



Near-saturated hydraulic conductivity of a sandy-loam soil a few months after incorporating compost or zeolite

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Abstract: Little is known about compost (C) and zeolite (Z) effects on hydrodynamic properties of near-saturated coarse-textured soils. These effects were tested for a sandy-loam soil by a mini-disk infiltrometer at three pressure heads ($h_0 = -6, -3$ and -1 cm) and a wide range of amendment percentages, pa (0–40%). Soil hydraulic conductivity, K_{-6} , K_{-3} and K_{-1} , depending on h_0 , was determined 3.5 and 8.0 months after the treatment with C and 5.0 and 10.5 months after that with Z. With the C, more amendment determined smaller K_{-6} (by 1.7–3.0 times), stable K_{-3} and larger K_{-1} (3.4–4.4 times) values on both sampling dates. With the Z, the most frequent result was that the soil hydrodynamic parameters did not change with pa . Time effects were more appreciable with the C (means for the two sampling dates differing by 2.1–3.8 times, depending on h_0) than the Z (means differing by 1.1–1.7 times). The soil treated with Z was more permeable than that treated with C in the first sampling date (percentage differences, Δ , between corresponding means = 38% – 103%, depending on h_0) but not in the second date (Δ values varying from –61% to 4%). In the first year after the treatment, near-saturated soil hydrodynamic behaviour can change appreciably following C addition but the same effect is not expected for the Z. Future investigations should include independent determination of soil pore and particle size distributions.

Keywords: Organic soil amendment; Mineral soil amendment; Coarse-textured soils; Near-saturated soil; Hydrodynamic parameters; Mini-Disk Infiltrimeter.

1 INTRODUCTION

Amending coarse-textured soils can mitigate their limitations to a sustainable land use due to loose structure, poor water retention, rapid drainage and high vulnerability to nutrient leaching and erosion (Reynolds et al., 2009; Garbowski et al., 2023; Castellini et al., 2024). Different types of amendment are available on the market and a broad distinction can be made between organic and mineral amendments. The compost (C) is an organic amendment that derives from humification and stabilization of organic wastes including sewage sludge, manure, municipal solid waste and green waste (Huang et al., 2016). Zeolites (Z) are mineral amendments constituted by microporous crystalline hydrated aluminosilicates (Ghasemi et al., 2016). The open three-dimensional structure allows this amendment to store water and improve nutrient availability for plants (Ghorbani et al., 2022).

The experimental information currently available on the hydrodynamic behavior of amended coarse- or relatively coarse-textured soils is mainly focused on saturated soil hydraulic conductivity, K_s , and this information is not unique even for soils with a similar texture. For example, with reference to sandy-loam soils, amending the porous medium with C determined an increase of K_s in the investigation by Kranz et al. (2023) and a decrease in that by Whelan et al. (2013). An increase of K_s in a Z amended sandy-loam soil was reported by Ghorbani et al. (2022) and a decrease by Satriani et al. (2025). A variety of effects is not surprising since, for a given soil, amendment effects on soil hydraulic properties depend on many factors including nature and particle size distribution of the used amendment, application rate, elapsed time after soil amendment (Bondi et al., 2024; Glăb et al., 2025).

All soil pores are hydraulically active when K_s is determined but full saturation of well permeable soils rarely occurs under natural field conditions (Dohnal et al., 2016). Therefore, amendment effects should also be explored by considering hydraulic conductivity of the saturated soil matrix, that is establishing flow processes that intentionally exclude fragile and unstable macropores (Dohnal et al., 2010; Jarvis et al., 2013). Infiltration experiments at little negative pressure heads can be performed at this aim (Schneider et al., 2009) since matrix pores remain water-filled at water pressure head values varying approximately between -3 cm and -10 cm (Topp et al., 1997; Reynolds and Topp, 2008).

Autovino et al. (2026) recently used a mini-disk infiltrometer (MDI) to determine C and Z effects on hydraulic conductivity, K , of a near-saturated sandy-loam soil (established pressure head, h_0 , values varying between -6 and -1 cm). The data, that were collected in the first 1.5 months after amending the soil, showed that larger C percentages induced a decrease of K that instead did not change with the percentage of Z. Moreover, the soil treated with the organic amendment experienced a more appreciable decrease of K during the investigation period than that treated with the mineral amendment.

A question that requires new investigations is establishing whether and to what extent an information obtained immediately after the treatment remains valid after a longer incubation of the amendments. There are at least two reasons why these investigations are necessary.

A reason is that near-saturated soil hydraulic conductivity depends on soil structure (Reynolds et al., 1995; Wang et al., 2023), that is destroyed or appreciably altered when the amendment is incorporated into the soil. A recovery of soil structure can however occur after alteration, for example due to biological activity

or the alternation of wetting and drying cycles (Bodner et al., 2013; Fomin et al., 2023). These processes influence soil pore characteristics and hence the soil's ability to transmit water. Consequently, amendment effects could vary with time since the soil pore size distribution varies regardless of the treatment.

Another reason is that organic amendment effects are expected to vary with time (Weber et al., 2007; Cannavo et al., 2014) and hence evaluation of advantages and disadvantages of soil amendment with organic products can be inaccurate or at least incomplete when temporal variability in their effects on soil behavior is disregarded (Kok et al., 2023). For example, for the same soil sampled in this investigation, Bondi et al. (2024) recognized that the maximum benefits of C application on soil physical quality (SPQ) were achieved within approximately the first six months following the treatment. Afterwards, the SPQ did not vary or it deteriorated, depending on the considered indicator. Instead, time variations of Z effects appear less probable or in any case slower due to the mineral nature of this amendment. Therefore, temporal variability of C and Z effects could differ due to the different nature of the two amendments as the organic amendment may be associated with a biological activity (Zeiner et al., 2024) that does not appear to be attributable to the biologically inert mineral amendment. Consequently, an assessment of these effects made on a certain date could not coincide with an assessment made on another date.

