

A METHODOLOGY TO DETERMINE WATER VAPOUR DIFFUSION CHARACTERISTICS OF GEOMATERIALS

K. R. Arsha Lekshmi¹

D. N. Arnepalli²

¹Research Scholar (PhD), ²Associate Professor, Department of Civil Engineering, Indian Institute of Technology Madras, Chennai – 600 036.

¹arsha.lekshmi@gmail.com

²arnepalli@iitm.ac.in

ABSTRACT: Water vapour diffusion is a predominant moisture transport mechanism in an unsaturated soil due to the presence of either thermal gradient or concentration gradient. In such soils as water content decreases, the continuity of liquid films is lost and, as a result water movement is mainly in the form of water vapour. The knowledge of water vapour migration characteristics of geomaterials are important in performance evaluation of underground buried services, compacted/geosynthetic clay liners, geothermal energy utilization, thermally enhanced clean-up of contaminated sites and the containment facilities for disposal of high-level nuclear waste. In view of this, the present study describes a methodology to investigate the water vapour diffusion through geomaterials under isothermal conditions. Further the study evaluates the effect of particle size and compaction state on water vapour diffusion characteristics of the soils.

1 INTRODUCTION

Recently, due to the innumerable applications in the field of geotechnical and geoenvironmental areas, the diffusion of water vapour through geomaterials has been a topic of paramount interest. An in-depth knowledge of water vapour migration characteristics of geomaterials are imperative for the performance evaluation of underground buried services, compacted/geosynthetic clay liners, geothermal energy utilization, thermally enhanced clean-up of contaminated sites and the containment facilities for disposal of high level nuclear waste (Cleall et al., 2013).

In unsaturated soils, moisture transfer is primarily in the form of vapour and liquid states, which in turn depends on the moisture content. For acutely dry unsaturated soil, the liquid film becomes discontinuous and as a result water in the pores gets transported mainly in the form of water vapour. The impetus behind the vapour transport is due to the gradient in vapour pressure. The factors such as temperature, moisture, and salt concentration fluxes can impose a vapour pressure gradient. The water vapour movement occurs from an area of moist soil with a high vapour pressure to a dry soil region where the vapour pressure is low. Under isothermal conditions, moisture movement happens without the presence of a temperature gradient i.e., it migrates as a result of moisture gradient.

The movement of water vapour in soils especially under isothermal conditions has been studied experimentally by many researchers (Hanks, 1958;

Rose, 1963; Jackson, 1964). Evgin and Svec (1988) conducted studies on compacted silty soil to determine the water vapour diffusion coefficients under isothermal conditions. The effect of porosity and temperature on the water vapour diffusion properties of dry silty clay of different aggregate sizes has been thoroughly investigated (Jabro, 2009). It has been observed from this study that, the rate of water vapour diffusion through dry silty clay is enhanced with the increase of temperature. On the other hand, the rate of diffusion through the dry soil is decreased when the porosity soil is reduced due to the increased sorption of water by the soil.

The moisture movement in soil under a thermal gradient has been extensively investigated by many researchers (Gurr et al., 1952; Cary, 1964; Evgin and Svec, 1988; Yong et al., 1997; Villar et al., 1996, Cleall et al., 2013). It has been concluded from the studies that in an unsaturated soil moisture migrates in the form of vapour by diffusion, along a thermal gradient, from a region of higher temperature to a region of lower temperature. The vapour gets condensed when it reaches a relatively colder region, thereby causing a local increase in water content. This impending increase of water content in the lower temperature region results in the back flow of water in its liquid state towards the higher temperature region.

In view of the above, this article presents an experimental methodology to determine the water vapour diffusion coefficient under isothermal conditions. Various samples of different grain size were considered. The diffusion coefficients are calculated using the experimentally obtained vapour

flux values. The effect of grain size and compaction state on the diffusion characteristics is also evaluated.

2 THEORY

Quantitative description of steady vapour flux, q_v ($\text{kg/m}^2\text{s}$) can be represented by Fick's first law (Philip and de Vries, 1957, Cassel et al., 1969).

