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Reduced weed growth with different paving constructions

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Summary

The recent phaseout of herbicide use on public pavements in Flanders has triggered the development of alternative weed control strategies. Besides the search for effective non-chemical curative methods, there is also a need for strategies that prevent or reduce weed growth on pavements. In this study a paving experiment was set up under a rain shelter to investigate the effects of four construction factors on weed growth: joint filling material, joint width, organic pollution of the joint filling material and type of bedding layer. Paving mini-plots were oversown with a mixture of dominant, hard-to-control weed species found on pavements. The inhibitory effect on weeds was determined by examining initial weed density and weed coverage over a 2-year period. More weed growth was found in pavings with wide joints and organically polluted joint filling materials. High permeability of the bedding layer resulted in higher weed cover. The coarse-grained filling materials and the sodium silicate-enriched sand Dansand® were associated with less weed cover than the fine-grained filling materials. Our results show there is potential for preventing weed growth using suitable paving materials and appropriate high-standard construction and maintenance of pavements.

Keywords: hard surfaces, urban areas, pavements, weed prevention, joint filling materials, weed coverage, non-chemical weed control.

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Introduction

To meet the European Water Framework Directive requirements for pesticide residues, the Flemish government agreed to phase-out the use of herbicides on public pavements by 2015. This phase-out has triggered the development of new alternative weed control strategies. A wide range of alternative weed control methods exists (Rask & Kristoffersen, 2007), but all have disadvantages compared with pesticide use. Non-chemical weed control methods need to be applied more often than commonly used pesticides such as glyphosate, which causes an almost complete kill of the existing higher plants with one to two treatments a year (Augustin *et al.*, 2001). This implies high costs for municipalities, as labour is much more costly than chemicals. Non-chemical weed control methods often use large amounts of fuel, thus contributing to atmospheric sink effects (greenhouse gasses, smog, ozone layer; Kempenaar *et al.*, 2007). Reducing the

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frequency of weed control treatments is therefore a challenge in terms of costs and in terms of environmental impact.

To obtain an acceptable weed level in the street scene, both preventive and curative strategies will be necessary when herbicides are no longer in use. On established pavements, weed growth can be prevented by regularly sweeping to prevent accumulation of organic matter in the joints (Kempenaar *et al.*, 2009). Newly constructed pavements can be designed to prevent weed establishment and development (Guldemond *et al.*, 2007; Rask & Kristoffersen, 2007). Weed growth is affected by the amount of open area between pavers (joint width) and the availability of light, water and nutrients (Benvenuti, 2004; Kempenaar *et al.*, 2006; Fagot *et al.*, 2011). Joint filling materials with different technical characteristics are available and even special weed preventive joint filling materials have been developed. But the efficiency of these materials is not well quantified, particularly not over longer periods of time and in combination with other weed preventive measures.

In this study, we quantified the effects of four different construction parameters on weediness of the pavement. The construction parameters were as follows: (i) joint filling material, (ii) joint width, (iii) organic pollution of the joint filling material and (iv) type of bedding layer material. The effects of these parameters were investigated by assessing total seedling and initial species density, on total weed coverage and on weed species composition of the established vegetation.

Materials and methods

Paving experiment

In May 2009, a paving experiment with 96 block paving plots was set up in Melle, Belgium (50°58′42′N; 3°49′06′E), and weed dynamics were monitored until November 2010. The trial was designed to evaluate the relative susceptibility of the paving systems to weed ingress. The experiment was conducted under a plastic rain shelter to remove variability in weed coverage and weed composition caused by heavy rainfall, bird manure deposition, damage by birds (e.g. removal of joint fillers) and patchiness of seed rain. The sides of the shelter were left open up to 100 cm high for natural ventilation. Hence, temperatures, light intensity and relative humidity closely follow natural diurnal and seasonal fluctuations, making our environment representative of an open air experiment. Average temperature and humidity values inside and outside the rain shelter during the experimental periods are given in Table 1. Paving plots were installed in concrete containers with an open bottom (Rasterflor 60 cm × 40 cm, height 25 cm) and had a surface of 0.129 m^2. Each paving plot consisted of a conventional (non-permeable) concrete block paving formed by 11 cm × 11 cm pavers (thickness 8 cm) on top of a bedding layer (4 cm), supported by a base layer (13 cm; Fig. 1). The base layer was identical for all plots and consisted of coarse limestone with grain size in a range of 2–20 mm (2/20 mm). The dimensions of the structure were in accordance with the recommendations for *in situ* paving

Table 1 Average temperature and relative humidity inside and outside the rain shelter during the experimental period

	Average temperature (°C)		Average relative humidity (%)	
Period	Inside	Outside	Inside	Outside
June 2009	27.8	16.5	61	69
July 2009	31.2	18.7	62	70
August 2009	29.6	19.4	62	66
September 2009	24.9	15.8	69	78
October 2009	17.4	11.3	76	83
November 2009	14.4	9.7	83	84
December 2009	6.2	2.9	89	89
January 2010	2.1	0.1	85	91
February 2010	5.2	2.5	82	86
March 2010	13.4	6.7	67	72
April 2010	20.1	10.3	62	65
May 2010	23.1	11.2	64	76
June 2010	27.7	17.4	63	70
July 2010	30.0	20.5	64	67
August 2010	25.3	17	73	78
September 2010	22.3	14.2	76	84
October 2010	15.7	10.6	85	83
November 2010	11.8	6.1	95	88
Summer 2009	28.6	18.0	64	71.3
Summer 2010	25.9	17.2	70	76.3
2-year period*	19.3	11.7	73	77.7

*The screening period (May 2009–November 2010), Summer 2009 (July 2009–September 2009) and Summer 2010 (July 2010–September 2010).

