A Simple Device for Field and Laboratory Measurements of Soil Air Permeability

Mohammad Hossein Mohammadi*
Dep. of Soil Science
College of Agric. Engin. & Tech.
Post Code 3158777871
Univ. of Tehran
Karaj, Iran

Marnik Vanclooster
Earth and Life Inst.
Univ. Catholique de Louvain
Croix du Sud 2, Box 2
B-1348 Louvain-la-Neuve, Belgium

We designed a simple, robust, accurate and portable air permeameter to measure soil air permeability, K_a, in the laboratory and in the field. The permeameter uses a hand-made manometer, a graded cylinder to measure air discharge volume and a soil sampler. The device allows the measurement of K_a at several levels of pressure difference, subjected to a laminar air flow regime. To confirm the laminar flow regime and to examine applicability of the device, we measured air permeabilities in laboratory conditions and in situ along a hillslope at a wide range of soil air contents under different pressure gradients. The results confirm that the developed cost efficient and robust device yields reliable measurements of K_a in the laboratory and in the field.

The soil gas phase is a major constituent of unsaturated soils, and assessing transport of gas in soils has many scientific and engineering applications. Examples are the assessment of CO_2 and N_2 transport in soil nutrient and C cycling studies, or the assessment of volatile organic pollutants in soil pollution and remediation studies (Stępniewski, 2011).

Gases in soil are mainly transported by (i) diffusion forced by a concentration gradient or (ii) bulk convective movement forced by a pressure gradient (Jury and Horton, 2004). The latter process depends on the ability of a soil to conduct a gas by convective flow. This ability, defined as the “gas conductivity”, is similar to the hydraulic conductivity of water flow in response to a hydraulic gradient. To express conduction independent of the effects of fluidity, gas permeability (K_a) is calculated from the soil gas conductivity using the density and viscosity of gas. The K_a is highly influenced by soil water content (Schjønning et al., 1999). For instance, the gas sparging procedure, which uses injected gas to remove volatile contaminant from moist soil, strongly depends on the soil gas permeability controlled by the soil water content (Pleasant et al., 2014). Thus, it is essential to determine the soil water content-gas permeability functional relationship.

In addition, it has been reported that K_a and other soil physical parameters, such as saturated and unsaturated hydraulic conductivities (Huang et al., 2016) and soil gas diffusion coefficient (D_a) (Kamiya and Inoue, 2008; Hamamoto et al., 2011; Pla et al., 2017), are linked. Assessing gas permeability may therefore be useful to assess the hydraulic conductivity of soil. Also, indirect generic approaches (i.e., pedotransfer functions) can be developed to estimate K_a from basic soil information such as soil texture and soil bulk density. However, these approaches are still subjected to great uncertainties because of the complexity of the soil pore geometry (Chamindu Deepagoda et al., 2013; Pla et al., 2015, 2017).

Many laboratory and field methods have been developed to measure the gas permeability. They are classified into steady state and non-steady state methods. The steady state methods are based on the measurement of the steady-state flow rate of gas through a soil column subjected to a controlled or measured pressure difference (McCarthy and Brown, 1992). The devices allow the measurement of several com-

Core Ideas

- **A simple portable device to measure air permeability in the laboratory and field is designed and developed.**
- **The device measures air permeability values across a large range from approximately 0.1 to 500 μm^2.**
- **The cost of design and maintenance is economical.**

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*Corresponding author (mhmohmad@ut.ac.ir).

