016). Through nine data channels using a MatLab data acquisition and analysis script the equipment gives information of tri-axial acceleration, tri-axial loads and position.

Table 2 Showing the differences from the original OBST to the one adapted for show jumping surfaces.

Settings / Design	**Original**	**Adapted for Show Jumping**
Shoe	Casting rubber	Iron shoe size 2
Drop height	1.83 m	0.84m
Weight of falling mass	30 kg	33kg
Impact energy	540 J	272 J
Angle of long rails	12°	12°
Angle of short rails	7°	0° (hoof lands flat)
Spring and damper	Gas spring	Metal spring + Industrial damper

By using the data outputs from the measurement equipment the functional properties described in Chapter 2, Section 2.1 is measured to be able to evaluate the surface characteristics. Easily explained they were determined as following (Hernlund, 2016);

Surface firmness as peak vertical deceleration at impact
Cushioning as the peak vertical 43 force as the tri-axial load cell
Grip as the forward slide during loading
Responsiveness as the quotient of the compression and recoil time of the spring mass damper system.
Uniformity as the mean of the coefficient of variation (CV) which is the standard deviation divided by the mean for each functional property.

3 Equestrian Surfaces

All over the world the equestrian sport is exerted and especially outdoor arenas are very common since nearly each stable has its own. In Sweden one of the challenges is to build arenas that can stand the cold winters and the large precipitation.

This chapter will describe some of the commonly used foundations and top layers. However, there is no recipe for how to build the perfect surface since there are so many ways to build in and different constructions can give the same characteristics depending on the maintenance and specific materials used (Svenska Ridsportsförbundet, 2014). It will also describe the meaning of material properties and maintenance of the surfaces.

3.1 Material properties

To build a riding course that is well adapted for its purpose it is important to be aware of which material that is used and the characteristics they have. Normally the construction is divided in two parts, the foundation and the top layer (Svenska Ridsportsförbundet, 2014).

A course can be built in several ways and with different materials. However, what most of them got in common, at least for outdoor arenas, is shown in *Figure 2* and is that it has to be a good draining capacity to let water pass through the layers and not stay on the top (Lucky Rider, 2011).

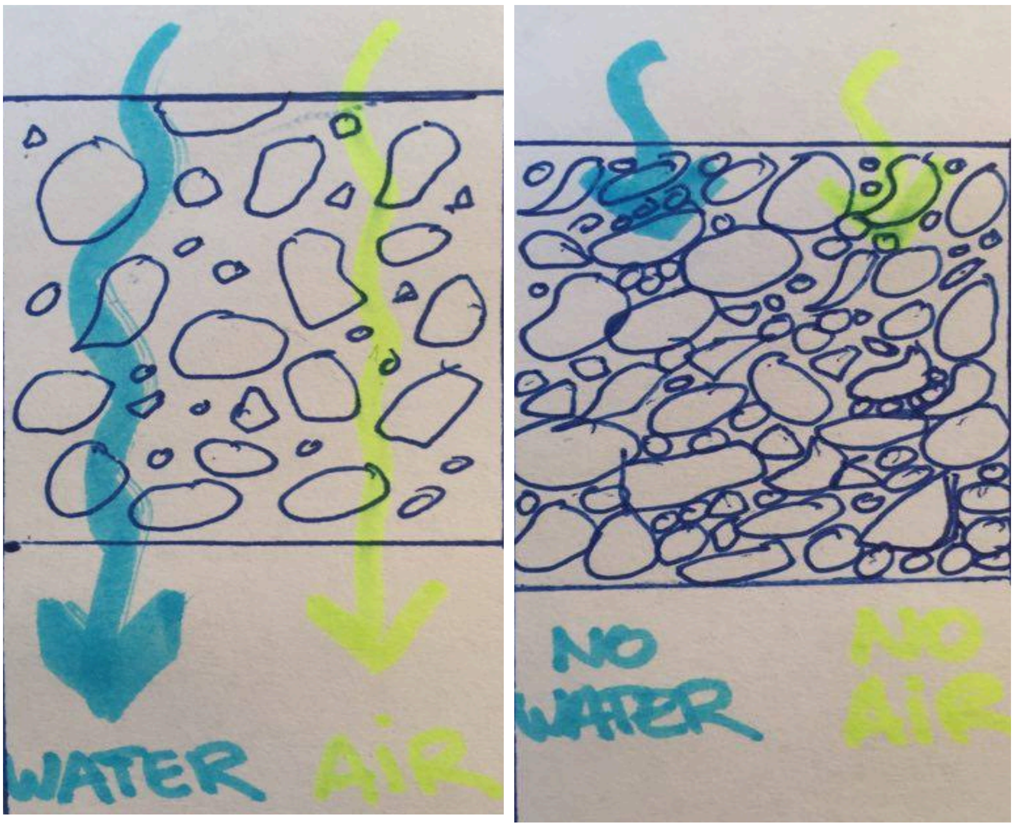

Figure 2 Showing the difference in draining capacity for material that compacts differently.

Due to material properties it is possible to evaluate some kinds of characteristics a course with the tested material will have, but still there are many other parameters to take into consideration such as maintenance etcetera (Horiba Scientific, 2016).

3.1.1 Size distribution

A very important factor for material characteristics is the size of the particles in it and by doing a sieving analysis the particle size distribution is received. The distribution has an essential role for the behaviour of the material according to permeability and compaction (Retsch , 2016).

An analysis of the size distribution is normally done by a sieving analysis. The sample is then put on top of a series of screens with decreasing mesh size and by a mechanism dispersed through the screens as illustrated in FIG (Particle Technology Labs, 2016). There are minimum standards for the size of the sand samples run through a sieving analysis in order to get a valid result, these are presented in *Table 3*.

Table 3 Showing the minimum sample sizes depending on fraction (FAS Sverige AB).

Fraction [mm]	Minimum sample size [g]
Filler	25
0-0.5	75
0-2	200
0-4	375
0-6	550
0-8	750
0-11	1000
0-16	1300

Doing a sieving analysis is a simple and cheap method to gain information about the material. The process is uncomplicated, time effective and quite precise (Retsch , 2016). To get such a precise result as possible, factors such as the sieving duration, sample size and if the sample is representative for the material are important (Particle Technology Labs, 2016).

The result from a sieving analysis gives information about the distribution of the material by giving the weight of the sample left on each mesh (Particle Technology Labs, 2016). Usually the result is displayed by a creating a size distribution curve showing the weight percentage of left material on each mesh, where on the y-axis the percentage of passed material is displayed and on the x-axis the particle size, as *Figure 3* shows. (Innopharma Technology, 2016). Depending on the grain sizes materials are divided into different soil types to facilitate the understanding and difference between materials by name, which is showed in *Table 4*.

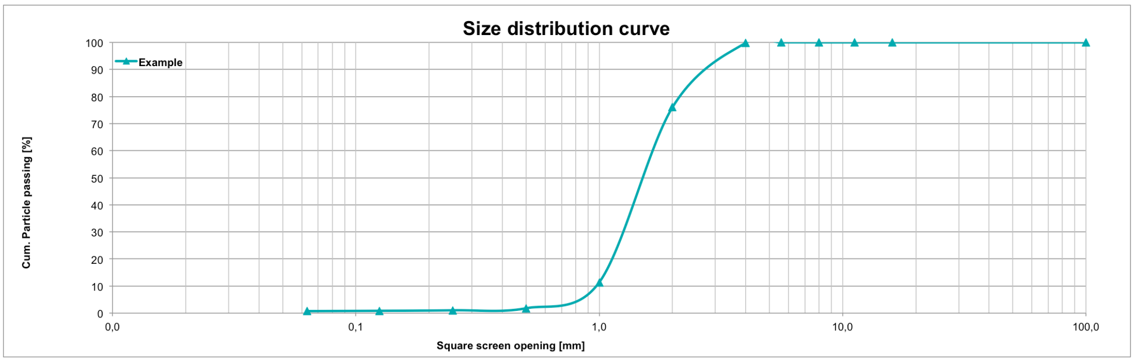

Figure 3 Example of a sieving curve.

Table 4 Classification of soil types (Karlsson & Hansbo, 1984).

Soil type	Grain size (mm)	
Block		600>
Stone		60-600
	Coarse stone	200-600
	Stone	60-200
Gravel		2-60
	Coarse gravel	20-60
	Gravel	6-20
	Fine gravel	2-6
Sand		0.06-2
	Coarse sand	0.6-2
	Sand	0.2-0.6
	Fine sand	0.06-0.2
Silt		0.002-0.06
	Coarse silt	0.02-0.06
	Silt	0.006-0.02
	Fine silt	0.002-0.006
Clay		<0.002

The material with size smaller than 0.063 mm is called fines (Svenska Ridsportsförbundet, 2014), Oliver Hoberg, an international footing consultant approved by FEI, and his colleague Karsten Koch recommend to have a maximum of 5% fines in a material used as top layer for a equestrian surface (Koch & Hoberg, Workshop Equestrian Surfaces, 2015).

Usually there are grains bigger or smaller than the specification of the ordered material tells. In the road building industry there is a standard for each fraction that tells the approved amount of these grains (Långh & Johnsson, 2005).

3.1.2 Particle shape

Another thing to look at on the material is the shape of the particles. This affects how the particles will stick together, and how hard compacted the surface will be. Rounder grains will be more compacted than angular ones (Lunds Universitet, 2014).

To measure the angularity there is an analysis done on material with a grain size bigger than 5.6 mm to get the flakiness (Granhage, 2009). It shows the ratio between the grains width and thickness, flakiness of 1 means that the width and thickness are even and a larger number means a bigger flakiness. On later days an index called the flakiness index is used, which is the SS-EN 933-3 in the Europe Standard, this tells the amount of particles in percent with flakiness over 1.6, which can be explained as a high flakiness. *Figure 4* shows the main difference between some particle shapes (Granhage, 2009).

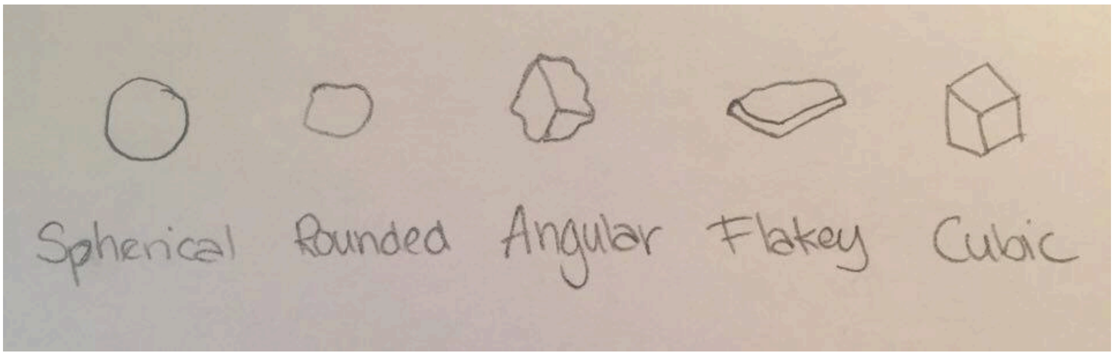

Figure 4 Different shaped of a grain.

3.1.3 Mineral content

To get the right conditions and a long lasting equestrian surface the mineral content is another factor that should be investigated. All sand, natural or crushed, is derived from rock in different ways and consists of different minerals (Bergström & Göransson, 2015). Minerals have different characteristics of which the most important in this case is hardness since it affects the life length of the material. Hard minerals will tear more on the horses' shoes and hooves while soft minerals breaks easier and can therefore change the properties of the footing (Bergström & Göransson, 2015).

