Comparison of Van Genuchten water retention model and Kießl-Künzel method in estimating the moisture diffusivity

Habib Jalili[1,2], Tariq Ouahbi[1], Said Taibi[1], Sarah Nassar[2], Joanna Eid [2], Ichrak Hamrouni[1]

1 Université Le Havre Normandie, Normandie Univ, LOMC, UMR 6294 CNRS, 76600 Le Havre, France.

[2] AI Environnement, FACEA Group, R&D Department, Noisy le Grand, France

Abstract. The building envelopes are subjected to dynamic climatic loading on the exterior surface and relatively stable indoor conditions on the interior. These dynamic loadings result in the transport of Heat, Air, and Moisture (HAM) across the structure. In addition to the time-varying external loading due to fluctuating weather conditions, the thermal and moisture storage characteristics of each component make the heat and moisture transport in the building envelope a transient and complex process (Jalili et al., 2024). Moisture diffusivity is a key material property in hygrothermal analyses of buildings. Despite the availability of various experimental methods, its experimental determination is still a challenge. However, to the best of our knowledge, fewer studies have focused on water retention models and their effects on hygrothermal transfer. This paper presents a comparison between the Kießl-Künzel method for estimating liquid diffusivity and the Van Genuchten model. Kießl-Künzel method is a simplest method depended on the water absorption test, but Van Genuchten model provides an alternative approach derivate from water retention curve.

Keywords: Kießl-Künzel method, Van Genuchten model, Liquid diffusivity, Capillary absorption test, Compressed earthen brick

Modalité de présentation Présentation orale

I. Introduction

Over the past two decades, hygrothermal simulations have increased significantly and are now widely used as a standard method for assessing the moisture performance of building materials. Hygrothermal simulation progressively outplacing the traditional dew point / Glaser method. Simulations according to the methodologies outlined in ("EN 15026:2007," n.d.)enable the calculations of temperature and moisture profiles in the wall envelope as affected by surrounding climate conditions. Various models are available to conduct these simulations, such as Delphin, MATCH, and WUFI (Jalili et al., 2024; Sawadogo et al., 2023; Zhang et al., 2016). Measuring the hygric properties of a material is a preliminary step in initiating hygrothermal modeling. These properties include moisture diffusivity, sorption and desorption characteristics, as well as water vapor permeability.

The transfer of moisture in porous building materials - these materials are found in almost all the building envelopes - can take place both within the hygroscopic range and over the hygroscopic range. The dominant factor that determines water storage and transport in the hygroscopic range is the presence of water vapor (Ma et al., 2017). Sorption isotherms and the level of vapor permeability can be used to describe moisture storage and transport. Liquid phase of water plays a dominant role in the over-hygroscopic range in contrast to the water vapor permeability which is dominant in hygroscopic domain, with moisture retention and permeability curves serving as key indicators (Ren et al., 2019). During the past decades, several identification methods emerged to facilitate the accurate determination of the moisture diffusivity from transient water content profile measurements (Boltzmann transform method, flow gradient method or inverse optimization methods). The latter profiles are commonly measured using the regular γ-ray method, X-ray method or nuclear magnetic resonance (NMR) method (Carmeliet and Roels, 2001). Measuring liquid permeability directly remains difficult, leading to the development of indirect methods for this purpose. Ren et al. (Ren et al., 2019)compared the various methods for estimating the liquid diffusion coefficient, X-ray method, the ruler method, the multi-step method and the Kießl-Künzel method. Indekeu et al. (Indekeu et al., 2022) adopted the Boltzmann transformation for their studied rammed earth material, and placed it on a relatively short ceramic brick and a contact filter paper. This can help avoid both liquefaction and expansion during the confined capillary absorption test, which is conducted on a composite specimen. The Boltzmann transformation is made compatible with this by taking into account the hydraulically equivalent height of these lower parts in terms of the rammed earth material on top.

Van Genuchten in 1980 (Van Genuchten, 1980) provided the closed-form analytical expressions for predicting the relative permeability and moisture diffusivity from water retention curve (WRC). In fact, reliable estimates of these parameters are especially difficult to obtain, partly because of its extensive variability in the field, and partly because measuring this parameter is time-consuming and expensive. Frequently used analytical expressions for these functions were proposed by Brooks and Corey (1964) (Brooks et al., 1964) and Kosugi (1994) (Kosugi, 1994) and etc.