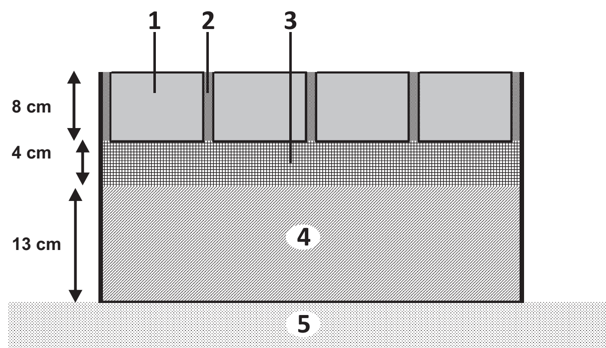

Fig. 1 Structure of the block pavings. **1**. Concrete block paving, **2**. Joint filling material, **3**. Bedding layer, **4**. Base layer, **5**. Well-draining surface.

constructions by the BRRC (2009) and the widely adopted technical specification PTV827 (http://www.copro.eu). Paving plots were arranged in a randomised complete block design with three replications. Paving plots comprised factorial combinations of five joint filling materials, two joint widths, two pollution levels and two bedding layer materials.

Tested joint filling materials (with their range of grain size indicated in brackets) were as follows: Dansand® (0/2 mm; a sodium silicate-enriched sand), white sand (0/2 mm), sea sand (0/2 mm), crushed limestone (0/6.3 mm) and crushed porphyry (2/6.3 mm). For all these materials, a set of physical (Table 2) and chemical (Table 3) characteristics was determined: water permeability [column test as developed by OCW (1968)], silt/clay fraction (grain size < 0.063 mm), sand fraction (grain size 0.063–2 mm; obtained by sieving), amount of plant available water [PF2-PF4.2; as described by Cornelis *et al.* (2005)], pH (KCl), electric conductivity (measured with electrode) and mineral composition [N (extraction in KCl, measurement with Continuous Flow Autoanalyser), K, P, Ca, Na and Mg (extraction in ammonium lactate, measurement with inductively coupled plasma)].

Two different joint widths were assessed for their influence on pavement weediness: narrow joints (3 mm, open area 5.56% of the pavement) and wide joints (11 mm, open area 14.47% of the pavement). The coarse-grained materials (porphyry and limestone) were only applied in wide joints, as their grain size was too large to fit in the narrow joints. In practice, the fine-grained materials (white sand, sea sand and Dansand®) were only applied in narrow joints. In this study, we used them in wide joints as well, to simulate older pavements with subsidence, or pavements that were poorly finished (e.g. wide joints around obstacles or along buildings or kerb lines). Indeed, joints with fine-grained joint filling materials can widen over time due to intensive use or frost.

Joint filling materials were evaluated in pure and organically polluted state. To mimic *in situ* organic pollution in joints, the joint fillers were mixed with air-dried fine compost with maximum particle size of 3 mm (chemical composition is given in Table 3) up to 10% by volume. This corresponds with 1.93–2.26% fine compost by weight, depending on the used joint filling material, and is comparable with organic matter content we found in joints of old pavements.

Bedding layer materials included in the test comprised crushed porphyry (2/6.3 mm) and crushed limestone (0/6.3 mm). The crushed porphyry has an open structure and is well-draining (hereafter named ‘open bedding layer’). The limestone has a higher amount of fine particles and hence is less water permeable (hereafter named ‘closed bedding layer’). The characteristics of the bedding layer contribute to the draining capacity of the entire pavement structure and are important for fast infiltration of rain water.