The general aim of this investigation was to evaluate the effects of two commercial soil amendments, that are an organic compost and a mineral zeolite, on the hydraulic conductivity of a near-saturated sandy-loam soil a few months after amending the soil. Specific aims included evaluation of i) amendment rate effects on the considered soil hydrodynamic parameters; ii) short-term temporal variation in amendment effects; and iii) differences between the two treatments.

2 MATERIALS AND METHODS

2.1 Soil, amendments, mixtures and microplots

The used soil and amendments and preparation of both the mixtures and the microplots were described in detail by Autovino et al. (2026) and therefore they were only summarized here. The soil was a sandy-loam (clay = 15.1%, silt = 29.0%, sand = 55.9%) and it was sieved through a 1 cm mesh before preparing the mixtures. Commercial compost (C) and zeolite (Z) supplied by GECOS (Italy) were used as organic and mineral amendments, respectively (Fig. 1). The particles with an equivalent diameter ≥ 0.25 mm represented the 98.3% for the C, the 73.1% for the Z and the 59.4% for the soil of the fine particle content (≤ 2 mm). Particles smaller than 0.25 mm were detected for both the soil and the Z but not for the C, if not in traces. Thus, the C was coarser than the soil. Instead, the Z and the soil had a more similar particle size distribution.



Fig. 1. Soil, compost and zeolite used in this investigation.

The two air-dried amendments were mixed with the soil at eight different percentages, p_a , by weight: 0% (i.e., control soil without amendment), 5%, 10%, 15%, 20%, 25%, 30%, and 40%.

High p_a values were included in this investigation since rather large amendment rates could be used in some cases, such as for greenhouse cultivation or other pot experiments, and considering a wide range of p_a values can be expected to yield a detailed representation of the effects of the treatment on a considered soil property (Autovino et al., 2026).

The soil was mixed with the amendment until obtaining a homogeneous mixture that was then gradually transferred into polypropylene boxes (60×40 cm²; height = 13 cm) using a hand scoop and then manually compacted to ensure uniform settling. Each microplot comprised an 8 cm layer of the mixture placed above a 3 cm drainage layer composed of expanded clay granules supplied by GECOS (Italy). To prevent migration of fine particles from the substrate into the drainage layer, a thin (< 1 cm) polypropylene geotextile was placed between the two layers. A total of sixteen microplots (8 amendment rates $\times$ 2 amendments) were realized. The microplots were prepared on 9-13 December 2024 and they were left in the laboratory until the last days of January 2025. Afterwards, the boxes were moved to open air.

2.2 Soil sampling experimental method

Mini-disk infiltrometers (MDI) were used to perform nearly one-dimensional (1D) infiltration experiments in the laboratory. At this aim, soil cores were collected from the microplots using 5.9-cm-inner diameter by 6-cm-high stainless-steel cylinders. Each cylinder was inserted vertically into the soil with the least possible pressure not to alter the sampled soil. A nylon guard cloth was attached to the base of the core to prevent soil loss from the bottom of the sample. To improve the contact between the MDI and the soil, its surface was gently levelled in the laboratory with a sharp knife and small amounts of loose soil were applied to the top of the sample if necessary.

To establish a given pressure head, h_0 (L), at the base of a soil core, a plastic box of 38 (length) $\times$ 17 (width) $\times$ 13 (height) cm³ was filled with a bed of sand and several small holes (diameter = 1 cm) were made on the walls of the box at a downward distance $h^* = h_0$ from the surface of the sand bed (Fusco et al., 2024). A metal net was glued to each hole to prevent sand from escaping. Water was added to the box to form a saturated zone below the holes and an unsaturated zone above them. At hydrostatic equilibrium, the soil water pressure head at the surface of the sand bed was assumed to be equal to h_0 . Different boxes were prepared, depending on the considered h_0 value ($h_0 = -6, -3, -1$ cm). The first established pressure head was $h_0 = -6$ cm. The soil cores were placed on the surface of the sand box and left to equilibrate for 24-48 hours. During this period, small volumes of water were periodically added to the box to maintain a constant h_0 value at the surface of the sand bed. Then, the MDI, set at this h_0 value, was placed on the soil surface by gently pressing the device and using a support to maintain it in place and infiltration was measured. The small space between the walls of the cylinder and the porous plate of the device was not sealed to enable air to freely escape from the soil core during the run. After the run, the soil sample was left to freely drain for nearly 12 hours. Then, the same core was equilibrated for 24-48 hours at -3 cm and the MDI run at $h_0 = -3$ cm was carried out. Finally, after another 12 hours of free drainage, the core was equilibrated for 24-48 hours at -1 cm and the last MDI run at $h_0 = -1$ cm was performed. Each individual run continued until the reservoir of the device emptied. Readings were taken visually at 1 to 5 min time intervals, with shorter intervals in the early stages of the run and for the higher (closer to zero) pressure heads. In this investigation, two sampling campaigns were carried out for each treatment. With the C, the experimental activities were carried out from 26 March to 30

April 2025 and from 16 July to 17 October 2025. Therefore, the 1st campaign started approximately 3.5 months after preparing the microplots whereas the 2nd campaign started 2.5 months after concluding the 1st campaign or 8.0 months after preparing the microplots. With the Z, the experimental activities were carried out from 8 May to 10 July 2025 and from 21 October to 5 December 2025. Therefore, the 1st campaign started approximately 5.0 months after preparing the microplots whereas the 2nd campaign started approximately 3.5 months after concluding the 1st campaign or 10.5 months after preparing the microplots. Fig. 2 summarizes meteorological conditions recorded by a weather station located few dozen meters from the study area, in the period varying between exposure of the boxes to open air and soil sampling. For each amendment and sampling campaign, three soil cores were collected from the control microplot ($pa = 0$) and four cores were collected from each amended microplot ($pa = 5\%$, 10% , 15% , 20% , 25% , 30% , and 40%). Therefore, a total of 31 soil cores were used. Overall, 372 MDI runs were performed in this investigation (2 amendments $\times$ 2 sampling campaigns $\times$ 31 soil cores $\times$ 3 pressure head values).