In this paper, moisture diffusivity targeted from water retention curve to enable its proper application to building materials as involved for the determination of the liquid water diffusivity. For this propose, water retention curve of the earthen brick has been provided and water absorption test performed which enables us to compare with Kießl-Künzel method. The novelty of our work is to investigated these two methods, VG method derivates moisture diffusivity from water retention curve and widely used Kießl-Künzel method applied in WUFI software ("Wufiwiki," 2025), provide an empirical formula depended on water absorption test.

II. Van Genuchten model and Kießl-Künzel method

II.1. Van Genuchten model

The WRC is derived by fitting the acquired paired data, including the measured moisture content and the corresponding preset water potential. There are various module and software to perform this optimization, the PySWR code (Memari and Clement, 2021), RETC software ("PC-PROGRESS

- RETC," 2025) and unsatfit (Seki et al., 2023) offer several computationally efficient solvers for fitting a nonlinear function to experimental data. In this study, the performance of the PySWR code is tested. The VG model is expressed as follows (Van Genuchten, 1980):

$$S_e = \frac{\theta - \theta_s}{\theta_s - \theta_r} = \frac{1}{(1 + |\alpha\,\psi|^n)^m} \tag{1}$$

$$K_r(S_e) = S_e^{\,0.5}\left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{2}$$

$$\frac{d\theta}{d\psi} = \frac{\alpha m}{1 - m}\,(\theta_s - \theta_r)\,Se^{\frac{1}{m}}\,(1 - S_e^{\frac{1}{m}})^m \tag{3}$$

$$D_w = \frac{K(\theta_l)}{\frac{d\theta}{d\psi}} = \frac{K_s\,K_r(S_e)}{\frac{d\theta}{d\psi}} \tag{4}$$

where θ is the volumetric water content (m^3/m^3); θ_r is the residual water content (m^3/m^3), θ_s is the saturated water content (m^3/m^3); ψ is the capillary pressure head (m); α (m^{-1}) is a parameter that is related to the inverse of the air entry pressure; n is a parameter that is related to the shape of the pore size distribution and m is typically related to the value of n via the expression: m = 1-1/n ; S_e is the effective saturation, and D_w (m^2/s) is the moisture or liquid diffusivity ; the term $\frac{d\theta_l}{d\psi}$ (m^{-1}) is the derivative of water content and pressure head which is called moisture capacity; $K_r(S_e)$ is a dimensionless relative permeability and $K_s\,(m/s)$ is the saturated hydraulic conductivity or kinematic permeability.

Memari et al. (Memari and Clement, 2021) proposed the graphical approach for estimating initial guess and upper-and-lower bounds values for VG parameters by graphically analyzing the experimental data. Parameter θ_s is one of the important parameters for the VG model along with the physical meaning that provides information about total porosity and the maximum WRC at saturation point. In our case for compressed earthen brick, θ_s was measured using the Kerdane oil method and kept constant during the fitting process. **Figure 1** indicates all the details of the proposed graphical approach for evaluating better initial guesses and parameter bounds.

Saturated hydraulic conductivity can be defined by Kozeny–Carman relation which describes the dependency of permeability on porosity and the diameter of the particles (Carman, 1997; Porter et al., 2013; Reia Da Costa and Skordos, 2012) :

$$K_s = k_s\,\frac{\rho_w g}{\mu} = A\,\frac{\emptyset^3}{(1 - \emptyset)^2}\,\frac{\rho_w g}{\mu} \tag{5}$$

$$K_s = k_s\,\frac{\rho_w g}{\mu} = \frac{{d_p}^2}{180}\,\frac{\emptyset^3}{(1 - \emptyset)^2}\,\frac{\rho_w g}{\mu} \tag{6}$$

Where A represents a constant value of 6.4 10^{-11} (m^2); $\emptyset$ is porosity; ρ_w ($\frac{kg}{m^3}$) is the density of water; μ (Pa.s) is the dynamic viscosity of water and g ($\frac{m}{s^2}$) acceleration of gravity; k_s (m^2) is the geometric or intrinsic permeability . In Eq. (6), d_p depicts the diameter of packed particles. **Figure 2** shows the parametric study on the Eq.5 and E.6 for better understanding of the Kozeny–Carman relations. The formulation of Eq. (6) assumes that porous media is homogeneous and isotropic and whole pores are presented as capillary with the same cross section area. In this parametric study, the dynamic viscosity and density of water were kept constant and not varied with temperature.

