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# Estimation of permeability function for concrete

## Estimation de la fonction de perméabilité du béton

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**ABSTRACT:** Due to the construction of underground structures and hazardous waste storages, understanding and modelling of seepage in concrete has become an important issue in life-span analyses. This study deals with the estimation of unsaturated permeability function for different concrete mixtures using the theory of water retention curve. The WRC is an essential unsaturated soil function, which can be determined not only for soil samples, but also for other porous media. The theory of unsaturated soil mechanics can be applied for modelling of seepage in porous medium and for concrete as well.

**RÉSUMÉ:** En raison de la construction de structures souterraines et de stockages de déchets dangereux, la compréhension et la modélisation des infiltrations dans le béton sont devenues un problème important dans les analyses de durée de vie. Cette étude traite de l'estimation de la fonction de perméabilité non saturée pour différents mélanges de béton en utilisant la théorie de la courbe de rétention d'eau. La courbe de rétention d'eau est une fonction essentielle du sol non saturé, qui peut être déterminée non seulement pour les échantillons de sol, mais également pour d'autres milieux poreux. La théorie de la mécanique des sols non saturés peut être appliquée à la modélisation des infiltrations en milieu poreux et au béton.

**Keywords:** concrete, permeability, water retention curve, permeability function

## 1 INTRODUCTION

In geotechnical engineering it is a frequent task to analyse and model seepage in soils. The theories of unsaturated soil mechanics can be applied to calculate and examine the water flow in other unsaturated porous material such as concrete too. This paper deals with determination of the unsaturated permeability function for four different concrete mixtures using the measured water retention curves.

Direct experimental measurements of the unsaturated permeability coefficient for a porous medium are difficult and time consuming. Different estimation methods have been constituted to calculate the permeability function (Figure 1). These estimation techniques can be divided into four categories: empirical models, statistical models, correlation models and regression models. The statistical models start with a physical model of the assemblage of pore channels through which water can flow. These procedures can be used to calculate the permeability function

when the saturated coefficient of permeability and the SWRC are known. These models assume that the permeability function and the SWRC are both closely related to the pore-size distribution of the soil. (van Genuchten 1980, Fredlund et al. 1994, Zhai and Rahardjo 2015 etc.).

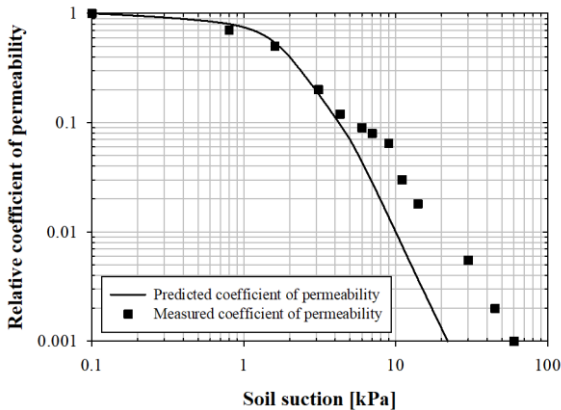


Figure 1. Predicted and measured relative permeability function for light clay after Fredlund et al. (2012) (data from Moore 1939)

The water retention curves characterize the water content of the porous medium as a function of suction. According to different methods the unsaturated permeability function can be determined based on water retention curves. These procedures are approximate but are generally adequate for analysing unsaturated soil mechanics problems (Fredlund et al. 2012).

Fredlund et al. (2011) divided the typical water retention curve into three distinct zones (Figure 2). In the first range, where the suction value is less than the air entry value, the soil is practically saturated, and the section is almost horizontal (boundary effect zone). In the second range, the suction value gradually increases above the air entry value and the water content is largely reduced while the air content is increasing (transition zone). On the last section the water content is only slightly reduced above the residual suction value (residual zone). The shape of the water retention curve depends significantly on the grain size distribution of soils (Ng and Menzies 2007).

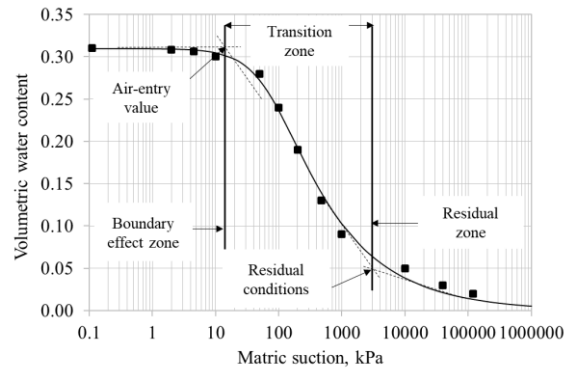


Figure 2. The three distinct zones of a typical water retention curve after Fredlund et al. (2011)

The shape of the water retention curve of some porous medium does not fit to this unimodal characteristic. There are soils that have not only one pores series but also larger and smaller pores. This type of soil has at least two peaks on its grain size distribution curve (e.g. gap graded soils) (Imre et. al 2012) and show bimodal or multimodal characteristic in water retention curve (Figure 3).