The hardness of a material can easily be determined by looking at how easy the surface of the specific material can get scratched by another material with a known hardness (Naturhistoriska Riksmuseet, 2015). When talking about hardness Mohs hardness scale is often used, showed in *Table 5*, where the softest material has a value 1 and the hardest and strongest 10. This indicates how easily the different materials will break depending on the mineral contents.

Table 5 Mohs harness scale (Naturhistoriska Riksmuseet, 2015).

Hardness	Mineral	Scratched by
1	Talc	Nearly everything
2	Gypsum	Fingernail
3	Calcite	Copper Penny
4	Flourite	Nail
5	Apatite	Glass / Knife
6	Orthoclase	Steel File
7	Quartz	Karborundum
8	Topaz	Karborundum
9	Corundum	Diamond
10	Diamond	Nothing

For equestrian surfaces it is recommended to have a mineral with a hardness of 7-8 on Mohs hardness scale (Hoberg, Workshop Equestrian Surfaces, 2015). When the footing material contains a too soft mineral the grains will break and a larger amount of filler will be created, which in time will affect the compaction and therefore the properties of the surface.

3.2 Common foundations

There are several different ways to build a riding course, but most of the constructions consist of one foundation layer and one top layer on top of the existing ground. Depending on the conditions, such as soil type, on the construction site different foundations are more or less advantageous to build (Svenska Ridsportsförbundet, 2014). The choice of material and how the foundation should work according to the top layer might have different demands, for example a permeable ground to drainage the water from the footing. However, since this project is done in Sweden, some foundations commonly used here in Sweden will be explained below with a description of the construction and the demands.

3.2.1 Macadam

This is probably the most common material used for foundations for equestrian surfaces in Sweden. A foundation on macadam is normally built in layers with various fractions increasing by depth to create a draining function, which demands a permeable ground beneath to let the water pass through, although it is possible to build with surface runoff as well (Svenska Ridsportsförbundet, 2014).

There are several different ways to build a foundation with macadam and the outcome depends on the stratigraphy and the properties of the used materials. The construction and choice of material is a vital part of the construction. In *Figure 5* two different types of macadam foundations are shown to illustrate the differences depending on choice of material and how to construct.

Figure 5 Two different construction of macadam foundations.

3.2.2 Ebb & Flow

Arenas with Ebb & Flow system are very common in other countries in Europe and in the US. The system is based on simulate the conditions of a sand beach, it combines the foundation and top layer in one with sand as material, either pure sand or sand mixed with fibres and textile. The system works as a pool since it is constructed through placing a proof rubber mat on a flat hardened ground, with drainage pipes in the bottom and then the sand is placed on top (Footing Solutions USA, 2015). Placing the drainage pipes beneath the sand gives the possibility to control the in and out flow of water, which means that the risk for overwatering or unreliable water systems decreases and that the moisture level in the material can easily be controlled to a constant level that creates similar conditions for the footing every day (FootingFirst, 2014). It also entails that less water is needed since there is no evaporation when watering from beneath. Due to that, an Ebb and Flow can be built on impermeable soil since it does not demand any natural drainage from the ground (Footing Solutions USA, 2015).

The reason to that it is not that common in Sweden yet is because the cold winters here cause problem for the watering system that the Ebb and Flow is built on (High Tide System, 2015). One solution to solve the problem in winter is to put less water in the system during the cold months and to add some salt to the sand, but then it needs to be taken into consideration that the characteristics will change (Svenska Ridsportsförbundet, 2014).

However, the advantages with this system are that; it creates constant moisture level in the footing, there is a high drainage capacity, the footing gets a high elasticity and it is possible to build on impermeable grounds without any natural drainage (Footing Solutions USA, 2015). It does not either demand as high maintenance as other arenas, since the watering part runs itself the maintenance needed is dragging the course to even out the surface (High Tide System, 2015).

3.2.3 Rubberground

Rubberground is a fragile material used in foundations for equestrian surfaces (HJ i Sjöbo AB, 2016). It consists of cut rubber pieces placed in the bottom of the foundation and creates an elasticity that never disappears and works for all types of riding disciplines (Equi Pro, 2016). The providers of the material, Equi Pro, announce that the advantages with this type of material are many; it decreases the risk of injuries on the horses' legs, it has an isolating ability that decreases the risk of freezing in winter. It is environmental tested at Luleå University of Technology and because of the elasticity in the foundation it gives the possibility to have a quite hard top layer (HJ i Sjöbo AB, 2016).

An equestrian surface with Rubberground is constructed by placing a geotextile mat on a flat hardened ground with a slope of 1-2% to create a water runoff. However, there is some draining capacity through the layers as well but not enough to handle large precipitation. On the geotextile a 15cm thick layer of Rubberground is placed and compacted, followed by a new later of geotextile. Thereafter followed by a minimum of 10cm stone dust compacted to a solid surface, which purpose is to protect the under laying material from the horses hooves and the harrow. The stratigraphy for a Rubberground foundation is illustrated in *Figure 6* based on the explanation above. On top of the stone dust the chosen top layer is placed, advantageously in periods to let the material settle by time (Luleå Tekniska Universitet, 2012).

Figure 6 Showing the layers of a Rubberground foundation, a top layer is to be put on top before ready to ride on.

3.2.4 Paddex

Paddex is a material that is ridden directly on top of, and which is produced by a melting process where limestone and grey stone is melted together (Paddex, 2014). Paddex it a quite stiff material that easily compacts by time according to a cementation process that starts in the material.

The properties of Paddex are; that it has a good absorption of the kinetic energy from the hoof, it gives a good grip, the surface hardness can be varied by harrowing, the material absorbs moisture easily, with a good construction and maintenance it is possible to use even in the winter, stable ground and an easy and quick construction phase (Paddex, 2014).

When building a surface with Paddex it is necessary to have a ground with moisture capture properties below the Paddex. The grass and its roots are removed from the ground at site and on the topsoil that is left a geotextile mat is placed to separate the ground and Paddex to prevent that clay and roots will get into the Paddex layer. On top of the geotextile Paddex is distributed in a layer of approximately 18cm in total where the top 4-7cm should not be as compacted as that underlying (Paddex, 2014). Based on the description above the stratigraphy is shown visually in *Figure 7*.

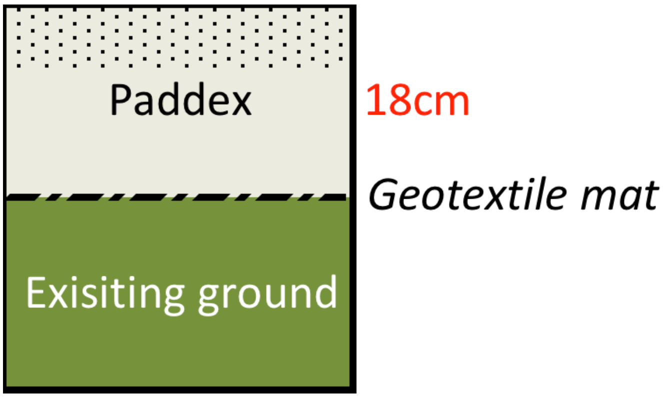

Figure 7 A picture showing how a course with Paddex is constructed.

3.3 Common top-layers

On top of the foundation the top layer is placed, often 10-15cm thick (Svenska Ridsportsförbundet, 2014). This is the layer that is ridden on and has direct contact with the horse. The characteristics of the material in this layer is therefore of high interest. There are some different materials that are commonly used as top-layers when building an arena, and they will be further described in the sub-chapters below.

3.3.1 Sand

Sand is a material where the size of the grains is between 0.06 and 2mm (Statens Geotekniska Institut, 2016). When buying sand for a riding course it is important to look at the specification because different sand consists of different minerals, has varying size distribution and different shape of the grains that are crucial for the result. To a top layer is it recommended to use sand and not gravel (Svenska Ridsportsförbundet, 2014). The material properties are further described in Section 3.1.

Nowadays natural sand is the most common sand to use for riding arenas (Svenska Ridsportsförbundet, 2015). But the natural sand is a finite resource, and therefore there is an on-going research to be able to provide a crushed material with the same characteristics as the natural one (Chalmers, 2012). Differences between natural and crushed material are that the natural normally has rounder grains and contains less filler and the crushed material both gets a more angular shape of the grains and contains more filler. This is due to the crushing process (Svenska Ridsportsförbundet, 2014).

An important factor to look at when ordering sand to a riding course is the sands pour point, especially when systems as Ebb and Flow are used. Different sand types has different properties depending on the material properties, when using pure sand as a top layer it is important to have knowledge about them to be able to perform the maintenance that's demanded for that type of material (Svenska Ridsportsförbundet, 2014). It has to be a sand with the right size distribution to create bonds in the material and keep it together so it will not be too loose but at the same time it can not compact too good because then it will become rock hard. That balance is not only depending on the material properties but also on the maintenance and especially the watering.

3.3.2 Sand with additives

Sand is the most common top layer, but it does not necessary have to be pure sand. Sand with additives as fibre and textile, woodchip or wax are also common to use (Svenska Ridsportsförbundet, 2014). Some different mixtures are explained below.

3.3.2.1 Textile and fibre

This type of material has become more and more popular on later days, and it is often called "fibre sand". It is very important to understand that "fibre sand" is not a fulfilled concept, since it is a mixture that consists of sand, fibre and textile pieces and therefore have varied properties depending on the characteristics of the materials (Svenska Ridsportsförbundet, 2014). In *Figure 8* the ingoing parameters in this type of mixture is shown.

Figure 8 A mixture divided into its three parts; sand, fibre and textile.

The ingoing materials have different functions, which also can change depending on type of each material. The typical effect with textile pieces is that the sand binds to them and becomes like sand paper, which increases the grip in the footing. The fibres increase the sands possibility to stand together. Furthermore, some types of fibres and textiles can also help to bind the water and keep the moisture in the footing (Svenska Ridsportsförbundet, 2014).

When choosing to mix fibre together with the sand in the top layer it is important to be careful with the choice of fibre and textile and to look at the specification to make sure that it does not contain glass fibre and that it is UV resistant because otherwise it will not last long (Koch & Hoberg, Workshop Equestrian Surfaces, 2015). Also, the amount of each part in the mixture is also crucial for the outcome. According to the document Equestrian Surfaces – a guide, a high amount of fibre is 12-16 kg fibres per ton sand and a low amount around 10 kg per ton sand. Not to forget the maintenance, if the footing is allowed to dry out the fibres will automatically come up to the top since they are lighter than the sand and therefore it is important to keep the footing evenly mixed and keep the moisture in it. The life length of the footing depends on the maintenance and materials (Svenska Ridsportsförbundet, 2014).

Furthermore, when it is time to change the material it is sorted as waste that can be expensive since it is large amounts. To be able to recycle the sand and fibres must be separated first, methods for this separation is under development to create a more sustainable recycling of the material (Svenska Ridsportsförbundet, 2014).

3.3.2.2 Woodchip

A very common top layer, especially at riding schools, is sand mixed with woodchips. Advantages with the woodchip are that it is cheap, creates a good elasticity in the footing and is a renewable material (Svenska Ridsportsförbundet, 2014). Furthermore, it demands proper maintenance and it is important to have in mind that since it is an organic material a decay process will start, especially when manure has been mixed into the footing, which can create a crust in the top layer that usually makes the surface slippery. To get rid of the problem it is needed to do maintenance as deep harrowing, explained in Section 3.4.2, is needed once in a while (Koch, Workshop Equestrian Surfaces, 2015).