For isothermal conditions, q_v is given by:

$$q_v = -D_V \left(\frac{\partial \rho_v}{\partial x} \right) \quad (1)$$

Where q_v is the vapour flux ($\text{kg/m}^2\text{s}$), D_v is the diffusion coefficient (m^2/s), ρ_v is the water vapour density (kg/m^3), and x is the distance (m).

Presuming that the equation of state for an ideal gas is valid considering the state of vapour, the concentration of vapour is given as a function of pressure and temperature. After modification of Fick's law, the diffusion coefficient can be written as,

$$D_V = \left(\frac{m}{At} \right) \times \left(\frac{dRT}{M_w S (R_1 - R_2)} \right) \quad (2)$$

where m is the amount of water vapour diffused through the sample (kg), A is the sample area (m^2), d is the thickness of the sample (m), t is the period of time corresponding to the transport of water vapour (s), R is the Universal gas constant (8.3143 J/mol/K), T is the absolute temperature (K), M_w is the molar mass of water (0.018 kg/mol), $R_1 - R_2$ is the difference in relative humidity under and above the specimen surface, S is the saturation vapour pressure corresponding to the absolute temperature (kPa).

3 MATERIAL SELECTION AND METHODOLOGY

The study is carried out by using various sizes of sand grains obtained by sieving medium grade sand. The sand samples are air dried before performing the experiments. The grain sizes of sand considered for the study are 2-1 mm, 1 mm-600 μm and 600 μm -425 μm .

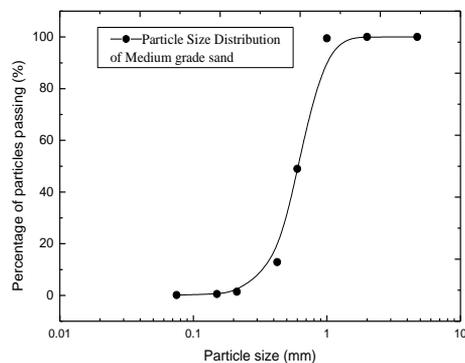


Fig .1 Grain size distribution of medium grade sand

Fig.1 shows the grain size distribution of the medium grade sand. The grain size distribution of the medium grade sand is conducted by dry sieve analysis according to the guidelines given by ASTM D422 (1994).

Specific gravity of the sand sample is found to be 2.65. For this purpose a helium gas pycnometer (Ultra Pycnometer, Quantachrome Instruments, USA) has been employed.

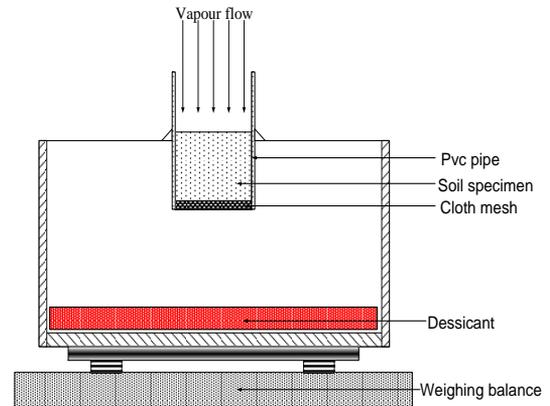


Fig .2 Experimental set up to study water vapour diffusion

Fig. 2 depicts the schematic view of water vapour diffusion apparatus. The sand sample is compacted to a desired density in a PVC pipe of diameter 36 mm and then attached to an air tight container. A non-sorbent cloth mesh screen is mounted at the bottom end of the PVC pipe to support the sand. The thickness of the soil specimen is 300 mm. The water vapour density inside the container is controlled by means of calcium chloride desiccant placed inside the container. The desiccant maintains the relative humidity value very close to zero inside the chamber. The relative humidity inside the humidity chamber is measured with the help of relative humidity sensors (Arduino DHT 22). The air and moisture tightness is ensured by sealing the container on all sides using silicon based polymer. The entire setup is then placed in a temperature and humidity controlled chamber and maintained the temperature of 25°C and a relative humidity of 70 percent.

