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Mechanisms and Modelling of Moisture Transport in Concrete: A Review

By

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Abstract

Over the course of service, reinforced concrete (RC) elements are subjected to both mechanical as well as environmental loadings. While the guidelines to facilitate efficient design of RC elements to withstand mechanical loading are well developed, the provisions to ensure durable performance under the given exposure conditions are rather inadequate and are mostly prescriptive across various standards. This frequently causes RC components to prematurely lose their durability, especially for the unconventional instances of material, structural design, and service conditions. Therefore, it becomes essential to develop reliable design guidelines, accounting for all the pertinent influences, to ensure a robust performance of RC elements over the desired period of service. Though there are many agents and phenomena that retrench the service life of RC elements, the presence of moisture has been long identified as a prerequisite for most of the degradation processes to initiate. This paper presents a critical discussion on the various moisture transport mechanisms in concrete as well as the modelling approaches commonly implemented for their description under isothermal and non-isothermal conditions. The study also emphasizes the necessity of considering realistic exposure conditions for the simulation of moisture distribution in structural concrete to facilitate a reliable estimation of service life.

Keywords: RC elements, Durability design, Service life, Degradation, Moisture transport, Exposure condition

1. Introduction

Concrete is the most often utilised building material in the modern period. An ability of concrete to mould into different shapes while fresh, and to gain strength with age makes it one of the most versatile building material. According to a report by Cement Sustainability Initiative, the worldwide concrete consumption for the year 2006 was 30 billion tonnes [1]. Though recent and accurate data for concrete consumption in India is not available, the fact that it ranks second in the consumption of cement worldwide is strongly indicative of the massive rate of concrete being consumed in the country [2]. Owing to the sheer scale of its application in growing infrastructure, the need to minimize the recurring cost of maintenance during service need not be overemphasized. The necessity relates closely to the efficient structural design and durability of RC elements.

ISO 13823 describes durability as the "capability of a structure or any structural component to satisfy, with planned maintenance, the design performance requirements over a specified period of time under the influence of environmental actions, or as a result of self-ageing process" [3]. Earlier, the compressive strength of concrete was considered to be an indicator of its durability. However, it is now well established through experience and research that these traits are not directly related, and hence strength should not be used as a proxy for durability of concrete. While the prevailing standards provide for the efficient design of RC elements to resist mechanical loading, the guidelines available to ensure durability are rather inadequate, coarse, and largely prescriptive in nature. This inefficiency often leads to the premature durability failure of concrete elements and structures.

The durability problems in RC elements encompasses a wide range of phenomenon namely, alkali-aggregate reaction, freeze-thaw action, chloride attack, sulphate attack, reinforcement corrosion etc. and call for the necessity of design for durability [4]. There are three major

approaches towards achieving durability, namely, the prescriptive approach, the performance-based approach and the durability design. The prescriptive approach relies on acquired experiences on the durability of existing structures but do not rationally consider the degradation phenomenon. The performance-based approach, on the other hand, specifies durability requirements in terms of degradation specific performance indicators of concrete which can be corelated to service life. The approach, however, requires the availability of long term in situ observations which could be used to formulate such correlations. The rising paradigm of durability design addresses the shortcomings of the other two approaches by rationally modelling the degradation processes in concrete. It therefore provides a reliable way to evaluate the potential service life of structural concrete with due regard to its properties and exposure conditions specific to a site.

The evolution of almost every degradation phenomenon in concrete is known to depend on its state of saturation. Therefore, the modelling of moisture transport in concrete is fundamental to the durability design of RC elements. This paper discusses the different mechanisms of moisture movement in concrete and their phenomenological modelling approaches. Thecontrast between isothermal and non-isothermal moisture transport models has been comprehensively reviewed. The solution methodologies both analytical (through Laplace and Fourier transforms) and numerical (Finite Difference and Finite Element) methods have also been duly elaborated. The paper also describes the various ambient conditions that affect the state of saturation of exposed concrete, thereby requiring consideration in the realistic simulation of degradation and service life.

