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Physical properties of synthetic bedding materials for free-stall dairy cow

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Rest is a prerequisite for the well-being of cows and they spend 40–50% of the time lying down. In this study the basic physical properties, the friction coefficient, heat flux as a function of time and softness of the bedding materials were measured. The heat flux to the bedding was shown to be large enough to affect the cow's heat balance. The friction coefficients of most of the tested materials were not within the recommended 0.3–0.5. However, the friction values are only indicative, as the material and the shape of the artificial hoof were not identical to natural hooves. There were also differences of almost an order of magnitude in the softness (Young's modulus) of the mats. Demands for softness vary according to the type of building and cow's physical condition, for instance a cow with an injured leg needs softer bedding. The properties of mats and beds varied considerably and the various properties did not correlate with each other. More information is needed concerning these values to animal welfare and health in order to be able to make recommendations of different physical material characteristics in different climate and housing conditions.

Key words: cows, synthetic bed, mats, bedding materials, physical properties

Introduction

The use of unheated cubicles for housing dairy cattle has increased in Finland since the 1990s. Straw is widely used as a bedding material, but weather conditions can greatly affect harvest yield and quality and the availability of dry straw. This, together with the need to reduce costs and mastitis (Hogan et al. 1989), has increased interest in reducing the use of organic bedding materials. Soft rubber mats and sand reduce the amount of organic bedding needed to maintain some flexibility (Irish and Martin 1983, Cermak 1988, Britten 1994). Bacteria content in sand has been reported to be lower than in organic bedding materials (Hogan et al. 1989), and cows lying on sand have fewer hock injuries than cows lying on sawdust or geotextile mattresses (Weary and Taszkun 2000). In unheated cubicle housing the thermal requirements of the

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cows vary according to the season, so the effects of different types of bedding on cow welfare have to be investigated at different temperatures.

Lying time, that is the frequency and duration of lying bouts, has been used to measure cow comfort (e.g. Natzke et al. 1982, Müller et al. 1989, Munksgaard and Simonsen 1995, Herlin 1997, Haley et al. 2000). Preference tests have been widely used as a measure of animal welfare (Duncan 1992) and cow comfort on different cubicle floorings (Natzke et al. 1982, Herlin 1997, Müller and Botha 1997).

Cows spend 40–50% of the time lying down (Webster 1993). Dairy cows need to optimize their lying time, as disturbed rest may affect milk production by reducing the secretion of growth hormone (Munksgaard and Løvendahl 1993). Reduced lying time is also associated with hoof disease and lameness (Singh et al. 1993, Leonard et al. 1994, Faull et al. 1996, Sonck et al. 1999). In free stall or cubicle housing, poorly designed stalls lead to reduced stall occupancy (O'Connell et al. 1993), and the type of flooring in the stall may affect time spent lying down (Natzke et al. 1982, Herlin 1997, Sonck et al. 1999). Leg injuries are an increasing problem and are most probably connected to the change in lying material (see Wechsler et al. 2000).

The physical properties such as softness, friction and the warmth of lying surfaces are clearly an essential part of comfort (Nilsson 1988, 1992). Webster claims that softness is the most important property (Webster 1993). Manninen et al. (2002) observed that, in winter, the cows in cold free-stall housing preferred well bedded concrete stalls more than scarcely bedded, soft rubber mats. In summer, no difference was detected. Optimal lying area material thus also seems to depend on climatic and housing conditions.

The time dependent heat flow into the cubicle may affect on how long the cows lie. Nilsson has studied the subject most recently and thoroughly (Nilsson 1992). The article contains an extensive reference list. Nilsson measured the heat flow indirectly by measuring the heating power to keep an artificial cow at a constant temperature. The heat flow was first measured directly for pigs (Spillman and Hinkle 1971). Pigs usually lie for rather long periods and thus the heat flow is constant and can also be calculated by measuring temperatures at various depths. On the contrary cows typically lie for one hour at a time. Therefore, the time dependence of heat loss to the floor is relevant.

The aim of this study was to explore the basic physical properties of most common bedding materials in Finland. They were to be used in connection with studies of the preferences of dairy cows for different kinds of stall flooring materials (Manninen et al. 2002). In this study friction (static friction coefficient), softness (Young's modulus) and thermal properties (heat flux) of various commercial mats and beds were compared. The static friction was measured by moving an artificial hoof along a dry or wetted material. The softness was measured by pressing a ball or an artificial hoof against the material and measuring the deformation as a function of compressive force. The heat flux into the material from an artificial cow was measured with a heat flux sensor.

