Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)
 ISBN 978-0-9946261-4-1

Laboratory testing of water flow in building materials

Tests en laboratoire de l'écoulement de l'eau dans les matériaux de construction

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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 measuring of drying water retention curve, the estimation of the wetting water retention curve using the theory of lateral shift and the determination of unsaturated permeability function for different concrete mixtures that provide a substantial characteristic for the investigation and modelling of seepage through the pores of concrete. The characteristic of the WRC of concrete refer to the complex pore system of the concrete that is made up of opened macropores and capillary pores. According to the complex pore system of the concrete, the bimodal function of Fredlund & Xing (1994) model was used for curve fitting. The fitted curves were used to estimate the permeability function using Fredlund et. al (1994) model.

RÉSUMÉ : En raison de la construction d'ouvrages souterrains et de stockages de déchets dangereux, la compréhension et la modélisation de l'écoulement de l'eau à travers le béton sont devenues un sujet majeur pour les analyses de durée de vie. La courbe de rétention d'eau (WRC) 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. Cet article traite de la mesure de la courbe de rétention d'eau de séchage, l'estimation de la courbe de rétention d'eau de mouillage en utilisant la théorie du déplacement latéral et la détermination de la fonction de perméabilité non saturée pour différents mélanges de béton qui fournissent une caractéristique substantielle pour l'étude et la modélisation de l'infiltration à travers les pores du béton. La caractéristique du WRC du béton se réfère au système de pores complexe du béton qui est composé de macropores ouverts et de pores capillaires. Selon le système complexe de pores du béton, la fonction bimodale des modèles de Fredlund et Xing (1994) a été utilisée pour l'ajustement des courbes. Les courbes ajustées ont été utilisées pour estimer la fonction de perméabilité à l'aide de Fredlund et. modèle al (1994).

KEYWORDS: Concrete; water retention curve; unsaturated permeability function; lateral shift.

1 INTRODUCTION.

Several studies in the literature have shown that the theories of unsaturated soil mechanics can be applied to calculate and examine the water flow in other unsaturated porous material such as concrete, asphalt and geotextile (Park & Fleming 2006, Renken et al. 2016, Pap et al. 2018). This paper deals with the measuring of the drying water retention curve and the estimation of the wetting water retention curve using the technique of lateral shift (Fredlund 2000, Pham 2002, Pham et al. 2003, Zhai et al. 2015) for six different concrete mixtures. The unsaturated permeability function of these concrete types tested which provides an essential input data to model the water flow in building materials was also estimated using the measured WRCs.

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

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. These procedures are approximate but are generally adequate for analyzing unsaturated soil mechanics problems (Fredlund et al. 2012).

Fredlund et al. (2011) divided the typical water retention curve into three distinct zones: boundary effect zone, transition zone and residual zone (Figure 1). The shape of the water retention curve depends significantly on the grain size distribution of soils (Ng & Menzies 2007).

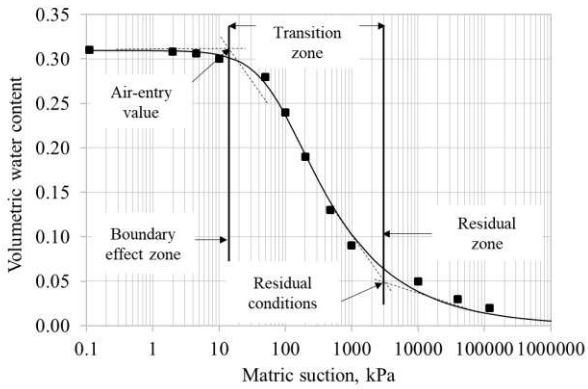

Figure 1. The three distinct zones of a typical water retention curve after Fredlund et al. (2011).

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 2 & Figure 3).

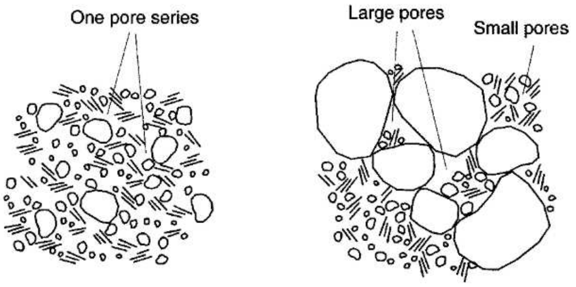

Figure 2. Structures of unimodal and bimodal soils after Zhang and Chen (2005).