After establishing the block pavings, each plot was oversown with a mixture of four dominant, hard-to-control weeds on pavements, as indicated by Fagot *et al.* (2011): *Poa annua* L. (annual meadow-grass), *Taraxacum officinale* F.H. Wigg. (dandelion), *Plantago major* L. (greater plantain) and *Trifolium repens* L. (white clover). Per plot, the seed mixture was made up of 100 germinable seeds per species (i.e. 775 germinable seeds m^{-2}) and manually sown in the joints between the pavers. Sown seeds were covered with a thin layer of corresponding joint filling material. All sown seeds were locally collected in summer and autumn 2008 on urban pavements. Each species in the seed mixture contained seeds of four different populations. Pavings were watered three times a day by automatic sprinkler irrigation (2.1 mm rainwater per day). Annual (767 mm) and seasonal water gifts (189, 193.2, 193.2 and 191.1 mm in winter, spring, summer and autumn respectively) were comparable to mean annual (852 mm) and seasonal rainfall (220, 188, 225 and 220 mm in winter, spring, summer and autumn respectively) in Belgium over the past 30 years. During the entire experimental period (2009–2010), wind-borne seeds from outside the shelter were kept out the rain shelter by attaching a fine-mesh windbreak gauze to the open sides of the rain shelter. Inside the rain

Table 2 Physical characteristics of the joint filling materials

Material	Water permeability ($m\ s^{-1}$)	Fraction small particles <0.063 mm (%)	Fraction 0.063–2 mm (%)	Plant available water (volumetric %)†
Dansand®	$3.33*10^{-4}$	1.8	98.2	1.73
White sand	$3.33*10^{-4}$	0.2	99.8	1.18
Sea sand	$3.37*10^{-4}$	0.1	98.9	0.33
Limestone	$3.04*10^{-3}$	14.4	32.4	8.10
Porphyry	$1.60*10^{-3}$	1.4	1.2	0.12

†Difference in soil water content between PF2 and PF4.2.

Table 3 Chemical characteristics of the joint filling materials and fine compost

Material	Mineral N (mg/100 g)	P (mg/100 g)	K (mg/100 g)	Ca (mg/100 g)	Na (mg/100 g)	Mg (mg/100 g)	EC (μS cm^{-1})	pH (KCl)
Dansand®	<1	10.1	2.4	26.8	402	<1	1070	9.57
White sand	<1	0.5	2.4	8.5	2.2	<1	12.5	7.55
Sea sand	<1	9.4	6.0	2230	60.6	25.5	457	8.52
Limestone	<1	1.2	4.8	17 474	47.6	194.8	811	8.39
Porphyry	<1	2.5	18.8	654	9.2	43.8	68	8.13
Fine compost	48.8	23.7	258	1280	142.2	143.3	1275	6.04

shelter, all seed dispersal was prevented by removing all inflorescences before they set seed. No weed control or sweeping operations were executed on the paving plots during the entire experimental period.

The effect of paving plots on weeds was determined by examining total seedling density, initial species density, total weed coverage and species coverage. Initial species density was recorded 2 months after sowing by counting the number of living plants of a species in each paving plot area. The sum of the initial species densities over all sown species was defined as the total seedling density. Total weed coverage was recorded monthly by taking pictures of each plot from a height of 45 cm above the ground. Species coverage, that is, the relative area covered by each species in a paving plot (calculated by dividing the estimated species coverage by the estimated total coverage by all weed species), was determined in August 2009 and August 2010. All coverage percentages were determined using Image J Software and were expressed in % coverage of the paving surface.

The weediness of a paving during a given screening period was calculated as the number of days total weed coverage exceeded a predefined limit (=2%) of acceptable maximum weed coverage. This limit is commonly used by municipalities as a threshold for weed control at moderately prioritised areas in Belgium. Daily values for total weed coverage were obtained by linear interpolation between consecutive monthly ratings of total weed coverages. Daily values for total weed coverages were calculated for three screening periods separately, namely the entire 2-year period (May 2009–November 2010) and for the summers of 2009 and 2010 (July–September). As the weed coverage declines during winter, these summer data depict a situation with maximum weed coverage.

Data analysis

In our incomplete factorial experiment with four factors, not all combinations between joint filling materials and joint widths were tested. Hence, to avoid computations for analysis of variance (ANOVA) on different subsets of the original data set, the experiment was analysed as an $8 \times 2 \times 2$ complete factorial experiment with eight combinations 'filling material and joint width' (hereafter named 'paving type'), two organic pollution levels and two bedding layer materials, for a total of 32 factorial treatment combinations arranged in a randomised complete block design with three replicates (96 experimental units in total). Paving types comprised two coarse-grained fillers combined with wide joints and all six factorial combinations between three fine-grained fillers and two joint widths. Effects of joint filling material and joint width were derived by calculation of orthogonal contrasts for weediness and total seedling density.

The open-source program R, version 2.11.1 (R Development Core Team, 2010) was used to carry out all statistical computations. To investigate the effect of different paving constructions, two sets of ANOVAS were performed. A first set of ANOVAS was performed on data of initial weed density collected 2 months after sowing (July 2009), namely total seedling density (over all species) and initial species density (of the four sown species separately). A second set of ANOVAS was executed on weediness data (number of days with weed coverage >2%) for the three screening periods (2-year period, summer 2009, summer 2010) separately.

To examine shifts in flora composition over time, a third set of ANOVAS was performed on data regarding species coverage in the two summer periods (August 2009 and August 2010). As mosses (Musci) appeared spontaneously on the block pavings during the experimental period, analyses were executed separately for the four sown weed species and for mosses.

For comparison of treatment means, the least significant difference (LSD) test was used. *P*-values below 0.05 were considered significant. Homogeneity of variance was evaluated by Levene's test and by plots of residuals against predicted values. All data tested met normality assumptions.