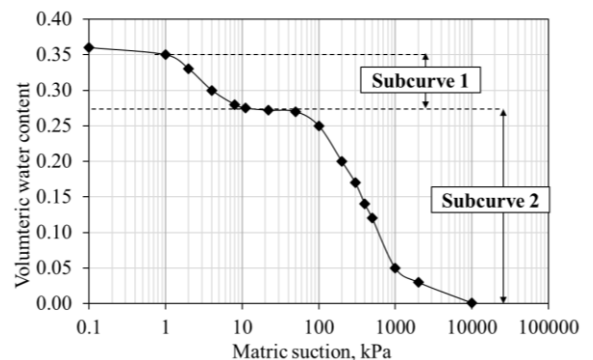


Figure 3. The characteristic of a bimodal water retention curve after Satyanaga et al. (2013)

During laboratory tests the water content is generally measured at exact suction values only. Therefore, a large number of unimodal and bimodal closed-form, empirical equations have been recommended to best fit laboratory data for water retention curves (van Genuchten 1980, Mualem 1976, Fredlund and Xing 1994, Satyanaga et al. 2013 etc.).

The scope of study was to examine that the definitions, concepts, theories and calculation methods used in geotechnical engineering could be applicable to provide substantial input data for modelling of water flow through the pores of concrete.

## 2 MATERIALS AND METHODS

### 2.1 Concrete types and samples

For the laboratory tests we prepared four concrete mixtures. The water-cement ratio varied between 0.45 and 0.50. The water used for each mixture was constant at 180 l/m<sup>3</sup>. Portland cement composite (CEM II) with strength class 42.5 N was used. The percentage of clinker content was 80-94 % and the slag content was 6-20 %.

Washed, segregated and dried sand and gravely sand were used as aggregates. The aggregate was composed using 40 % of 0/4 mm, 25 % of 4/8 mm and 35 % of 8/16 mm fractions.

Polymer fiber was used for A2 concrete mixture to extend the range of the concrete properties. The fiber content was 0.35 % by volume.

Superplasticizer based on polycarboxylic solution dispensed into concrete mix to adjust the appropriate consistency of the mixture. Penetron Admix integrated crystalline additive was used as waterproofing admixture for A3 concrete mix. Table 1 presents the tested concrete mixtures.

*Table 1. Summary of concrete mixtures.*

Mix- ture No.	Amount of ce- ment [kg/m <sup>3</sup> ]	w/c ratio	Fiber rein- force- ment	Water- proofing admix- ture
A1	360	0.50	-	-
A2	400	0.45	polymer	-
A3	360	0.50	-	Penetron
A4	400	0.45	-	-

The water retention curve was measured by three different methods due to the wide range of

suction values. Each procedure demanded distinct size of samples. Therefore, core samples from each concrete type with height of 25 to 50 mm and diameter of 50 mm were prepared for the measurement. The ratio between the maximum particle size and the height of the specimens varied from 0.32 to 0.64. This may seem a bit high at first sight but considering that the tests do not aim to obtain mechanical (i.e. strength or deformation) properties but water content only, these ratios are considered acceptable.

The measurement of drying water retention curve is also time consuming. To avoid any mass change due to healing during the tests, the prepared concrete specimens were tested after age of 100 days. At this time the residual properties of concrete are recovered.

### 2.2 Measuring methods for water retention curves

#### 2.2.1 Sand/kaolin box

In sand/kaolin box were measured the water content at pF 0, pF 1, pF 1.5, pF 2.0 and pF 2.5 (0.1 kPa, 1 kPa, 3.2 kPa, 10 kPa and 31.6 kPa) suction values. During the measurement, the suction values were controlled by positioning the water surface related to the position of tested samples. Determination of the water content was performed by weighing. Time interval of the measurement was approx. two weeks per suction value.

#### 2.2.2 Pressure membrane extractor

The water content of pF 3.4 and pF 4.2 (251.2 kPa and 1584.9 kPa) suction values was determined in pressure membrane extractor using axis translation technique. During the test the water pressure was controlled, and an overpressure developed in the apparatus. The samples tested in the pressure membrane extractor were saturated initially. The time interval of the measurement was one week per point.

### 2.2.3 Vapour equilibrium technique

At high suction range other procedures are needed to control the suction. Applying the vapour equilibrium technique, the relative humidity can be controlled by using diverse chemicals and salts (Ng and Menzies 2007). The principle of humidity control is that equilibrium develops between the water content of the samples and the relative humidity of the surroundings. During our measurements three different chemicals were used to adjust the 95.6%, 90% and 31% relative humidity values in desiccator. Table X shows the used chemicals and corresponding pF values. The mass of the samples was measured weekly until a constant value has been reached. The measurement took approx. two months.