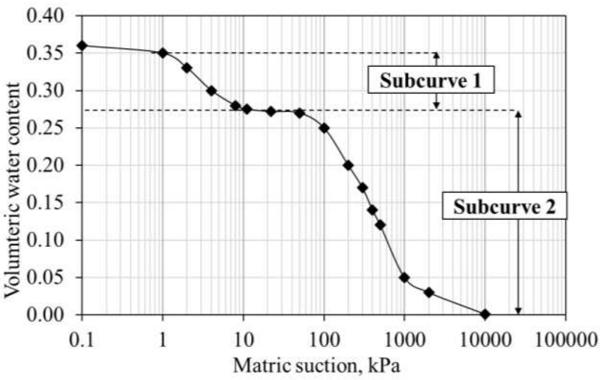

Figure 3. The characteristic of a bimodal water retention curve after Satyanaga et al. (2013).

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 (Mualem 1976, van Genuchten 1980, Fredlund & Xing 1994, Satyanaga et al. 2013).

The scope of study was to provide substantial input data (i.e. water retention curve, unsaturated permeability function) for modelling of seepage in concrete.

2 MATERIALS AND METHOD

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 fiber was used for M5 and M15 concrete mixtures 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 M7 concrete mix. Composition of the tested concrete mixtures can be found in Table 1.

Table 1. Summary of concrete mixtures tested.

Mix No.	*Amount of cement (kg/m3)*	*w/c ratio*	*Fiber reinforcement*	*Waterproofing 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 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*

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 cavitation 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.

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 vapor equilibrium technique, the relative humidity can be controlled by using diverse chemicals and salts (Ng & 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 four different chemicals were used to adjust the 95.6%, 90%, 75.3% and 31% relative humidity values in desiccator. Table 2 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 vapor equilibrium technique were saturated initially. The measurement took approx. three months.

Table 2. Selected chemicals and corresponding suction values.

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 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 (Leong & Rahardjo 1997). 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. (2013) or some modified procedure (Zhang & Chen 2005) 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 Fredlund & Xing (1994) function. The fitting process was made by Solver Add-in in Excel software.

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

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

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.

Figure 4 to 9 present the degree of saturation as function of suction for six different concrete mixtures using Fredlund & Xing (1994) bimodal equation. 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.

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 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).

4 ESTIMATION OF THE WETTING WATER RETENTION CURVE

The drying water retention curve is generally the first curve determined for a material, as reaching the equilibrium on the drying side is quicker than on the wetting side. The wetting curve is usually estimated by assuming an appropriate lateral shift for the drying curve. It can be also assumed that the drying and wetting curves are parallel to one another in the inflection point portion of the curves (Fredlund et al 2011, Pham et al. 2013).

Thus, the wetting WRC is estimated by a horizontal translation to the left in the semi-logarithmic space. 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 constants for all curves. The percent shift of the WRCs, ξ, is defined on a logarithmic scale. Therefore, a 100 % shift corresponds to one log scale of change. This means that the *a* fitting parameter will have to change by one order of magnitude. (Fredlund et al. 2011)

The percent lateral shift of the WRCs, ξ, can be written as follows (Fredlund et al. 2011):

$$\xi=100\left[\log(\psi_{ad})-\log(\psi_{aw})\right] \tag{2}$$

where ψ_{ad} is the suction at any point along the drying WRC, and ψ_{aw} is the suction at any corresponding water content on the wetting WRC. With the former formula, the lateral shift can be determined from any point at the curve.

The Eq. (2) representing the lateral shift of the WRC can be rearranged such that the suction on a congruent WRC can be computed from the drying curve. Then, Eq. (2) can be written as follows (Fredlund et al. 2011):

$$\psi_w=10^{(\log\psi_d-\xi/100)} \tag{3}$$

Pham et al 2013 analyzed the lateral shift between the drying and wetting WRCs for published data from various researchers. It was found that the largest shift between the drying and wetting curves existed for clay soils (50-100), and the smallest shift occurred for uniform sand soils (15-35).

