Laboratory testing of seepage in concrete

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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 (WRC) is an essential unsaturated soil function, which can be determined not only for soil samples, but also for other porous media. This paper deals with the determination of drying water retention curve for six different concrete mixtures that provide a substantial characteristic for the investigation and modelling of seepage through the pores of concrete. According to the complex pore system of the concrete, the bimodal function of van Genuchten (1980) and Fredlund and Xing (1994) models were used for curve fitting. The fitted curves were used to estimate the permeability function using Fredlund et. al (1994) model.

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. This paper deals with the measuring of the drying water retention curve for six different concrete mixtures and the estimation of the unsaturated permeability function for these concrete types tested.

The water retention curves characterize the water content or the degree of saturation of the porous medium as a function of suction, or inversely, it depends on the measuring method of the curve. According to different methods the unsaturated permeability function can be determined based on water retention curves. The knowledge on water retention curve helps analysing the soil hydraulic response, or eventually its hydro-mechanical response [1].

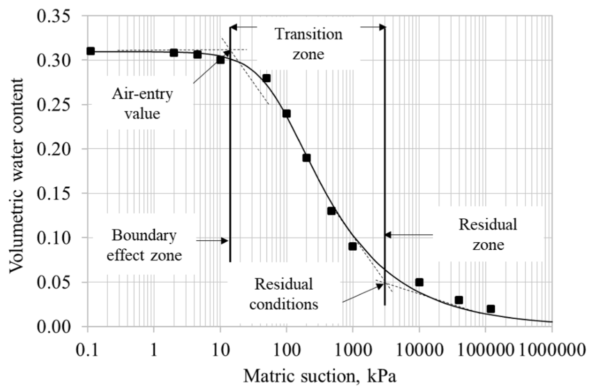

Fig. 1. The three distinct zones of a typical water retention curve after Fredlund et al. [3].

Fredlund et al. [2] divided the typical water retention curve into three distinct zones (Fig. 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 [3].

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) [4] and show bimodal or multimodal characteristic in water retention curve (Fig. 2 and Fig 3.).

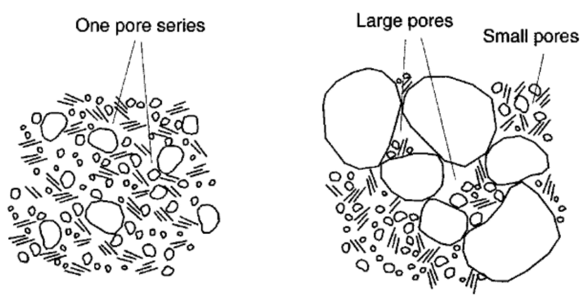

Fig. 2. Structures of unimodal and bimodal soils after Zhang and Chen [16]

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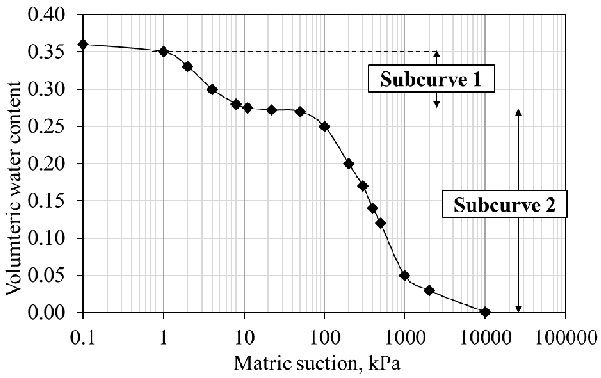

Fig. 3. The characteristic of a bimodal water retention curve after Satyanaga et al. [13]

Many types of devices and test procedures have been used for measuring the WRC. Much of the original laboratory testing equipment was developed in the agricultural discipline. These devices provide an applied matric suction or provide a controlled total suction. Matric suctions are applied to a soil specimen through use of a high-air-entry disk. The axis translation technique is used to develop a differential air and water pressure without producing cavitations in the water phase. Matric suctions can be applied as high as about 1500 kPa using pressure plate equipment. A controlled relative humidity environment is used to establish a fixed total suction. The specimens get into equilibrium with the surrounding vapor pressure. The relative humidity is converted to total suction through use of the Kelvin equation. [1]

During laboratory tests only exact points of the WRC is generally measured. Therefore, it is necessary to fit a mathematically descriptive function to the measured points for feasibility. Several unimodal and bimodal closed-form, empirical equations have been recommended to best fit laboratory data for water retention curves [5, 6, 7, 8].