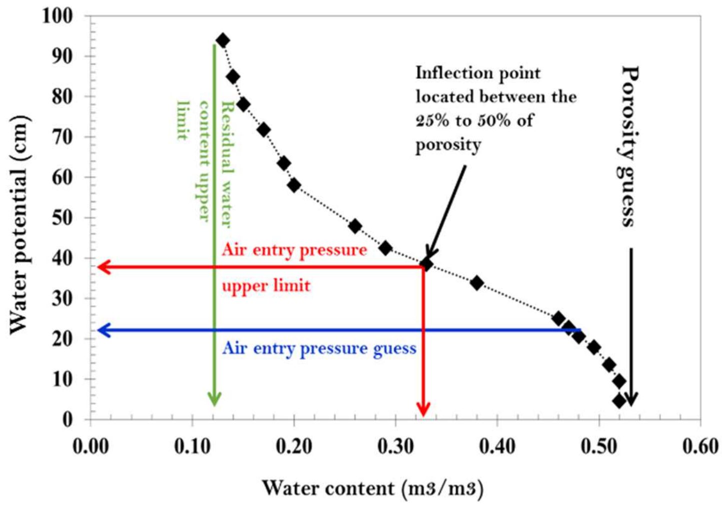

FIGURE 1. Graphical approach for estimating the initial guess values, and lower and upper bounds for VG model parameters.

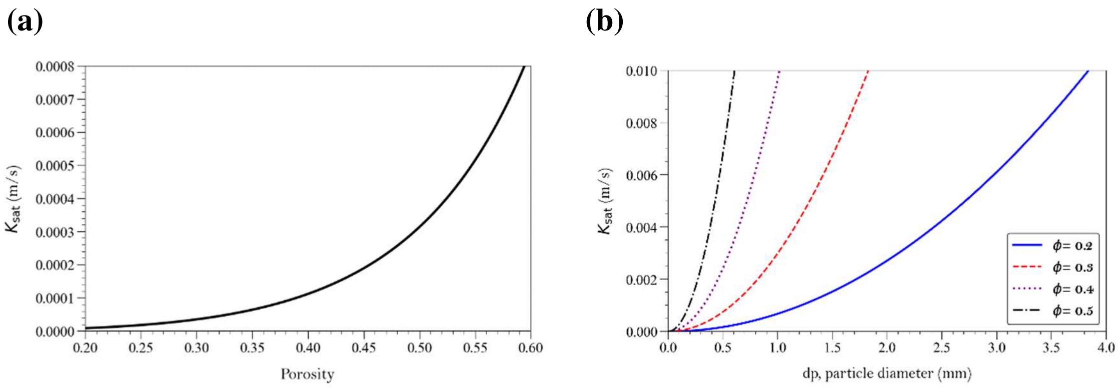

FIGURE 2. Parametric study on (a) the Eq. (5) and (b) Eq. (6).

II.2. Kießl-Künzel method

Beside the derivation of D_w from VG model, there is also another estimation method based on an empirical formula that only resort to the standard capillary absorption test based on EN ISO 15148 ("EN ISO 15148: 2002," n.d.). Eq. (7) was first proposed by Kieβl for building materials (Kiessl, 1983; Ren et al., 2019),then adopted by Künzel and implemented in the hygrothermal software WUFI® (Künzel, 1995).

$$D_w = 3.8 \left(\frac{A_{cap}}{w_{cap}}\right)^2 1000^{\frac{w}{w_{cap}}-1} \quad (7)$$

According to Eq. (7), the A_{cap} (kg/ $(m^2 \sqrt{s})$) and w_{cap} (kg/m^3) values obtained from a single capillary absorption test would be sufficient to estimate the moisture diffusivity; w (kg/m^3) is the water content. In this study, we also include this method for comparison.

III. Results and discussion

III.1. WRC for compressed earthen brick and water absorption test

The fitted VG model to experimental water retention data is obtained for compressed earth brick. Optimized parameters and initial values of VG model are listed in **Table 1.** The initial guess is defined by the graphical approach with the measured porosity or saturated water content. Fitted VG model was illustrated in **Figure 3** with positive, negative and central uncertainties. The uncertainties calculated from standard error of the parameter estimate and covariance matrix of the fitted parameters (Hu et al., 2015; Zhai and Rahardjo, 2013). In Figure 4a, fitted VG model is double highlighted with volumetric water content in y-axis.