A guideline in the document *Equestrian Surfaces – a guide* (Svenska Ridsportsförbundet, 2014), says that about 30% woodchip in the mixture is preferable together with a good sand for the purpose. It is also recommended to change the footing after 3-5 years of use, depending on the decomposition of the material, however a mixture like this with a hard wood will last longer since the woodchips then can stand larger strains.

A big advantage with this mixture is the ease of recycling the material. It is very environmental friendly since it only consists of organic materials and can therefore be spread on a field when it is time to change the footing (Svenska Ridsportsförbundet, 2014).

3.3.2.3 Wax

Waxed sand is not so very common in Sweden, but it does exist. The advantages with waxed sand is that it demands less water, creates high cohesion and friction in the top layer without clogging the drainage with smaller particles (Svenska Ridsportsförbundet, 2014). Anyway, the material is sensitive to the climate and its characteristics can vary rapidly according to the temperature since the wax has a tendency to get hard when cold outside and on the other hand soft when warm.

Some disadvantages with waxed sand are that the wax breaks down by time and the material might therefore have to be re-waxed, which is very costly, and also that it is hard to get rid off when it is not going to be used anymore (Svenska Ridsportsförbundet, 2014).

3.3.3 Rubber

A course can be built with a top layer consisting of sand mixed with rubber, as *Figure 9* shows, or only rubber. The main reason to use rubber is to prevent freezing and extend the period for when the course is possible to use and also to create some elasticity in the footing (Miljöförvaltningen i Lund, 2013).

The biggest problem with rubber is the environmental aspect. The rubber pieces are often produced from old recycled car decks and can contain both heavy metals and distillate aromatic extract oils, DAE (Ronneby, 2016). The DEA oils have a high concentration of aromatic carbon structured and can be classed as carcinogenic (Nya Däckcentralen i Solna, 2007). In the past, cable chips used to be an alternative on riding courses but it is impermissible to use it now according to the negative effect on the environment (Svenska Ridsportsförbundet, 2014). They consist of small plastic pieces that are a waste product from when electric cables are scrapped and contain heavy metals and other substances that are hazardous for the environment (Ronneby, 2016).

When building a course with rubber it is very important to use a material that is environmental tested. However, changing the material is very costly since it is not recyclable and therefore hard to get rid off (Miljöförvaltningen i Lund, 2013).

Figure 9 Rubber and gravel on a riding course.

3.4 Maintenance

This part is often forgotten even though it is important to create and keep an appropriate footing. Of course the construction and choice of material are also important, but even a course with the best materials could be a disaster without the proper maintenance (Hoberg, Workshop Equestrian Surfaces, 2015).

The most common parts of the maintenance are watering and harrowing, they are affecting almost every footing no matter which choice of top-layer that is made (Svenska Ridsportsförbundet, 2014). These two types of maintenance together with a short chapter about winter maintenance are described below.

3.4.1 Watering

Different top-layers needs different amount of water, but often much more than expected since the moisture is and will always be a crucial part of the footings function. It determines how stiff or loose the footing will appear, and it is the only way to create elasticity (Hoberg, Gothenburg Horse Show, 2016). The moisture in the footing will affect how large forces that the horse will be exposed to, in *Figure 10* measurement with the OBST shows these forces some days before and after a rainfall (The University of Maine, 2014). It is clear to see the importance of watering the footing to keep as good and equivalent properties from one day to another.

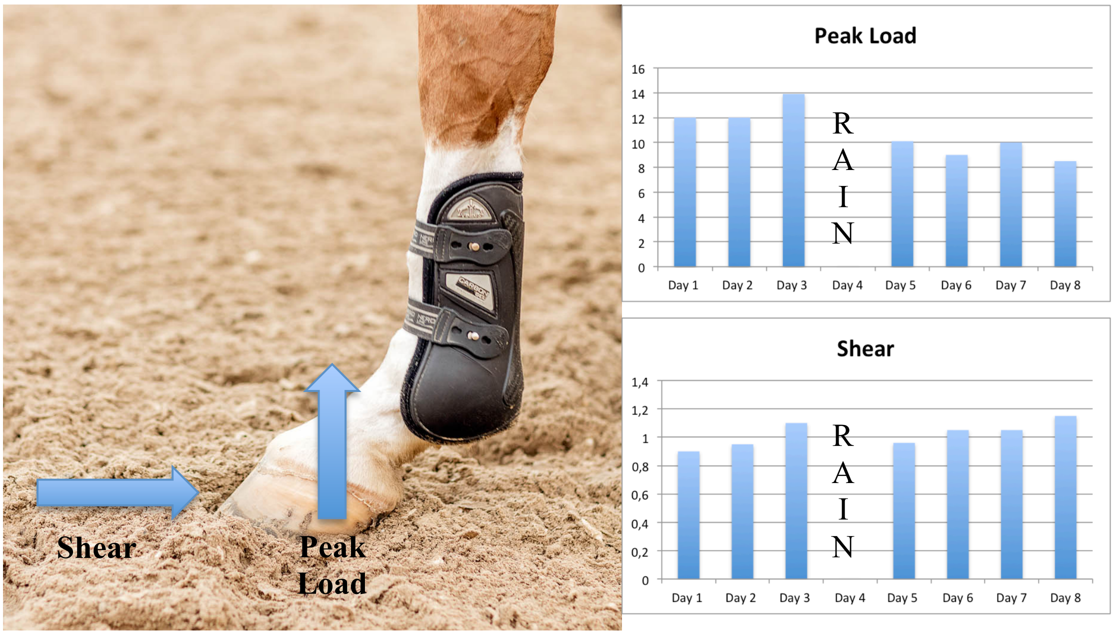

Figure 10 *A diagram showing the variation in forces on a racing track the days before and after rainfall* (The University of Maine, 2014).

To water a riding course there are different techniques, which one that is best depends on the material, construction, if it is indoor or outdoor and the climate at site. Oliver Hoberg recommends to water manually by a hose indoors to be able to spread the water evenly due to the risk of over watering and a problem to get rid of too much water (Hoberg, Gothenburg Horse Show, 2016). This is especially a risk on temporary arenas that does not contain a foundation with a draining capacity but only an impermeable surface below the sand. Outdoors there should always be a draining capacity in the ground, to be able to get rid of water from rainfall, so there it is more effective to water with a water tank.

Sprinkler systems are also an option for watering, placed in the ceiling or on the rim of the arena (Svenska Ridsportsförbundet, 2014). Effective since it does not need manpower, but the evaporation needs to be taken into account especially in windy days if it is outdoor and also in summer when the temperatures are higher. Just a ordinary garden sprinkler is not recommended due to the large amount of water gathered just around the sprinkler, and because of the unreliable working process (Hoberg, Gothenburg Horse Show, 2016). It is an advantage to have an construction that makes it possible to water from underneath since it is believed to achieve the best condition when having a lot of moisture in the material but a bit less in the uppermost centimetres (Svenska Ridsportsförbundet, 2015).

3.4.2 Dragging

Daily dragging the course is a must to get an even and eligible surface that should be done daily no matter which material is used. There are different ways of doing the dragging according how to drive, which harrow to use and how deep the harrow should dig (Svenska Ridsportsförbundet, 2014).

When driving to fill in the holes created during riding it is preferable to drive in small circles on the course (Koch, Workshop Equestrian Surfaces, 2015). Partly to run over each section two times, one in each direction and therefore fill the holes with materials from both sides, see *Figure 11* that shows the driving pattern. The straight lines that are common to see at riding arenas are mostly for aesthetics, and are therefore nice to end up with to get a nice surface for the eye (Hoberg, Gothenburg Horse Show, 2016). It is also an advantage to go different direction the follow day to not entrain the material at the same direction and end up with more material in one side (Svenska Ridsportsförbundet, 2014).

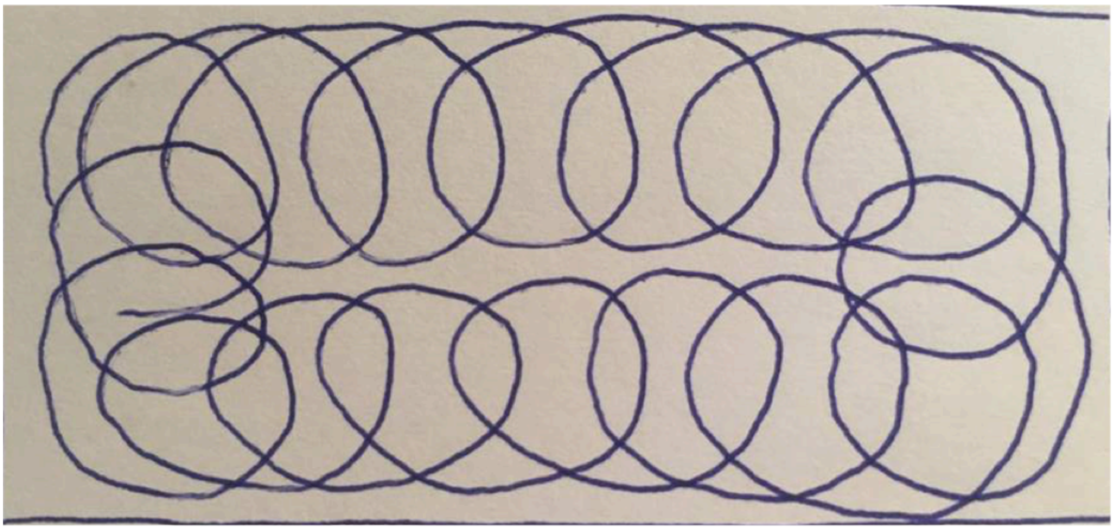

Figure 11 *Illustration over the driving pattern to move material and even out the surface.*

There are also a lot of different harrows, some customized for specific footings. Which one that should be used is a question regarding type of material in the footing, the purpose of use and the demanded characteristics such as if it is wanted to fluff it up or compacting (Svenska Ridsportsförbundet, 2014).

As an example two different harrows were used at Gothenburg Horse Show 2016 depending on desired effect of the maintenance. The first one, shown in *Figure 12*, has a plank in the front to be able to move material, the plank is followed by spikes to mix the uppermost centimetres of the material and in the end it has rubber wheels followed by a flat steel plate in the back that compacts the footing. The other harrow, shown in *Figure 13*, has spikes in the front to mix and a grid roller in the back that breaks down lumps in the sand. This type of harrow does not compact as much as the other one so the footing is a bit more loosened. Normally the harrow with rubber wheels is used before jumping classes to compact the footing so it can stand the high forces in the landing phase and the one with grid roller for dressage to fluff the surface up a bit.

Figure 12 Harrow with rubber wheels for compaction.

Figure 13 Harrow with grid roller.

How deep a harrow should dig depends on what type of maintenance that is performed, but it should never go deeper than the thickness of the top layer. For daily maintenance it is the uppermost centimetres that should be affected while for top layers mixed with organic material, e.g. woodchip, there is a need of deep harrowing once in a while. This depends on the crust that can be created in the bottom of the top layer according to compaction and manure in the footing, and deep harrowing is easily explained to turn the whole top layer to break the crusts. How often a deep harrowing should be done depends on how many horses and riding hours the course is exposed to (Svenska Ridsportsförbundet, 2014).