Theory

Heat flux

The cow mimics an infinite heat reservoir with constant temperature T_1. If a semi-infinite obstacle with constant temperature $T_2 < T_1$ is placed in contact with the reservoir, a time-dependent heat flux q (W m^{-2}) from the reservoir occurs (Andromeda and de Witt 1990)

$$q = -\lambda \left.\frac{\partial T}{\partial x}\right|_{x=0} = \frac{\lambda}{\sqrt{\pi \alpha t}}\left(T_2 - T_1\right), \tag{1}$$

where λ and α are the heat conductivity and the heat diffusivity of the obstacle, respectively. The heat flux is thus proportional to $t^{-1/2}$, i.e. its limit is infinite when t approaches zero. When heat flux is plotted as a function of time, on a log-log-scale we should get a straight line with slope –1/2. When the heat flux and the area of the cow against the floor are known, the heat power flow Φ = qA may be calculated. This is necessary if the heat balance of the cow is to be calculated. If the total heat balance is zero, the cow feels comfortable, otherwise it feels either hot or cold. The thermal comfort of cow depends on the type of building and temperature. In warm conditions good insulation will induce sweating and in cold conditions large heat flow causes chilling. Bedding material has to be chosen according to the conditions in the building.

A cow is covered by fur, a thin insulating layer with thickness δ and heat conductivity λ which can be described as a heat transfer coefficient h = λ/δ. When this is included, we have a new equation for the heat flux (Incropeda and de Witt 1990)

$$q = \left(T2 - T(0,t)\right)$$

$$\frac{T(x,t) - T1}{T2 - T1} = erfc\left(\frac{x}{2\sqrt{\alpha t}}\right) - \left[\exp\left(\frac{hx}{\lambda} + \frac{h^2 \alpha t}{\lambda^2}\right)\right]$$

$$\left[erfc\left(\left(\frac{x}{2\sqrt{\alpha t}}\right) + \frac{h\sqrt{\alpha t}}{\lambda}\right)\right], \quad (2)$$

Softness

If a material of area A and thickness x is pressed with a force F, the thickness changes by Δx. If Δx is linearly proportional to F (linearly elastic material), then Young's modulus E is defined by the Hooke's law

$$\Delta x = \frac{1}{E} x \frac{F}{A}, \quad (3)$$

The deformation increases as values of E decrease, soft materials have a low modulus value. There are no recommendations for the softness of a bed material. Demands for softness vary according to the building type. In free-stalls the animals only rest on the beds, but in tied-stalls they are on the beds all the time. The bedding needs to be soft enough to be comfortable but must allow movement. Hard bedding induces chafes and very soft bedding induces instability during movements (Nilsson 1988, Dumelow 1995, Tierney and Thomson 2001). The bedding acts also as cushioning material during kneeling and rising and for this purpose a soft material is good, but stability is reduced when standing on this material (Tierney and Thomson 2001).

Friction

If a standing load does not start to move on a cubicle material, when a horizontal force F is applied to it, the coefficient of static friction μ of the material-load pair at that instance is defined by the equation

$$F = \mu mg, \quad (4)$$

where m is the mass of the load and g is the acceleration due to gravity. The static friction coefficient comes from the smallest force that is capable to start the load moving. A horizontal force develops during walking or when a cow stands up or lies down. Static friction is always larger than dynamic friction when the hoof slips on the material.

The friction should not be too low or too high. A low coefficient of friction indicates a slippery bed and a high friction material causes chafing. A suitable value for friction is 0.3–0.5 (Wander 1970, Beer 1976, Bähr and Türpitz 1976, Nilsson 1978). When changing the bedding material it is probably important that the new material has at least the same coefficient of static friction as the one the cow is already used to, otherwise the new material is more slippery and the cow can hurt itself before it gets used to it.

Material and methods

Seven materials commercially available in Finland were chosen. Their properties are given in Table 1.

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Table 1. Description of the bedding materials.