The scope of study was to examine that the definitions, concepts, theories, testing and calculation methods used in soil mechanics could be applicable to provide substantial input data for modelling of seepage in concrete.

2 Materials and methods

2.1 Concrete types and samples

For the laboratory tests we prepared six concrete mixtures. The water-cement ratio varied between 0.45 and 0.50. 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 M5 and M15 concrete mixtures 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 M7 concrete mix. Table 1 presents the tested concrete mixtures.

Table 1. Summary of concrete mixtures tested

Mix No.	Amount of cement (kg/m^3)	w/c ratio	Fibre rein-forcement	Water-proofing admix.
M1	360	0.50	-	-
M5	400	0.45	polymer	-
M7	360	0.50	-	Penetron
M13	360	0.40	-	-
M15	400	0.50	polymer	-
M17	400	0.45	-	-

The drying 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 samples were bored and cut from concrete cube with size of 150×150×150 mm. 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 2 shows the main properties of the tested samples, namely the dry volumetric weight, void ratio and porosity.

Table 2. Physical characteristics of the concrete mixtures

Mix No.	Dry volumetric weight (kN/m^3)	e	n (%)
M1	22.81±0.50	0.11±0.01	10.1±0.9
M5	22.64±0.26	0.11±0.01	9.8±0.7
M7	22.66±0.41	0.11±0.01	10.1±0.9
M13	23.36±0.51	0.09±0.01	8.3±0.3
M15	22.80±0.44	0.11±0.03	9.8±2.0
M17	22.84±0.13	0.11±0.01	9.8±0.4

2.2 Measuring methods for water retention curves

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. The sample measured in sand/kaolin box were saturated initially. Time interval of the measurement was approx. two weeks per suction value.

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 was 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.

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 [3]. 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 four different chemicals were used to adjust the 95.6%, 90%, 75.3% and 31% relative humidity values in desiccator. Table 3 shows the used chemicals and corresponding pF values. The mass of the samples was measured weekly until a constant value has been reached. The sample tested using vapour equilibrium technique were saturated initially. The measurement took approx. three months.

Table 3. Summary of concrete mixtures tested

Chemicals	Temperature [°C]	Relative humidity (%)	pF value	Suction (kPa)
Sulfuric acid	20.0	95.6	4.79	6208
Zinc sulphate	20.0	90	5.16	14537
Sodium chloride	25.0	75.3	5.59	38905
Calcium chloride	24.5	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 so that the permeability function could be determined [9]. 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 formula like Satyanaga et al. [7] or some modified procedure [10] that can take into account the large-pore series and small-pore series should be used to fit the measured data.

Therefore, the fitting of the WRC to the measured data was performed using the bimodal version of van Genuchten [8, 10] and Fredlund and Xing [5, 10] functions.

Van Genuchten [8] 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 and the bimodal method can be written as follows [9]:

$$\theta(\psi) = \theta_{sl} \cdot \frac{1}{[1+(a_l\psi)^{n_l}]^{m_l}} + \theta_{ss} \cdot \frac{1}{[1+(a_s\psi)^{n_s}]^{m_s}} \tag{1}$$

Where θ_{sl} is the saturated water content for the large-pore series, θ_{ss} is the saturated water content for the small-pore series, ψ is the suction, a_l, n_l and m_l are fitting parameters for the large-pore series component, a_s, n_s and m_s are fitting parameters for the small-pore series component.