binations of pressure differences and flow rates of the same soil sample which results in a fast and accurate determination of K_a (Schjønning and Koppelgaard, 2017). Grover (1955) proposed a steady state technique in which constant and low pressure (0.03 to 1 kPa) can be applied. He devised a permeameter with a float that is open only at the bottom and forms a gas chamber. A thin walled cylinder is suspended to keep the chamber centered. This method was further adopted for use in the field with incorporating a sensitive manometer and flowmeter (Bowen and Liang, 1988). Ball et al. (1981) designed two chambers with a constant pressure difference to measure resultant gas flow from a soil core enclosed within two chambers. In this method, the pressure difference and flow rate are measured accurately, and the enclosure of the soil core makes it possible to maintain an uniform boundary condition of water content, pressure, and temperature. This method has been recommended as the standard method to measure K_a in the laboratory by Ball and Schjønning (2002) and has been used by many researchers with some modifications (e.g., Wang et al., 2014; Pugliese and Poulsen, 2014; Wang et al., 2015). The method of Ball et al. (1981) has an advantage that the soil bulk density can also be measured in the same apparatus with minimally disturbed field samples held in their sampling cylinder (Smith, 2000). The equipment of Ball et al. (1981) allows the direct use of samples with 76- or 150-mm diameter and a length of 50 or 100 mm (Smith, 2000). This method requires a couple of devices such as a compressed gas cylinder with one or two pressure regulators, a micromanometer, a precision flow regulator, two precision flowmeters, two metal cylinders with removal metal plates, a tapered collar and a sample holder. Recently, Rouf et al. (2012) developed a new unified system to measure soil water characteristics curve (SWCC), bulk density, and K_a on the same sample under a controlled matric potential. This method, however, allows the measurement of the SWCC, bulk density, and K_a sequentially during wetting and drying cycles, but requires additional devices such as a soil moisture sensor, a porous plate, a tensiometer, and oxygen electrodes.

In the non-steady state methods, the rate of decrease of the gas pressure is measured in a chamber supplying a gas that flows through a soil. Subsequently, the K_a is calculated (Kirkham 1946). The decrease of gas pressure results in changes in the gas temperature and introduces therefore some uncertainties in the measurements (Smith et al., 1997). To reduce this problem, Smith et al. (1998) insulated the air chamber and developed a method that takes into account the variation of temperature during the experiment. This method was also modified to measure the K_a in disturbed soil samples (Niu et al., 2012). Despite of well-developed theoretical bases, these methods are less common than the steady state methods (Ball and Schjønning 2002; Poulsen et al., 2008).

Iversen et al. (2001) developed a portable air permeameter to measure K_a that builds on the methods of Grover (1955) and the shape factor model of Liang et al. (1995). Similarly, Jalbert and Dane (2003) designed a lightweight, handheld, single-reading device for fast measurements of K_a near the soil surface. The device makes use of two interchangeable air probes.

