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# 肋条型仿生镇压辊减粘降阻试验*

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**摘要:** 基于臭蜣螂腹侧面的几何结构,设计了9种肋条型仿生镇压辊。肋条结构采用具有良好疏水性的超高分子量聚乙烯材料。采用 $L_9(3^4)$ 正交表,考察了土壤干基含水率为20%时,肋条结构底面宽度 $W$、高宽比 $R$、镇压辊载荷 $F$ 和面积比 $K$ 对镇压辊粘附土壤量和牵引阻力的影响。结果表明:在试验条件下,与普通镇压辊相比,仿生镇压辊在保证适宜玉米生长容积密度前提下具有明显的减粘效果,减粘率最高可达41.08%;合理的肋条结构尺寸可使仿生镇压辊的减阻率达11.75% ~39.40%。采用极差法对试验结果进行分析,得到了影响镇压辊粘附土壤量和牵引阻力因素的主次顺序及最优水平,并探讨了各因素对镇压辊粘附土壤量和牵引阻力的影响。

**关键词:** 仿生肋条 镇压辊 牵引阻力 土壤粘附 土壤压实

**中图分类号:** S222.23; Q811 **文献标识码:** A **文章编号:** 1000-1298(2014)04-0135-06

## 引言

镇压辊是农业机械中典型的滚动触土部件,用于播种后压实土壤。适当的镇压可以使种子与土壤紧密接触;减少土壤中的大孔隙,加强土壤毛细管作用;也可对种子在土壤中的深度差异进行微调节,使种子播深趋于一致[1-2]。研究证明,适当的土壤压实能够提高作物产量[3-8]。但是在镇压过程中,镇压辊容易粘附土壤,不仅影响种子发芽,而且会降低作业效率,增高能耗。所以减轻土壤对镇压辊表面的粘附,使土壤能够形成适当的土壤坚实度,具有重要的现实意义。

目前,关于土壤压实的研究,大多数集中在拖拉机及其牵引的机具对农田土壤过度机械压实的危害及其对应的解决措施[9-19]。而对于土壤镇压辊来说,压得太实或太松,都不利于种子的出苗。理想的镇压辊,应在保证所需压实作用前提下具有较低的牵引阻力,减少土壤粘附现象。

研究表明:土壤洞穴动物体表的几何结构是其在黏湿土壤环境中活动自如的主要原因之一[20-24]。基于臭蜣螂腹侧面的几何结构,本文设计肋条型仿生结构,并将它与防粘减阻材料超高分子量聚乙烯(UHMWPE)相集成,应用于滚动触土部件镇压辊上。采用正交试验方案在室内土槽进行试验,考察干基含水率为20%时,肋条结构底面宽度、高宽比(肋条高度/肋条底面宽度)、轮子载荷和面积比(肋条结构在柱面上投影面积之和与镇压辊表面积之比)4个因素对镇压辊减粘降阻的影响。

## 1 肋条型仿生镇压辊的设计

基于臭蜣螂腹侧面具有减粘减阻功能的几何结构[25](图1),设计出具有肋条型几何结构的仿生镇压辊,实体模型如图2所示。仿生镇压辊表面肋条结构的尺寸如图3所示,图中 $W$ 表示肋条底面宽度,$H$ 表示肋条断面高度。

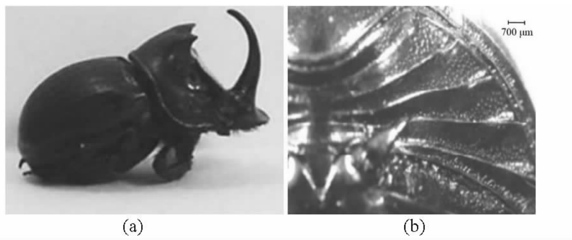


图1 臭蜣螂及其腹侧面的几何结构

Fig.1 Dung beetle *Copris ochus* Motschulsky and its geometrical structure on ventral surface of dung beetle