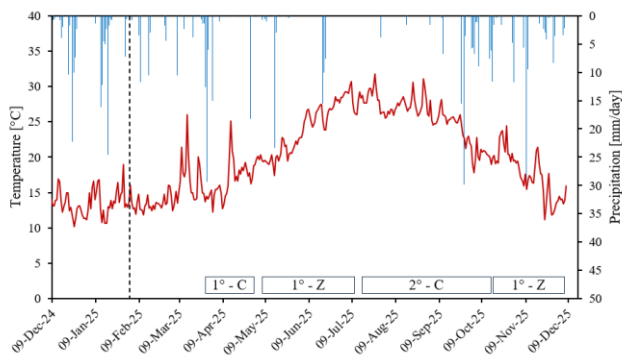


Fig. 2. Average daily air temperatures and precipitation during the investigation period starting on December 9, 2024, with the preparation of the microplots. The vertical dashed line indicates the day the microplots were exposed to atmospheric conditions. The rectangles indicate the durations of the two measurement campaigns (1° and 2°) for compost (C) and zeolite (Z).

2.3 Calculations and data analysis

The MDI data were collected by applying the same pressure head at the two ends of the soil core. Therefore, the assumption was that a unit hydraulic gradient (UHG) was established at steady-state, i.e., the pressure head was the same throughout the soil core. Consequently, steady-state flux density was equivalent to the unsaturated soil hydraulic conductivity corresponding to the imposed pressure head, i.e., K_{-6} , K_{-3} and K_{-1} (mm/h) for $h_0 = -6$, -3 and -1 cm, respectively. Two different estimates of steady-state flux density were obtained for each run. In particular, an estimate (ir_s , mm/h) was obtained by linear regression of the last cumulative infiltration, I (mm), vs. time, t (h), data points and another estimate (sl , mm/h) were obtained as the slope of the linear regression line fitted to all I vs. t data points and forced to pass through the origin of the axes. For each run, similarity between ir_s and sl values was used as a consistency criterion. In addition, for each soil sample, ir_s and sl were expected to decrease with smaller (more negative) h_0 values. Only datasets satisfying these criteria were retained for further K analysis.

For each amendment (C, Z) and sampling campaign (1st, 2nd), amendment rate effects on K_{-6} , K_{-3} and K_{-1} were determined. Time effects on each considered soil hydrodynamic parameter were then evaluated for the two treatments. Finally, amendment

effects on soil hydrodynamic parameters were determined for both sampling campaigns.

Linear regression analysis procedures were applied to establish if a soil parameter changed as pa varied. The statistical significance of the correlation coefficient, R , was determined by a two-tailed t test at $P = 0.05$ (Glantz, 2012). Obtaining $R = 0$ suggested that the soil parameter did not depend on the amendment rate. The intercept of a statistically significant relationship represented the value of the considered soil property without any treatment whereas the slope was expressive of the rate at which that property varied by adding the amendment (Bondi et al., 2024; Castellini et al., 2025). Two regression lines were compared by F and t tests at $P = 0.05$ (Glantz, 2012). Finally, F and two-tailed t tests at $P = 0.05$ were applied to compare two means.

3 RESULTS

3.1 Development of the soil hydraulic conductivity dataset

For most of the 372 laboratory runs with the MDI, the I (mm) vs. t (h) relationship was nearly linear from the early stages of the infiltration process (Fig. 3a), denoting that the infiltration rates, ir (mm/h), did not vary appreciably during the run. In some cases, however, the I vs. t relationship appeared to some extent concave downward (Fig. 3b) or upward (Fig. 3c). In these cases, stabilization of ir was preceded by an initial phase in which infiltration rates decreased or increased, respectively.

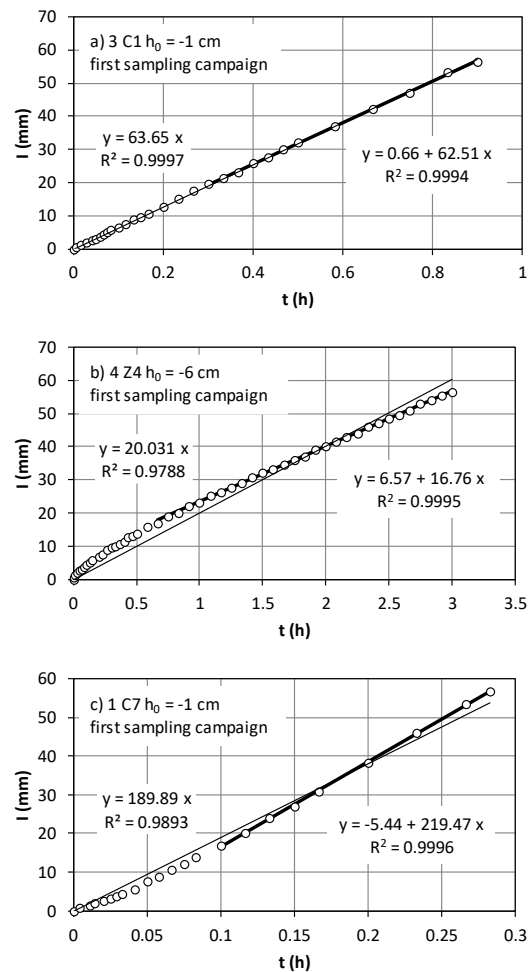


Fig. 3. Examples of the cumulative infiltration, I , vs. time, t , curves for the laboratory one-dimensional mini-disk infiltrometer runs of the first sampling campaign and associated linear regression lines obtained by i) the last I vs. t data points, and ii) all I vs. t data points,

forcing the line to pass through the origin of the axes: a) 3 C1 $h_0 = -1$ cm run; b) 4 Z4 $h_0 = -6$ cm run; c) 1 C7 $h_0 = -1$ cm run.