As discussed in Section II.2, to compare the method of VG with the Kießl-Künzel model, water absorption test was experimentally conducted on the same compressed earthen brick used for water retention test. Further details of the procedure are referred in EN ISO 15148 ("EN ISO 15148: 2002," n.d.) The results of water absorption test are summarized in Table 2.

TABLE 1. The optimized parameters of VG model and initial values.

	θ_r	θ_s	n	α (1/m)	R^2
VG model	0 ± 0.0104	0.331	1.25 ± 0.0218	0.54 ± 0.178	0.9437
Initial guess	0	0.331	1.1	0.2	-
Lower bounds	0	0.331	1.1	1	-
Upper bounds	0.02	0.331	10	0.018	-

TABLE 2. Results of water absorption test for earthen brick.

	A_{cap} (kg/ $(m^2 \sqrt{s})$)	w_{cap}(kg/m^3)	Hight (cm)	Surface of sample (cm²)
Earthen brick	0.5172	275.976	7.52	58

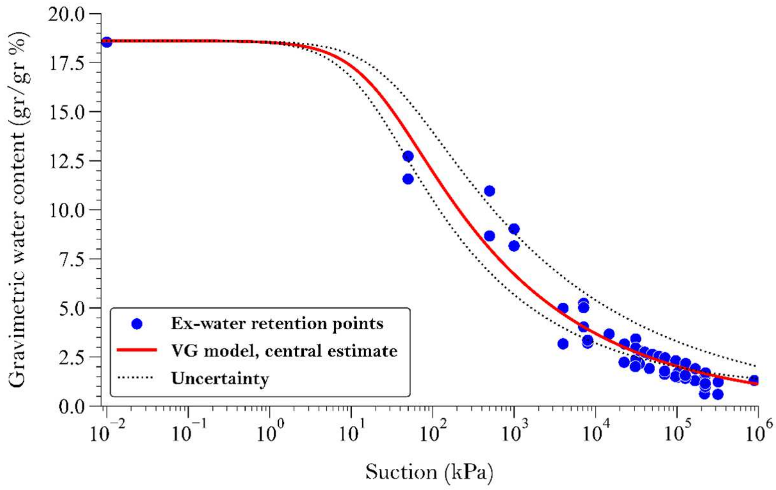

FIGURE 3. Experimental water retention points for compressed earthen brick and fitted curve with uncertainty.

III.2. Comparison of VG and Kießl-Künzel models

As explained before, the moisture diffusivity can be estimated directly from $\boldsymbol{A_{cap}}$ and $\boldsymbol{w_{cap}}$ by Eq. (7). With this Kießl-Künzel method, the moisture diffusivity of the target material is successfully determined using the $\boldsymbol{A_{cap}}$ and $\boldsymbol{w_{cap}}$ values of respective sample. The results are presented in **Figure 4**d. As described by **Eq. (7)**, the moisture diffusivities exhibit straight lines when plotted on a logarithmic scale. To compare it with VG model, we fitted the model as described in previous section, and then saturated hydraulic conductivity is estimated based on **Eq. (5)** and Kozeny–Carman relation. In our case, the saturated hydraulic conductivity is 4.9835 10^{-5} (m/s), calculated using a water density of 998 (kg/m^3), the dynamic viscosity of 0.001 (Pa. s) and the porosity of 0.331.

Geometric or intrinsic permeability ($\boldsymbol{k_s}$), is considered to be a unique property of a material, and it is independent of fluid property such as viscosity as well as of fluid pressure as long as inertial effect is negligible compared with viscous force. Thus, permeability can be determined from the microstructure of porous medium, such as pore size and connectivity, irrespective of fluid type. However, unsaturated permeability or relative permeability is a function a water content. Utilizing the optimized parameters of the VG model along with **Eq. (2)** and **Eq. (3)**, it is possible to plot the moisture capacity and relative permeability corresponding to the retention points of the compressed earthen brick, as illustrated in **Figure 4b** and **Figure 4c**. Subsequently, by applying **Eq. (4)** and estimating the saturated hydraulic conductivity as previously described, the moisture diffusivity based on the VG model is plotted, as shown in **Figure 4d**. As a result, at lower water content corresponding to the lower humidity ranges, D_w reaches its minimum values in the range 10^{-12}, which is expected due to the significant influence of water vapor permeability under such conditions. In other word, water vapor permeability is a major driving potential of water transfer in lower humidity range.