2. Moisture Transport Mechanisms in Concrete

Moisture movement in concrete manifests in liquid and vapor states through the mechanisms of diffusion, absorption and surface creep, acting simultaneously, being regulated by the geometric characteristics of pore spaces and their saturation states. The transport process is

generally driven by a pressure gradient induced as the net effect of external pressure heads, gravitational and hydraulic potentials, where the latter is a function of capillary and surface forces. The following sub sections describe the various transport mechanisms in concrete.

2.1 Diffusion

Diffusion is a mechanism by which moisture can pass through concrete under concentration gradient. This mechanism allows moisture to pass through unsaturated pores of concrete. Generally, diffusion is expressed in terms of flux F *(mol/m²/s)*, and given by Fick's first law asstated in Eq. 1:

$$F = D\frac{dC}{dx} \qquad (1)$$

Where C is concentration (mol/m^3), D is the diffusion coefficient (m^2/s) and x is the spatial distance (m).

Diffusion process is of three types: ordinary diffusion, Knudsen diffusion, and surface diffusion[5, 6]. Ordinary diffusion occurs in both low RH and high RH ranges and it is driven by concentration gradient. It is more profound in pore size range of 50 nm to 10μm which is the typical pore size range for capillary pores. On the other hand, Knudsen diffusion widely occursin gel pores and partially in capillary pores when the pore size is smaller than or equal to the mean free path of water molecules [7]. Surface diffusion primarily takes place when water molecules are adsorbed in pore walls of concrete under low RH conditions. Ordinary diffusionis faster compared to the other two types of diffusion and hence is taken as the representative for mass diffusion in concrete.

2.2 Sorption

When pores of concrete are unsaturated, they gain or lose moisture by sorption process. Sorptionis defined as the accumulation of moisture on the pore walls from surrounding moisture. The

mechanism is divided into three types: a) Exchange sorption, which takes place due to interaction of different charges between pore walls and water molecules, b) Physical sorption, which is due to van der Waal's attraction between moisture and pore walls and c) Chemical sorption, which is characterised by chemical bonding between adsorbate and adsorbent. Moisture movement by sorption plays a major role in low RH range (<45%). Several models like Freundlich model [8], Langmuir model [9], BET model [10] have been developed to fit sorption isotherms for vapour but they are applicable to only low RH range as in higher ranges

i.e., between 50% to 100% RH, sorption isotherms include sorption as well as capillarity.

Hence, capillary transport is also an important mechanism of moisture transport in concrete.

2.3 Capillary Absorption

Concrete moisture movement caused by a capillary pressure gradient is referred to as capillary transfer. According to Laplace's equation, the primary factors affecting capillary absorption are the liquid's surface tension, viscosity, density, angle of contact with the pore wall, and radius. Generally, a sorptivity test is carried out to measure capillary absorption in concrete and the relation is expressed as a square root law[11] .

$$A = C + St^{1/2} \qquad (2)$$

Where A is a term relating to the water intake, S is the sorptivity and t is the elapsed time.

2.4 Evaporation

Evaporation is the change of state of water from liquid to vapor and the associated transport ofvapour mechanism by which moisture leaves the concrete. Evaporation of water at building surfaces governs the flow of moisture through building surfaces. The difference in temperaturebetween the concrete surface and ambient air creates a convective heat flow towards the surfacethus leading to evaporation of moisture from concrete [12].