To determine the wetting WRCs of concrete mixtures former studies were used. Pap et al. (2018) estimated the wetting WRC using the theory of lateral shift. This calculation was validated by numerical back analysis of water watertightness test. It has been found that the value of lateral shift in concrete is higher than in the case of soils. The values were between 145 and 215 for concrete prepared with CEM II AS 42.5 N. Based on this study, a value of 180 was used as a mean value for lateral shift to estimate the wetting curves from the measured drying curves. Figure 4 to 9 show the estimated wetting WRCs.

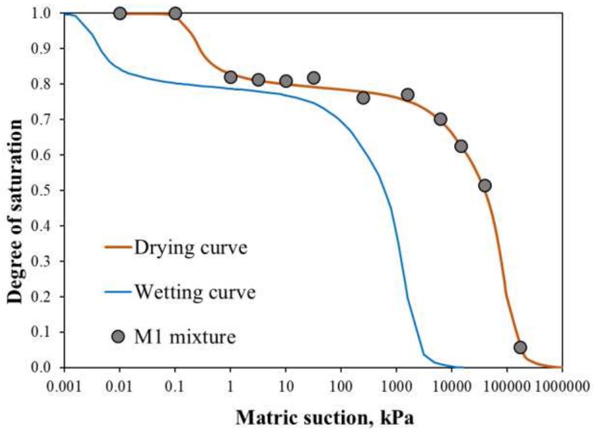

Figure 4. The fitted and estimated water retention curve for M1 concrete mixture.

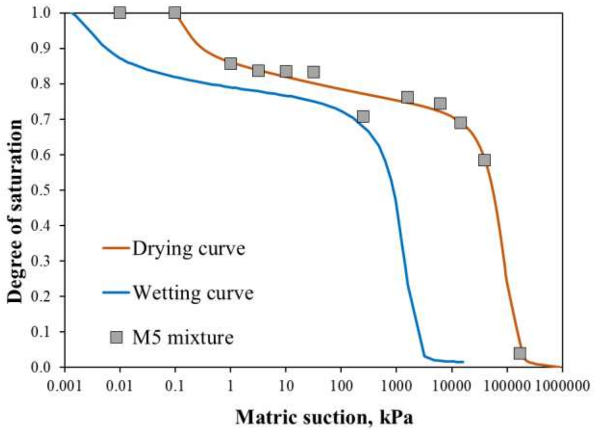

Figure 5. The fitted and estimated water retention curve for M5 concrete mixture.

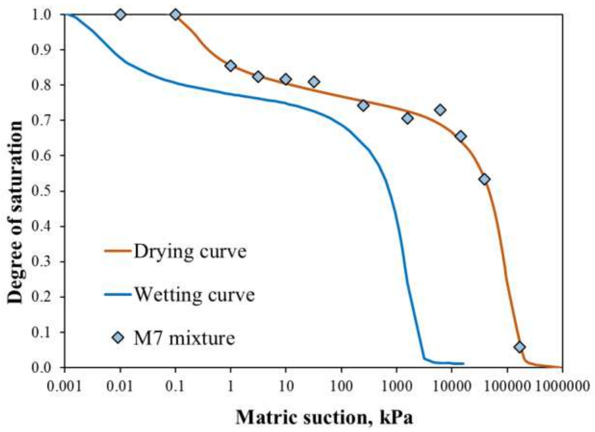

Figure 6. The fitted and estimated water retention curve for M7 concrete mixture.

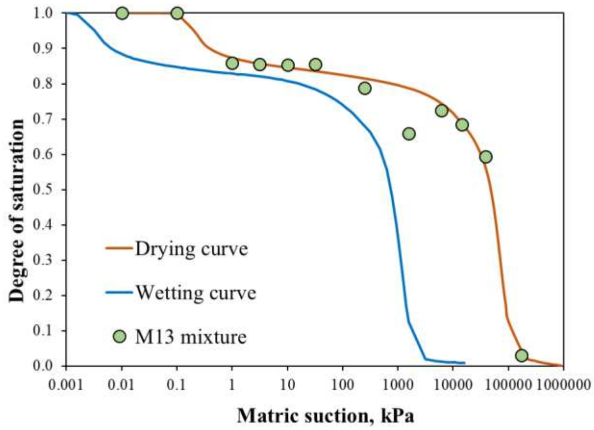

Figure 7. The fitted and estimated water retention curve for M13 concrete mixture.