	UBO	RM 20N	KEN	KSL	Cow Comfort	Bovirex	KEW
Thickness, mm	17	20	20	30	22	38	30
Material	Natural rubber	rubber	rubber	rubber	EVA[1]	EVA[1]	rubber/soft
Upper side	grooved	patterned	patterned	patterned	patterned	patterned	patterned
Underneath	grooved	toggles	toggles	toggles	smooth	studs	smooth

[1] ethylene vinyl acetate foam

Heat fluxes into the material from an artificial cow were measured with commercial TNO heat flux sensors (model PU11, Sensor Technology) at four separate points. The sensor diameter was 25 mm. Temperatures of artificial cow and the material were measured with T-type thermocouples. The heat flux sensors and thermocouples were connected to a HP34970A-data logger. The data was recorded once a second during the first 6 minutes, then every 15 seconds during the first hour and after that once a minute. A plastic bag filled with water was used as a heat reservoir in order to make the contact with bedding as good as possible. The water in the bag was heated up to normal cow body temperature (39°C) and it was kept uniform by circulating it with a pump in order to reduce the insulating effect of the stagnant layer. The initial temperature of the bedding was 10°C. Several repetitive measurements were made for each material.

Friction was measured using an artificial hoof made of acryl. The hoof was 45 mm × 50 mm × 110 mm (contact area 45 mm × 110 mm) and it was pulled on the mat material using a railed carriage and an electrical motor. Pulling force was measured using a strain gage sensor and the data was collected with 20 Hz frequency with HBM-MVD 2555 amplifier. The data was transferred via RS-port to a PC for calculations. The hoof could be loaded with weights of 30, 90, 120 and 170 kg. The surfaces were either dry or wetted. To wet the surface 0.1 l water was poured to the place hoof situated. For each surface five test runs were first made and after that the five final measurements. This ensured good repeatability of results.

The softness was measured by pressing both the hoof and an steel ball against the material using an INSTRON universal testing machine. The steel ball (diameter 10 cm) mimicked the kneecap. The force was applied to the material with the testing machine and the measurement was stopped at 4.5 kN force. For each bedding material three test runs were made and the results are averaged from that data.

Results

Heat flux followed the theoretical equation of Eq. (1) (Fig. 1). In order to better show the dramatic change of heat flux as a function of time, linear scales have been used in Figure 1. At longer times the finite thickness causes deviations from the theoretical values. The differences between materials were significant, by as much as a factor of three. Both the values and differences are large enough to cause significant changes in the total heat balance. The optimal value of heat flux depends on the housing and climatic conditions, so it is not possible to give a recommendation for this value without heat balance calculations. Summer and winter can demand different kinds of bedding materials.

The friction measurements also followed the theoretical assumptions (Fig. 2). The initial peak in the force due to maximum static friction was followed by an almost constant force which was due to dynamic friction. The friction coefficients for dry materials for various loads were calculated from Eq. (4) (Fig. 3 and Table 2). Within experimental accuracy the static friction coefficient was independent of load. An interesting point in the friction data (Fig. 3 and Table 2) was that wetting the material with water did not noticeably change

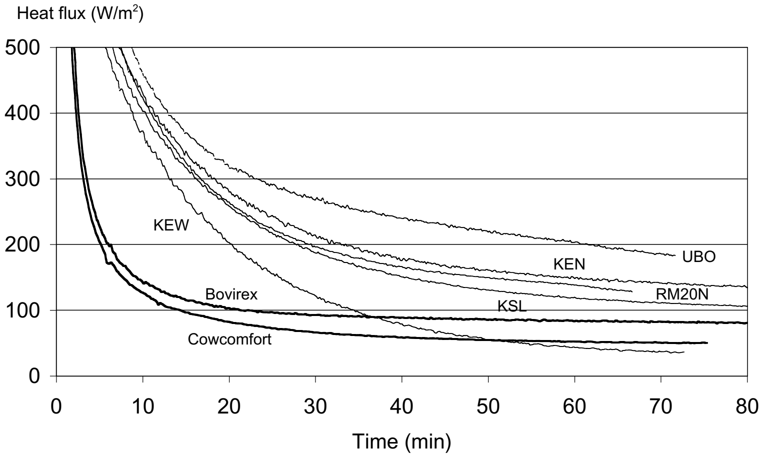

Fig. 1. Heat flux into the bedding materials as a function of time. The initial temperature of the bedding was 10°C.