As it is evident from the description of the various moisture transport mechanisms that it is strongly associated to the pore structure of concrete. There are gel pores, capillary pores, hollow shell pores, and air voids in the wet cement matrix of concrete. Apart from the pore distribution of concrete, the microstructure properties such as geometry and shape of pores also play relevant role in moisture transport mechanism. Researchers have developed many complicated as well as simple models for representing the microstructure of concrete, for example, the Power's model [13] took a representative part of the material comprising of either two or three layers of C-S-H gel which roll to become fibres. Jennings proposed a model for microstructure of concrete where he considers C-S-H gel as roughly spherical units which flocculate to form larger units [14]. Pradhan et *al*. [15] have given relations to determine pore size distribution of normal strength concrete using mercury intrusion porosimetry (MIP) which can be used as an input to determine the hydraulic diffusivity and subsequently the moisture distribution in concrete. These models have significantly contributed towards understanding the microstructure of concrete and its effect on moisture transport mechanism. Most of the above-mentioned models though very rigorous in their formulation are generally under the assumption that the microstructure of concrete does not change with the flow of liquids and gases through them and they do not account for the change in pore size, geometry, distribution and tortuosity of concrete. Also, some of the models requires determination of characteristic pore parameters employing high end equipment [15]. These limitations triggered the necessity of modelling moisture transport in concrete following other approaches. The subsequent sections deal with various modelling techniques employed to obtain moisture profiles in concrete.

3. Modelling of Moisture Transport in Concrete

3.1 Isothermal Moisture Transport

Experimentally, moisture profiles in concrete is obtained using high end equipment like MIP

[15] Nuclear Magnetic Resonance (NMR) imaging [16], infrared spectroscopy, ultrasonic methods etc. All these equipments are very expensive and interpretation of their output also requires specialised skills. One simple way of determining moisture profile experimentally is by gravimetric measurements, but this method also is not free from human error. These few points of concern with experimental techniques paved way towards numerical modelling of moisture transport in concrete.

Numerical modelling of moisture transport in unsaturated porous media was based on saturatedflow in porous media. Early researches in this area, was by Buckingham [17] in 1907 who emphasized on the fact that concrete is not always in completely dry or saturated condition andextended Darcy's Law for saturated flow to the case of unsaturated conditions. Richard furtherimprovised on Buckingham's hypothesis by combining extended Darcy's law and mass balance principles thereby developing governing equations for unsaturated moisture transport in porous medium known as Richard's equation [18]. It was during this time that multiphase transport model for unsaturated porous media was also developed in work by Bear which was further used to simulate drying of cementitious materials [19].

While all these major theoretical developments took place during the earlier half of 1900, morerigorous modelling of moisture transport under drying-wetting cycles which is the most ideal condition for degradation of concrete was carried out in the last two decades. Early researchincluded simple models which considered same sorption curve for both wetting and drying. But researches by Maekawa et *al.* [20], Johannesson et *al.* [21] have proved that sorption hysteresis is a characteristic feature of moisture behaviour in concrete. This development led

to more complicated modelling taking into account sorption hysteresis in concrete which comprises of pioneering work by Espinosa et *al.*, [22] giving the ink-bottle pore method, and other work by Ranaivomannan et *al.* [23]. Some researchers also modelled the hysteresis phenomenon in concrete by modifying models from soil sciences. The limitations of these models lie in the fact that they require the estimation of parameters which has to be obtained by fitting from experimental data and determination of many other parameters that accentuate the chances of error in the numerical result.

Although there are few models available for modelling isothermal moisture transport in concrete, the basic Richard's equation as stated in Eq. 2 continues to be one of the most used model.

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left(D(\theta)\frac{\partial\theta}{\partial x}\right) \quad (2)$$

Where, θ is the volumetric moisture content (m3/m3), t is time (s), x is the spatial distance (m),

(θ) is the moisture dependent hydraulic diffusivity (m2/s).