For each run, the stabilized ir value obtained by linear regression of the last I vs. t data points, ir_s , was initially compared with the slope of the linear regression line fitted to all I vs. t data points and forced to pass through the origin of the axes, sl (Fig. 3). A similarity between ir_s and sl was expected when the I vs. t relationship was nearly linear for the entire infiltration process whereas $ir_s < sl$ and $ir_s > sl$ denoted a downward and an upward concavity of this relationship, respectively. The ir_s/sl ratio was calculated for each run and the runs were ordered by increasing ir_s/sl values. Runs yielding too small or too high values of ir_s/sl were excluded from subsequent analysis since they were considered to denote an unacceptable discrepancy between the expected outcome of the experiment, that is a nearly stable flow rate from the early stage of the established process, and what instead happened. In accordance with Reynolds (2013), a run was considered possibly acceptable if ir_s/sl fell within the 0.75 to 1.25 range of values.

Another check of the data was then carried out by considering the $N = 359$ possibly acceptable runs. In particular, for each individual soil sample, the data were ordered by decreasing values of the established pressure head ($h_0 = -1, -3$ and -6 cm) since the expectation was to obtain decreasing ir_s and sl values with more negative pressure heads. When this result was obtained, the data collected on the considered sample for the three h_0 values were included in the dataset. Otherwise, the doubtful data were eliminated. For example, if infiltration rates (either ir_s or sl) decreased according to the $h_0 = -1$ cm $>$ $h_0 = -6$ cm $>$ $h_0 = -3$ cm sequence, the result for $h_0 = -1$ cm was considered valid since it was larger than the infiltration rates obtained with the two smaller pressure heads. Infiltration rates for $h_0 = -6$ and -3 cm were instead excluded since the sign of the difference between these two runs was unrealistic and it was not possible to establish

if the reason was that the infiltration rate was too high for $h_0 = -6$ cm or too small for $h_0 = -3$ cm.

Finally, a soil hydraulic conductivity dataset (K_1 , K_3 and K_6) was developed for each amendment and sampling campaign assuming that K coincided with ir_s . This last choice was made in accordance with Fusco et al. (2024), suggesting that ir_s is more expressive of the stabilized part of the flow process as compared with sl .

A total of 93 infiltration runs were carried out for each amendment and sampling campaign since three h_0 values were applied on three replicated samples for $pa = 0$ and four replicated samples were prepared for $pa = 5\%, 10\%, 15\%, 20\%, 25\%, 30\%$ and 40% . With the C, the successful runs were 83 (89% of the total) and 89 (96%) in the 1st and the 2nd sampling campaigns, respectively. With the Z, the successful runs were 70 (75%) in the 1st campaign and 73 (78%) in the 2nd one. Therefore, the success rate of the MDI runs varied with the amendment and it was larger with the C than the Z. This result did not appear occasional since it was obtained twice. For given amendment, sampling campaign and established pressure head ($N = 31$ runs), the data that were excluded from the subsequent analysis varied from zero (C, 2nd campaign, $h_0 = -1$ cm) to 10 (Z, 1st campaign, $h_0 = -3$ cm).

3.2 Amendment rate effects

With the C, K_1 increased significantly with pa on both sampling dates ($R^2 = 0.47$ for the 1st campaign and 0.49 for the 2nd one; $R > 0$ in both cases) (Fig. 4). In particular, an increase of pa from 0 to 40% determined a 4.4 times higher K_1 value on the 1st campaign and a 3.4 times higher value on the 2nd campaign. On the 1st campaign, yielding 27 valid data on a total of 31 runs, the five (19% of the total) highest K_1 values (≥ 155 mm/h) were obtained for $pa \geq 25\%$.

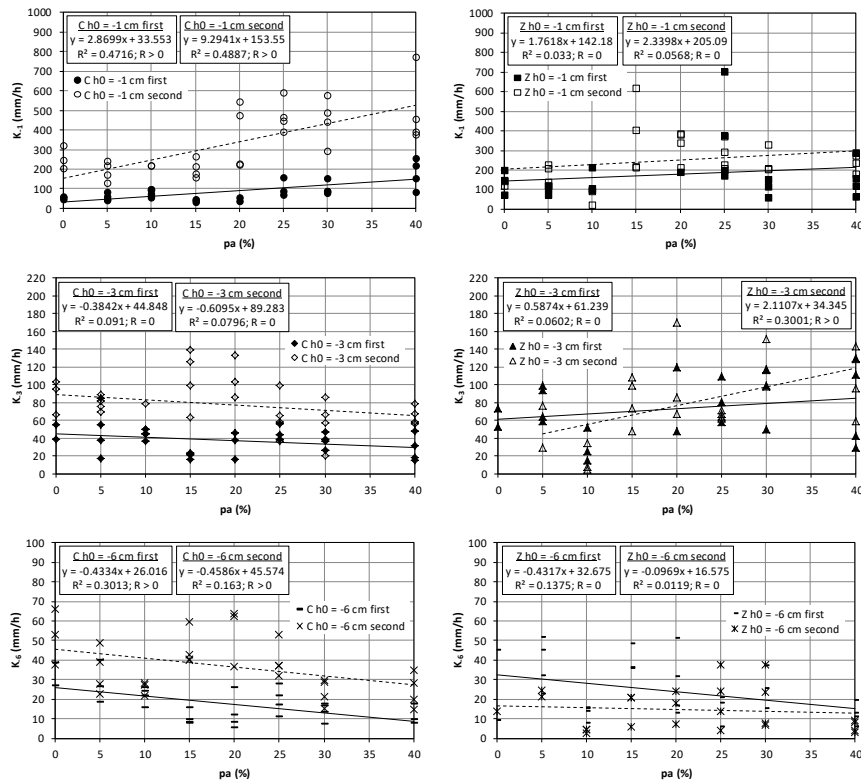


Fig. 4. Relationships between the soil hydraulic conductivity, K , and the percentage of amendment, pa , for the two amendments (compost, C; zeolite, Z), the two sampling campaigns (first, second) and the three established pressure heads, h_0 , at both ends of the soil sample (K_1 for $h_0 = -1$ cm; K_3 for $h_0 = -3$ cm; K_6 for $h_0 = -6$ cm).