3.4.3 Winter

In Sweden the winter can be quite cold and that needs some preparation to be able to ride, above all outdoors, that season of the year. A recommendation is to water less and to spread out salt and harrow it down in the top layer before the temperatures decreases and the ground starts freezing (Svenska Ridsportsförbundet, 2014). It is preferable to use salt on a course maximum 2-3 times a year, and the amount of salt depends on if it is indoor or outdoor. As can be predicted it is recommended to use more outside since the conditions at an outdoor riding course are much more crucial since the rain- and snowfall has direct contact with the ground.

There are different types of salt and some split options about which of them should be used on riding courses regarding the horse's welfare. But according to a Swedish farrier there is nothing that indicates that the hooves are damaged by salt (Berg, 2015). Actually, he had another interesting thought of that it might be disinfectant for the hooves with some salt occasionally.

However, there is one reason to be aware of how much salt you add into the surface because it is suspected salt can create crystals that can clog the drainage that can cause problems in the future (Svenska Ridsportsförbundet, 2014).

4 Case studies

During the project the ability to visit different arenas and competitions to gather information, experiences and knowledge were given. In this section the two ones with the most influence for this report are described.

4.1.1 Särö riding course

At a stable in Särö, south of Gothenburg, a new outdoor riding course had been built but did not work properly. The problem was that every time it rained it stood 5cm of water above the top layer on the course. An attempt to improve and solve this problem had already been done when the visit took place. That attempt included removal of the top layer and adding several drainage pipes in the macadam foundation and then reset the top layer on its place. This attempt was without any success.

When visiting the course the first thing noticed was the sand used as top layer. It was a material with fraction 0-8mm prepared by mechanical crushing and what could be evaluated at site was that the size distribution was way to spread. So the first conclusion was that the top layer was the problem since it was not permeable enough due to the high compaction level, which proved to be right as they removed the top layer, waited for a rainfall and then saw that the foundation swallowed water just fine.

After some weeks a sample of another material, delivered from the same provider as the first one, was provided. When looking at the new material and comparing it to the old one that did not work, there was no major difference. The wide spread of the fraction, shape and flakiness was similar which indicated the same problem that they already had experienced. However, by finding another top layer that were permeable enough for the precipitation in the area the problem was solved.

It was very exciting to be involved in a problematic project like this since it gave a good overview for how important the material properties are. It was very helpful to experience it on site, and see the problem with your own eyes.

4.1.2 Gothenburg Horse Show

During Gothenburg Horse Show 2016, the great possibility to join the footing experts Oliver Hoberg and Karsten Koch were given. Of course the opportunity was taken and 11 long and exhausting but still so fun, valuable and useful days were spent in Scandinavium, Gothenburg. From day one when the ice was covered to the end of the last class of the show experiences were collected both by watching and doing which were very educating, exciting and fun.

To see, be a part of and understand all the work behind the transformation of an arena that is usually used for ice hockey to a horse arena were great. Firstly the ice was covered by a geotextile mat to prevent sand to get in touch with it and then a 15cm thick layer of Styrofoam where placed with the function to isolate the cold from the ice and to protect the ice from cracks due to the loads from vehicles maintaining the arena. Right on top of the Styrofoam the sand is placed in a 14cm thick layer, the sand is reused from previous years and is originally from Belgium mixed with textiles and fibres to obtain the desirable conditions. The footing are compacted by using a roller, see *Figure 14*, and thereafter water by hand manually, see *Figure 15*, until the moisture content in the footing satisfies the responsible, in this case Oliver and Karsten. At a temporary arena the footing is more or less soaked in water to create appropriate conditions with a relatively thin layer of sand.

Figure 14 A picture of rolling the footing in Scandinavium.

Figure 15 Watering the arena manually by a fire hose.

During these days the possibility to ask many questions to these experts was used and the answers were very helpful, not only for this project but also for creating an understanding of all parts in the footing business. It was very appreciated to be so welcomed and involved in their work.

5 Laboratory Measurements

It is possible to gather a lot of information from measurements and researches on materials. In this project some laboratory analyses has been done in the laboratory at Chalmers University of Technology to look at the different material characteristics. 15 different sands were investigated and after the laboratory measurements divided into three different groups were five were fine sands with fraction 0-0.3mm called F1-F5, three sands between 0-5mm called S1-S3 and seven coarser sands between 0-8mm called C1-C7.

The different methods of measurements and analyses, preparation and performance of the laboratory analysis can be found in this chapter.

5.1 Sieving analysis

The process of a sieving analysis is more detailed described in Chapter 3, Section 3.1.1. The sands were analysed by using a sieve shaker that moves the material in horizontal circles were used. The test sample was prepared by being dried in the oven in 110°C and then representatively divided into smaller samples. The sample sizes varied but in the range of the minimum standards presented in *Table 3*, but most of the samples were between 500 and 1000g.

The sieving shaker was on for 10minutes for fractions where the suppliers' specification told that biggest particle size were above 1mm and for 15minutes for fractions with biggest particle size below 1mm. The mesh sizes used for this analysis were; 16, 11.2, 8, 5.6, 4, 2, 1, 0.5, 0.25, 0.125 and 0.063mm.

Based on the results from the sieving test a sieving curve was designed for each group of sands, which can be found in Section 5.3.

5.2 Camsizer

Retsch Technology has developed the equipment called Camsizer that is an automatic method to evaluate the size and shape of the particles in a material (Retsch Technology, 2007). The technology consists of two digital cameras with one basic and one zoom, which by digital image processing can optimize the particle analysis. The range of measurement is from 30microns to 30millimiters with an extreme accuracy and a fully automatic process. The sand sample is put in a feed channel that makes all particles fall through the measurement field while the two cameras records, the basic camera the larger particles and the zoom camera the smaller ones. Size of test samples in this study was between 200-500g depending on grain size. Smaller samples for material with smaller grain size and vice versa.

The output obtains all information about the particles size and shape in real time, which is a big advantage since graphical result is visible during the process running (Horiba Scientific, 2016). In this study two parameters about the particle shape were evaluated after running a sample in the Camsizer and they are b/l_3 that presents the aspect ratio where the minimum width is divided by the maximum length of the particles and the SPHT which stands for sphericity, and gives a value for the shape were an ideal sphere has 1 and as lower value the more angular particle (Retsch Technology, 2009).

5.3 Result and analysis

From the laboratory measurements the results showed both similarities and differences in the materials. In both analyses it should be taken into consideration that the sample size varied and that the samples were not only different sizes but also quite small and might therefore not be representative for all material on a riding course. For the Camsizer the settings for each test are possible errors. These are two uncertainties that need to be taken into consideration while evaluating the results from the laboratory.

The outcome from the sieving analysis was gathered in size distribution curves where the sands in the same fractions were put into the same graph, see *Figure 16, Figure 17 and Figure 18.*

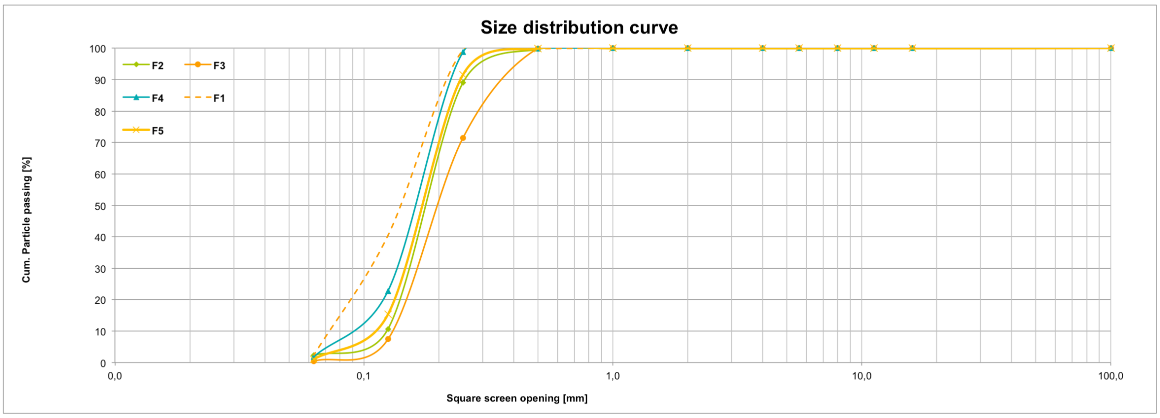

Figure 16 Size distribution curve for sands with fraction 0-0.3mm.

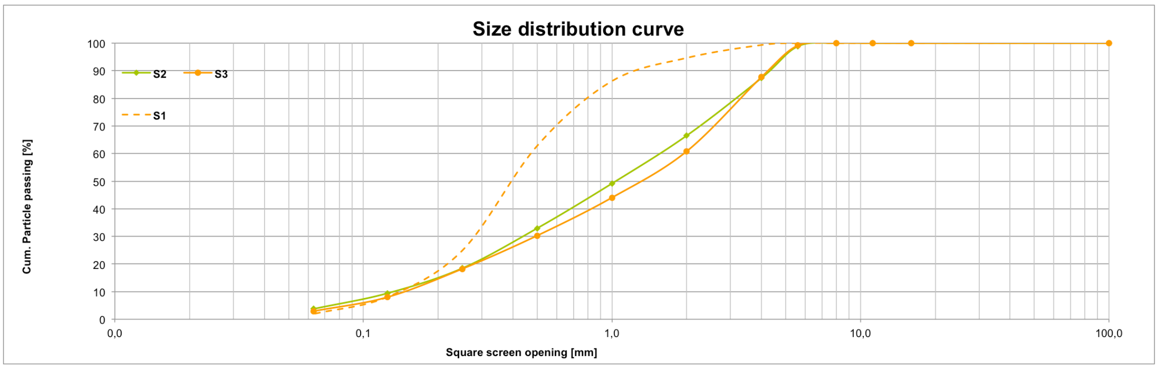

Figure 17 Sieving curve for sands with fraction 0-5mm.

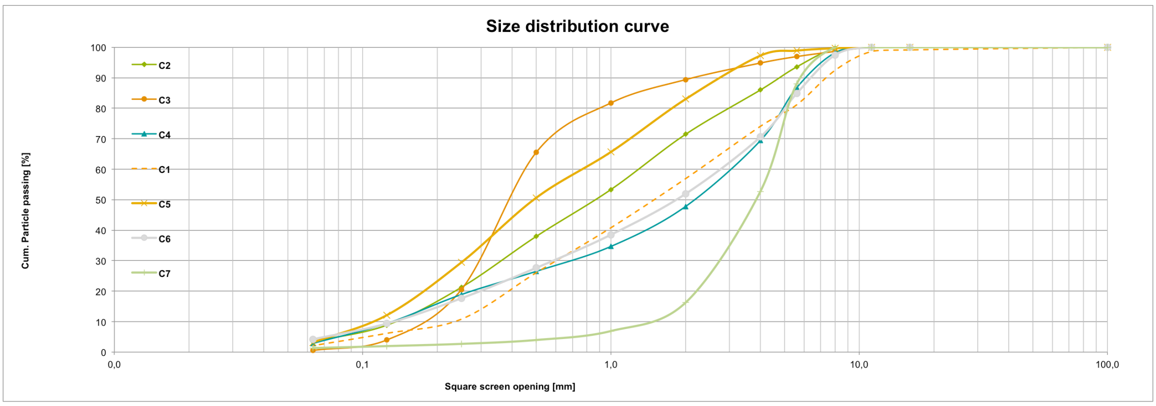

Figure 18 Sieving curve for sands with fraction 0-8mm.

What can be seen is that the sands specified as 0-5 and 0-8 from the suppliers differs a lot from each other, which will affect the characteristics for the footing. A widespread distribution creates a harder compacted surface since, as explained before, the smaller grains then fills in the voids between the bigger ones and do not leave any space for air and water. However, it is not desirable to have a to small spread of the particles in the range either, because a material like that will not compact enough to create a even and stable footing for the horses.