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 [5] is proved to be applicable for the description of the water retention curves of non-soil materials too [11]. The formula includes a correction factor that extends the suction range from residual suction to fully dry state. The bimodal model of Fredlund and Xing [5, 10] is the following:

$$\theta(\psi) = \theta_{sl} \cdot \left[1 - \frac{\ln\left(1+\frac{\psi}{\psi_{rl}}\right)}{\ln\left(1+\frac{10^6}{\psi_{rl}}\right)}\right] \cdot \frac{1}{\left\{\ln\left[e+\left(\frac{\psi}{a_l}\right)^{n_l}\right]\right\}^{m_l}} + \theta_{ss} \cdot \left[1 - \frac{\ln\left(1+\frac{\psi}{\psi_{rs}}\right)}{\ln\left(1+\frac{10^6}{\psi_{rs}}\right)}\right] \cdot \frac{1}{\left\{\ln\left[e+\left(\frac{\psi}{a_s}\right)^{n_s}\right]\right\}^{m_s}} \tag{2}$$

Where $\theta(\psi)$ is the volumetric water content at the given suction value, ψ is the suction value, θ_{sl} and θ_{ss} are the saturated volumetric water content for the large-pore and the small-pore series, a_l, n_l and m_l are fitting parameters for the large-pore series component, ψ_{rl} and ψ_{rs} is the value of suction to the residual volumetric water content for the large-pore and small-pore series, a_s, n_s and m_s are fitting parameters for the small-pore series component. The fitting parameters of WRCs for both methods are listed in Table 4 and Table 5.

Fig. 4 to 9 present the degree of saturation as function of suction for six different concrete mixtures using two different fitting procedures. It seems the water content decreases in 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

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successfully solved in case of laboratory testing of asphalt samples [12].