On the 2nd campaign, yielding 31 valid data, the 13 (42%) highest K_1 values (≥ 376 mm/h) were obtained for $pa \geq 20\%$. Therefore, the increase of K_1 with pa mainly occurred because particularly high K_1 values were obtained with large percentages of amendment. As compared with the 1st campaign, the 2nd campaign was characterized by a higher percentage of particularly high K_1 values and also by a decrease of the lowest pa value yielding high K_1 values. Regardless of the sampling campaign, the amendment percentage did not influence significantly K_3 ($R^2 \leq 0.09$; $R = 0$ in both cases). Instead, larger pa values yielded smaller K_6 values, even if the K_6 vs. pa relationships were rather scattered ($0.16 \leq R^2 \leq 0.30$; $R > 0$ in both cases). An increase of pa from 0 to 40% determined a 3.0 times smaller K_6 value on the 1st campaign and a 1.7 times smaller value on the 2nd campaign. With the Z, none of the relationships between K and pa was statistically significant ($R^2 \leq 0.14$; $R = 0$) with a single exception (Fig. 4) since K_3 increased with pa in the 2nd campaign ($R^2 = 0.30$; $R > 0$). In particular, K_3 was predicted to increase by 3.5 times as pa increased from 0 to 40%. In this case, however, no valid K_3 data were available for $pa = 0$. Therefore, the data suggested that more C i) determined an increase of K in the closest to saturation conditions ($h_0 = -1$ cm), ii) did not affect K in intermediate conditions ($h_0 = -3$ cm) and iii) induced a decrease of K in the more unsaturated soil conditions ($h_0 = -6$ cm). These effects were detected on two different sampling campaigns separated by a period of experimental inactivity of nearly 2.5 months. In both cases, the increase of K_1 was more convincing than the decrease of K_6 since $R^2 \geq 0.47$ was obtained in the former case whereas R^2 did not exceed 0.30 in the latter case. The treatment with the Z was predominantly ineffective on both sampling campaigns since there was a single and rather weak sign ($h_0 = -3$ cm; 2nd campaign; $R^2 = 0.30$) that adding more Z determined an increase of K .

3.3 Comparing the two sampling campaigns

For a given variable (K_1 , K_3 , K_6) and a given treatment (C, Z), a comparison between the results obtained in the two sampling campaigns was carried out. Taking into account that many

K vs. pa relationships were not statistically significant (Fig. 4), a single dataset including all data regardless of pa was developed for given variable, amendment and sampling campaign. An F test and a two-tailed t test at $P = 0.05$ were then applied to compare two means.

The t test was not paired since different soil samples were used in the two campaigns. Percentage differences, Δ (%), between two corresponding means were calculated by comparing the later with the earlier mean. With the C, the K_1 and K_6 vs. pa relationships were statistically significant on both sampling dates (Fig. 4). Therefore, in these particular cases, the similarity between the two regression lines was also tested using F and t tests at $P = 0.05$ in accordance with Glantz (2012).

With the C, K_1 , K_3 and K_6 were significantly higher in the 2nd sampling campaign than the 1st one (Table 1). In particular, after a time interval of nearly 2.5 months, Δ was equal to 107–108% for the two smaller pressure heads ($h_0 = -6$ and -3 cm) and it increased to 278% for $h_0 = -1$ cm. Relative data variability decreased a little between the two campaigns since the CV values were equal to 43–64% in the 1st campaign and to 36–51% in the 2nd one, depending on h_0 . Both the intercepts and the slopes of the two K_1 vs. pa relationships differed (Fig. 4). The slopes of the two K_6 vs. pa relationships were statistically similar but the intercepts differed.

With the Z, K_1 increased significantly and it became less variable (CV decreasing from 80% to 48%) between the two sampling campaigns, performed approximately 3.5 months apart (Table 1). In particular, Δ was equal to 44% in this case. Instead, K_3 did not change since the two means differed by 11% and the CV values were relatively similar (46–53%). Finally, K_6 decreased significantly ($\Delta = -41\%$) as time elapsed and it also became a little more variable (CV increasing from 60% to 73%). Therefore, time effects differed between the two treatments. The soil amended with the C became more permeable to water for all established pressure heads and particularly for the highest value whereas an increase of K was only detected with the Z for the highest h_0 value. In the other cases, K did not vary or it decreased.

Table 1. Summary statistics of the soil hydraulic conductivity values for different pressure heads, h_0 (K_1 , K_3 and K_6 corresponding to $h_0 = -1$, -3 and -6 cm, respectively), obtained in the soil samples amended with compost and zeolite in two subsequent sampling campaigns.

Variable	Statistic	Compost, C		Zeolite, Z		Percentage differences, Δ (%)
		1 st campaign	2 nd campaign	1 st campaign	2 nd campaign	
K_1 (mm/h)	N	27	31	22	26	+277.7% (C, 2 nd vs. 1 st)
	Min	34.3	95.2	62.4	24.7	+43.5% (Z, 2 nd vs. 1 st)
	Max	254.7	772.4	704.1	621.5	+102.8% (1 st , Z vs. C)
	Mean	86.7 (a)(c)	327.4 (a)d	175.8 (b)(c)	252.3 (b)d	-22.9% (2 nd , Z vs. C)
	CV (%)	64.0	50.5	79.7	47.8	
K_3 (mm/h)	N	28	29	21	23	+107.2% (C, 2 nd vs. 1 st)
	Min	14.7	20.1	15.1	5.3	+11.4% (Z, 2 nd vs. 1 st)
	Max	85.3	139.2	129.6	169.6	+94.2% (1 st , Z vs. C)
	Mean	37.5 (a)(c)	77.7 (a)d	72.8 b(c)	81.1 bd	+4.4% (2 nd , Z vs. C)
	CV (%)	42.6	35.5	46.3	53.0	
K_6 (mm/h)	N	28	29	27	24	+107.9% (C, 2 nd vs. 1 st)
	Min	5.4	14.6	5.7	2.5	-41.1% (Z, 2 nd vs. 1 st)
	Max	40.0	66.2	51.4	37.6	+38.3% (1 st , Z vs. C)
	Mean	17.7 (a)(c)	36.9 (a)(d)	24.5 (b)(c)	14.5 (b)(d)	-60.8% (2 nd , Z vs. C)
	CV (%)	51.8	39.3	59.7	73.1	

Note: For a given variable, means followed by the same lowercase letter enclosed in parenthesis were significantly different according to an F test and a two-tailed t test at $P = 0.05$. Means followed by the same lowercase letter not enclosed in parenthesis were not significantly different.

