Measurement of water retention curve for different concrete mixtures

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ABSTRACT: Due to the construction of underground structures and hazardous waste storages, understanding and modelling of water flow through concrete has become a major topic for life-span analyses. The water retention curve is an essential unsaturated soil function, which can be determined not only for soil samples, but also for other porous media. This study deals with the determination of water retention curve for different concrete mixtures that provide a substantial characteristic for the investigation and modelling of water flow through the pores of concrete. Our aim was to obtain the main characteristics of WRC for concrete and to investigate if there are significant differences between the WRCs of different concrete types. Hence, four different concrete mixtures that are commonly used in practice were examined. These concrete mixtures were made with two different cement quantities, two different water-cement ratios, with and without fibre reinforcement and with and without crystalline waterproofing admixture. The van Genuchten (1980) model, the original Fredlund and Xing (1994) model and a modified version, that showed consistency with the measured data, were used for curve fitting. The fitted curves were used to estimate the permeability function using van Genuchten (1980) and Fredlund et al. (1994) models.

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 measuring the water retention curve and determination the unsaturated permeability function for four different concrete mixtures.

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 1). 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).

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 2).

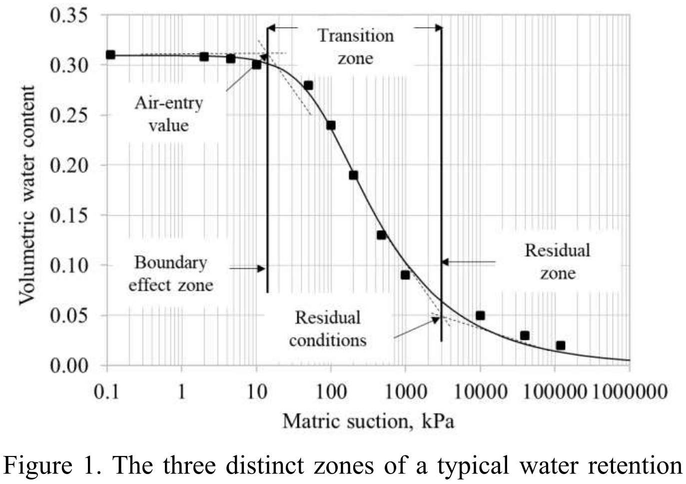

Figure 1. The three distinct zones of a typical water retention curve after Fredlund et al. (2011).

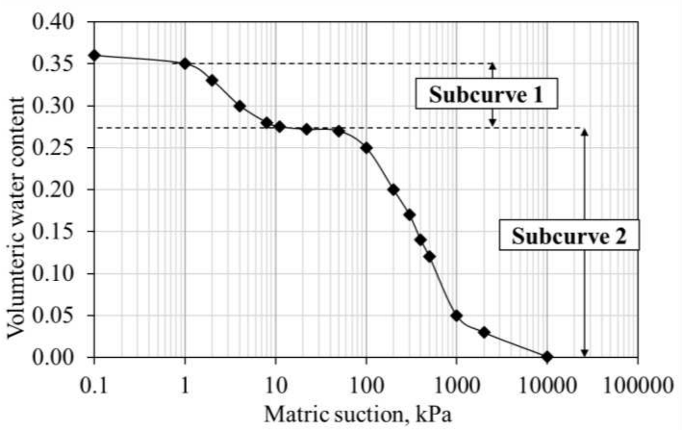

Figure 2. The characteristic of a bimodal water retention curve after Satyanaga et al. (2013).

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

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 coefficient using theoretical considerations of the pore-size distribution of soil. These procedures are related to the characteristic of the water retention curve and are commonly referred to as indirect methods for the estimation of the unsaturated permeability function (e.g. van Genuchten 1980, Fredlund et al. 1994, Zhai and Rahardjo 2015).

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^3. 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 gravelly 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 fibre was used for C2 concrete mixture to extend the range of the concrete properties. The fibre 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 C3 concrete mix. Table 1 presents the tested concrete mixtures.