Results

Total seedling density, 2 months after sowing

Total seedling density was affected by interactions between paving type and organic pollution level (Table 4). In pavings with Dansand®, total seedling density was significantly lower than in pavings with all other joint filling materials, irrespective of organic pollution level (Table 5). Within pavings with wide joints filled with pure filling materials, seedling density was threefold to fourfold lower in porphyry than in white sand or sea sand. Seedling densities were 27% lower in pavings with pure sea sand than in pavings with pure white sand (Table 6). Joint width significantly affected seedling density in pavings with pure joint fillers, but not in pavings with organically polluted fillers: lowest densities were found in narrow joints (Table 6).

Initial species density, 2 months after sowing

For all sown species, significant interactions between paving type and organic pollution level were found (Table 4). Species density of all sown species was significantly lower in Dansand® than in all other joint filling materials, irrespective of pollution level or joint width (except for *P. major* in pavings with pure joint fillers; Table 5). In pavings with pure filling materials, species density of *T. officinale* was about twofold higher in white sand and limestone than in sea sand or porphyry. In pavings with wide joints filled with pure fillers, all species except *T. officinale* exhibited twofold to 12-fold lower densities in pavings with porphyry than in pavings with white sand or sea sand. However, differences in seedling densities among filling materials were less pronounced when filler materials were organically polluted. In pavings with wide joints, species densities of *P. major* were equally low in pavings with pure limestone, pure porphyry and pure Dansand®.

In pavings with the same unpolluted joint filling material (excluding Dansand®), densities of *T. officinale*, *P. major*, *T. repens* and *P. annua* were, respectively, 8–30%, 33–73%, 16–45% and 17–40% lower (not always significantly) in narrow joints than in wide joints. These differences were most pronounced for pavings filled with pure sea sand.

With the exception of pavings filled with Dansand®, densities of all species were generally higher (not always significantly) when joint filling materials were organically polluted. These differences were most pronounced in pavings with narrow joints (36–89%, 83–387%, 17–133% and 12–45% higher densities for *T. officinale*, *P. major*, *T. repens* and *P. annua* respectively), particularly for pavings with sea sand.

Total weed coverage (weediness)

Significant interactions between paving type and organic pollution level were found (Table 4), irrespective of the time period. For pavings with wide joints, weediness over the 2-year period was lowest in pavings filled with Dansand® and highest in pavings filled with sea sand, irrespective of pollution level (Table 5). Within pavings with narrow joints, weediness was lower when Dansand® was used instead of white sand or sea sand, irrespective of pollution level. Weed suppressive ability of Dansand® decreased over time, particularly in pavings with wide joints as indicated by the significant higher weediness in pavings with polluted Dansand® in the 2-year period and in the summer of 2010. During the 2-year period, pavings with sea sand were weedier than pavings with white sand, irrespective of pollution level (Table 6).

During the 2-year period, weediness was always higher in pavings with wide joints than in pavings with narrow joints, except for unpolluted Dansand® (Tables 5 and 6).

In pavings with wide joints, weediness during the entire 2-year period was 17–647% higher in organically polluted joint filling materials than in pure joint filling materials. In pavings with narrow joints, differences in weediness between pairs of pure and polluted joint filling material were less pronounced, except for sea sand. In the summer of 2009, a higher weediness in pavings with organically polluted materials was found in white sand, sea sand (except for wide joints) and the coarse-grained joint fillers limestone and porphyry. In the summer of 2010, higher weediness was only found in pavings with wide joints filled with limestone and Dansand®.

During the 2-year period, weediness was higher in pavings laid upon a closed bedding layer than in pavings laid upon an open bedding layer (closed bedding layer, 192.1 days vs. open bedding layer, 163.9 days; LSD = 27.0 days) as illustrated in Fig. 2.

Flora composition of established paving vegetation

Significant interactions between paving type and organic pollution level were found for relative species coverage of sown species, irrespective of summer period (August 2009 or August 2010; Table 4). In August 2009 (Table 7), all sown species were relatively less abundant (in terms of relative coverage) in pavings with Dansand® than in pavings with other joint filling materials (Table 7). In pavings with wide joints, *T. officinale* was 1.2–14.5 times more abundant in

Table 4 Analysis of variance of data of total seedling density (2 months after sowing), initial species density (2 months after sowing), weediness (during 2-year period, in summer 2009 and summer 2010) and relative coverage of weed species (in August 2009 and 2010)

Effects/interactions	d.f.	Total seedling density (seedlings per plot)	Initial species density (seedlings per plot)				Weediness (number of days with total weed coverage >2%)			Relative coverage of weed species (%)									
										August 2009					August 2010				
			TAR	PLA	TRI	POA	2 years†	Summer 2009	Summer 2010	TAR	PLA	TRI	POA	Musci	TAR	PLA	TRI	POA	Musci
Paving type	7	***	***	***	***	***	***	***	***	***	***	***	***	NS	NS	***	NS	**	***
Bedding layer material	1	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS
Organic pollution	1	***	*	***	**	**	***	***	**	***	***	***	***	NS	*	NS	*	NS	NS
Paving type × bedding layer material	7	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Paving type × organic pollution level	7	***	*	***	**	**	**	***	**	**	***	***	***	NS	NS	NS	NS	NS	NS
Bedding layer material × organic pollution level	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Paving type × bedding layer material × organic pollution level	7	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

d.f., degrees of freedom; TAR, *Taraxacum officinale*; PLA, *Plantago major*; TRI, *Trifolium repens*; POA, *Poa annua*.