In general, changes were more appreciable with the organic amendment (means differing by 2.1-3.8 times, depending on h_0) than the mineral one (means differing by 1.1-1.7 times). Therefore, the soil amended with the Z was overall more stable than that treated with the C even if the time interval between the two sampling campaigns was a little longer in the former case (3.5 months) than the latter one (2.5 months).

3.4 Comparison between the two amendments

For a given campaign (1st, 2nd), the means of K_{-1} , K_{-3} and K_{-6} obtained with the two amendments were also compared by an F test and a two-tailed t test at $P = 0.05$. In this case, Δ (%) was obtained by comparing the mean for the soil treated with the Z to that obtained with the C. In the 1st campaign, significant differences between the two treatments were detected for all h_0 values (Table 1) and the soil treated with the Z had larger K values than that amended with the C. In particular, differences increased monotonically with h_0 since Δ was equal to 38% for K_{-6} , 94% for K_{-3} and 103% for K_{-1} . The mineral amendment yielded similar or a little more variable data as compared with the organic amendment since the CV values were equal to 46-80%, depending on h_0 , in the former case and to 43-64% in the latter one.

Different results were instead obtained in the 2nd sampling campaign. In particular, Δ for K_{-1} was equal to -23% and the two means of K_{-3} differed by 4%. In these two cases, differences between corresponding means were not significant. Relative variability of the data was similar for K_{-1} ($CV = 48$ -51%, depending on the amendment) but the Z yielded more variable K_{-3} values than the C ($CV = 53\%$ against 36%). Instead, the value of Δ for K_{-6} was equal to -61%, indicating a significantly smaller conductivity in the soil treated with the Z than in that amended with the C. Relative variability of K_{-6} was appreciably larger in the former case ($CV = 73\%$) than the latter one ($CV = 39\%$).

Therefore, amendment effects differed between the two sampling campaigns. The conclusion of the 1st campaign was that the soil treated with the Z was more permeable than that treated with the C, the more so the higher the value of h_0 applied for the MDI run. Instead, the 2nd campaign suggested a similarity between the two treatments for high pressure heads ($h_0 \geq -3$ cm) but also that the mineral amendment made the soil less able to transmit water in more unsaturated conditions ($h_0 = -6$ cm) as compared with the organic amendment.

3.5 Summary of amendment effects

In summary, this investigation suggested that: i) with the C, more amendment determined smaller K_{-6} , stable K_{-3} and larger K_{-1} values on both sampling campaigns. Moreover, K increased significantly between the two campaigns for all pressure heads; ii) with the Z, the most frequent result was that the soil hydrodynamic parameters did not change with pa . Changes in K values between the two campaigns were either not significant or significant but smaller than those observed with the C, depending on h_0 ; iii) the soil amended with the Z was more conductive than that treated with the C for all h_0 values in the first campaign; and iv) amendment effects disappeared (K_{-3} and K_{-1}) or changed sign (K_{-6}) in the second campaign, mainly due to the more intense dynamics of the soil treated with the organic amendment as compared with that of the soil treated with the mineral amendment.

4 DISCUSSION

Soil hydrodynamic behaviour depends on the characteristics of the porous system and hence on pore number, size, connectivity, continuity, tortuosity and roughness (Reynolds et al., 1995; Vervoort and Cattle, 2003; Rabot et al., 2018).

A decrease of soil hydraulic conductivity at or close to saturation following amendment incorporation can occur since the larger pore network parameters change (Dong et al., 2022). In particular, amendment particles can induce a decrease of pore number and size and they can also impede pore connection, interrupt their continuity and make the cavities overall rougher. For example, decreasing K_s values with larger Z percentages were due to development of a clay-like soil with more micro- and mesopores and less macropores than the non-treated soil in the investigation by Satriani et al. (2025). This interpretation agrees with other investigations reporting some physical pore obstruction due to organic amendment addition in coarse-textured soils (Villagra-Mendoza and Horn, 2018; Wanniarachchi et al., 2019). Another reason why hydrodynamic parameters can decrease in an amended soil, particularly in those treated with organic amendments, is that more amendment induces more soil water repellency (Müller and Deurer, 2011; Głab, 2014; Leelamanie and Manawardana, 2019), hindering soil water transport processes (Wahl et al., 2003; Lichner et al., 2007; Nyman et al., 2010; Ebel and Moody, 2020).

On the other hand, soil hydrodynamic properties can also increase following amendment. With reference to the C, this increase was documented for example by Aggelides and Londra (2000) for a loamy and a clay soil, Kranz et al. (2020) for some urban soils, and Kranz et al. (2023) for a sandy-loam, a silt-loam and a sandy-clay-loam soil. Ghorbani et al. (2022) reported an increase of K_s after addition of Z to a sandy-loam soil. This increase can occur since the C contributes to structure formation and stabilization (Rivier et al., 2022) or because more C induces larger pore sizes (Dong et al., 2022). A similar interpretation can be suggested for the Z given that a larger mean weight diameter of water stable aggregates was detected by Mirzaei Aminiyan et al. (2015) for a loamy-sand soil and more macroporosity was reported by Ghorbani et al. (2022).

Interpreting the amendment rate effects detected in this investigation (Fig. 4) also in light of the wide variety of results reported in the literature requires specifying the context in which the experiment was carried out. In particular, the C was coarser than the soil whereas the Z and the soil had a more similar distribution of particles smaller than 2 mm. Moreover, particles smaller than 0.25 mm were detected for the soil and the Z but not, if not in traces, for the C. The organic amendment but not the mineral one induced a no more than slight soil water repellency to the treated soil (Autovino et al., 2026).