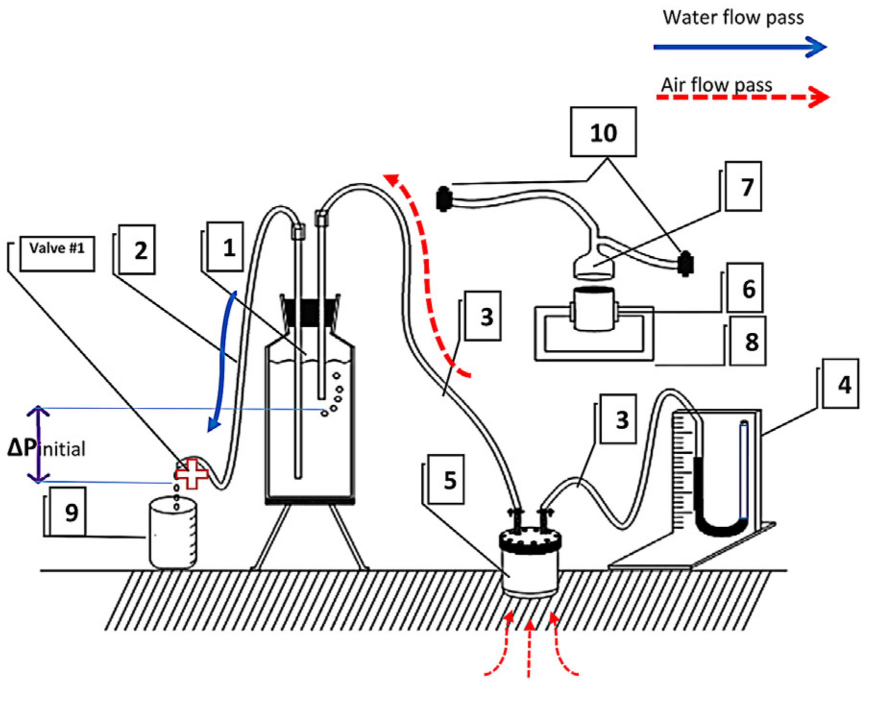


Fig. 1. Schematic illustration of field and laboratory set up for measuring in situ and ex situ air permeability. Parts are (1) Marriotte bottle; (2) Water effluent tube to regulate the approximate control of pressure difference (ΔP); (3) Clear plastic tube linking the Marriotte bottle, manometer, and the metal cap or rubber cap of the soil core sample; (4) simple handmade water manometer to show the difference in air pressure between the end faces (top and bottom) of the in situ soil (or soil core sample); (5) thick metal cylinder with sharpened walls for insertion and an upper metal cap containing two conduits; (6) Kopecky ring containing undisturbed soil sample; (7) flexible rubber (or metal) leak-free cap attached to the soil core sample; (8) fixed clamp to hold the soil core sample; (9) graduated beaker or cylinder to measure the volume of effluent water; and (10) valves connecting the laboratory setup with the device.

From this brief review, we conclude that a variety of devices and methods already exists for measuring K_a, but few methods have been demonstrated to be accurate and inexpensive in acquisition and maintenance. We therefore consider that scope exist to further develop inexpensive portable methodologies for the field and laboratory measurement of K_a.

The objectives of this study was therefore to design and test a new portable device adapted to rapid field and laboratory determination of the soil air permeability K_a in the approximate range of 0.1 to 500 μm^2. For the test of the apparatus, measurements of K_a were performed on selected undisturbed soil samples in situ at different values of water content and pressure gradient.

MATERIALS AND METHODS

Figure 1 shows a schematic of the simplified air permeameter that consists of the following parts (as numbered in Fig. 1):

1. Marriotte bottle filled with water (~15 dm^3) extensible up to 50 dm^3

2. Water effluent plastic tube to regulate the approximate control of pressure difference. The values of ΔP is initially regulated by the vertical distance between level of water tap ("Valve #1") and the bottom of air inlet tube in the Marriotte bottle;
3. Clear plastic tube linking the Marriotte bottle, manometer, and the metal cap or rubber cap of the soil core sample;
4. A simple handmade water manometer sensitive to ±0.2 cm water change. This manometer directly shows the difference in air pressure between the end faces (top and bottom) of the in situ soil (or soil core sample);
5. A thick metal cylinder of 131.6-mm diameter and 200-mm length with an upper metal cap containing two conduits. Following Liang et al. (1995), the cylinder was sharpened on the inner wall (~30%) as well as the outer wall (~70%);
6. A Kopecky ring containing undisturbed soil sample with volume of 100 cm^3;
7. A flexible rubber leak-free cap attaching to the soil core sample (100 cm^3). It is replaced by a metal cylinder cap to measure air permeability in laboratory;
8. A fixed clamp to hold the soil core sample;
9. A graduated beaker or cylinder to measure the volume of effluent water which is nearly equal to the volume of transported air within the soil. The volume of water can also be determined accurately using the gravitational method. The water filling the beaker can be reused by pouring the water into the Marriotte bottle for a next experiment; and
10. Valves connecting the laboratory setup with the device.

For laboratory experiments, we sampled undisturbed cores in small soil cylinders. We carefully covered the inner wall of the metal cylinder and all joints with grease to prevent air leakage from along the soil–cylinder interface and from joints. We inserted the metal cylinder vertically into the soil by means of a hammer, using a guide to enable vertical insertion and with a wooden cap to avoid disturbing the top face of the cylinder. During the experiment, the tops of cores were connected to the rubber or metal cap of the device where the bottoms of cores were covered by a plastic grid lace. It was supposed that, when the end of the cylinder was closed, air would not flow through the device and subsequently water could not exhaust from the water tap (Valve #1). We checked the sealed apparatus for air leaks by submerging the end of installed cylinder and/or core under water and watched for discharging of water from the Marriotte bottle.