According to the recommendations found in the document *Equestrian Surfaces – a guide*, it is preferable to have sand with fraction 0-2mm on a riding course. Probably because of the problem with a varying distribution in the range for the coarser fractions, which can be seen from this laboratory analysis. Some of the sands in this test are used as footing material today meanwhile others are not, all the fine sands F1-F5 are used as well as the sands and coarser sand S2, S2, C3, C5 and C7. However, F1-F5 which are the sands between 0-0.3mm are used with additives, usually fibre and textile.

The size distribution is also possible to evaluate from the Camsizer outcome, but that has not been done in this study. Most interesting from the Camsizer analysis is the parameters about the particle shape since these can give information about how the material will behave, in *Table 6* it is possible to see the average value for the parameters SPHT (sphericity) and the aspect ratio b/l_3 for each sand.

Table 6 Shows the parameters for the particle shape from the Camsizer analysis.

Sand/Parameter	SPHT	b/l_3
F1	0.885	0.802
F2	0.873	0.777
F3	0.885	0.786
F4	0.888	0.793
F5	0.885	0.793
S1	0.833	0.754
S2	0.747	0.697
S3	0.75	0.69
C1	0.692	0.662
C2	0.723	0.67
C3	0.826	0.754
C4	0.736	0.68
C5	0.697	0.699
C6	0.744	0.677
C7	0.833	0.72

As can be seen the coarser sands has overall a more angular shape and the aspect ratio also decreases by larger particle size, with some exceptions that can probably be explained by the sands origin and production process. Nowadays natural sand is preferred before the crushed sand for riding courses because of the round shape of the grains that creates a good surface with an ability to keep water in between the grains and then create elasticity. However, this is one area where research is on going on to find out how to crush sand with the same properties as natural sand and avoid using the finite resource that natural sand actually is.

The most obvious characteristics to evaluate from the laboratory part, based on the information about particle shape and size distribution, are how the footing will compact and drainage.

6 Test areas

After the laboratory tests a couple of combinations of interest to further investigate by measuring at test areas were decided. The test areas built were approximately 2 times 2 metres, i.e. 4 square metres. The placement for the areas are outdoors on a field in Säve, a few kilometres north of Gothenburg, see *Figure 19*.

A total of three foundations and four top layers were tested, these are described in different chapters below. Also, there is a chapter explaining the measurements at site with the OBST and finally a chapter where the results are shown and analysed.

Figure 19 Overview of the construction site.

6.1 Foundations

For the test areas three different foundations were built and the reason for choosing those foundations is that they all have different construction and stratigraphy and also that the material used to build them all are quite easily available.

The construction is described for each foundation below, in text and with a picture of the stratigraphy. One common parameter for all the foundation is that each layer was compacted by a 200kg compactor with 6 crossings.

6.1.1 Macadam

First of all we have a macadam foundation, which was chosen to be in the test because it is a very common way to build a riding surface with material that is easy to get local. However, the specific macadam foundation for this project was chosen since it is one of the proposed in *Equestrian Surfaces – a guide.*

It is constructed by placing 13cm 16/32mm on a flattened ground, followed by 2cm of 4/8mm and then 12cm 0/5mm stone dust. On top of this the top layer will be placed. The stratigraphy for this test area is shown in *Figure 20*.

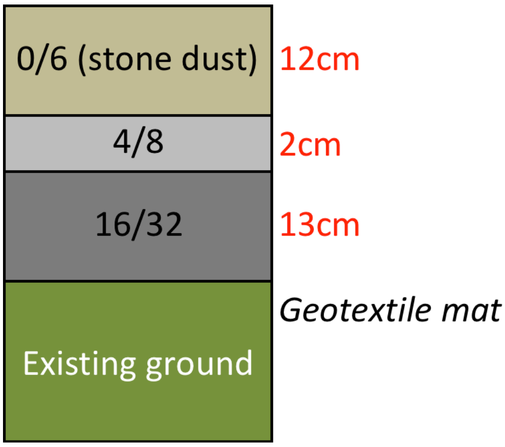

Figure 20 Showing the different layers of the macadam foundation.

As can be seen the layers are built by increasing grain size by depth to work draining, which is the most common way to build a macadam foundation since it takes advantage of the materials existing properties. The materials for the construction are delivered from local companies near the construction site.

6.1.2 Stone dust

Secondly, an area with only stone dust on top of a hard even ground was built. This type of foundation was not taken from any recommendation or document but only from experiences where people have built a quite cheap riding course by only stone dust. The fraction of the stone dust used in this test was 0/5.

The test area in this case was built by placing an geotextile mat on existing ground, followed by a few centimetres 0/32 macadam that were compacted to a flat and hard surface. Thereafter 12 cm of the stone dust were placed, and compacted, to create the test area and this is illustrated in *Figure 21*.

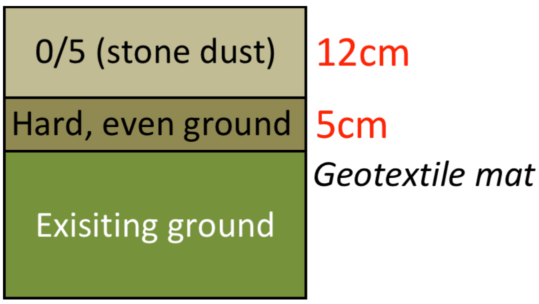

Figure 21 Showing the different layers built in the stone dust foundation.

6.1.3 Paddex

Then, as the last test area, we have the overall concept with Paddex that is interesting to test due to the simple construction and that no top layer is added. It is important to take into account that this material has a cementation process and since the test areas were built six days before the measurements the outcome can be affected. The material and its construction are further described in 3.2.4 Paddex. In *Figure 22* the appearance Paddex is shown.

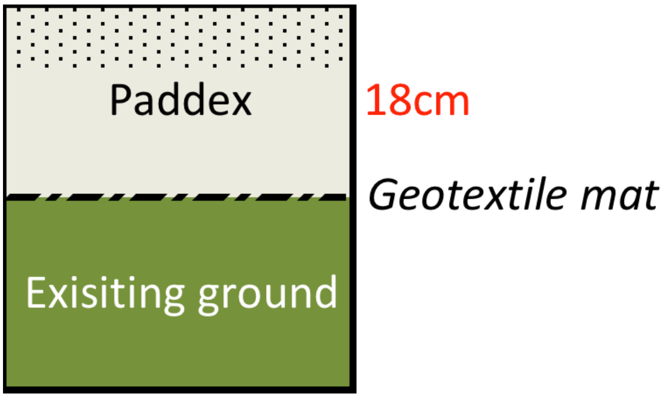

Figure 22 Stratigraphy of the area built with Paddex.

6.2 Top layers

Based on the laboratory part of the project, where several different sands provided as top layers for riding arenas were tested in two steps, three different sands were chosen to be tested on top of the macadam foundation. A fourth one was selected after looking at the provider's specification and comparing it to the ones manually tested in the lab. These different sands were selected since they were different from each other to see if that affects the riding course, each top layer were approximately 10cm thick. In this chapter each top layer is briefly described together with a size distribution curve of the material.

6.2.1 Sand 0-8

A sand whose specification tells a fraction of 0-8 but were more like 0-5 if looking at the size distribution curve from the sieving analysis in *Figure 23*. This sand was not mixed with anything just kept as it came form the supplier.

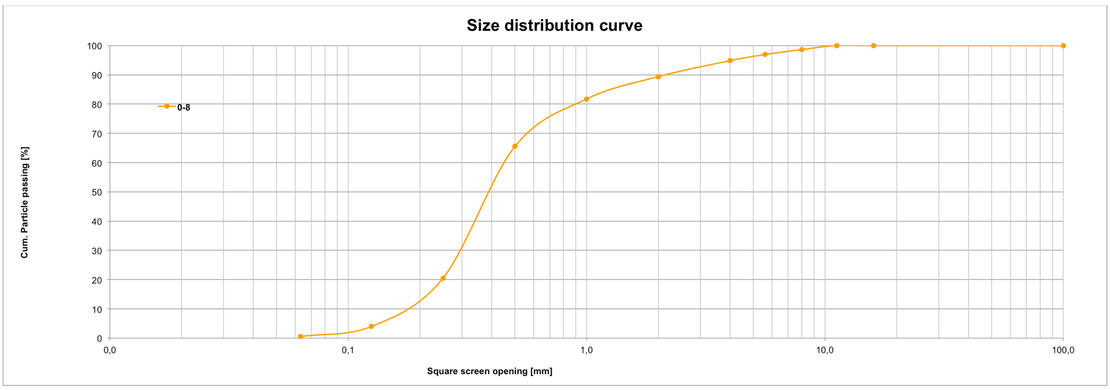

Figure 23 Sieving curve for the material of fraction 0-8mm.

6.2.2 Sand 0-2

This sand has a smaller fraction and has been through a special kind of sieving to divide the sand in different parts depending on grain sizes. This sand is a mixture of 10 % 0-0.5mm and 90 % 0.5-2mm. Note that this sand is the only one that has not been tested manually in the lab at Chalmers and therefore there unfortunately is no information about the particle shape. The sieving analysis is provided by the supplier and so is the size distribution curve shown in *Figure 24*.

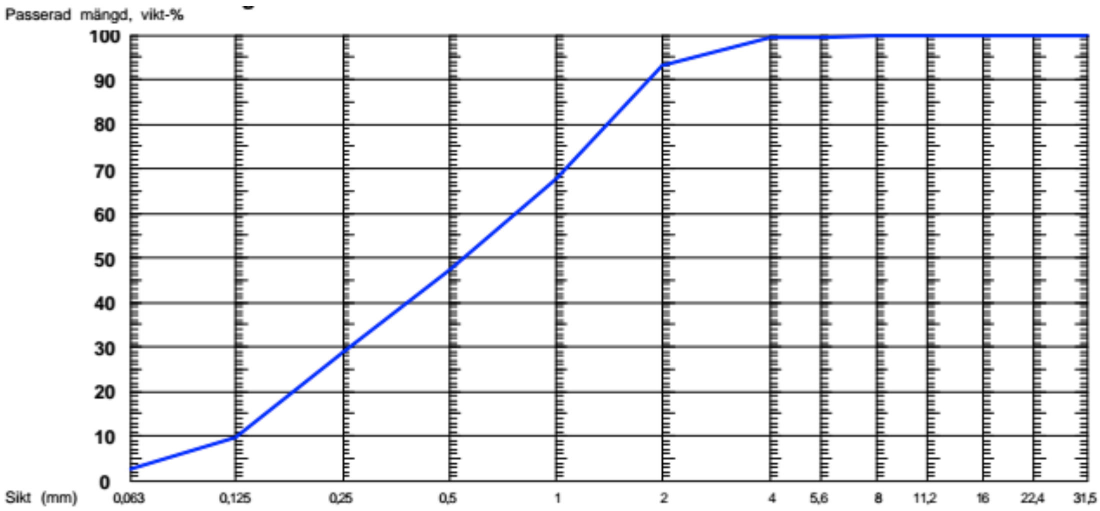

Figure 24 The sieving curve for the 0-2mm sand, provided by the supplier.

6.2.3 Stone dust 0-5

The third sand to be tested is a 0-5 that, after sieving, was found out to be more equivalent to the 0-8 presented in Section 6.2.1, see *Figure 25* and compare with the sieving curve in *Figure 23*. It is in between the EN 1342 Standard, used for construction business. Since there are no standards for material aimed for equestrian surfaces this sand was chosen in order to see what happens when using sand with that standard on riding courses.

