

Gas transport through concrete slabs

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Abstract

The ability of mat slabs (foundations) to shield in-door air space from contaminants vapor or/and gaseous pollutants migration from the subsurface has been explored. An expert system that employs the Dusty Gas Model (DGM) has been developed to assess the steady state, isothermal, and isobaric gas transport through concrete mat foundations. The DGM combines different gas transport flux mechanisms, such as the molecular, Knudsen, non-equimolar and viscous fluxes. The gaseous system has been modeled as a ternary system composed of the pollutant gas mixed with natural air components of Oxygen (O₂) and Nitrogen (N₂). Results indicate that the contaminant vapor flux is strongly affected by the water content's cement ratio and the radius of pores. For water cement ratio less than 0.6, capillary pores are not connected and diffusion through the gel pores is dominant. For water cement ratio greater than 0.6, capillary pores are connected and occupy a major part of cement paste and control diffusion. The effect of increasing radius of pores on total fluxes has been found negligible when Knudsen diffusion becomes insignificant compared to molecular diffusion. Also, Fick's law of diffusion has been found inadequate to study gaseous flux for small pores in which the Knudsen diffusion is significant.

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1. Introduction

Transport of Contaminant gases from subsurface systems (soils and groundwater) into indoor air space received great attention [1–6]. These contaminants are either from natural origin, e.g. the migration of Radon gas from certain earth crust materials; or released to the environment via oil spill; applications of pesticides; leaky underground storage tanks; etc. In an oil spill, for example, petroleum products are usually introduced to the environment as non-aqueous phase liquids (NAPL) and whenever the amount of released NAPL exceeds the amount retained by soil it will migrate through the unsaturated zone and reach the groundwater table and may then be transported at the capillary fringe and/or within the saturated groundwater zone. Some NAPL may be volatile (also known as volatile organic

compounds (VOCs)) and thus may transport in the vapor phase and diffuse into the basements of neighboring buildings. If the concentration of these compounds exceeds certain limits in indoor space, it may become hazardous to human health.

The rate at which a given gas or vapor will diffuse into a given basement depends on many factors including: soil type and structure; moisture content; type, thickness, material, and conditions of building foundation or sub-grade slab. These factors will determine the controlling mechanism of gas transport. Many sub-grade slabs are made of reinforced concrete because it is economical, weather proof, abrasion resistant, and load resistant. However, due to its porosity and crackability, concrete is not a priori impervious to vapors, gases, and organic fluids.

Estimation of contaminant gases concentration levels into in-door air space requires the quantification of several gas transport flux mechanisms in concrete slabs. In general, gases transport in porous media via one or

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more of several flux mechanisms [7,8], namely: molecular diffusion, Knudsen diffusion, surface diffusion, and viscous flux. Molecular diffusion dominates in large pore space and is commonly modeled by Fick's first law of diffusion, which states that the net flux of a gas component is linearly dependent on its concentration gradient and an effective molecular diffusion coefficient that considers the effects of the tortuous path and the connectivity of porous media. Knudsen diffusion usually dominates in porous media with extremely small pore radii or when the pores are blocked with water thus leaving small space for gas diffusion. Surface diffusion is extremely important when trying to study transient behavior of a given gaseous system. It is usually ignored when dealing with steady state fluxes since it is assumed that the rate at which gas molecules leave the porous media is the same as the rate at which it adsorbs to it and thus does not affect the total flux transport in the pore space. Viscous flux is a nonsegregative flux that drives all the gaseous components due to an overall external pressure gradient. For isobaric conditions this flow mode is neglected. In natural systems, however, gas transport includes all of these mechanisms.

Although many studies investigated gas transport in porous media [1,2,7–17] only few investigated gas flow through concrete [3–5]. These studies usually assume that gas transport occurs mainly due to molecular diffusion and that the gaseous system can be modeled as a binary gas mixture of air and the contaminant gas. Thus, Fick's law of diffusion is assumed applicable [18]. However, the adequacy of Fick's law to model multi-component gas transport in porous media has been recently questioned [2,13] and the necessity to perform multicomponent gas transport analysis that considers modes of transport other than molecular diffusion has been emphasized. The Dusty Gas Model (DGM) has been suggested for modeling gaseous transport in porous media to tackle these limitations [7,8].