The core samples were saturated in sandboxes and then successively drained to matric potentials of −2, −4, −6, and −10 kPa. To reach the matric potentials of −20, −50, −100, and −300 kPa, the pressure plate apparatus was used. Air permeability was measured at each matric potential. For each experiment, a constant initial pressure difference, ΔP_{i}, (0.06–4 kPa) was imposed by means of the Marriotte bottle until a steady-state flow rate was established. These initial pressure differences applied via the elevation of the water tap (Valve #1) may result in less actual pressure imposed on soil and measured with manometer, because of resistance to gas flow through the device (friction between the gas and the wall of the tubes, friction between adjacent layers of the gas itself or viscosity, and pressure loss as the gas passes through any joints, valves, bends, or components).

The ΔP_{i} was used to initial estimate and then, to control the air pressure difference across the soil. The steady-state air flux regime was controlled by the water discharge volume over time at the outlet of Marriotte bottle. All experiments were conducted at three to five different air pressures ($0.05 \text{ kPa} \le \Delta P \le 3 \text{ kPa}$) with at least three replicates to confirm laminar flow conditions.

A similar methodology was used to measure in situ K_{a}. In this case, the cylinder is inserted directly at the top of the soil surface.

The developed device was tested on a loamy soil along a 150-m hillslope situated in the Belgian loam belt (50.6669° N, 4.6331° W). Variability of the loamy soil type is large along such a hillslope. More details of the soil and the hillslope are described by Wiaux et al. (2014). We sampled soil cores and performed in situ K_{a} measurements at eight locations along the hillslope at several (seven to nine) water contents. To consider different field soil water contents, we measured K_{a} at different times before and after a rainfall event. When each individual in situ experiment was completed, one to two core samples were taken immediately on the spot where field measurements were made. Each core sample was covered with a plastic sheet to prevent drying and then transformed to the laboratory for the ex situ K_{a} experiment at the same water content.

The average volumetric air content ($\overline{\theta}_{\text{a}}$) was determined as a complement of the volumetric water content and total porosity. The volumetric water content was determined with the gravimetric method. The total porosity was inferred from the soil bulk density. Table 1 shows some properties of the tested soil and designed permeameter device.

Theory

The discharge of water from the Marriotte bottle results in a negative air pressure in the gas phase of bottle. We assume that the negative pressure is sufficiently small such that the effect of pressure on the gas volume could be ignored. Hence, we assume that the pressure difference causes a volumetric air flux that is equal to the water flux leaving the bottle. Air starts flowing by opening the regulator of the Marriotte bottle outlet tube (Valve #1). The pressure difference across the soil can be measured with the manometer (Part no. 4) and regulated by changing the ΔP (Part no. 2).

Table 1. Properties of soil, air, and air permeameter device.

Parameter	Variable	Value
Pressure difference	ΔP	50–2000 Pa†
Cylinder diameter	D	13.16 cm
Cylinder insertion depth in soil	H	13.16 cm‡
Kopecky ring cross section area	A_{s}	21 cm^2
Kopecky ring length	L_{s}	4.8 cm
Soil air-filled porosity	θ_{a}	0.03–0.24 $\text{m}^3\ \text{m}^{-3}$

† Some in situ experiments use 3000 Pa.

‡ Values of 40 to 190 mm were also examined.

In the case of laboratory measurements, one-dimensional flow will occur through the Kopecky device. One-dimensional advective steady-state laminar air flow in soils can be described using the following equation adopted from Kirkham (1946):

$$q = -A_s \frac{K_a \Delta P}{\eta L_s} \qquad [1]$$

where q is the volumetric air flux (m^3 s^{-1}), ΔP is the air pressure difference across the soil (Pa), L_s is the length of sample (m), K_a is the air permeability (m^2), A_s is the cross-sectional area of soil sample (m^2), and η is the dynamic viscosity of air (Pa·s). From Eq. [1], K_a can be derived immediately.