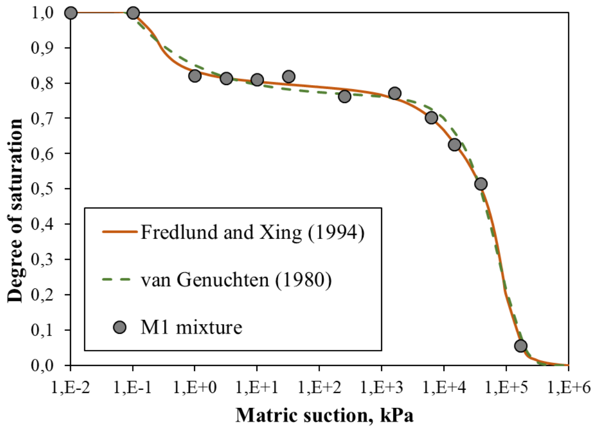

Fig. 4. The fitted water retention curve for M1 concrete mixture

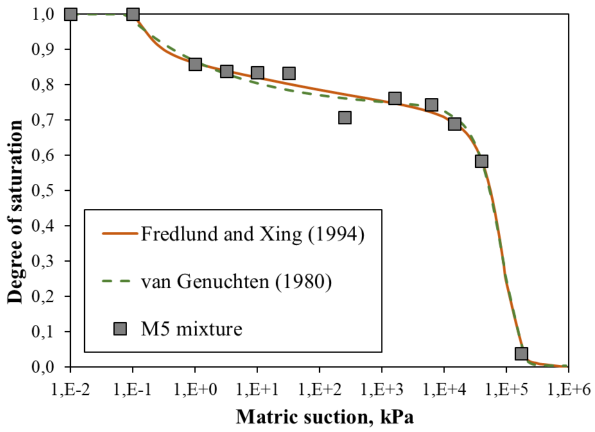

Fig. 5. The fitted water retention curve for M5 concrete mixture

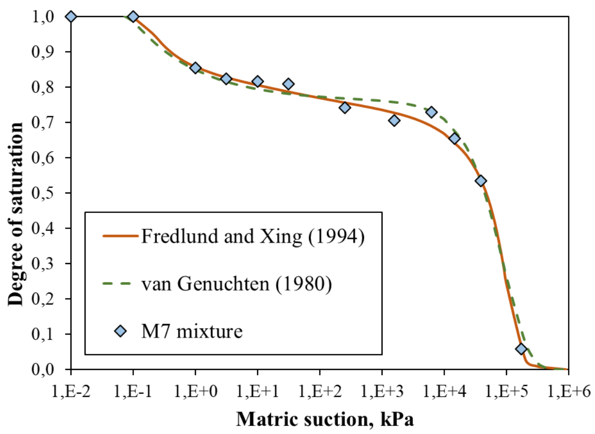

Fig. 6. The fitted water retention curve for M7 concrete mixture

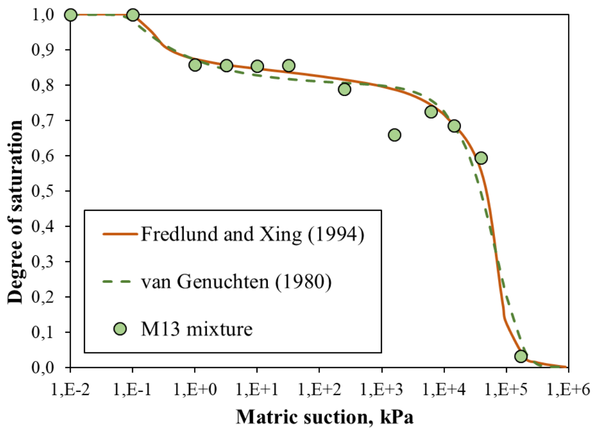

Fig. 7. The fitted water retention curve for M13 concrete mixture

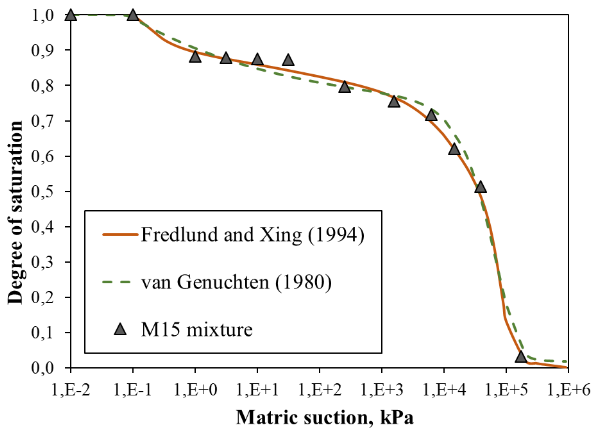

Fig. 8. The fitted water retention curve for M15 concrete mixture

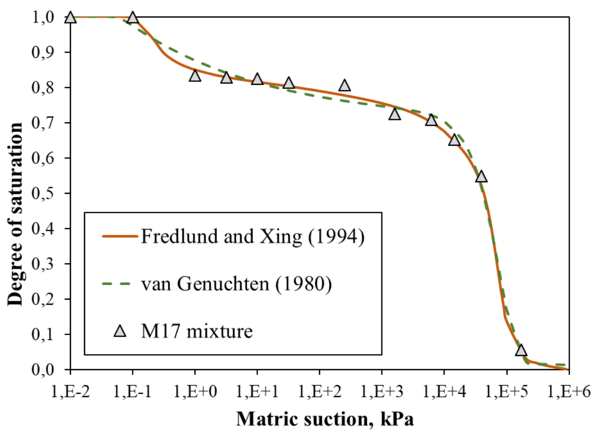

Fig. 9. The fitted water retention curve for M17 concrete mixture

Table 4. WRC fitting parameters using Fredund and Xing method

Mix No.	θ_{sl}	a_l	n_l	m_l	ψ_{rl}	θ_{ss}	a_s	n_s	m_s	ψ_{rs}
M1	0.239	0.168	4.20	0.616	19.94	0.759	87525	3.97	1.68	11260
M5	0.327	0.110	5.28	0.249	3.66	0.673	142859	2.55	6.76	161768
M7	0.331	0.138	2.82	0.360	6.76	0.669	142307	3.02	5.45	35342
M13	0.248	0.151	6.24	0.290	32.78	0.748	70497	4.64	1.86	24894
M15	0.288	0.123	4.20	0.226	9.08	0.712	95179	3.94	3.73	9602
M17	0.309	0.147	5.31	0.289	46.26	0.689	70579	4.24	1.82	26254