In this study, a theoretical investigation of the transport of gases through concrete subgrade slabs is conducted based on the Jackson's Equation of the DGM [7]. The gaseous system is treated as a ternary system composed of the gas to be studied (i.e., contaminant) mixed with the natural air components of Oxygen (O₂) and Nitrogen (N₂). Steady state, isothermal, and isobaric conditions are assumed and the molar fluxes of gases through cracked and uncracked concrete are estimated.

2. Gas transport through uncracked concrete

Gas transport through concrete depends on many factors, such as: the molecular weight and vapor pressure of the gas; the porosity; size and shape of pores, the thickness and conditions of the slab, and the

atmospheric pressure and temperature. The total molar flux of gases through concrete slab is evaluated herein based on the following form of the governing equations for ternary isobaric gaseous system [7]:

$$N_1^T = \frac{A_{12}A_{23}A_{31}}{X_1A_{23} + X_2A_{31} + X_3A_{12}} \times \left\{ \frac{\frac{A_1}{A_{23}} \left[\frac{X_2}{D_2^k} + \frac{X_3}{D_3^k} \right] - X_1 \left[\frac{A_2}{D_2^k A_{31}} + \frac{A_3}{D_3^k A_{12}} \right]}{\frac{X_1}{D_1^k} + \frac{X_2}{D_2^k} + \frac{X_3}{D_3^k}} \right\}, \quad (1)$$

where

$$\frac{1}{A_{is}} = \frac{1}{D_{is}^e} + \frac{1}{D_i^k D_s^k (X_1/D_1^k + X_2/D_2^k + X_3/D_3^k)} \quad (2)$$

$$A_i = \frac{\bar{P}}{RT} \nabla X_i, \quad (3)$$

where N_1^T is the molar flux of component 1, the pollutant, mol/m²s; i, s the 1, 2, 3 representing the pollutant gas, N₂, and O₂, respectively; X_i the mole fraction of component i ; D_i^k the Knudsen diffusion coefficient for component i , m²/s; D_{is}^e the effective binary diffusion coefficient for components i and s , m²/s; ∇_{xi} the gradient of mole fraction along slab thickness; R the ideal gas constant = 8.314×10^{-3} kPa m³/mol K; T the temperature, Kelvin (K); and P the pressure, kPa.

In order to apply this equation, it is assumed that: (1) steady state, isobaric and isothermal conditions prevail; (2) air consists of two component gaseous system (N₂ and O₂); (3) linear molar fraction variation for the diffusive gas through porous media; and (4) gas transport is limited to connected open-end pores that are assumed to be cylindrical in shape and of radius equals to the average pore radius.

The following subsections detail the estimation of molar fraction of species, the Knudsen and binary diffusion coefficients, and the molar flux calculations.

2.1. Molar fraction of species

Assuming a linear variation of the molar fraction through concrete, the molar fraction of the system is the average value at both sides of the slab. That is

$$X_i = (X_{Ai} + X_{Bi})/2, \quad (4)$$

where X_{Ai} and X_{Bi} are the molar fractions on both sides of the slab; side A is the indoor side of the structure; and side B is the external side of the slab.

Initially, the air indoor is assumed free from pollutants and the initial molar fraction of N₂ and O₂ are 78.00% and 22.00%, respectively. Accordingly, the number of moles of each component is calculated based on ideal gas law. For 1 m³ of air under 1 atm and 298.15 K, the number of moles of N₂ is $\{(0.78 \times 101.33)/[(8.31 \times 10^{-3})(298.15)] = 31.88$ mol/m³; number of moles of O₂ = $\{(0.22 \times 101.33)/[(8.31 \times 10^{-3})(298.15)] =$

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