(a) 雄性臭蜣螂 (b) 臭蜣螂腹侧面的几何结构

传统镇压辊和仿生镇压辊的基体所采用的材料为Q235钢,其直径为325 mm,宽为200 mm。UHMWPE肋条结构通过沉头螺钉固定在镇压辊表面。通过增减配重块来调节镇压辊的质量。

## 2 土槽试验

### 2.1 试验准备和试验方法

试验在吉林大学工程仿生教育部重点实验室室

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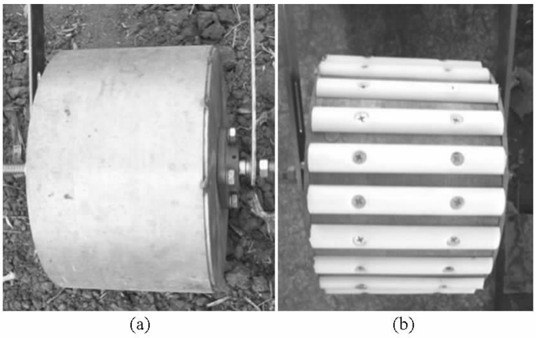



图 2 试验用镇压辊

Fig. 2 Press rollers

（a）传统镇压辊 （b）仿生镇压辊

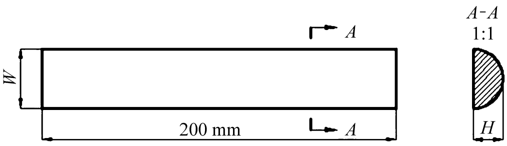



图 3 肋条结构尺寸

Fig. 3 Dimensions of ridge structure

内土槽进行，土槽长 40 m，宽 2.8 m，深 1.8 m。土槽土壤为东北地区的黄粘土，土壤塑限 $W_P$ 为 20.14%，液限 $W_L$ 为 36.17%。试验前，0～100 mm 土壤容积密度为 1.08 g/cm$^3$，100～200 mm 处土壤容积密度为 1.20 g/cm$^3$。人工调整土壤干基含水率为 20%。土槽台车的前进速度为 0.9 m/s。

镇压辊通过自制的轮架与 RSS03 型拉压传感器连接，传感器再通过一个自行设计连接装置与土槽台车相连，将镇压辊受到的牵引阻力转换成电信号，由 DH5923 型动静态应变仪采集信号并通过 1394 接口与计算机相连，将采集的信号传输到计算机。每次试验完成后，用硬毛刷将粘在镇压辊上的土刮下进行称量，从而考察镇压辊的粘附程度。土槽台车测试系统如图 4 所示。

图 4 土槽台车测试系统

Fig. 4 Measuring system used for drag resistance of press roller in an indoor soil bin

每组试验重复 3 次取平均值作为结果。为保证试验的可重复性，每次试验后对土槽内土壤进行翻整处理，用自制刮平装置将土壤刮平，再由 SZ－3 型土壤硬度计检测，保证每次试验前的土壤硬度误差在 10% 以内。

## 2.2 试验方案

试验的目的是通过正交试验，得出减粘降阻效果较好的肋条结构，并探寻各因素对镇压辊粘附土壤量和牵引阻力的影响。

试验因素为肋条结构底面宽度 $W$、高宽比 $R$（肋条高度/肋条底面宽度）、镇压辊载荷 $F$ 和面积比 $K$（肋条结构在柱面上投影面积之和与镇压辊表面积之比）。每个因素取 3 个水平，选用 $L_9(3^4)$ 正交表安排试验[26]。因素水平如表 1 所示，设计 9 种肋条结构，如图 5 所示。测试指标为镇压辊粘附土壤量和牵引阻力，同时采用环刀法测定每个镇压辊压后的土壤容积密度，以评价压实效果。

**表 1 正交试验因素水平**

**Tab. 1 Factor－level table of orthogonal test**

| 水平 | 因素 | | | |
|---|---|---|---|---|
| | 宽度 $a$/mm | 高宽比 $b$ | 载荷 $c$/N | 面积比 $d$/% |
| 1 | 20 | 0.3 | 300 | 25 |
| 2 | 30 | 0.5 | 500 | 50 |
| 3 | 40 | 0.7 | 700 | 75 |