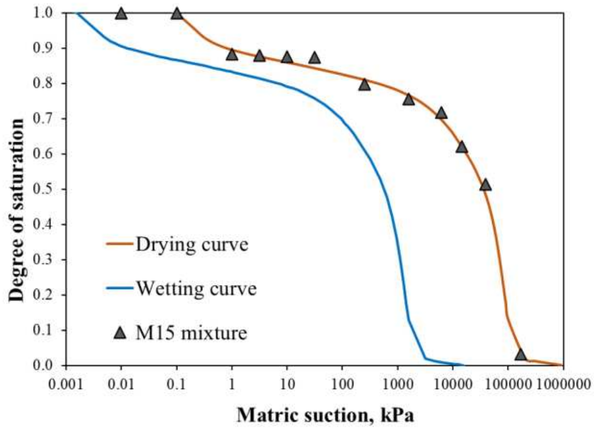

Figure 8. The fitted and estimated water retention curve for M15 concrete mixture.

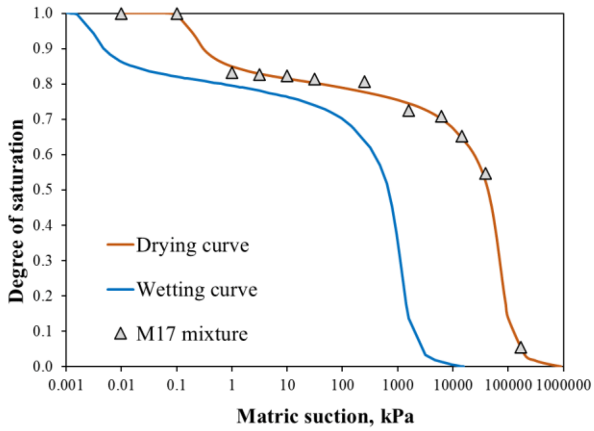

Figure 9. The fitted and estimated water retention curve for M17 concrete mixture.

4 DETERMINATION OF PERMAEBILITY 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. (1994) model was applied in this recent study.

Fredlund et al. (1994) procedure involves numerical integration along the WRC. The integration was performed by PTC Mathcad software. The equation is written in the following form:

$$k_r(\psi) = \frac{\int_{\ln(\psi)}^{b} \frac{\theta(e^y) - \theta(\psi)}{e^y} \theta'(e^y)\, dy}{\int_{\ln(\psi_{aev})}^{b} \frac{\theta(e^y) - \theta_s}{e^y} \theta'(e^y)\, dy} \tag{4}$$

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.

Figure 10 shows the normalized permeability functions for different concrete types, which demonstrates that the increasing suction causes a significant reduction in permeability by more order of magnitudes. The curves obtained are almost identical, but some differences can be observed. These results show that slightly different WRC curve may lead to different permeability function. 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. It can be also observed due to large hysteresis of the curves, the permeability coefficient of concrete is significantly smaller during the wetting process at the same suction value.

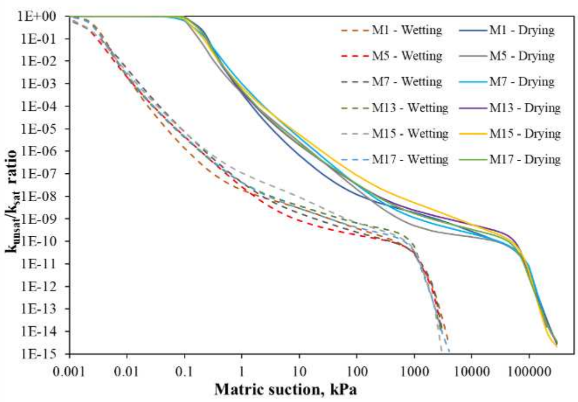

Figure 10. Normalized permeability functions for different concrete mixtures.

5 CONCLUSIONS

This study aims to provide input data for modelling of water flow in building materials such as concrete. A set of laboratory tests were performed in which 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 Fredlund & Xing (1994) model was 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. For the determination of the wetting water retention curve the lateral shift was used. The value of later shift has been determined based on previous studies.

The unsaturated permeability function was defined using Fredlund et. al. (1994) model. The results show that slightly different WRC curve may lead to different permeability function. This fact also implies that that proper fitting of the WRC is essential to proper estimation of unsaturated permeability.

Further investigations are in progress to specify the characteristic the WRC of concrete in low suction range and in the transition zone, furthermore, to clarify and validate hysteresis of water retention curve in case of concrete.

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