This is because of the simplicity of the equation as it does not involve many parameters. The Richard's equation contains just one parameter which is the hydraulic diffusivity which is different for wetting and drying (generally exponential in case of wetting and power function in case of drying) and takes into account the hysteresis. The hydraulic diffusivity functions for wetting and drying are given in Eqs. 3 & 4, respectively.

$$D_r(\theta_r) = D_{dry\_wet}e^{n\theta} \quad (3)$$

$$D_r(\theta_r) = D_{w\_dry}\left[\alpha_0 + \frac{1-\alpha_0}{1+\left(\frac{1-\theta_r}{1-\theta_c}\right)^{n*}}\right] \quad (4)$$

$$\theta_r = \frac{\theta-\theta_0}{\theta_s-\theta_0} \quad (6)$$

Where *Dr(θr)* is the hydraulic diffusivity in terms of non-dimensional moisture content *θr(m²/s)*,*θs* is the saturation moisture content *(m3/m3)*, *θ0* is the moisture content at capillary dry state, and *Dd_wet* is the wetting diffusivity in capillary dry state *(m²/s)*. The value of n ranges from 6-8 for building materials and typically has a value of 6 for dry concrete (Hall). *Dw_dry* is the drying diffusivity in completely wet state *(m²/s) α0* is the ratio of minimum to maximum diffusivity and the parameters *n** and *θc* characterize the spread and location of drop of curve respectively.

The solution of this equation can be developed by analytical approaches [24], Finite DifferenceMethod (FDM) and Finite Element Method (FEM) [12][25]. Summary of few of the research work is presented in Table 1.

Table 1. *Studies for isothermal moisture transport in concrete*

References	Approach	Assumptions/ Limitation
Terheiden [26]	Gravimetric approach: Conducted mass measurement on slices of concrete samples to determine moisture distribution	• 1D moisture transport • Isothermal condition
Cunningham [27]	Fourier Transforms were used to provide steady analytical solutions with periodic boundary conditions for temperature and moisture, where moisture flow was dictated by temperature and moisture gradients.	• 1D moisture transport
Taher et *al.* [28]	Application of an implicit numerical scheme and Kirchhoff's transformation to obtain the moisture distribution profile Profiles were simulated for two cases. First case was assuming same diffusivity for wetting and drying and second case used different diffusivity functionsfor wetting and drying	• 1D moisture transport • Homogenous material • Initial saturation is constant
Simo et *al.* [29]	4th and 5th order Runge Kutta method was employed using DOPRI5 integrator (Fortran code)	• 1D moisture transport
Li et *al.* [30]	Solved Richard's equation using finite difference method. Implicit predictor-corrector scheme appliedto obtain numerical solution for Richard's equation.	• 1D moisture transport • Isothermal condition

3.2 Non-Isothermal Moisture Transport

Moisture and heat transport is considered as a coupled phenomenon that take place simultaneously in concrete. The correct examination of these two phenomena is important to accurately predict moisture flow in concrete for durability design of concrete. Apart from determination of durability of concrete, the study of this coupled phenomena also leads to evaluation of thermal performance of RC structures, building energy conservation system and design of Heating, ventilation and air conditioning (HVAC) system. Moisture transport is influenced by both moisture and temperature gradients since the majority of RC structures experience both moisture and temperature changes at the same time [31]. Both the effect of temperature gradient on moisture transfer and the effect of moisture gradient on heat transfer are caused when moisture and temperature gradient are present at the same time. The "Soret effect" [31] is the term used to describe how a temperature differential affects moisture transport. Around 1950, Philip et al. [32] made extensive theoretical advancements on coupled heat and moisture transport in concrete. Since the 1960s, there has been significant advancement in this field thanks to models created by Luikov [33] and Whitaker [34], which simultaneously accounted for evaporation and condensation as well as many other factors like heat conduction, the capillary effect, liquid and molecular diffusion, and many others. The two models that are currently most frequently employed in the research on non-isothermal moisture transport in porous media are Luikov's and Philip's. Recently Qin et al. [35] have also proposed a model for non-isothermal moisture transport along with an experimental procedure for the determination of moisture diffusivity and thermal gradient coefficient. These basic theoretical models have formed strong base for the study of non-isothermal moisture transport. Researchers have generally simulated non- isothermal moisture transport in building materials by solving these governing differential equations using different approaches and by making simple modifications to these models.