图 5 9 种 UHMWPE 肋条结构

Fig. 5 Nine types of UHMWPE ridge structures

## 2.3 试验结果分析

### 2.3.1 减粘降阻效果

试验方案及试验结果之极差分析如表 2 所示。表中 0-1、0-2、0-3 号试验分别为传统镇压辊在载荷为 1、2、3 水平下的粘附土壤量和牵引阻力。

减粘率计算式为

$$R_a = \frac{M'_a - M_a}{M_a} \times 100\% \tag{1}$$

式中 $M'_a$——仿生镇压辊的粘附土壤量

$M_a$——传统镇压辊的粘附土壤量

减阻率计算式为

$$R_x = \frac{P'_x - P_x}{P_x} \times 100\% \tag{2}$$

式中 $P'_x$——仿生镇压辊的牵引阻力

$P_x$——传统镇压辊的牵引阻力

数值中，正值表示粘附土壤量、牵引阻力增加，负值表示粘附土壤量、牵引阻力减小。数据精确到

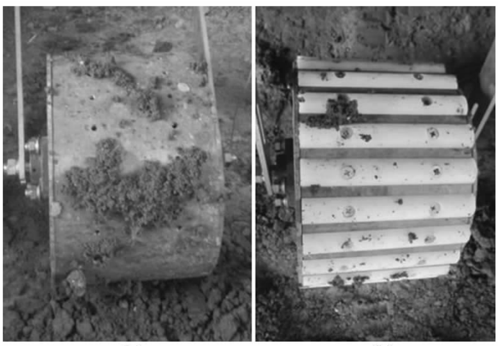
表 2　试验方案和试验结果极差分析

Tab. 2　Test scheme and range analysis of results

| 试验号 | 因素 | | | | 粘附土壤量 $M$/g | | | 减粘率 | 牵引阻力 $P$/N | | | 减阻率 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $A$ | $B$ | $C$ | $D$ | $M_{i1}$ | $M_{i2}$ | $M_{i3}$ | $R_a$/% | $P_{i1}$ | $P_{i2}$ | $P_{i3}$ | $R_x$/% |
| 1 | 1 | 1 | 1 | 1 | 29.75 | 31.38 | 36.05 | −6.55 | 32.40 | 39.25 | 31.77 | 19.45 |
| 2 | 1 | 2 | 2 | 2 | 26.50 | 30.35 | 22.50 | −18.41 | 67.96 | 61.59 | 64.78 | 6.22 |
| 3 | 1 | 3 | 3 | 3 | 66.85 | 57.85 | 53.50 | −5.86 | 102.54 | 106.28 | 106.78 | 54.79 |
| 4 | 2 | 1 | 2 | 3 | 11.95 | 17.40 | 21.50 | −30.93 | 32.82 | 41.23 | 36.82 | −39.40 |
| 5 | 2 | 2 | 3 | 1 | 23.65 | 13.20 | 21.50 | −29.45 | 196.85 | 200.10 | 270.46 | 227.35 |
| 6 | 2 | 3 | 1 | 2 | −4.50 | −12.50 | 2.50 | −32.83 | 97.18 | 91.88 | 99.00 | 227.54 |
| 7 | 3 | 1 | 3 | 2 | −4.35 | −1.85 | 5.50 | −41.08 | 67.44 | 87.19 | 86.66 | 18.35 |
| 8 | 3 | 2 | 1 | 3 | −3.55 | −0.45 | 10.50 | −27.89 | 23.27 | 21.66 | 21.35 | −23.44 |
| 9 | 3 | 3 | 2 | 1 | 9.20 | 21.85 | 19.50 | −24.60 | 54.86 | 50.17 | 56.43 | −11.75 |
| 0-1 | 0 | 0 | 1 | 0 | 41.35 | 39.68 | 44.00 | | 24.79 | 33.35 | 28.43 | |
| 0-2 | 0 | 0 | 2 | 0 | 50.68 | 59.00 | 55.25 | | 57.19 | 65.58 | 60.16 | |
| 0-3 | 0 | 0 | 3 | 0 | 85.20 | 52.10 | 70.65 | | 65.25 | 68.67 | 69.95 | |
| $M_{j1}$ | 354.73 | 147.33 | 89.18 | 206.08 | | | | | | | | |
| $M_{j2}$ | 94.70 | 144.20 | 180.75 | 64.15 | 试验指标：镇压辊粘附土壤量 | | | | | | | |
| $M_{j3}$ | 56.35 | 214.25 | 235.85 | 235.55 | 主次因素：$A$、$D$、$C$、$B$ | | | | | | | |
| $\overline{M}_{j1}$ | 118.24 | 49.11 | 29.73 | 68.69 | 优水平：$A_3$、$D_2$、$C_1$、$B_2$ | | | | | | | |
| $\overline{M}_{j2}$ | 31.57 | 48.07 | 60.25 | 21.38 | 最优组合：$A_3D_2C_1B_2$ | | | | | | | |
| $\overline{M}_{j3}$ | 18.78 | 71.42 | 78.62 | 78.52 | | | | | | | | |
| $R_{Mj}$ | 99.46 | 23.35 | 48.89 | 57.13 | | | | | | | | |
| $P_{j1}$ | 613.35 | 455.58 | 457.75 | 932.28 | | | | | | | | |
| $P_{j2}$ | 1 066.33 | 928.02 | 466.66 | 723.67 | 试验指标：镇压辊牵引阻力 | | | | | | | |
| $P_{j3}$ | 469.03 | 765.11 | 1 224.29 | 492.75 | 主次因素：$C$、$A$、$B$、$D$ | | | | | | | |
| $\overline{P}_{j1}$ | 204.45 | 151.86 | 152.58 | 310.76 | 优水平：$C_1$、$A_3$、$B_1$、$D_3$ | | | | | | | |
| $\overline{P}_{j2}$ | 355.44 | 309.34 | 155.55 | 241.22 | 最优组合：$C_1A_3B_1D_3$ | | | | | | | |
| $\overline{P}_{j3}$ | 156.34 | 255.04 | 408.10 | 164.25 | | | | | | | | |
| $R_{Pj}$ | 199.10 | 157.48 | 255.51 | 146.51 | | | | | | | | |