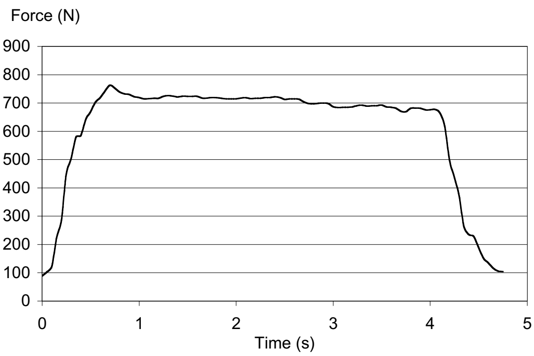

Fig. 2. Example of friction measurements for the KEW mat with 90 kg load. The applied force is given as a function of time. The static friction coefficient is calculated from the maximum force.

the friction coefficient. In Figure 3 some friction coefficients with load 170 kg are missing because the pulling force limits of the test system were reached. The 120 kg load was not used if the 170 kg load was measurable.

Results from the softness also showed significant differences between materials, both with the iron ball method (Fig. 4) and using the artificial hoof (Fig. 5). The pushing force in the iron ball test was not linearly dependent on deformation since the effective area over which the load is distributed increases when the ball penetrates into the material. The behaviour of the KEW-mat was very different from the others. This is due to the very soft material underneath the rubber mat. Finite element

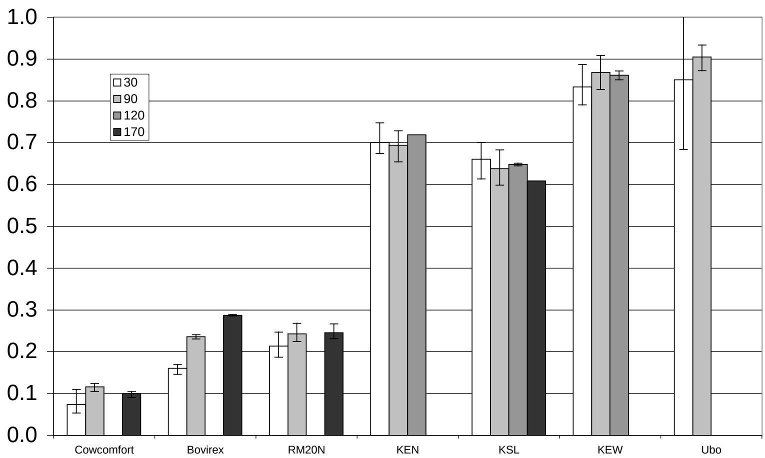

Fig. 3. Static friction coefficients for dry material loaded with 30, 90, 120 and 170 kg. The error bars give the range of five repetitions.

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Table 2. Physical properties of bedding materials. The friction coefficient was calculated from Eq. (4), the Young's modulus from Eq. (3) using the artificial hoof measurements (Fig. 5). The heat flux values at the two representative time instances were taken from the test series of Figure 1. The penetration of the (model) kneecap when the load is 400 kg are taken from the test series of Figure 4.

	Friction coefficient		Young's	Heat flux		Deformation
	dry	wet	modulus (MPa)	10 min. ($W m^{-2}$)	60 min. ($W m^{-2}$)	at 400 kg (mm)
KEN	0.70	0.54	5.4	430	150	10
KSL	0.64	0.58	4.6	400	120	14
RM20N	0.23	0.29	5.5	420	140	10
Ubo	0.88	0.92	10.8	460	200	7
Bovirex	0.23	0.23	6.3	140	80	27
Cowcomfort	0.10	0.07	6.7	120	50	16
KEW	0.85	0.68	1.5	370	40	23

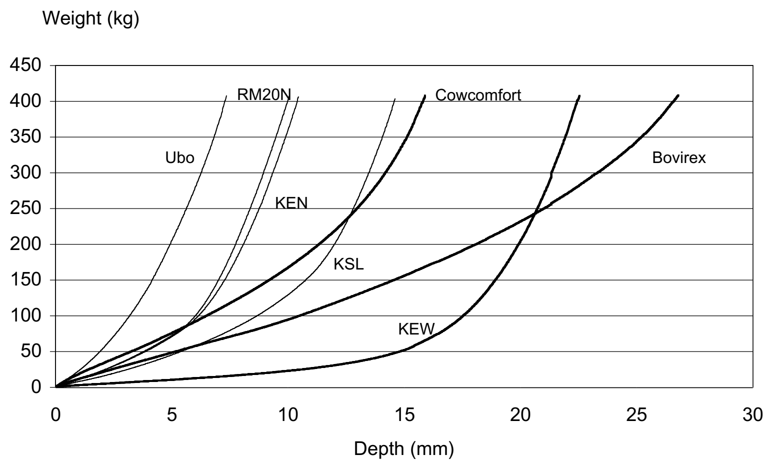

Fig. 4. Deformation as a function of the pressing force using the steel ball.