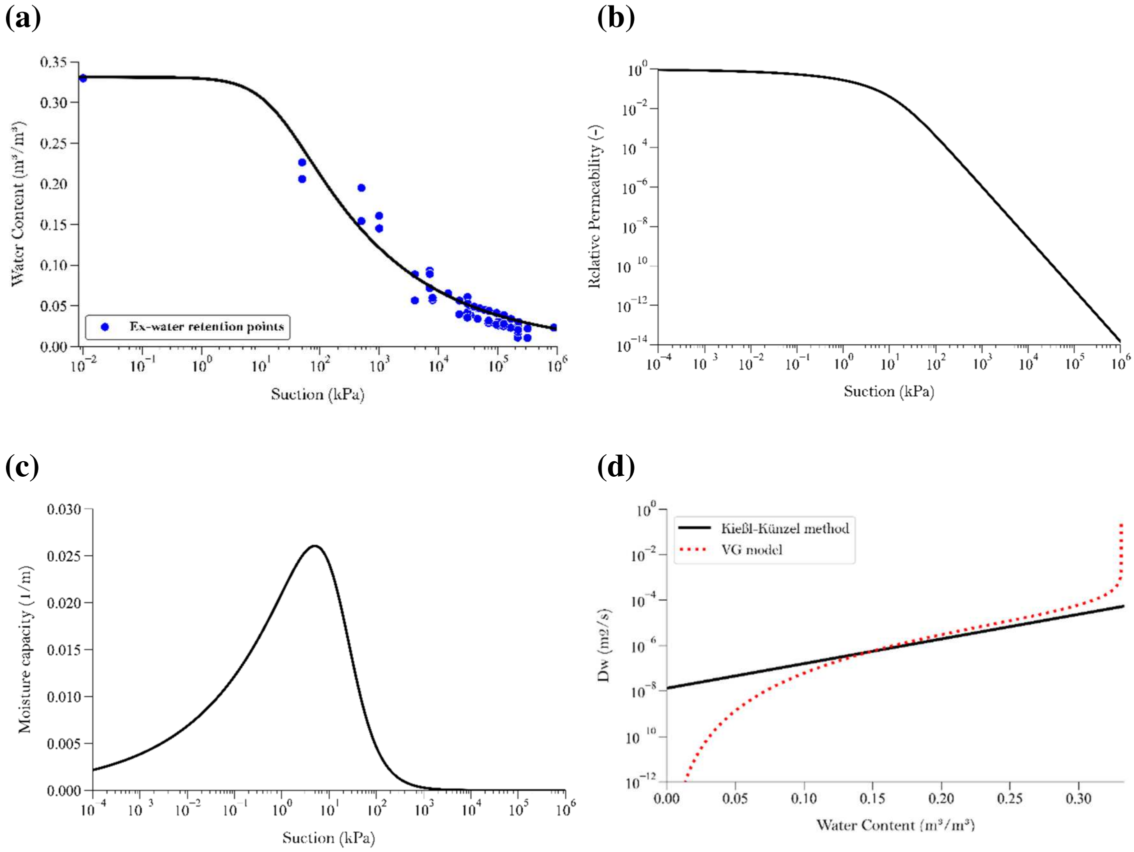

FIGURE 4. (a) Water retention curve based on the VG model using the fitted parameters in Table 1; (b) Obtained relative permeability; (c) Moisture capacity and (d) Comparison of the moisture diffusivity as estimated by Kießl-Künzel and VG models.

IV. Conclusion

This research compares the moisture diffusivities obtained from two methods during the capillary absorption test and water retention data. This study focuses on compressed earthen brick, a porous building material. The Kießl-Künzel method offers a straightforward and practical approach; however, its accuracy diminishes, particularly at very high or low levels of water content or relative humidity. As an alternative, the VG model provides a good estimation of liquid diffusivity, but under certain conditions such as an accurate estimation of saturated permeability and a well-fitted parameterization of the retention curve. Future work will focus on estimating water vapor permeability from the water retention curve, as well as analyzing saturated permeability using classical experimental techniques such as triaxial tests, oedometer tests, and falling-head methods.

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