注：表 2 中是将粘附土壤量的数据减去 100 进行的，目的是简化计算，不影响试验结果的分析[26]。

小数点后两位。传统镇压辊和仿生镇压辊作业后的粘附情况如图 6 所示。



(a)　　(b)

图 6　镇压后粘附情况

Fig. 6　Soil adhesion after compaction

（a）传统镇压辊　（b）仿生镇压辊

应用极差分析法得出，在土壤干基含水率为 20% 时，影响镇压辊粘附土壤量的主次因素为 $A$、$D$、$C$、$B$，各因素的优水平分别为 $A_3$、$D_2$、$C_1$、$B_2$ 影响镇压辊牵引阻力的主次因素为 $C$、$A$、$B$、$D$，各因素的优水平分别为：$C_1$、$A_3$、$B_1$、$D_3$。

试验结果方差分析如表 3 所示。由于本试验设计无空列，所以用 $\dfrac{S_j/f_j}{S_{e2}/f_{e2}}$，临界值为 $F_\alpha(f_j, f_{e2})$ 的方法检验。查 $F$ 分布表得：$F_{0.1}(2, 18) = 2.62$，$F_{0.05}(2,18) = 3.55$，$F_{0.01}(2,18) = 6.01$。

对试验指标为镇压辊粘附土壤量的结果进行方差分析，得到：土壤干基含水率为 20% 时，$F_A > F_{0.01}(2,18)$，$F_B > F_{0.05}(2,18)$，$F_C > F_{0.01}(2,18)$，$F_D > F_{0.01}(2,18)$，$A$、$C$、$D$ 因素为显著因素，$B$ 为次要因素。

对试验指标为镇压辊牵引阻力的结果进行方差分析，得到：土壤干基含水率为 20% 时，$F_A > F_{0.01}(2,18)$，$F_B > F_{0.01}(2,18)$，$F_C > F_{0.01}(2,18)$，$F_D > F_{0.01}(2,18)$，$A$、$B$、$C$、$D$ 因素均为显著因素。