Table 5. WRC fitting parameters using van Genuchten method

Mix No.	θ_{sl}	a_l	n_l	m_l	θ_{ss}	a_s	n_s	m_s
M1	0.248	11.95	5.69	0.072	0.760	1.56×10^{-6}	1.19	12.2
M5	0.270	13.05	15.46	0.017	0.730	9.80×10^{-7}	1.69	57.7
M7	0.248	11.95	5.69	0.072	0.760	1.34×10^{-6}	1.18	12.2
M13	0.200	11.95	5.69	0.072	0.799	1.59×10^{-6}	1.16	12.3
M15	0.275	12.32	9.06	0.019	0.726	9.43×10^{-7}	1.26	31.8
M17	0.300	16.16	7.23	0.027	0.701	8.49×10^{-7}	1.59	79.0

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.

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 [13].

The curves using van Genuchten and Fredlund and Xing methods are similar to each other, but in most cases the Fredlund and Xing model was proved more flexible for other porous medium [11].

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. Fredlund et al. [14] model was applied in this recent study

Fredlund et al. [14] procedure involves numerical integration along the WRC. The equation is written in the following form:

$$k_r(\psi) = \frac{\int_{\ln(\psi)}^{b} \frac{\theta(e^y)-\theta(\psi)}{e^y}\theta'(e^y)\,dy}{\int_{\ln(\psi_{aev})}^{b} \frac{\theta(e^y)-\theta_s}{e^y}\theta'(e^y)\,dy} \quad (3)$$

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

Fig. 10 shows the normalized permeability functions for concrete. Pap et al. [13] defined the drying water retention curve for concrete mixtures using Fredlund et al [14] method and estimated the wetting curve using theory of lateral shift [15, 16, 17, 18]. These wetting curves were produced by horizontal translation of the drying curve to the left and validated by numerical back analyses of water penetration tests. The *a* fitting parameter of the WRC equations generally control the lateral shift of the drying and wetting WRCs. The *n* and *m* fitting parameters are kept constant for both curves. The permeability function determined are in good agreement with the function defined by Pap et al. [13] but we can observe some difference in high suction range. 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 high suction range.

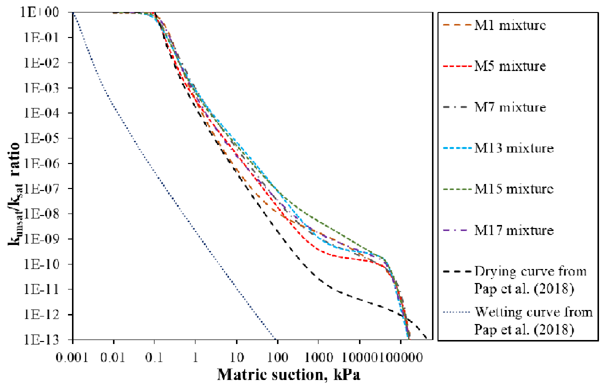

Fig. 10. Normalized permeability functions for different concrete mixtures

5 Conclusion

A set of laboratory tests were performed to investigate the applicability of unsaturated soil mechanics theories of seepage problems in concrete. In total six different concrete mixtures were tested for water retention by sand/kaolin box method, pressure membrane extractor and vapour equilibrium technique. Due to the complex pore system of concrete the bimodal form of van Genuchten and Fredlund and Xing models were used to approximate the water retention curve based on measured data points. 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 Fredlund et. al. [14] model. The estimated functions fit well to the function of Pap et al. [13] 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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