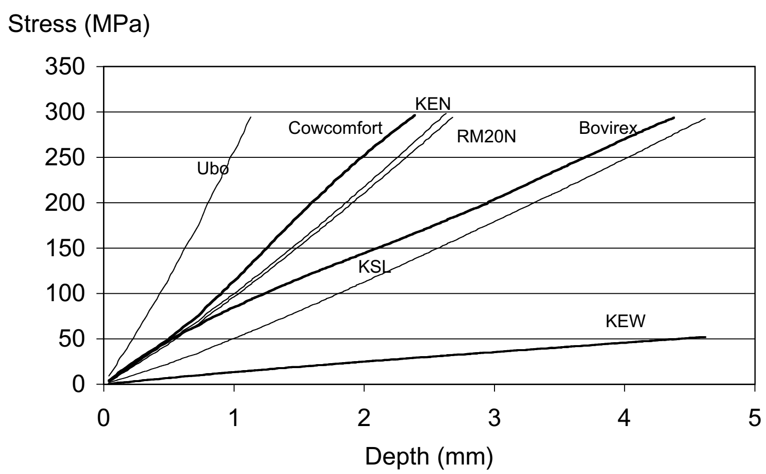

Fig. 5. Deformation as a function of the stress using the artificial hoof.

method (FEM) -calculations with ABAQUS-program (ABAQUS, Inc.) were also performed. They were in agreement with the experimental results.

Discussion and conclusions

As animal houses and indoor conditions differ in many respects, it is useful to study the physical properties of various bedding materials in order to see which of the materials is optimal for the heat balance of cows in winter or summer or in a free-stall or tied-stall and which of the materials is most cost effective and safe.

The physical properties of bedding materials vary considerably in all the respects studied (Table 2). The heat flux to the bedding was shown to be large enough to affect the cow's heat balance. The total heat production of a milking cow is about 1 kW. Heat loss to the floor during the first minutes may well be of the same magnitude taking into account the area of the cow against the floor and the low temperature of the bedding in winter (Fig. 1). The heat flux after 60 min gives information about the comfort of the bedding material over longer lying times. A low value indicates a 'warm' material and a high value indicates a 'cold' material. In cold conditions a 'warm' material is preferable, but in warm conditions it can be too hot. Heat flux after 10 minutes tells if the material feels warm or cold just after lying down and it can have an effect on the attractiveness of the material. Initially comfortable bedding may become uncomfortable over a longer period, and similarly an uncomfortable bed may become comfortable.

It should be noted that heat balance calculations in the literature are based on steady state conditions, i.e. the situation when the heat flow has stabilized, which takes about an hour. The relevance of this is questionable, since the typical lying time of milking cows is only one hour. The Eqs. (1) and (2) facilitate more sophisticated calculations where the time dependence of the phenomena can also be included. Equally recommendations for the suitable temperature range in the stall are at most based on static, non-dynamic, calculations. It is evident that the recommendable temperature range depends on the heating power of the animal, i.e. whether milking cows or beef cattle are being considered and on the bedding material and the housing conditions. The results give good basic information for choosing suitable bedding material in varying conditions after the heat balance calculation is performed for the chosen situation. It is evident that in winter and in summer or on the other hand for milking and for non-milking cows different kinds of thermal properties of lying materials are the best for cow's well-being.

The friction coefficients also vary. There are clearly both slippery and non-slippery materials. If we compare the results to the recommended friction of 0.3–0.5 (Wander 1970, Beer 1976, Bähr and Türpitz 1976, Nilsson 1978), we found that most of the tested materials are not in this range. However, the friction values were not absolute, as the material and the shape of the artificial hoof were not identical to natural hooves, the results are only indicative and they should be used solely for comparison purposes. Friction values will also change during usage since urine, manure and wear influence friction. In order to better compare friction characteristics beds should also be compared with each other after some usage time. Furthermore, the connection between slipping and friction coefficient is not straightforward. If the floor is slippery, the cow walks more carefully and will not slip.