In case of in situ air permeability measurements, the air flow through the soil beyond the end of the air permeameter (i.e., deeper than the cylinder insertion depth) is not one-dimensional. Flow divergence beyond the outflow end of an inserted soil ring can be addressed by applying an empirical factor (Λ). The in situ K_a can subsequently be calculated by using the rearrangement of adjusted Eq. [1] as (Grover, 1955; Liang et al., 1995; Chief et al., 2008):

$$K_a = \frac{1}{\Lambda}\frac{\eta q}{\Delta P} \qquad [2]$$

where Λ is the empirical shape factor which may be regarded as an estimate of the A_s/L_s quotient in Eq. [1]. The empirical shape factor is derived from the inserted cylinder geometry as follows (Jalbert and Dane, 2003):

$$\Lambda = D\left[\left(\frac{\pi}{4}+\frac{D}{H}\right)\left(1+\frac{D}{H}\right)^{-1} ln\left(1+\frac{D}{H}\right)\right] \qquad [3]$$

where H is the cylinder insertion depth (m), and D is the cylinder diameter (m). This shape factor agrees most closely with the soil-specific values determined for field soils (Chief et al., 2006). However, it may underestimate the in situ K_a for the strongly structured soils.

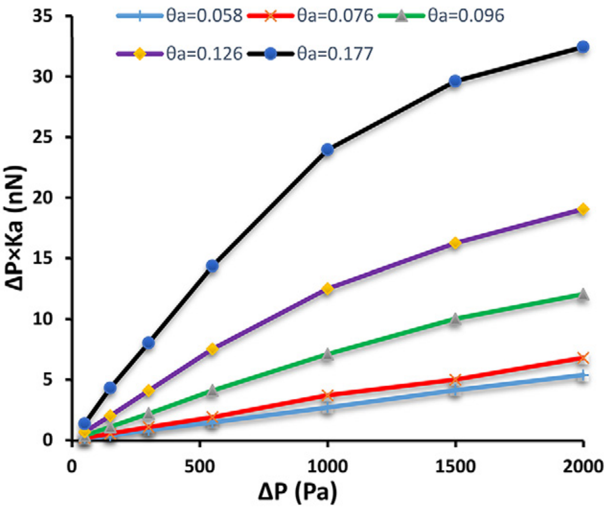


Fig. 2. Relationships of pressure (ΔP, Pa) and force of Darcian flow ($\Delta P{\cdot}K_a$, nN) for laboratory air permeability measurements in an intact soil (summit of landscape described by Wiaux et al., 2014) with different air content (θ_a).

The equation of Mason and Monchick (1965) was used to calculate air viscosity η (Pa·s):

$$\eta=(1717+4.8T)\times 10^{-8} \qquad [4]$$

where T is air temperature (°C).

The above-mentioned simple data analysis is only valid when laminar flow occurs. This condition was verified by measuring K_a in the laboratory and in situ on the different initial soil air contents and different applied pressure gradients.

RESULTS

Laminar Flow Analysis

For each core, at each measurement point, flow rate (q) and pressure gradients (ΔP) were measured at five pressure differences to confirm laminar flow conditions. Figure 2 shows the measured $\Delta P{\cdot}K_a$ (product of measured volumetric air flow rate, dynamic viscosity, and soil length divided by soil area) as a function of pressure difference (ΔP) for a laboratory soil sample at different air contents (θ_a). The slope of each curve estimating the K_a remains nearly constant with the ΔP at low θ_a ($R^2 > 0.98$). For high θ_a, the slope is only constant at low ΔP ($R^2 > 0.99$), and decreases considerably at high ΔP. Hence, measurements reveal linear relationships between q and the ΔP at low θ_a and ΔP. In these conditions, the laminar flow regime for K_a measurements is applicable.