Table 2. Selected chemicals and corresponding suction values

Chemicals	Relative humidity [%]	pF value	Suction [kPa]
Sulfuric acid	95.6	4.79	6208
Zinc sulphate	90	5.16	14537
Calcium chloride	31	6.21	161588

## 3 FITTING METHODS OF WATER RETENTION CURVES

As mentioned above, during the test for the water retention curve, we can only measure few points of the function. Therefore, it is necessary to fit a function to the measured points that the permeability function can be determined. The fitting of the WRC to the measured data was performed using the van Genuchten (1980) and Fredlund and Xing (1994) methods.

Van Genuchten (1980) model is the most commonly used relationship for soils to fit the water retention curves. The model has been developed to determine the permeability function of soils. The van Genuchten (1980) model can be written as follows:

$$\theta(\psi) = \frac{\theta_s}{[1+(a\psi)^n]^m} \quad (1)$$

Where  $\theta_s$  is the saturated water content,  $\psi$  is the suction,  $a$ ,  $n$  and  $m$  are fitting parameters.

Due to the asymptotic nature of the equation, it is limited to the range between the air entry value and the residual suction value.

The model developed by Fredlund and Xing (1994) is proved to be applicable for the description of the water retention curves of non-soil materials too (Park and Fleming 2006). The formula includes a correction factor that extends the suction range from residual suction to fully dry state. The natural logarithm model of Fredlund and Xing (1994) is the following:

$$\theta(\psi) = C(\psi) \cdot \frac{\theta_s}{\{\ln(e+(\psi/a_f)^{n_f})\}^{m_f}} \quad (2)$$

Where  $\theta(\psi)$  is the volumetric water content at the given suction value,  $\psi$  is the suction value,  $\theta_s$  is the saturated volumetric water content,  $a_f$ ,  $n_f$  and  $m_f$  are fitting parameters,  $\psi_r$  is the value of suction to the residual volumetric water content.

The correction factor can be defined as follows:

$$C(\psi) = 1 - \frac{\ln(1+(\psi/\psi_r))}{\ln(1+(10^6/\psi_r))} \quad (3)$$

Where  $\psi_r$  is the value of suction to the residual volumetric water content.

According to the measured data and the pore size distribution (complex pore system) of concrete it is emerged that the concrete may have bi-modal characteristic on water retention curve. This suggests that such formulas like Satyanaga et al. (2013) should be used to fit the measured data, however due to the large number of parameters and limited number of measured points fitting such a complex curve was not feasible.

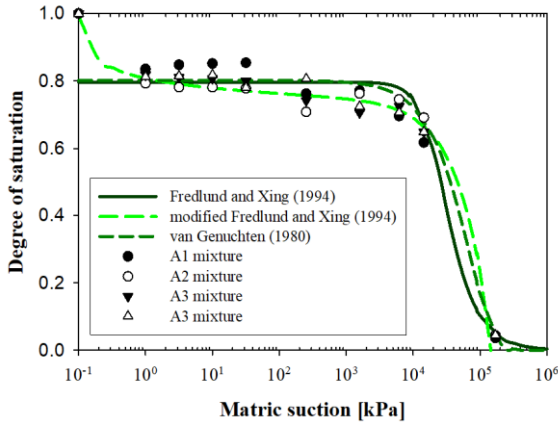


Figure 4. The measured and fitted water retention curve for concrete

Figure 4 presents the degree of saturation as function of suction for four different concrete mixtures using three different fitting procedures. The WRCs of the tested concretes are almost identical, therefore only the fitted WRC of A2 mixture is shown on Figure 4. It seems the water content decreases with two steps. This characteristic of water retention curve of concrete can be explained by the complex pore system of concrete. The complex pore system is made up of opened macropores and capillary pores. On low suction range the water is quickly removed out of the opened macropores of the concrete since the water movement is caused by gravity. Further investigation is required in range of 0.1 to 1 kPa to estimate the desorption method at low suction value. This is a very challenging task, but it has been recently successfully solved in case of laboratory testing of asphalt samples (Renken et al. 2016). Water evaporation during concrete solidification generates capillary pores where the surface tension prevents water to leave the structure of the concrete up to a higher suction value dependent on the surface tension. In high suction range the exact characteristic is not indisputable hence more points are needed for the accurate fitting process.

The results (i.e. the almost identical WRCs) imply that the exact composition of concrete (e.g.

fiber reinforcement, admixtures) does not influence the characteristic of the pore and the capillary system significantly. This is in good agreement with earlier findings related to WRCs of concrete samples (Pap et al., 2018).