There were also differences of almost an order of magnitude in the softness (Young's modulus) of the mats. Some of the mats were very soft and some were hard. Demands for softness vary according to the type of building and a cow with an injured leg needs softer bedding. The material has to be comfortable enough for lying and moving on the bed. Nilsson (1988) has given recommendations for the softness values which are based on the floor preference of cows. According to Nilsson (1988), in the iron ball test a suitable sinkage is 10–25 mm, when the load is 200 kg. All the materials except Ubo are approximately within this range (Fig. 4).

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The properties of mats and beds varied considerably and the various properties did not correlate with each other. More information is needed concerning these values to animal welfare and health in order to be able to make recommendations of different physical material characteristics in different climate and housing conditions.

Bedding materials have to fulfill the demands of both the animals and farm workers or farmers. For the animal welfare aspects are the most important and from the human perspective hygiene, durability and economy are significant. When different stall types and weather conditions are included, the choice of bedding material is not straightforward, but the materials have to be chosen case by case. The results of this study should help in the decision-making process.

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SELOSTUS

Synteettisten makuualustamateriaalien fysikaaliset ominaisuudet

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Tuotantoeläinten hyvinvointiin on viime vuosina alettu kiinnittää enemmän huomiota kuin aikaisemmin. Lypsylehmien parsien mukavuutta on pyritty lisäämään parsimatoilla ja viime aikoina parsipatjoilla ja -pedeillä. Näiden ns. synteettisistä materiaaleista valmistettujen alustojen yleistymistä on lisäksi edesauttanut niiden mahdollistama parsien kuivittamisen vähentäminen eli säästö työmäärässä. Parren mukavuutta lehmän kannalta on selvitetty eri tutkimuksissa, ja tärkeimmiksi parren fysikaalisiksi ominaisuuksiksi lehmän kannalta ovat nousseet kitka, pehmeys ja lämpövirta.

Tämän tutkimuksen tavoitteena oli mitata Suomessa myytävien makuualustojen lehmien hyvinvoinnin kannalta tärkeimmät fysikaaliset ominaisuudet. Tutkimusmenetelminä käytössä olivat lepokitkakertoimen määrittämiseen vetokoe, pehmeyden määrittämiseen puristuskoe ja lämpöominaisuuksien määrittämiseen lehmämalliin perustuva lämpövirtakoe.

Kitkan suositusarvona on 0,3–0,5. Jos kitka on suurempi, seurauksena on hiertymiä, jos se on alhaisempi, seurauksena on liukastumisia. Mattojen (UBO, RM 20N, KEN, KSL, Cow Comfort, Bovirex ja KEW) kitkat vaihtelivat melkoisesti eivätkä kaikki matot olleet suositusrajoissa. Käytössä kitka-arvot muuttuvat lannan, virtsan ja kulumisen vaikuttaessa, ja vertailtavuuden vuoksi olisi hyvä tehdä kitkamittauksia myös käytössä olleista matoista.

Mattojen pehmeydet vaihtelivat pehmeistä koviin. Pehmeysvaatimukset vaihtelevat esim. lehmien sorkkien kunnon mukaan. Sorkkaongelmainen lehmä valitsee pehmeämmän alustan kuin tervesorkkainen. Kova alusta aiheuttaa hiertymiä ja pehmeällä alustalla seisominen on epävakaata. Pehmeyden suosituksena on 10–25 mm painuma 200 kg:n kuormalla. Lähes kaikki matot ovat tällä alueella.

Mattojen lämmönjohtavuus ei ole yksiselitteinen, koska olosuhteiden vaihdellessa myös lämpövirran mattoon pitäisi muuttua. Kylmässä pieni lämpövirta on hyväksi ja kuumassa päinvastoin. Materiaalin houkuttelevuuteen vaikuttaa myös sen lämpövirta lehmän asettuessa makuulle. Materiaali voi olla alussa mukava, mutta pidemmän ajan jälkeen liian kuuma tai päinvastoin.

Tuloksia tulkittaessa on kuitenkin syytä kiinnittää huomiota eri kriteereiden keskinäiseen järjestykseen mattovalintaa tehtäessä. Esimerkiksi Suomen olosuhteissa käytössä on yleensä lämmin tuotantorakennus ja tällöin alustan eristävyydellä ei ole niin suurta merkitystä. Näissä olosuhteissa kriteerien järjestys mattovalintaan vaikuttamisessa voisikin olla seuraava: kitka, pehmeys, lämpövirta.