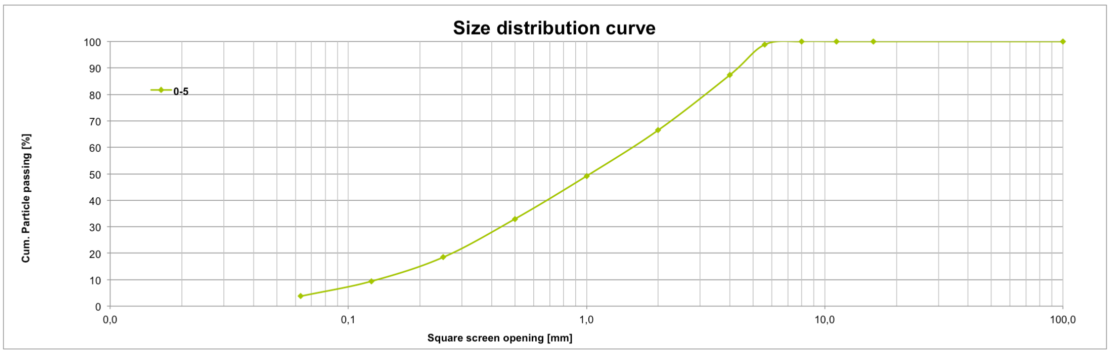

Figure 25 Size distribution curve for the 0-5mm material.

6.2.4 Sand 0-0.2 mixed with textile and fibre

Finally, a sand with additives ordered mixed from the supplier will be tested. This material contains approximately 20kg textile per ton sand, which is referred as a lot regarding to the Equestrian Surfaces – a guide, and is therefore interesting to test and see if some load will increase according to that. The size distribution curve for the pure sand that the mixture is done with is shown in *Figure 26*.

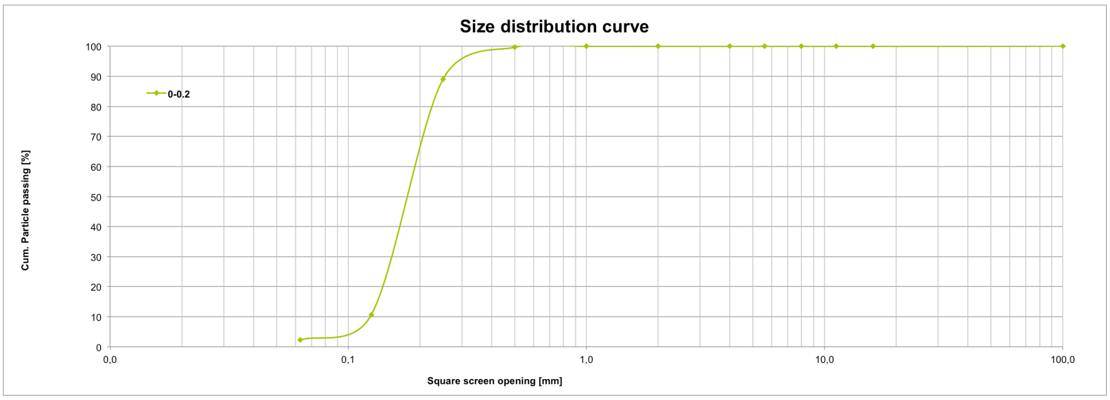

Figure 26 Size distribution curve for the sand in the mixture.

6.3 Measurement with OBST

Finally, the measurements on each test area and for each combination of the macadam area with various top layers were done. The equipment used was the OBST, further described in Chapter 0, Section 2.2. Each test area was measured in the middle with six drops at the same spot to get a representative value for the footing. Also, this can imitate the situation when horses land at the same point after a fence, to see how the footing changes after some hits.

Before the six measurements on each area the uppermost centimetres of the footing were raked in order to mimic the harrowing process of a footing. On the macadam foundation the top layer was changed between the measurements and compacted by a 200kg compactor and thereafter raked on top before the measurement took place. Between the measurements no maintenance was done, so the hoof hit the exact same spot again.

The data from the measurements were then further evaluated in a MatLab script that already was developed and ready to use for this purpose.

6.4 Result and analysis

First of all, it is important to consider that undetected measurement errors may have occurred and should be taken into account while analysing the results. Furthermore, the incline of the two tower drop axis on the OBST were not measured before each measurement to be at 12° so that may affect the result as well, exactly how is not known.

Unfortunately there were a lot of problems with the measurements on the test areas, which were the main part of the thesis. There only exists one OBST in Sweden and it is the only one, of the four existing in the world, which is adapted for show jumping surfaces. Due to the lack of time that arose and non-delivery of material the measurement plan had to be reduced, which sadly affected the outcome and possibilities to evaluate them. Instead of four test areas there were three and only one with varying top layer. The measurements were done regardless moisture level since there was a problem with the soil moisture meter. Also, there were only done measurements at one spot, in the middle, of each test area and not on different places as intended.

However, from the outcome the parameters maximal vertical load, maximal vertical acceleration, response and grip were investigated. Response and grip do not have any unit but the unit for vertical load is kN and for vertical acceleration G, which is equal to 9,82m/s^2. A high vertical load indicates a hard surface with less cushioning and a high value of the grip indicates a good grip that means a quick deceleration in the horizontal movement when the hoof is in contact with the ground. The responsiveness gives a hint of how quick the footing responses from the second it is hit and until gives back forces to the hoof on its way up again. Finally, the vertical acceleration shows how the horse can move in vertical direction in the footing.

As mentioned before each test area was measured at the same spot six times and in *Figure 27*, *Figure 28*, *Figure 29* and *Figure 30* below the results from each measurement according to each parameter is presented. There are some peaks that cannot be explained by anything other than measurement errors, since they do not seem to be realistic according to the others. However, in Appendix I the values for each measurement are presented in different tables.

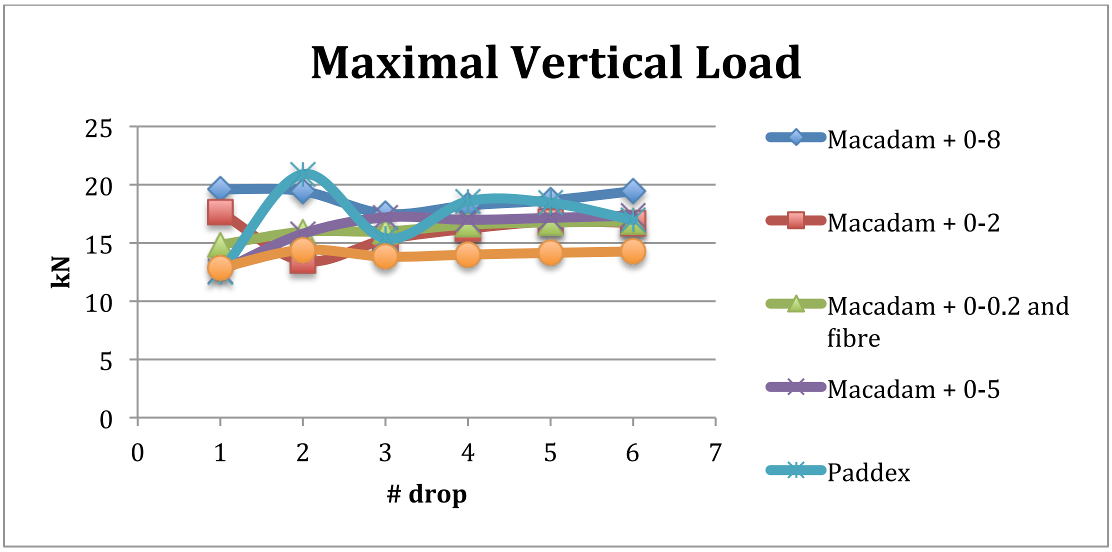

Figure 27 *Plot with data from all six measurements regarding the parameter Maximal Vertical Load.*

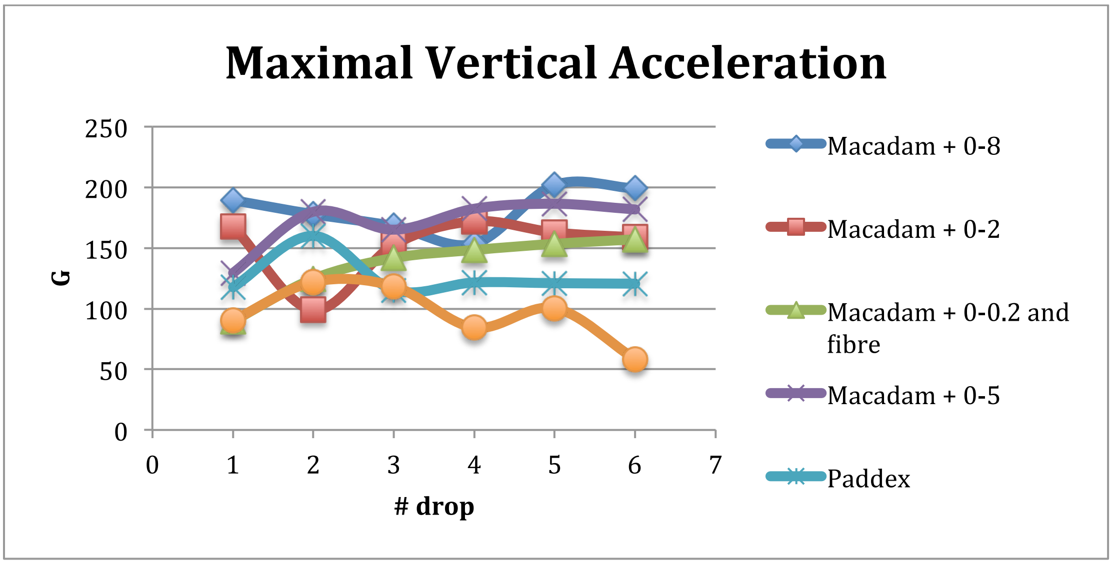

Figure 28 *Plot with data from all six measurements regarding the parameter Maximal Vertical Acceleration.*

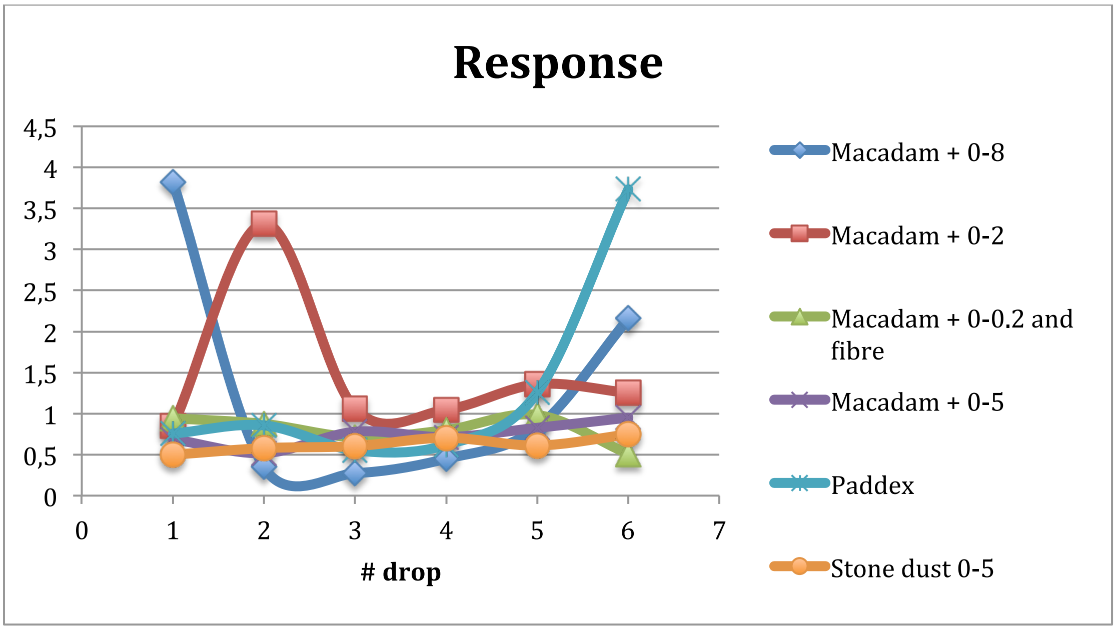

Figure 29 *Plot with data from all six measurements regarding the parameter Response.*