综合镇压辊粘附土壤量和牵引阻力的正交试验结果，肋条宽度是影响镇压辊粘附土壤量的首要因素，同时也是影响镇压辊牵引阻力的重要因素。在试验范围内，肋条宽度越大，仿生镇压辊减粘效果越明显。当肋条宽度为 40 mm 时，仿生镇压辊的粘附

表 3 正交试验结果方差分析

Tab. 3 Variance analysis of orthogonal test results

| 试验指标 | 方差来源 | 偏差平方和 $S_j$ | 自由度 $f_j$ | 均方和 $\overline{S}_j$ | $F$ | 显著性水平 $\alpha$ |
|---|---|---|---|---|---|---|
| 粘附土壤量 | $A$ | 5 856.18 | 2 | 2 928.09 | 85.51 | 0.01 |
| | $B$ | 347.97 | 2 | 173.98 | 5.08 | 0.05 |
| | $C$ | 1 219.75 | 2 | 609.87 | 17.81 | 0.01 |
| | $D$ | 1 866.32 | 2 | 933.16 | 27.25 | 0.01 |
| | 误差 | 616.34 | 18 | 34.24 | | |
| | 总和 | 9 906.55 | 26 | 381.02 | | |
| 牵引阻力 | $A$ | 21 584.62 | 2 | 10 792.31 | 50.27 | 0.01 |
| | $B$ | 12 798.44 | 2 | 6 399.22 | 29.81 | 0.01 |
| | $C$ | 43 024.52 | 2 | 21 512.26 | 100.20 | 0.01 |
| | $D$ | 10 742.06 | 2 | 5 371.03 | 25.02 | 0.01 |
| | 误差 | 3 864.51 | 18 | 214.70 | | |
| | 总和 | 92 014.16 | 26 | | | |

土壤量和牵引阻力最小。

面积比也是影响镇压辊粘附土壤量的主要因素。从试验结果的综合分析来看,面积比不是越小越好,也不是越大越好,面积比为 50% 时镇压辊具有最佳的减粘效果。面积比对镇压辊牵引阻力而言是影响最小的因素,镇压辊的牵引阻力随着面积比的增大而减小的。

相对于肋条宽度、面积比来说,镇压辊载荷不是影响镇压辊粘附土壤量的重要因素,从正交试验极差分析结果来看,在试验所取的载荷范围内,镇压辊的粘附土壤量随着载荷的增大而增大;而载荷对镇压辊牵引阻力的影响最为明显,载荷越大,镇压辊的牵引阻力越大。

肋条高宽比对镇压辊粘附土壤量和牵引阻力而言都是影响很小的因素,且对镇压辊粘附土壤量的影响最小。高宽比取值为 0.3 和 0.5 时,镇压辊粘附土壤量相差不大,而当高宽比为 0.7 时镇压辊粘附土壤量最大,这是因为高宽比取值太大会使得土壤卡在两肋条之间。在本试验中,高宽比为 0.5 时镇压辊粘附土壤量最小;而高宽比在试验范围内取值最小时,镇压辊的牵引阻力最小。

根据极差分析和方差分析的结果,通过综合平衡法,对粘附土壤量和牵引阻力 2 个试验指标进行综合考察,得到影响镇压辊性能的因素主次顺序为 $A$、$C$、$D$、$B$,肋条结构尺寸最优组合为 $A_3B_1C_1D_2$。

**2.3.2** 压实效果

镇压作业后的土壤容积密度如表 4 所示。根据文献[27],玉米最适宜的土壤容积密度,黑土上为 1.0 ~ 1.3 g/cm$^3$。从试验结果来看,肋条型仿生镇压辊同普通镇压辊一样,均能达到适宜玉米生长的土壤容积密度。