$*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$.

†The screening period (May 2009–November 2010), Summer 2009 (July 2009–September 2009) and Summer 2010 (July 2010–September 2010).

Table 5 Mean total seedling density (2 months after sowing), initial species density (2 months after sowing) and weediness for all paving types at two organic pollution levels

Organic pollution level	Paving type	Total seedling density (seedlings per plot)	Initial species density (seedlings per plot)				Weediness (number of days with total weed coverage >2%)		
			TAR	PLA	TRI	POA	2 years	Summer 2009	Summer 2010
Polluted	1: Dansand/Narrow	0^{c}	0^{b}	0^{d}	0^{c}	0^{c}	6^{e}	0^{b}	0^{c}
	2: Dansand/Wide	0^{c}	0^{b}	0^{d}	0^{c}	0^{c}	111^{d}	0^{b}	55^{a}
	3: White sand/Narrow	234^{ab}	47^{a}	66^{b}	52^{ab}	69^{ab}	146^{d}	77^{a}	0^{c}
	4: White sand/Wide	283^{a}	45^{a}	95^{a}	68^{a}	75^{a}	346^{b}	84^{a}	57^{a}
	5: Sea sand/Narrow	237^{ab}	42^{a}	84^{ab}	54^{ab}	56^{b}	238^{c}	70^{a}	24^{bc}
	6: Sea sand/Wide	243^{ab}	31^{a}	86^{ab}	55^{ab}	70^{ab}	454^{a}	84^{a}	48^{ab}
	7: Limestone/Wide	200^{b}	45^{a}	29^{c}	54^{ab}	72^{ab}	344^{b}	70^{a}	36^{abc}
	8: Porphyry/Wide	204^{b}	34^{a}	65^{b}	49^{b}	57^{b}	268^{bc}	84^{a}	14^{c}
Pure	1: Dansand/Narrow	0^{c}	0^{d}	0^{d}	0^{d}	0^{d}	0^{d}	0^{d}	0^{c}
	2: Dansand/Wide	0^{c}	0^{d}	0^{d}	0^{d}	0^{d}	15^{d}	0^{d}	0^{c}
	3: White sand/Narrow	176^{a}	34^{b}	36^{bc}	44^{b}	61^{a}	85^{cd}	38^{b}	8^{c}
	4: White sand/Wide	231^{a}	49^{a}	53^{ab}	53^{b}	74^{a}	219^{b}	52^{b}	34^{ab}
	5: Sea sand/Narrow	101^{b}	22^{bc}	17^{cd}	23^{c}	39^{b}	60^{cd}	12^{cd}	3^{c}
	6: Sea sand/Wide	195^{a}	24^{bc}	65^{a}	42^{b}	64^{a}	389^{a}	84^{a}	51^{a}
	7: Limestone/Wide	209^{a}	54^{a}	9^{d}	74^{a}	72^{a}	126^{c}	35^{bc}	9^{c}
	8: Porphyry/Wide	59^{b}	15^{c}	5^{d}	21^{c}	19^{c}	44^{cd}	0^{d}	25^{bc}
LSD		59	14	21	18	15	83	24	26

LSD, least significant difference; TAR, *Taraxacum officinale*; PLA, *Plantago major*; TRI, *Trifolium repens*; POA, *Poa annua*.
No significant differences between figures with the same letter (superscript) (Fischer's LSD, $P = 0.05$), comparison within species and pollution level only. Standard error of mean difference = LSD/$t_{0.9750}$ ($t_{0.9750} = 2.0$, d.f. = 62).

Table 6 Orthogonal contrasts for total seedling density and weediness (during 2-year period) of paving types with fine-grained joint filling materials at two organic pollution levels

Description of contrast	Paving types compared†	Organic pollution level	Total seedling density (seedlings per plot)		Weediness during 2-year period (number of days with total weed coverage >2%)	
			Mean comparison	*P*-value	Mean comparison	*P*-value
Wide joints vs. narrow joints	(2 + 4 + 6) vs. (1 + 3 + 5)	Polluted	175 vs. 156	NS	304 vs. 130	***
		Pure	142 vs. 93	***	207 vs. 49	***
White sand vs. sea sand	(3 + 4) vs. (5 + 6)	Polluted	258 vs. 240	NS	246 vs. 346	**
		Pure	203 vs. 148	**	151 vs. 225	**

NS, non-significant.
*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$.
†For explanations of figures: see Table 5.

limestone than in sea sand or white sand, irrespective of pollution level; for *P. major*, the reverse was true. In August 2010 (Fig. 3), the differences in relative coverage between paving types were only significant for *P. annua* and *P. major*; in pavings with wide joints, *P. annua* was most abundant in sea sand, whereas *P. major* was most abundant in pavings with porphyry. The only sown species that occurred in Dansand® was *P. major*, although it did not reach high densities (Fig. 3). *Plantago major* was more abundant in pavings laid upon a closed bedding layer than when an open bedding layer was used (closed bedding layer, 23.5% vs. open bedding layer, 9.2%; LSD = 9.8%).