More C determined a decrease of K in the more unsaturated soil conditions, was irrelevant in intermediate conditions and induced an increase of K in the closest to saturation conditions (Fig. 4). A possible explanation of this variable C effect can be suggested taking into account that i) some physical pore obstruction due to amendment addition can be expected to occur in coarse soils (Villagra-Mendoza and Horn, 2018; Wanniarachchi et al., 2019), and ii) organic amendments can determine a rapid macro-aggregation of the soil (Wortmann and Shapiro, 2008; Yu et al., 2015; Rivier et al., 2022) and also an increase of soil hydraulic conductivity at saturation (Aggelides and Londra, 2000; Kranz et al., 2023). According to Wortmann and Shapiro (2008), for example, 15 days can be enough to induce an increase in large, water-stable macro-aggregates following C addition.

Likely, adding the amendment determined some physical pore obstruction but an attenuation of the pore obstruction effects occurred a certain time after the treatment due to soil re-organization processes. This attenuation remained practically imperceptible for the smallest pressure head, and hence with reference to the smallest conductive pores. In this case, more C continued to determine more pore obstruction. However, reorganization processes were enough to determine the onset of a direct relationship between K and pa when the largest conductive pores were activated with the highest-pressure head. In other words, the first pores experiencing an improvement in their hydraulic efficiency were the largest ones. An appreciable increase of K in close to saturation conditions required however using rather large amounts of C ($pa \geq 20\%$, Fig. 4). Amendment rate effects on both K_{-1} and K_{-6} were more appreciable in the first sampling campaign (variations by 3.0–4.4 times, depending on h_0 , in the $0 \leq pa \leq 40\%$ range of values) than the second one (variations by 1.7–3.4 times). This result agreed with other investigations suggesting that compost addition effects on soil properties can vary quite rapidly (Schneider et al., 2009). In particular, for the same soil of this investigation, Bondi et al. (2024) recognized that the beneficial effects of compost amendment on soil physical quality were highest within the first six months and then they decreased.

Amending a sandy-loam soil with Z can be expected to either induce an increase or a decrease of soil hydraulic conductivity at or close to saturation. The increase occurs since more macropores are formed (Ghorbani et al., 2022) whereas the decrease occurs since the amendment induces a sort of clay-like behaviour of the treated soil (Satriani et al., 2025). According to this investigation, a third possibility is that the Z does not alter the hydrodynamic properties of a nearly saturated sandy-loam soil. In other words, there can be cases in which Z addition does not promote macropore development nor it induces formation of a clay-like soil.

Some clarification is necessary to explain why the data of this investigation were not numerically compared with those by Autovino et al. (2026) even if the two experiments were carried out on the same microplots at different times and K was determined with the MDI in both cases. However, the application methodology of the device and the data analysis procedure differed between the two investigations. In this investigation, a variant of the UHG method was applied to establish a 1D infiltration process only controlled by gravity on an initially nearly saturated soil sample. In the investigation by Autovino et al. (2026), instead, the MDI was applied to establish a three-dimensional (3D) process on an initially drier soil and the data were analyzed according to Zhang (1997) and Dohnal et al. (2010). The reason of this methodological difference was that the earlier investigation, based on $N = 192$ MDI runs, was carried out in the laboratory immediately after preparing the microplots with air-dry soil. Instead, the new investigation was carried out after exposing the microplots to open air for several weeks during the rainy season. A larger number of infiltrations runs ($N = 372$, corresponding approximately to a nearly two times larger sample size) was expected to improve robustness of the collected experimental information but it required a long and very intensive experimental work that was practically impossible to make in the field. Hence, collecting soil cores and performing laboratory MDI runs was unavoidable. Soil hydrodynamic parameters close to saturation are known to be extremely sensitive to many factors (Reynolds et al., 2000; Braud et al., 2017) and little is known, to the best of our knowledge, about the actual comparability of the two applied methods to perform the MDI runs. The only known investigation is that by Fusco et al. (2024) reporting that their 1D experiment

tended to generally yield higher K values than the 3D experiment, more noticeably for the smallest pressure heads. Even if more comparisons between the two MDI application methodologies should be carried out, the available information suggested that numerically comparing MDI data collected with different experimental methodologies could be an inappropriate choice.

The caution about a numerical data comparison did not impede overall summarizing the information collected in the two investigations since trends and amendment rate effects were not expected to qualitatively vary with the MDI application method.

Autovino et al. (2026) recognized that the near-saturated soil hydraulic conductivity generally decreased with larger amendment rates for the C treatment whereas it was independent of pa for the Z treatment. Using the organic amendment determined a significant decrease of K between two subsequent sampling campaigns in the first weeks after the treatment whereas using the mineral amendment determined a smaller or even not significant decrease of K .

Some results of this new investigation were similar to those previously obtained while others were different. In particular, it was confirmed that, with the C, K decreased with more amendment in the most unsaturated conditions and also that the effect of pa was nearly negligible with the Z (Fig. 4). Moreover, soil hydrodynamic parameters overall exhibited less temporal variability in the soil treated with the Z than in that treated with the C (Table 1). In this investigation, however, K increased between two subsequent sampling campaigns for the C amended soil and K_{-1} increased with larger amendment rates of C.

Therefore, both investigations suggested that the soil treated with the Z showed a limited sensitivity to the amendment addition and also that this amendment did not induce appreciable temporal variations of the tested soil hydrodynamic parameters. Instead, the soil treated with the C exhibited a larger sensitivity to amendment addition. Initially, that is a few weeks after the treatment, more C determined smaller K values and K generally decreased with time. After a few months of incubation, however, more C determined larger K values in the closest to saturation conditions and K increased with time. Therefore, the organic amendment had an appreciably larger effect on soil hydrodynamic behavior in the close to saturation conditions as compared with the mineral amendment that was instead more neutral from a hydrodynamic point of view.