表 4 镇压后土壤容积密度

Tab. 4 Soil bulk density after compaction g/cm$^3$

| 深度/mm | 试验号 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 0-1 | 0-2 | 0-3 |
| 0 ~ 100 | 1.16 | 1.20 | 1.24 | 1.21 | 1.23 | 1.14 | 1.25 | 1.14 | 1.19 | 1.15 | 1.22 | 1.26 |
| 100 ~ 200 | 1.24 | 1.25 | 1.30 | 1.26 | 1.28 | 1.23 | 1.29 | 1.21 | 1.24 | 1.25 | 1.28 | 1.29 |

## 3 结论

(1) 基于臭蜣螂腹侧面的几何结构,设计了 9 种肋条型仿生镇压辊。肋条结构采用具有良好疏水功能的超高分子量聚乙烯材料。采用 $L_9(3^4)$ 正交表方案,考察了土壤干基含水率为 20% 时,肋条结构断面宽度 $W$、肋条高度与肋条底面宽度之比 $R$、镇压辊载荷 $F$、肋条结构在柱面上投影面积之和与镇压辊表面积之比 $K$ 对镇压辊粘附土壤量和牵引阻力的影响。

(2) 试验因素对镇压辊粘附土壤量和牵引阻力的影响并不一致。与传统镇压辊相比,正交试验中的所有仿生镇压辊在能达到适宜玉米生长的容积密度的前提下,均实现了显著的减粘效果,减粘率最大可达 41.08%;4、8、9 号试验的仿生镇压辊起到了降阻作用,分别减阻 39.40%、23.44% 和 11.75%。

(3)在试验条件下,根据综合平衡法得到减粘减阻效果最优的肋条型仿生镇压辊的尺寸为肋条宽度 40 mm,高宽比 0.3,载荷 300 N,面积比 50%。

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# Reduction of Soil Adhesion and Traction Resistance of Ridged Bionic Press Rollers

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**Abstract**: The phenomenon of soil adhesion occurred widely when conventional press roller worked. To solve the problem, nine biomimetic press rollers with bionically ridged structures were designed learning from the geometric structure of the ventral surface of dung beetle (*Copris ochus* Motschulsky). Bionically ridged structures using ultra high molecular weight polyethylene material, which possessed good hydrophobic properties, were modeled on the surfaces of press rollers. Orthogonal tests of $L_9(3^4)$ were performed in an indoor soil bin with a moisture content (dry basis) of 20%. The effects of the bottom width of ridge section ($W$), ridge height to width ratio ($R$), roller loads ($F$) and the area ratio ($K$) on soil adhesion and traction resistance were determined. The results showed that under the identical conditions, all bionic rollers exhibited lower adhesion than a conventional roller against soil in a suitable compaction for corn, and the maximal adhesion reduction rate was 41.08%. The bionic roller with ridged structure with reasonable dimensions could reduce the traction force by 11.75% ~ 39.40% than conventional roller. The order and optimal levels of the experiment factors influencing soil adhesion and resistance were determined by range method. The impact of the different factors on the soil adhesion and resistance of press roller was discussed.

**Key words**: Bionic ridge  Press roller  Traction resistance  Soil adhesion  Soil compaction

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# Multi-source Image Registration for Canopy Organ of Apple Trees in Mature Period

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**Abstract**: In order to construct colorful 3-D spatial structure of canopy accurately, apple tree canopies of maturation period were set for research object, and a PMD camera and a color camera were used to acquire multi-source organ images of apple tree canopies, which aimed at studying registration of multi-source images. SIFT algorithm was used to extract characteristic points from multi-source images and RANSAC algorithm optimized by objective function was adopted to purify feature vectors, which overcame scale change and effect of light. Bilinear mapping algorithm was employed as spatial mapping between multi-source images to avoide inaccuracy of using affine transformation to solve space mapping. The registration test in orchards with different natural environment showed that the method proposed was suitable for registration of multi-source images of apple tree canopies, and the registration accuracy could be 88.2% in sunny day of light environment, 84.2% in sunny day of backlight environment, 72.7% in cloudy day. The research finding could provide maintenance assurance for picking and yielding links of apple orchard after 3-D reconstruction of canopies.

**Key words**: Canopy of apple trees  Multi-source images  Registration  PMD camera  Color camera