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.

Table 1. Summary of concrete mixtures.

Mixture No.	Amount of cement, kg/m^3	w/c ratio	fibre reinforcement	Waterproofing admixture
C1	360	0.50	-	-
C2	400	0.45	polymer	-
C3	360	0.50	-	Penetron
C4	400	0.45	-	-

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 (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 measurement calcium-chloride-hexahydrate was used to adjust the 31 % relative humidity in desiccator which is related to pF 6.21 (162 181 kPa). The mass of the samples was measured weekly until a constant value has been reached. The measurement took approx. two months.

3 FITTING 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 for feasibility. 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:

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

where θ_s = the saturated water content; ψ = the suction; a, n and m = 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:

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

where $\theta(\psi)$ = the volumetric water content at the given suction value; ψ = the suction value; θ_s = the saturated volumetric water content; a_f, n_f and m_f = fitting parameters; ψ_r = the value of suction to the residual volumetric water content.

The correction factor can be defined as follows:

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

where ψ_r = 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 bimodal 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 3 presents the degree of saturation as function of suction for concrete using three different fitting procedures. The WRCs of the tested concretes are almost identical, therefore only the WRC of C1 mixture is shown on Figure 3. 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. fibre 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. 2015).

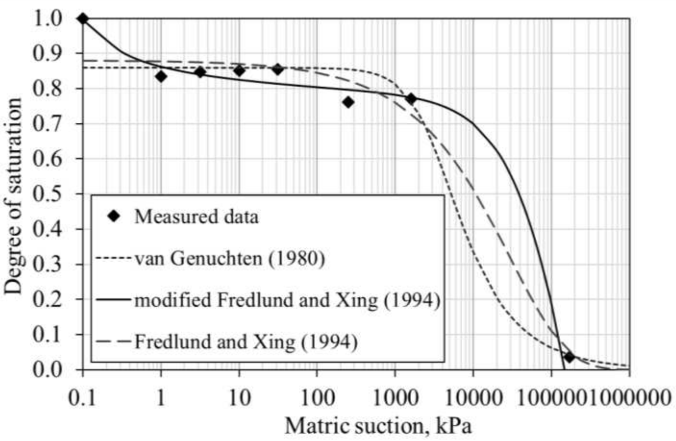

Figure 3. The fitted water retention curve for concrete.

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:

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

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:

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

where b = the upper limit of integration; y = dummy variable of integration representing the logarithm of suction; θ' = derivative of the WRC equation; e^y = natural number raised to the dummy variable power.

Figure 4 shows the normalized permeability functions for concrete. Pap et al. (2015) 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. (2015). Figure 4 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.

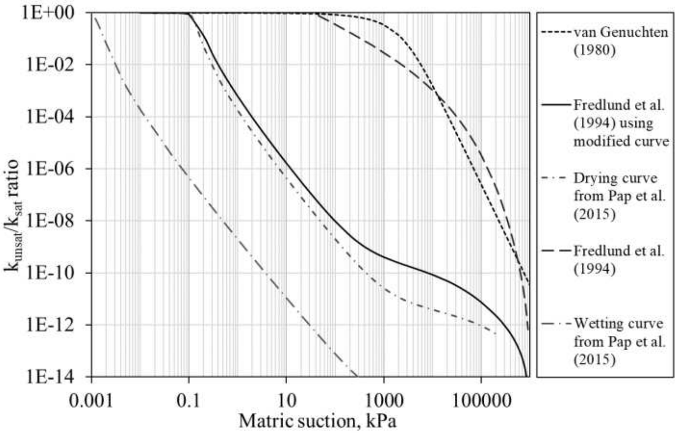

Figure 4. Normalized permeability functions for concrete.

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 (1944) 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. 2015) 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. (1944) model. The estimated function from modified curve fits well to the function of Pap et al. (2015) but the results show that slightly different WRC curve may lead to significantly different permeability function. This fact also implies that 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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