Measurements overall carried out suggested the following physical interpretation. Immediately after adding the C, the soil hydrodynamic behavior is mainly influenced by the occurrence of physical pore obstruction phenomena and, perhaps, a weak water repellency. Given the rather coarse characteristics of the soil amendment, more C determines a more marked decrease of K regardless of the established pressure head in the $-6 \leq h_0 \leq -1$ cm range of values. In the few weeks following preparation of the soil/amendment mixture, some settlement of the porous medium also occurs. Presence in the soil of the organic amendment, particularly in the case of high percentages, determines or favors processes of reorganization of soil structure. During this stage, the physical obstructive action remains detectable with reference to the smaller pores. Instead, the larger pores become hydraulically more active, perhaps because they increase in number, size or continuity. Reorganization of soil structure determines development of an overall more conductive porous medium. The mechanism suggested for the C does not apply to the Z, consisting of particles that are rigid, biologically inert and dimensionally more similar to those of the soil. There is not an effect of the amendment rate since adding the amendment does not alter appreciably the soil pore size distribution. The mineral nature of

the amendment does not favor soil structural reorganization processes attributable to the treatment. Rigidity of the Z particles contributes to a certain stability of the soil pore size distribution.

In this investigation, a comparison was established between the means of a given soil hydrodynamic parameter for the two treatments (C, Z) or for two sampling dates with a given treatment, in accordance with other investigations (Bondi et al., 2024; Autovino et al., 2026). Each established comparison was homogeneous since the two datasets were developed with exactly the same experimental methodology, that is three replicated measurements for $pa = 0$ and four replicated measurements for each amendment rate greater than zero. For some comparisons, sample sizes of the two datasets differed due to the failure of some runs but the choice was not to reduce sample sizes of the larger dataset by arbitrarily neglecting an information that was actually collected with the treatment. Each dataset also included the runs performed with $pa = 0$ since, in practice, some heterogeneity in the distribution of the amendment will be more or less unavoidable (Autovino et al., 2026) and there can be points of the treated area that are not reached by the amendment. An experiment making use of different amendment doses including $pa = 0$ seems therefore appropriate to predict the overall response of the field soil with reference to the variables of interest.

A point of strength of the experimental methodology applied in this investigation is the possibility to describe in some detail the relationship between K and the amendment rate since many pa values are considered. However, with the same overall sample size, an alternative methodology could be performing more replications for a reduced number of amendment rates. In this case, testing time changes of K by also specifically distinguishing between the amended ($pa > 0$) and the untreated ($pa = 0$) soil could be easier. In the future, the two methodologies should perhaps be compared in order to establish a link between the applied experimental methodology and the questions that can be attempted to be answered.

Finally, a question that cannot be ignored is the fact that the success rate of the MDI runs was appreciably smaller in the soil samples amended with the Z (143 valid runs on a total of 186 runs, that is the 76.9% of the total number of runs) than in those amended with the C (172 valid runs or the 92.5%). Runs yielding smaller or larger ir_s/sl values than those considered plausible ($0.75 \leq ir_s/sl \leq 1.25$) were four with the C and nine with the Z. Runs yielding implausible K values (for example, $K_{-6} > K_{-3}$) were 10 in the former case and 34 in the latter one. Therefore, most failures occurred because there was a discrepancy between the order of the established h_0 values and that of K for a given soil sample. A poor contact between the disk of the device and the infiltration surface, yielding unreliable infiltration data (Close et al., 1998), perhaps occurred occasionally and more frequently in the samples amended with the Z than in those amended with the C. However, this explanation was not very convincing since the exposed soil surface did not show clear differences between the two amendments and, in any case, small amounts of loose soil were applied to the top of the sample when necessary. Each soil sample was equilibrated at a given pressure head at its base before using the MDI and the procedure was repeated three times on a given soil sample since the infiltration runs were carried out for three h_0 values. Therefore, each soil sample was subjected to some unavoidable disturbance, even if any attempt to prevent any soil alteration was made. Organic matter is expected to prevent degradation of soil pore structure by mechanical stresses (Zhang et al., 2005). Therefore, a more plausible explanation could be that the soil amended with the C experienced a stronger resistance to alteration caused by the repeated use of the same sample than the soil amended with the Z, that was overall more

fragile and hence easier to disturb during the laboratory activities.

5 CONCLUSIONS

In this investigation, an organic amendment promoted an appreciably more intense dynamics of the hydrodynamic behavior of a sandy-loam soil as compared with a mineral amendment. In particular, the experiment suggested that larger percentages of compost (C) induced, after a few months of incubation, smaller K_{-6} , stable K_{-3} and larger K_{-1} values. Using this organic amendment also determined an increase of all soil hydrodynamic parameters in subsequent sampling campaigns. Instead, the zeolite (Z) had a more limited or even negligible impact on these parameters and on their temporal variability. Combining the data collected in this investigation with those already available for the same soil suggested a physical interpretation of the results overall obtained. Immediately after adding the C, the soil hydrodynamic behavior is mainly influenced by physical pore obstruction phenomena because of which more C determines a more marked decrease of K . Soon after the treatment, some settlement of the porous medium also occurs. Presence in the soil of large amounts of the organic amendment favors however soil structure reorganization processes that start to become hydrodynamically perceptible with reference to the largest pores. These processes also determine development of an overall more conductive porous medium. This interpretation is not valid for the Z since this mineral amendment does not alter appreciably the soil pore size distribution and does not favor soil structural reorganization processes. In conclusion, in the first year after a single addition of the amendment, the consequences on the near-saturated soil hydrodynamic behavior can be appreciable if the C is used and nearly negligible if the Z is instead applied. In light of the experience that was made and the results that were achieved, future experiments should also include independent determinations of soil pore and particle size distributions in order to support or refute the suggested interpretation. In any case, more investigations on close to saturation soil hydrodynamic parameters should be carried out since these parameters are hydrologically relevant given that field soils are rarely fully saturated but the available experimental information on their dependence on soil amendment is still scarce. Additional investigations should include determining temporal changes of soil properties in untreated soils in order to compare time effects between different amended soils but also between treated and untreated soils. These experiments should also be carried out in the field to capture vegetation effects on the soil hydrodynamic response. According to this investigation, it can be suggested that sampling campaigns should be temporally more intensive in the soils treated with the C than in those amended with the Z. For hydrological modelling purposes, the hydrodynamic behavior of a sandy-loam soil amended with the C seems more complex to describe than that of a similar soil amended with the Z.

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