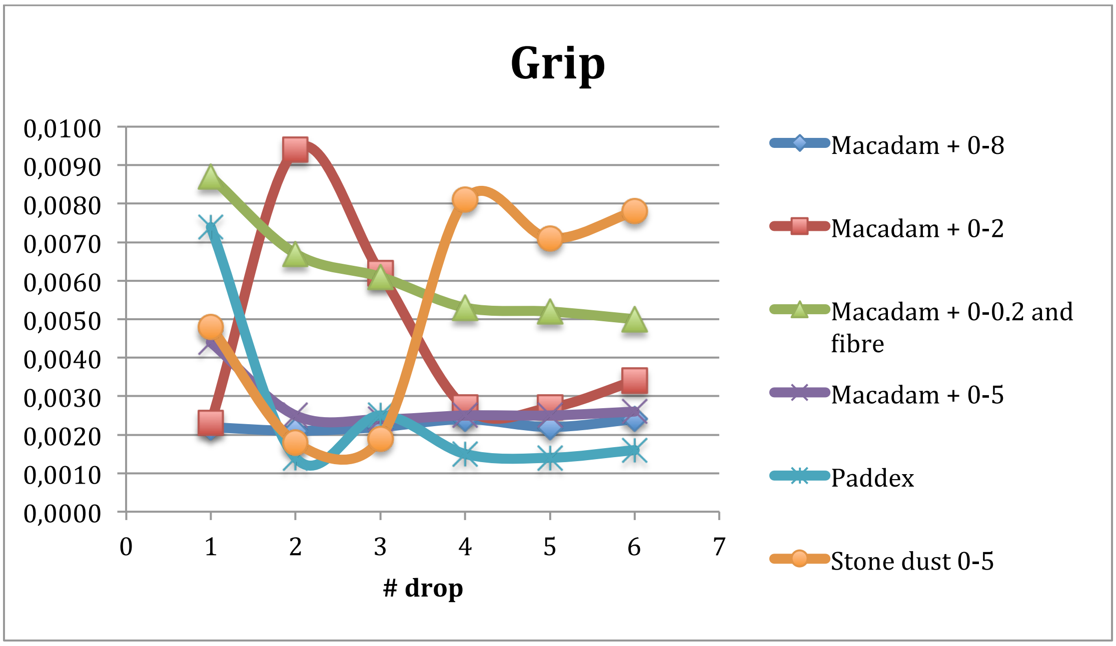

Figure 30 *Plot with data from all six measurements regarding the parameter Grip.*

To create a better overview of the result and take consideration to the measurement errors and disturbance for the sensors the data has been gathered in *Table 7* as mean values from the measurements to give a more representative value. In the table the highest and lowest value are marked with red respectively green colour. Also, this was done in order to give a clear overview and make it possible to easy understand and evaluate the results.

Table 7 Shows the results from the OBST measurements for each combination.

MEAN VALUES				
	Maximal Vertical Load [kN]	Maximal Vertical Acceleration [g]	Response	Grip
Macadam+0-8	18.815	181.614	1.31	0.0023
Macadam+0-2	16.019	152.119	1.48	0.0045
Macadam+0-0.2	16.156	135.815	0.80	0.062
Macadam+0-5	16.172	170.831	0.75	0.0028
Paddex	17.125	126.002	1.3	0.0018
Stone dust 0-5	13.915	95.576	0.62	0.053

As can be seen there are some differences in the results, the most obvious is that for the macadam foundation with various top layers the vertical load and vertical acceleration decreases with finer fraction and that can probably be explained by as coarser material used as top layer the greater compaction. A higher vertical load indicated a compacted material that will have less cushioning effect. Also, the finer fraction of the top layer the grip increases, and the top layer with fibre got the highest grip as could be expected from the literature study.

However, it is interesting that the foundation with only 0-5mm has such a low value for the maximal vertical load and acceleration according to the others and a good grip as well. This may be caused by measurement errors otherwise that would be very interesting to further investigate. Furthermore, a very interesting thing is that the macadam foundation with 0-5mm as top layer differs a lot from the foundation with 0-5 mm on all parameters. Actually, it is the same material, but one with the macadam foundation beneath and one working as both foundation and top layer. This indicates that there is a correlation between the different layers, exactly how they interact is not possible to evaluate from this study.

Furthermore, it is shown that Paddex is a quite hard compacted surface, even though it has not finished the cementation process yet, with a low grip for the horses. However, it should be taken into consideration that since Paddex compacts well it is not sure that the raked surface corresponds to a harrowed one that is the common way to maintain a riding course.

7 Conclusion

It was very clear differences in the material properties seen from the laboratory tests and according to that some properties of a material can be detected. Therefore, one conclusion is that the specification of a material should always be investigated before ordering any material for the top layer on a riding course.

In order to set up an accurate analysis for the testing the main deviations are the measurement errors. However, in field it was impossible to provide tests that were exactly identical to each other, mainly considering the layer thicknesses of the different top layers since no construction laser was used and therefore the layer thickness were not precise and identical during the different measurements. Also, according to the crossings with the compactor different material might compact differently and there was no consideration taken to the compaction degree. Furthermore, the moisture was not possible to control and another uncertainty in the accuracy of the measurements are the short time span that did not let the material settle by natural causes.

To draw a conclusion to this thesis the research questions will be answered below.

What impact does the foundation have on the characteristics of an equestrian surface?
According to the results from the OBST measurements the big differences in the 0-5 foundation and the macadam foundation with a 0-5 top layer indicate that the foundation do have an impact on the characteristics since the biggest difference appeared there although it was the exact same material. It is also shown by looking at the quite similar results in vertical load and acceleration for the different top layers that also indicate that the foundation helps to keep the load between a quite small range.

How does different top layers influence the condition of the footing?
In this thesis it is also shown that different top layer does influence the footing, mostly for response and grip where it differs and the smaller fraction of the material gives the better grip and lower response. Also, both the vertical load and acceleration decreases by smaller fraction of the material used as top layer.

What differences can be seen between different spots at riding course, for example the middle and in a corner?
Unfortunately there is no possibility to answer the question about how different spots acts different or similar since there was only one measurement point at each area due to lack of time during the measurements.

However, Equestrian surfaces are a complex topic with deficient research and to do something that is possible to draw a general conclusion from it has to be a bigger study with more measurements. Anyhow with more combinations and different materials for the test areas there would probably be possible to see a more clear connection to draw general conclusions from. According to that, some ideas of possible improvements and further studies have been proposed in the chapter below.

Finally, according to the problems during the measurements and the reduction of tests it is hard to draw any concrete conclusion of this study. But to fulfil the aim that is set up for this thesis it is possible to fill in the table for three functional properties, this is done in *Table 7* where the measurement data from the OBST measurements are presented.

7.1 Improvements and possible further studies

The main improvement to be done regarding footing is to create guidelines that are useful, both for competitions, championships but also for the public. These guidelines should regard all different ingoing parameters such as material, construction and maintenance and also take into consideration the exercised discipline and if it is a temporary course or a permanent curse. For example, when building infrastructure there are a document called AMA that basically stands for *General Material and Construction Description* and this is something that should be emulated and aimed for in further studies of equestrian surfaces, above all to be useful to private persons or amateurs that are going to build a riding course at home. This requires a lot more research in order to generalize horses to base the guidelines on and to be able to draw conclusions according to actual data and measurements so the research will fully be based on objective measurements. However, this will request more technical skills and an interdisciplinary collaboration with veterinarians, experts and probably FEI. The grading of a footing should essentially be connected to the sustainability of a horse bones and tendons to prevent injuries.

Also, there should be a geotechnical investigation, like for the road industry, to be able to take advantage of existing soil properties and to choose construction type based on the existing conditions.

Moreover, it would be interesting to have another student writing a thesis similar to this one to broaden the study. By doing more combinations of different foundations and top layer and also include compaction rate, moisture content and to measure over a longer time span. Actually, there is a lack of research at this area considering the whole system and all the ingoing parameters such as materials, foundation type, top layer, layer thicknesses and compaction rates. There are a lot of measurements on temporary arenas, test areas with only top layers and of course on existing courses as well. But the problem with the existing courses are that usually the owner does not know the ingoing parameters mentioned above and then the outcome can not be used or compared to others because of the lack of information in it. It is not useful to compare two courses with complete different constructions and materials when regarding the aspects of connection between foundation and top layers.

Furthermore, a certificate should be developed and be compulsory for companies that sells a concept and constructs riding courses to prove that they are professionals and know what they are doing. This would probably prevent failed constructions and not cause any danger for the horses.

Finally, an accessible measurement equipment or method for everyday use should be developed to be able to control the conditions and do a proper maintenance depending on the course properties at the specific time. However, the equipment may not have to be as detailed or precise as the OBST but to be comparable and correspond to the most crucial outcomes for normal use. Maybe this could further on also be comparable to different laboratory analyses for a more efficient work with the progresses.