Similar to isothermal modelling, there are three main approaches employed towards modellingof non-isothermal moisture transport in concrete. The governing coupled differential equationsare either solved analytically, mainly by application of Laplace transforms and Fouriertransforms, or by other numerical methods like finite difference method or finite element method. Experimental determination of non-isothermal moisture transport is still rare becauseit is very difficult to determine experimentally the double dependency of moisture transport ontemperature as well as moisture gradient at the same time. However, there are few researcherswho have attempted to study this phenomenon experimentally [36], while others have resortedmostly to analytical and numerical techniques. Table 2 summarizes the work carried out by few research along with the approaches the adopted along with the assumptions and limitations of their approaches and solutions.

Table 2. *Studies on non-isothermal moisture transport*

Reference	**Approach**	**Assumption/ Limitations**
Pandey et *al.* [37]	Eigen value analysis approach to solve simultaneous heat and moisture transfer. A new method was employed which was a combination of bisection and Newton-Raphson method	Constant transport coefficients Governing PDE's considered as linear Complex roots in the solution were neglected leading toinaccuracy of resultsobtained
Fudym et. *al.* [38]	Thermal quadrupole formalism method was used to solve the Luikov's equation	
Tripathiet *al.* [38]	Hankel transform was used for space variable and Laplace transform was used for time variable todetermine mass and heat transfer distribution	
Isgor et *al.* [39]	Finite element method was used to solve moisture transport coupled with carbon dioxide transport andheat transport Realistic environmental conditions were considered for heat transport	Two-dimensional moisture transportwas considered. System consideredas non-linear

It is evident from the points mentioned in Table 2, that most of the analytical solution considers the moisture and heat transport phenomena as a linear problem. However, it is investigated andconclude by many researchers [Prata and Fudym] that considering linear models is suitable only when temperature gradients are low, and when moisture contents are either below or abovethe critical moisture content, i.e., when liquid phase becomes continuous. But practically the liquid phase is never continuous in concrete microstructure due to discontinuity of pore

distribution. This forms a major limitation in such studies. Finite element studies by Isgor et *al.* [39] though takes into account atmospheric elements like radiation to simulate the heat transfer but it does not consider rainfall or any such factor as boundary condition in the moisturetransport simulation. Although, there has been extensive study in the field of non-isothermal moisture transport, the need for a non-isothermal moisture transport under realistic environmental condition is still debatable. According to a recent study by Wang et al. [], increasing temperature in the isothermal situation (where there is no temperature gradient) has no impact on moisture transport in concrete. However, the introduction of a thermal gradient has a major impact on moisture transport, and the significance grows as the temperature gradient's steepness does as well. This study was carried under standard lab conditions by embedment of sensors within the specimen and did not incorporate realistic environmental conditions. Therefore, such conclusions in cases when concrete is exposed to realistic exposure condition is still a grey area and need more research.

Summary and Conclusion

As summarized in the above section that most of the studies are focussed on application of numerical techniques for simulation of moisture transport in concrete. Boundary conditions and initial conditions are an integral part of any numerical solution scheme. The reliability of the numerical solution strongly depends on the boundary conditions implemented. In most of the experimental studies, the concrete samples were extensively subjected to uniaxial wetting or drying under constant temperature and RH condition. But in practical situations, concrete structures are rather subjected to the environment which rarely has a constant RH or temperature conditions. Though studies in this direction are very few. A study by Andrade et *al*. studies the variation of temperature on concrete samples exposed to natural rainfall [40]. More recent study by Ryu et *al.* have studied evolution of moisture distribution in concrete

samples subjected to artificially simulated rain [41]. It is very important to incorporate significant meteorological components for the study of coupled heat and moisture transport in concrete. With rigorous exploration of literature, this study perceives solar radiation, rainfall, wind and temperature as the most relevant parameters towards exposure condition design. The need of the hour is to use all these factors in conjunction for rational modelling of moisture transport in concrete.

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