Under isothermal conditions, the vapour movement occurs due to the presence of concentration gradient. The test is conducted by varying the relative humidity across the specimen keeping the temperature constant. The difference in vapour pressure between the top and bottom of the specimen causes the moisture flow through it from humidity chamber to the container resulting in the increase in weight of desiccant calcium chloride. The rate of moisture movement can be measured by weighing the change in weight of the

desiccant, periodically. The weights are recorded with the help of a high precision weighing balance having the precision of 1 μg . The test is terminated when a steady state flow of vapour is attained. Further, experiments are carried for different particle gradations over a range of dry unit weights. Fig.3 shows the gain in water vapour by the desiccant per unit area of sample per unit time for a soil specimen of 32 % porosity and passing through 2 mm and retaining on 1 mm (designated as P2 R1). Similar plots can be made for all samples. The slope of this graph yields the vapour flux. The value of vapour flux is substituted in the equation (2) to determine the water vapour diffusion coefficient. The saturation vapour pressure at 25°C is taken as 3.169 kPa (CRC Handbook of Chemistry and Physics, 2006).

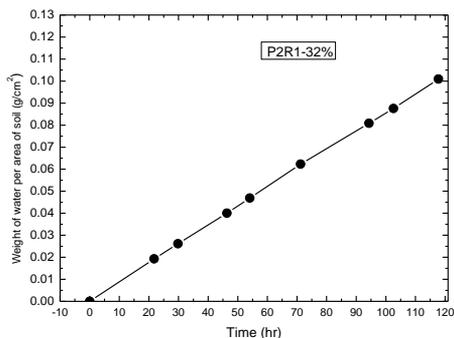


Fig. 3 Moisture flux of soil specimen P2R1

4 RESULTS AND DISCUSSIONS

Fig. 4 indicated the variation of diffusion coefficients with porosity for different gradations of soil. In the plot P2R1 and P1R600 represents the soil passing through 2 mm sieve and retaining on 1 mm and, passing through 1 mm sieve and retaining on 600 μm respectively. The porosity is varied over a wide range from 32 percent to 40 percent. It is evident that as the porosity increases the diffusion coefficient increases irrespective of the grain size. This is because of the fact that as the structure becomes more pervious, the space for the seamless movement of vapour increases. Furthermore as the particle size increases, the pore diameter eventually increases causing a higher diffusion coefficient with gradation.

The main limitation of this experiment is the longer test duration which can result in poor reliability and reproducibility. The experiment needs to continue several weeks and this can lead to problem such as inconsistent environmental conditions and material degradation. A slight change in relative humidity can substantially affect the vapour movement. An error in measuring the change in weight of the desiccant can also affect the accuracy of the method. This

methodology is not desirable for soils with expansive clay minerals in them such as bentonite. For such soils a separate methodology need to be developed.

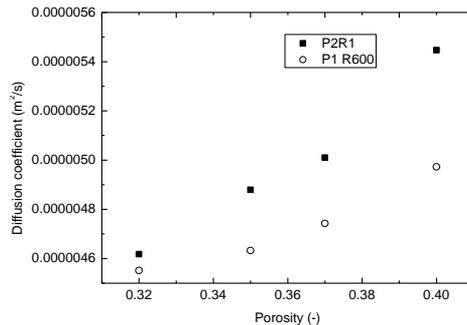


Fig. 4 Variation of water vapour diffusion coefficient with porosity

5 CONCLUSIONS

An experimental set up to carry out the water vapour diffusion studies under isothermal conditions has been developed. The study was carried out for different aggregates of sizes 2mm-1mm, 1mm-600 μm and 600 μm -425 μm . The diffusion coefficient of each soil sample has been calculated based on the experimental results and the variation of diffusion coefficients with respect to porosity has been established. From the experimental studies it is found that the water vapour diffusion coefficient is dependent on the porosity and the soil gradation.

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