The curves using van Genuchten (1980) and Fredlund and Xing (1994) methods are similar to each other, but the models do not take into account the first point of the measured data with appropriate weight. These models in this form cannot describe two air entry values. The Fredlund and Xing (1994) model was proved more flexible for other porous medium (Park and Fleming 2006) thus we have modified the model as in the first member the 1 000 000 kPa changed to 150 000 kPa.

#### 4 ESTIMATION OF PERMEABILITY FUNCTION

The estimation methods for describing the permeability functions can be classified into different categories. There are proposed estimation models that are based on statistical assumptions regarding the pore distributions. These models are based on the interpretation of the WRC. Van Genuchten (1980) and Fredlund and Xing (1994) models were applied in this recent study. Van Genuchten (1980) model is expressed as follows:

$$k_r = \frac{\{1 - (a\psi)^{n-1} [1 + (a\psi)^n]^{-m}\}^2}{[1 + (a\psi)^n]^{m/2}} \quad (4)$$

The method uses the same parameters that were previously defined for WRC fitting.

Fredlund et al. (1994) model used the Fredlund and Xing (1994) WRC equation to compute the permeability function. The procedure involves numerical integration along the WRC. The equation of Fredlund et al. (1994) is written in the following form:

$$k_r(\psi) = \frac{\int_{\ln(\psi)}^b \frac{\theta(e^y) - \theta(\psi)}{e^y} \theta'(e^y) dy}{\int_{\ln(\psi_{aev})}^b \frac{\theta(e^y) - \theta_s}{e^y} \theta'(e^y) dy} \quad (5)$$

where  $b$  is the upper limit of integration,  $y$  is dummy variable of integration representing the logarithm of suction,  $\theta'$  is derivative of the WRC equation,  $e^y$  is natural number raised to the dummy variable power.

Figure 5 shows the relative permeability functions for concrete. Pap et al. (2018) defined the drying water retention curve for concrete mixtures using Fredlund et al. (1994) method and estimated the wetting curve using theory of lateral shift (Fredlund 2000, Pham 2002, Pham 2003). These latter results were validated by numerical back analyses of water penetration tests. The permeability function determined from calculated curves by modified Fredlund and Xing (1994) model are in good agreement with the function defined by Pap et al. (2018). Figure 5 also indicates that the curves obtained by Fredlund et al. (1994) and van Genuchten (1980) model are significantly different from the other curves hence the fitting method of the WRC shifts considerably the function of unsaturated permeability. This fact calls the attention to the importance of proper WRC definition. It is essential to have more measured point at the very low suction part and in the transition zone. Further research is going on to clarify these questions.

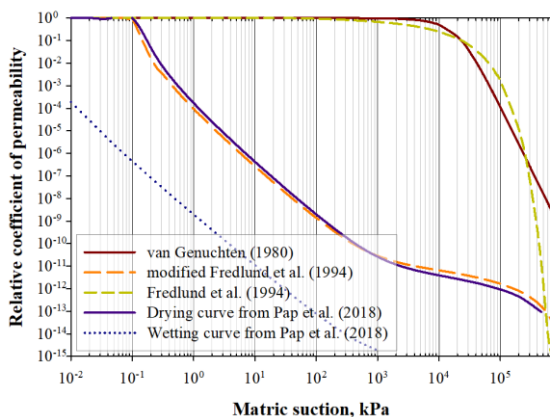


Figure 5. Relative permeability functions for AI concrete mixture

## 5 CONCLUSIONS

A set of laboratory tests were performed to investigate the applicability of unsaturated soil mechanics theories of seepage problems in concrete. In total four different concrete mixtures were tested for water retention by sand/kaolin box method, pressure membrane extractor and vapour equilibrium technique. Van Genuchten (1980), Fredlund and Xing (1994) and a modified form of Fredlund and Xing model were used to approximate the water retention curve based on measured data points. Due to the complex pore system of concrete bimodal correlations may be needed to estimate the water retention curve of concrete (e.g. Satyanaga et al. 2013) but additional measurements are needed to evaluate this characteristic, especially at very low suctions and at the transition zone of the WRC. The obtained water retention curves show that despite the huge differences between the concrete mixtures the WRCs were almost identical to each other, so the concrete type had little effect on the water retention characteristics.

The unsaturated permeability function was defined using van Genuchten (1980) and Fredlund et al. (1994) model. The estimated function from modified curve fits well to the function of Pap et al. (2018) but the results show that slightly different WRC curve may lead to significantly different permeability function. This fact also implies that proper fitting of the WRC is essential to proper estimation of unsaturated permeability.

Further tests are in progress to specify the characteristic the WRC of concrete in low suction range and in the transition zone.

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