To quantify the deviation from the laminar flow regime, we also calculated a percentage deviation between K_a estimated for all pressures relative to the lowest pressure and we did not find any systematic error up to pressure of 1 kPa (Fig. 3). Figure 3 shows that for all θ_a, relative error is less than ±10% when $\Delta P \leq$ 1 kPa. The relative error of 10% has been accepted with regard to standard methods (e.g., see Ball and Schjønning., 2002). Similar analysis was observed for in situ K_a measurements.

Figure 4 illustrates the $\Delta P{\cdot}K_a$ to ΔP relationships for in situ K_a determinations at different averaged air contents ($\overline{\theta_a}$) for a soil situated at the summit of the hillslope. The equation and coefficient of determination (R^2) of the best line are shown above each curve. The high values of R^2 (0.9922–0.9983) demonstrate that, for in situ K_a measurements, the laminar flow hypothesis is reasonably valid for a wide range of θ_a and a wider

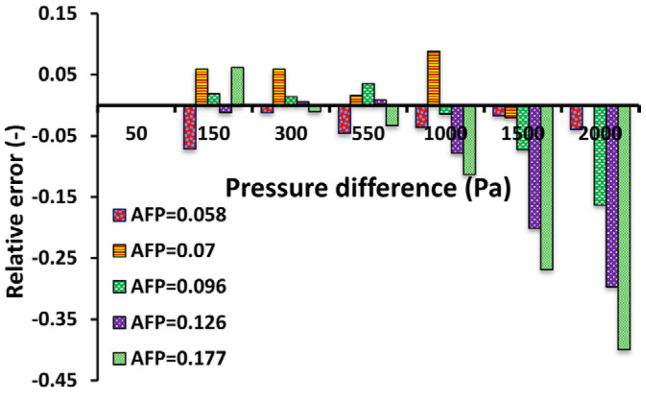


Fig. 3. Relative error (%) for different gas pressure (ΔP, Pa) applied to measure ex situ air permeability at a range of air filled porosity (AFP).

range of ΔP (0.05 to 3 kPa). This is attributed partially to the actual path length of air flow in soil, which for in situ measurements is larger than H and core length L_s. Literature suggests that the maximum ΔP for measuring the K_a is 1 kPa (Ball and Schjønning, 2002; Hamamoto et al., 2009; Schjønning et al., 2013). We observe that the linearity shown in Fig. 2, 3, and 4 is well respected below 1 kPa. Subsequently, we suggest 1 kPa as the upper limit of ΔP for the determination of K_a with the developed device. However, larger ΔP (up to 2 kPa) could eventually be applied for in situ moist soils, with respecting linearity hypothesis (Fig. 4). At larger ΔP, non-laminar flow could occur. A nonlinear relationship between ΔP and q at a high pressure gradient for different soil materials was also reported by Schjønning et al. (2013) and Schjønning and Koppelgaard (2017). Schjønning and Koppelgaard (2017) showed significant errors in estimates of K_a if the nonlinear pressure losses were ignored when applying ΔP as low as 100 Pa. We suggest measurements at two or more levels of pressure difference to test and ensure for a linear air flow regime.

For flow through a pipe, laminar flow occurs when the Reynolds number is <2300. So when the maximum $K_a = 1000\ \mu m^2$, $\Delta P = 1$ kPa, $A = 2 \times 10^{-3}$ m^2, and $L = 0.05$ m, a tube with diameter of 5 mm can still establish a laminar flow. This is largely above the expected pore diameter in the present soil.