The relative coverage of Musci was always lower than 1% in August 2009; it rose to 95% in August 2010. In pavings with narrow joints, relative coverage was lowest in Dansand® (Fig. 3). In pavings with wide joints, coverage was lowest in porphyry.

Discussion

The reported effects based on the mini-pavement experiment under semi-natural conditions are relevant

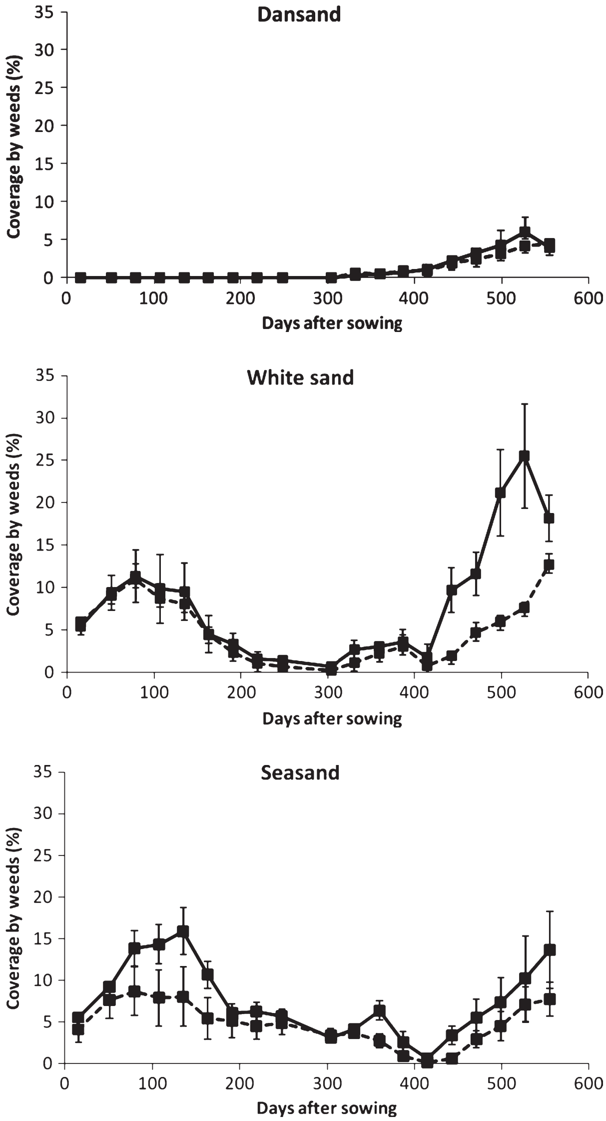

Fig. 2 Evolution of the weed coverage of paving plots over time and the effect of the type of bedding layer. Results are shown for paving types with wide joints, filled with organically polluted fine-grained joint filling materials: Dansand®, white sand and sea sand. Data for open bedding layers are depicted as dashed lines, data for closed bedding layers as solid lines. Vertical bars denote standard errors.

for *in situ* pavements. Firstly, all tested combinations between joint filling material, joint width, organic pollution level and bedding layer are represented in *in situ* pavements even though some of them are technically not ideal. Secondly, apart from rainfall, which was kept frequent and at low intensity per turn, environmental conditions closely resembled *in situ* conditions in temperate regions.

Initial species density

For three of the four test species (*P. annua*, *P. major* and *T. repens*), species density was affected by joint width. The extent of this effect was dependant on interactions with joint filling material and organic pollution level, but when significant effects were found, species densities were lower in pavings with narrow joints, compared with pavings with wide joints. This is in line with Melander *et al.* (2009) and Fagot *et al.* (2011), who found that weed species grew less easily in pavements with narrow joints than in wide joints. However, *T. officinale* did not show a clear preference for wide joints, most likely due to its strong and deep tap root (Kutschera, 1960; Stewart-Wade *et al.*, 2002) that can penetrate rapidly beneath the concrete pavings and bring up essential minerals and water from the deep soil.

Contrary to pavings with white sand, sea sand or course-grained fillers, pavings with Dansand® joint filler remained weed-free during the first 2 months after sowing. This is caused by the excess of sodium salt (Table 3) present in Dansand®, which increases the osmotic pressure of the soil water hence preventing seeds and roots from absorbing water. We observed 51% less *T. officinale* (in wide joints), 48% less *T. repens* (in narrow joints) and 37% less *P. annua* (in narrow joints) in pure sea sand than in pure white sand, 2 months after sowing. This effect is probably due to higher salinity and a lower amount of plant available water (Tables 2 and 3) in the former, as the grain size distribution of these materials is comparable. *Plantago major*, a relatively salt tolerant species (Radyukina *et al.*, 2009), did not show a preference for white sand over sea sand.