References

Berg, B. (2015, 10 01). Hur påverkar saltade ridbanor hästens hovar. (L. Johansson, Interviewer) Gothenburg.
Bergström, L., & Göransson, M. (2015, 02 24). Workshop Equestrian Surfaces. *Materialkunskap*. (L. Johansson, Interviewer)
Biologically Applied Engineering. (2015). *Biomechanical Hoof Tester*. Retrieved 05 27, 2016 from Biologically Applied Engineering: http://www.bioappeng.com/Horse/OBST.html
Chalmers. (2012, 10 03). *Bakgrund*. Retrieved 05 11, 2016 from Uthållig produktion av finkorniga produkter från bergmaterial: http://www.chalmers.se/ppd/uthprod-sv/om-projektet/bakgrund
Equi Pro. (2016). *Rubberground*. Retrieved 04 22, 2016 from Equi Pro Equestrian Surfaces: http://equi-pro.se/index.php?option=com_content&view=article&id=2&Itemid=4
FAS Sverige AB. (n.d.). *Fördelning av stenmaterial.* Retrieved 05 27, 2016 from Asfaltsskolan: http://www.asfaltskolan.se/metoder/fasmetoder/fas221-02.pdf
FEI. (2016). *FEI Books*. Retrieved 05 20, 2016 from FEI: http://www.fei.org/fei/about-fei/publications/fei-books
FEI. (2014, 04 17). *World's most extensive equine surfaces study published*. Retrieved 05 20, 2016 from FEI: https://www.fei.org/news/world%E2%80%99s-most-extensive-equine-surfaces-study-published
Footing Solutions USA. (2015, 10 23). *The Ebb and Flow arena systems*. Retrieved 04 22, 2016 from Footing Solutions USA: http://www.footingsolutionsusa.com/ebb-flow-system/
FootingFirst. (2014, 01 01). *Ebb and Flow systems*. Retrieved 04 22, 2016 from FootingFirst: http://footingfirst.com/ebbandflow.html
Granhage, L. (2009). *Kompendium i vägbyggnad.* Bygg och miljöteknik , Geologi och geoteknik. Göteborg: Chalmers Tekniska Högskola.
Hästsverige. (2013, 10 18). *Jakten på det perfekta underlaget*. Retrieved 05 24, 2016 from Hästsverige: http://www.hastsverige.se/underlag-for-hoppning.html
Hernlund, E. (2016). *Sport Surfaces in Show Jumping.* Veterinary Medicine and Animal Science, Anatomy, Physiology and Biochemistry. Uppsala: Swedish University of Agricultural Sciences.
High Tide System. (2015). *Hemligheten med High Tide System*. Retrieved 11 05, 2015 from High Tide System: http://hightidesystem.se/hemligheten-med-high-tide-system/
Hippson. (2008, 05 23). *Nyckeln till hållbarhet: Förstå sammanhanget*. Retrieved 05 20, 2016 from Hippson: http://www.hippson.se/artikelarkivet/hasthantering/forsta-sammanhanget-fa-hallbar-hast.htm
HJ i Sjöbo AB. (2016, 04 22). *Ridbanor i Skåne*. Retrieved 04 22, 2016 from HJ i Sjöbo AB: http://www.hjisjobo.se/ridbanor.aspx
Hoberg, O. (2016, 03 24). Gothenburg Horse Show. (L. Johansson, Interviewer)
Hoberg, O. (2015, 02 25). Workshop Equestrian Surfaces. (L. Johansson, Interviewer)
Horiba Scientific. (2016). *Camsizer*. Retrieved 05 20, 2016 from Hosiba Scientific: http://www.horiba.com/scientific/products/particle-characterization/particle-size-analysis/details/camsizer-602/

Innopharma Technology. (2016). *Particle Size Distribution*. Retrieved 05 17, 2016 from Innopharma Technology: http://www.innopharmalabs.com/tech/applications-and-processes/particle-size-distribution
Karlsson, R., & Hansbo, S. (1984). *Jordarternas indelning och benämning.* Byggforskningsrådet. Svenska geotekniska föreningen (SGF).
Koch, K. (2015, 02 25). Workshop Equestrian Surfaces. (L. Johansson, Interviewer)
Koch, K., & Hoberg, O. (2015, 02 25). Workshop Equestrian Surfaces. (L. Johansson, Interviewer)
Långh, R., & Johnsson, A. (2005). *Stenmaterial vid asfaltstillverkning.* Bygg och miljöteknik. Göteborg: Chalmers Tekniska Högskola.
Lucky Rider. (2011, 05 07). *Dags för egen ridbana*. Retrieved 05 20, 2016 from Lucky Rider: http://www.luckyrider.se/dags-for-egen-ridbana/
Luleå Tekniska Universitet. (2012, 03 28). *Ridbanor*. Retrieved 05 22, 2016 from Luleå Tekniska Universitet: http://www.ltu.se/research/subjects/Geotechnical-engineering/Dackatervinningsportalen/Funktioner/Ridanlaggning
Lunds Universitet. (2014). *Perkolationstest av naturgrus och bergkross för att undersöka användbarheten till infiltrationslager och infiltrationsförstärkning i små avloppsanläggningar.* Retrieved 05 27, 2016 from http://blogg.regionkronoberg.se/miljo-bygg/wp-content/uploads/sites/10/2014/05/Perkolationstest.pdf
Meershoek, L., Roepstorff, L., Schamhardt, H., Johnston, C., & Bobbert, M. (2001). *Joint moments in the distal forelimbs of jumping horses during landing.* Veterinary Medicine, Fundamental and Clinical Human Movement Sciences, Veterinary Anatomy and Physiology, Equine Studies,. Equine Veterinary Journal.
Miljöförvaltningen i Lund. (2013, 01 14). *Kabel - och gummiflis på ridbanor.* Retrieved 05 24, 2016 from Miljöförbundet Blekinge Väst: http://www.miljovast.se/1719
Nationalencyklopedin. (2016). *Siktning*. Retrieved 05 22, 2016 from NE: http://www.ne.se/uppslagsverk/encyklopedi/l%C3%A5ng/siktning
Naturhistoriska Riksmuseet. (2015, 11 26). *Mineralens egenskaper*. Retrieved 05 22, 2016 from Naturhistoriska Riksmuseet: http://www.nrm.se/faktaomnaturenochrymden/geologi/mineralochmeteoriter/mineralensegenskaper.326.html
Nya Däckcentralen i Solna. (2007, 10 16). *Vanliga frågor i debatten om HA-oljor*. Retrieved 05 24, 2016 from Nya Däckcentralen i Solna: http://www.nyadackcentralen.se/ndc_informerar/HA-oljor.htm
Paddex. (2014, 02 27). *Paddex Ridbana*. Retrieved 05 11, 2016 from Paddex: http://www.merox.se/index.pl/paddex
Particle Technology Labs. (2016). *Sieve Analyses*. Retrieved 05 17, 2016 from Particle Technology Labs: http://www.particletechlabs.com/sieve-analyses
Peterson, M., McIlwraith, C., & Reiser, R. (2008). *System Development for In-Situ Charactrerization of Thoroughbred Horse Racing Track Surfaces.* USA: Biosystems Engineering.
Retsch . (2016). *Sieve analysis*. Retrieved 05 17, 2016 from Retsch Solution in Milling and Sieving: http://www.retsch.com/news/details/news_detail/1191
Retsch Technology. (2007). *CAMSIZER® Particle analysis with digital image processing.* Germany: Retsch Technology.

Retsch Technology. (2009). *CAMSIZER Characteristics.* Retsch Technology.
Roepstorff, L. (2015, 10 09). Möte Ridbaneunderlag Examensarbete Chalmers. (L. Johansson, Interviewer) Uppsala.
Ronneby. (2016, 02 09). *Gummi- och kabelflis i ridanläggningar*. Retrieved 05 24, 2016 from Ronneby.se: http://www.ronneby.se/sv/bygga-bo-miljo/miljoskydd/lantbruk/gummiflis-och-kabelflis-i-ridanlaggningar/
Statens Geotekniska Institut. (2016, 02 13). *Jordarter*. Retrieved 05 11, 2016 from Statens Geotekniska Institut: http://www.swedgeo.se/sv/kunskapscentrum/om-geoteknik-och-miljogeoteknik/geoteknik-och-markmiljo/jords-hallfasthet/lera-och-kvicklera/
Stiftelsen Hästforskning. (2015). *Få grepp om underlaget*. Retrieved 11 30, 2015 from Forskning: http://hastforskning.se/forskning/forskningsrapporter/artiklar-ur-nyhetsbladet/fa-grepp-om-underlaget/#.VlwVwd8vdE4
Svenska Ridsportsförbundet. (2010, 04 07). *Friskvårdsfrågan - fakta och argument*. Retrieved 05 20, 2016 from Svenska Ridsportsförbundet: http://www3.ridsport.se/Svensk-Ridsport/Opinion/Valet2010/Nyheter/Valnyheter/Ridsportenochfriskvarden-faktaochargiment/
Svenska Ridsportsförbundet. (2014). *Ridunderlag - en guide .* Stockholm: Svenska Ridsportsförbundet.
Svenska Ridsportsförbundet. (2015, 01 20). *Statistik och kort fakta om ridsport*. Retrieved 11 30, 2015 from Svenska Ridsportförbundet: http://www3.ridsport.se/Svensk-Ridsport/Statistik/
Svenska Ridsportsförbundet. (2014, 03 18). *Unik guide om ridunderlag*. Retrieved 05 20, 2016 from Svenska Ridsportsförbundet: http://www3.ridsport.se/RidklubbRidskola/Nyheter/2014/03/Unikguideomridbaneunderlag/
Svenska Ridsportsförbundet. (2015, 02 25). Workshop om Ridbaneunderlag. (S. Ridsportsförbundet, Interviewer)
The University of Maine. (2014). *Grayson jockeyclub.* Retrieved 05 26, 2016 from Racetrack Surfaces and Technology Integration: https://www.grayson-jockeyclub.org/resources/peterson14.pdf
Tidningen Ridsport. (2016, 03 06). *Statistik visar sportens baksida*. Retrieved 05 20, 2016 from Tidningen Ridsport: http://www.tidningenridsport.se/Nyheter/Sverige/2016/3/Statistik-visar-sportens-baksida/
Tollig, E. (2011). *Subjektiv och objektiv bedömning av underlag på svenska hopptävlingar på elit- och nationell nivå.* Institutionen för anatomi, fysiologi och biokemi, Veterinärmedicin och husdjursvetenskap. Uppsala: Sveriges Lantbruks Universitet.

Appendix I

MACADAM + 0-8				
#	Max vertical load [kN]	Max vertical acceleration [g]	Response	Grip
1	19,6294	19,6294	3,8246	0,0022
2	19,4423	19,4423	0,347	0,0021
3	17,4986	17,4986	0,2741	0,0022
4	18,2194	18,2194	0,4487	0,0024
5	18,6578	18,6578	0,8284	0,0022
6	19,443	19,443	2,1566	0,0024

MACADAM + 0-2				
#	Max vertical load [kN]	Max vertical acceleration [g]	Response	Grip
1	17,617	167,7041	0,8522	0,0023
2	13,4511	99,0257	3,3143	0,0094
3	15,2731	152,4914	1,0578	0,0062
4	16,2159	172,0172	1,0473	0,0027
5	16,8326	162,7107	1,3571	0,0027
6	16,7263	158,7653	1,252	0,0034

MACADAM + 0-0.2 and fibre				
#	Max vertical load [kN]	Max vertical acceleration [g]	Response	Grip
1	14,8394	89,632	0,94	0,0087
2	15,9559	124,5979	0,8738	0,0067
3	15,9827	141,7567	0,7117	0,0061
4	16,5705	148,3469	0,7981	0,0053
5	16,7592	153,448	0,9824	0,0052
6	16,8255	157,1108	0,508	0,0050

MACADAM + 0-5				
#	Max vertical load [kN]	Max vertical acceleration [g]	Response	Grip
1	12,5648	129,4742	0,6897	0,0044
2	15,7884	179,839	0,5181	0,0025
3	17,1957	165,0902	0,7783	0,0024
4	16,9829	182,3658	0,7131	0,0025
5	17,1506	186,4464	0,8261	0,0025
6	17,3495	181,7714	0,9505	0,0026

PADDEX				
#	**Max vertical load [kN]**	**Max vertical acceleration [g]**	**Response**	**Grip**
1	12,4806	117,6374	0,7542	0,0074
2	20,8964	159,954	0,8558	0,0014
3	15,3939	115,2909	0,5521	0,0025
4	18,574	121,5738	0,6183	0,0015
5	18,442	120,98	1,2575	0,0014
6	16,9658	120,5742	3,7321	0,0016

STONEDUST 0-5				
#	**Max vertical load [kN]**	**Max vertical acceleration [g]**	**Response**	**Grip**
1	12,8611	90,2304	0,4966	0,0048
2	14,4024	121,9695	0,5788	0,0018
3	13,8238	118,3993	0,6033	0,0019
4	13,9943	84,3451	0,7045	0,0081
5	14,1453	100,3038	0,6109	0,0071
6	14,2651	58,21	0,7456	0,0078