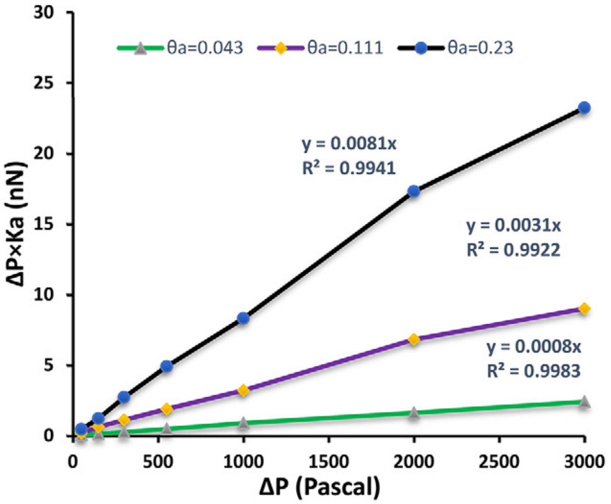
Comparison of In Situ and Ex Situ Measurements

The D to H ratio of the developed device was fixed at 1 for most of the in situ experiments. The scale effect and domain heterogeneity (in terms of soil physical characteristics and water content) may become considerable if cylinder insertion depth increases (i.e., the D to H ratio decreases) in particular for soils with thin upper layer. Yet, the ratios between 0.65 and 3 were examined as well (results not shown).

Figure 5 shows the comparison of in situ and ex situ measurement of the K_a, using the developed device and analysis technique. The reasonable agreement between in situ data and laboratory data for represented soils shows that the developed device can be used reasonably to measure the K_a in the laboratory and field. The scattering of data around the 1:1 line in Fig. 5 is due to the scale effect, heterogeneity in the soil profile, variability in the water content, variation of the shape factor effect and soil sampling procedure (Chief et al., 2006). However, it was beyond the scope of this study to evaluate the issue for variation of data. The scale effect can be a source of disagreement between in situ and laboratory data in particular for cracked and highly structured soils, but large macropores were not observed within the studied soil.

CONCLUSION

We designed and developed a simple portable device for measurement of air permeability in laboratory and field. This permeameter has an air-flow capacity of 15 dm^3 (expandable to 50 dm^3), can be used on any landscape position without an external support, and can be easily transported in the field. The device was tested in the laboratory and field, and is capable of delivering a maximum flow rate of 20 cm^3 s^{-1}. It measures the K_a values across a large range from approximately 0.1 to 500 μm^2. We used handmade manometers to measure low pressure gradients and further we suggested measurements at two or more levels of pressure difference to test for a linear relationship between air flow and pressure gradient. The water bottle to supply air flow can be easily refilled and consequently the measurements can be conducted with any limitation and charge need. Moreover, this device does not need to use any gas supplier capsules and power source such as batteries. In addition, the cost of design and maintenance is low. The drawback of the design is that it is sensitive for gas inlet leakage and that during operation liquid cannot be added, since it would change the pressure control.



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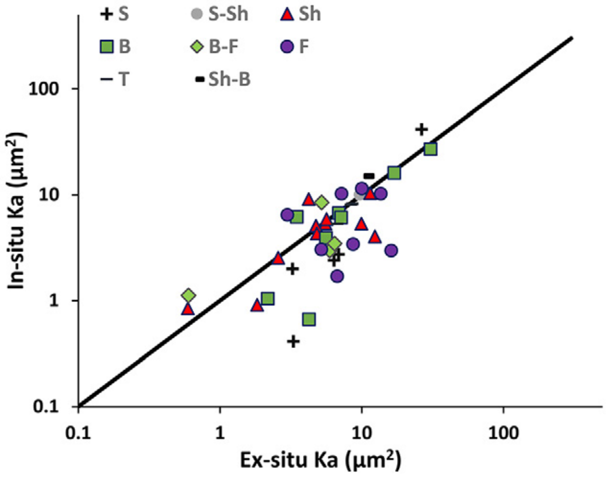

Fig. 5. In situ versus laboratory air permeability (K_a) measurements for eight location of the toposequence using the developed device and Jalbert and Dane (2003) shape factor. Locations of soil: S, summit; S-Sh, between summit and shoulder; Sh, shoulder; Sh-B, between shoulder and backslope; B, backslope; B-F, between backslope and footslope; T, toeslope.

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