In pavings with wide joints, overall seedling density was up to 74% lower in joints filled with pure porphyry than in joints with pure white sand. This can be explained by the coarse structure of the material and hence the very low amount of plant available water (Table 2). In pavings where the porphyry was organically polluted, this effect disappeared due to an increase in mineral content and amount of plant available water.

Total weed coverage

Weed cover was lower in unpolluted joint filling materials, although not always significantly. During the second summer of the experiment, the difference between pure and polluted joint filling materials became less pronounced. This can be explained by the accumulation of dead plant material in the unpolluted pavings after the first test year and by the appearance of mosses on all pavings in the absence of sweeping operations.

Pavings with narrow joints tended to be less weedy than pavings with wide joints, but the extent

Table 7 Mean relative species composition of established paving vegetation in August 2009 for all paving types at two organic pollution levels

Pollution level	Paving type	*Taraxacum officinale*	*Plantago major*	*Trifolium repens*	*Poa annua*	Musci
Polluted	1: Dansand/Narrow	0^{b}	0^{d}	0^{c}	0^{c}	0.0^{a}
	2: Dansand/Wide	0^{b}	0^{d}	0^{c}	0^{c}	0.0^{a}
	3: White sand/Narrow	12^{ab}	52^{b}	13^{ab}	23^{b}	0.0^{a}
	4: White sand/Wide	6^{b}	58^{ab}	16^{a}	18^{b}	0.4^{a}
	5: Sea sand/Narrow	10^{b}	68^{a}	4^{bc}	18^{b}	0.0^{a}
	6: Sea sand/Wide	5^{b}	66^{ab}	5^{bc}	24^{b}	0.0^{a}
	7: Limestone/Wide	23^{a}	15^{c}	6^{bc}	55^{a}	0.0^{a}
	8: Porphyry/Wide	9^{b}	55^{ab}	8^{ab}	28^{b}	0.0^{a}
Pure	1: Dansand/Narrow	0^{c}	0^{e}	0^{d}	0^{d}	0.0^{a}
	2: Dansand/Wide	0^{c}	0^{e}	0^{d}	0^{d}	0.0^{a}
	3: White sand/Narrow	25^{ab}	55^{ab}	7^{cd}	12^{c}	0.0^{a}
	4: White sand/Wide	28^{ab}	37^{c}	19^{b}	18^{bc}	0.0^{a}
	5: Sea sand/Narrow	18^{b}	42^{b}	14^{bc}	25^{ab}	0.0^{a}
	6: Sea sand/Wide	2^{c}	63^{a}	3^{cd}	30^{a}	0.8^{a}
	7: Limestone/Wide	33^{a}	22^{cd}	39^{a}	5^{cd}	0.0^{a}
	8: Porphyry/Wide	38^{a}	23^{c}	32^{a}	8^{cd}	0.0^{a}
LSD		12	15	7.8	12	0.6

LSD, least significant difference.
No significant differences between figures with the same letter (Fischer's LSD, $P = 0.05$), comparison within pollution levels only. Standard error of mean difference = $\text{LSD}/t_{0.9750}$ ($t_{0.9750} = 2.0$, d.f. = 62).

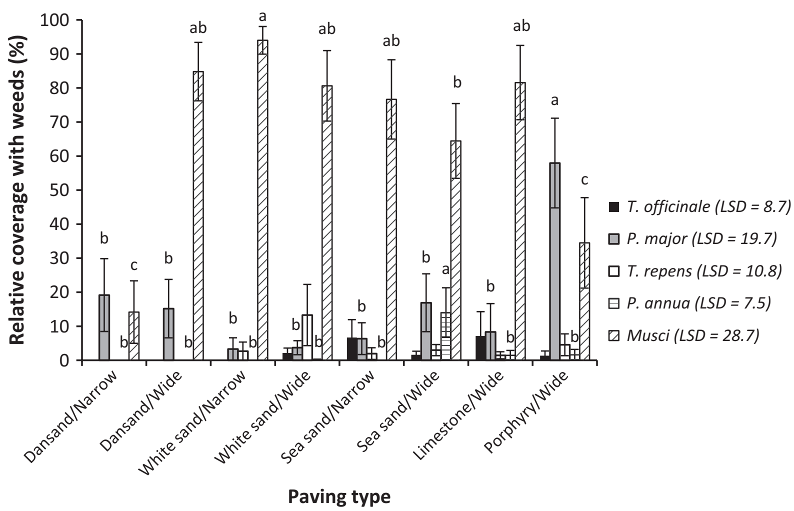

Fig. 3 Effects of the paving types (combination of joint filling material and joint width) on relative coverage of weed species in August 2010. Vertical bars denote standard errors. No significant differences between values of the same species with the same letter (only depicted for species that were significantly affected by paving type).

of this effect was mediated by joint filling material and organic pollution level. When the joints were filled with pure joint filling materials, this trend was most pronounced for sea sand (6.4 times lower during the 2-year period) and for white sand (2.5 times lower during the 2-year period). In the presence of organic pollution, the trend became clear for Dansand® too: 17.6 times lower during the 2-year period. All fine-grained joint filling materials were low in plant essential elements and plant available water (Tables 2 and 3) and hence had weed suppressive abilities. Only when organic material was added, weeds could make use of the extra space, water and essential elements available in wide joints, compared with narrow joints.

The favourable effect of organic material on weed coverage was most pronounced for Dansand® and for the coarse joint filling materials (limestone and porphyry). This means that Dansand® lost some of its weed suppressive capacity when organically polluted. Adding organic material (fine compost in our experiment) lowered pH and increased soil water availability, creating better opportunities for weed germination and survival. During the second summer, this loss in weed suppressive capacity can mainly be attributed to moss growth. Mosses are well-known pioneer plants in pavements (Benvenuti, 2004). They used the wet conditions during winter to establish, explaining the differences in moss coverage between the 2 years, as the experiment was set up in May 2009.

Pavings laid upon open bedding layers were less weedy than pavings laid upon closed bedding layers and the difference grew with time. This trend was most pronounced when joints were filled with fine-grained organically polluted joint filling materials. Indeed, compared with the closed bedding layer, the open bedding layer can contain a lower amount of plant available water (Table 2).

Pavings with pure sodium silicate-enriched sand Dansand® were 2.9–8.5 times less weedy than pavings with pure coarse-grained filling materials (porphyry and limestone) during the 2-year period or 14.6–26.3 times less than the pure fine-grained white sand and sea sand. Significance of these effects was dependent on the screening period. When fine compost was added, the coarse materials showed an intermediate weediness between Dansand® and the standard fine-grained materials, due to the increased availability of nutrients and water. Contrary to Dansand®, weed coverage decreased strongly during the second summer in pavings filled with porphyry. This can be explained by the disappearance of the annual *P. annua* and the low amount of moss growth on porphyry. The fine compost filled the cavities in the coarse structure of the porphyry and did not stay at the surface. So, presumably mosses could not find a suitable surface for germination in porphyry, even when organically polluted.

Flora composition of established paving vegetation

The relative coverage of sown species and spontaneously appearing mosses was not affected by the type of bedding layer (except for *P. major*), but was affected by the joint filling material used in the paving. Mosses became more prevalent over time; during the first summer (2009) almost no mosses occurred and during the second summer (2010) mosses amounted for more than 64% of the weed coverage on all pavings. Dansand® that remained weed-free during the first summer became infested by mosses and to a minor extent by *P. major* during the second summer. The latter species is known to be relatively NaCl-tolerant (Radyukina *et al.*, 2009) and may better resist conditions of physiological drought imposed by constant low release of sodium. This shows that Dansand® could not suppress weed growth forever, but weed coverage remained among the lowest and flora consisted mainly of mosses, which are less problematic in terms of weed management. *Taraxacum officinale* was more abundant on pavings with limestone. Indeed, *T. officinale* is naturally rich in calcium and hence prefers calcium-rich substrates (Ata *et al.*, 2011). *Poa annua* grew well on all substrates (except Dansand®) during the first summer. As this is an annual species and inflorescences were removed before they could set seeds, *P. annua* was scarcely present during the second summer. From a broader pollution perspective of Dansand®, leaching of sodium out of the root-zone is expected to be small under natural conditions with alternate wet and dry weather; sodium leached out by rainfall will migrate upwards due to evaporation and capillary movement of water during dry conditions. Furthermore, sodium silicate-enriched quartz sands release their sodium slowly over time.

Conclusions

Based upon our results, a good strategy to prevent weeds starts with the construction of a pavement on a bedding layer with high permeability. Joints should be narrow and filled with fine-grained (grain size up to 2 mm) conventional filling materials, for example white sand and sea sand, provided that the technical construction of the pavement is such that joints will remain narrow. This can, for example, be performed by installing firm kerb stones, which are well connected with the pavement, or by avoiding obstacles in pavements. If circumstances require wide joints, these should be filled with coarse-grained (grain size up to 6.3 mm) conventional filling materials, for example porphyry and limestone. Weed preventive joint filling materials, in our case sodium silicate-enriched sand Dansand®, can reduce weed growth, regardless of joint width, but they are much more expensive than conventional joint filling materials. It is inevitable that joints become organically polluted after time. Organic material improves growing conditions for weeds, irrespective of joint filler. To keep pavements as clean as possible, one will need regular sweeping operations to limit organic pollution or to remove superficial layers of organic material. Among the four weeds tested, there were species-specific responses to the joint filling materials. If new materials are to be tested for their weed preventive or suppressive ability, it may be important to evaluate them against a broader range of pavement weed species.

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