Durability and Exposure Conditions of Cementitious Materials

Deterioration Mechanisms

By Jonathan E. Dongell

There is a substantial amount of literature to be found regarding specific types of deterioration of concrete or shotcrete placed in various exposure conditions. This paper presents an introduction and methodical view of mass transport and its role in various exposure conditions given the presence of sufficient moisture. A simplified lineal-progression chart showing the various mass transport-induced deterioration mechanisms that facilitate deterioration is introduced. The overall objective of this article is to offer a simplified interpretation of the difficult concepts of mass transport and deterioration mechanisms.

Material-Related Contributing Factors

For a cementitious material placed in an exposure condition that is considered to be aggressive, there is a direct correlation between the susceptibility of that material and the rate of deterioration. Therefore, while this article deals only with mass transport and mechanisms of deterioration, it must be stated that mixture designs that minimize permeability and construction practices that provide uniformity in density and consolidation and mitigate cracking and other defects are key factors in producing a durable cementitious material. Additionally, the use of durability enhancers (pozzolanic or polymeric) within the mixture design, or the implementation of appropriate post-placement protective measures, help to ensure that the structure remains sound and achieves its anticipated service life.

Physical-Induced Deterioration versus Mass Transport-Induced Deterioration

Typically, the deterioration of a cementitious structure is the result of a multi-mechanism phenomenon. Freezing-and-thawing deterioration, for example, is often thought of as strictly deterioration by expansion and contraction of the material due to temperature gradient; however, accelerated damage can occur due to mass transport mechanisms and accompanied deleterious reactions. Mass transport allows moisture, salt, or other deleterious ions to move into, out of, and within the matrix of the cementitious structure. Salts can precipitate out of solution or crystallize, filling voids, cracks, and space around aggregate created by expansion and contraction. This filling of matrix space creates restriction, which increases internal stress upon further expansion and contraction. Associated stress-induced cracking accelerates the rate of deterioration of the structure. Mass transport may also provide the means by which deleterious ions enter the matrix, or facilitate the localized buildup of certain ions, which in turn may initiate secondary deleterious reactions.

Mass Transport

In general, the term "mass transport" as it relates to concrete is used to describe the overall mechanism by which matter is moved into, out of, within, or through the cementitious matrix. While mass transport mechanisms can proceed wherever water or sufficient moisture is present, whether or not matter is present in solution to transport, it is nevertheless the presence of deleterious material (salts or ions) or the existence of some chemical gradient between the water and cementitious material that is of concern. Therefore, mass transport is typically thought of as a combination of both water or moisture and material in solution. Mass transport can be divided into two main transport mechanisms of "convection" or "wicking" (refer to Fig. 1).

Convection

Convection is the transport of a material in solution by **diffusion** and **advection**. Diffusion is a transport mechanism resulting in the random spreading or mixing of material in solution. Advection is a transport mechanism caused by a directional bulk motion of fluid (water or moisture) resulting in the directional transport of material in solution. For example: if dye were poured into a river, advection would be the force (in this instance hydraulic force) carrying the dye downstream via bulk motion, and the spreading of the dye plume outward in an ever-

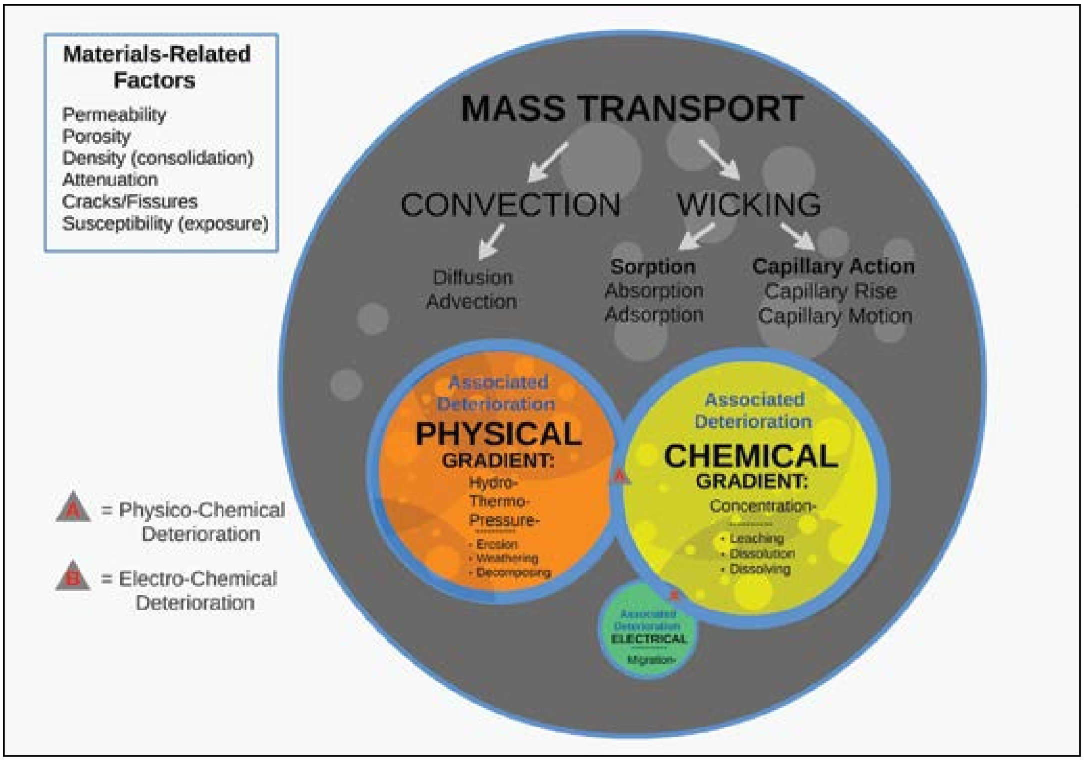

Fig. 1: Deterioration mechanism of a water contact environment

growing random fashion would be diffusion. In Fig. 2, an 8 in. (200 mm) pre-saturated concrete cylinder is placed in a bucket with 9 in. (230 mm) of standing water. The resulting convection transport mechanism is due to concentration gradient of (x) ions. Subsequent random spreading of the (x) ions is diffusion due to a chemical concentration gradient.

Wicking

Wicking is the movement of water or moisture and the transport of the material in solution by **sorption** and **capillary action**. Sorption is the transport of water, moisture, and material in solution by the combination of absorption and adsorption (refer to Fig. 2). Absorption is the permeation of water or moisture and material in solution into a dry or under-saturated cementitious matrix. This process can also be reversed, from a wet cementitious material to a dry or under-saturated soil. Adsorption is the physical adhesion of atoms, ions, or molecules to the compounds and solid surfaces within the cementitious matrix.

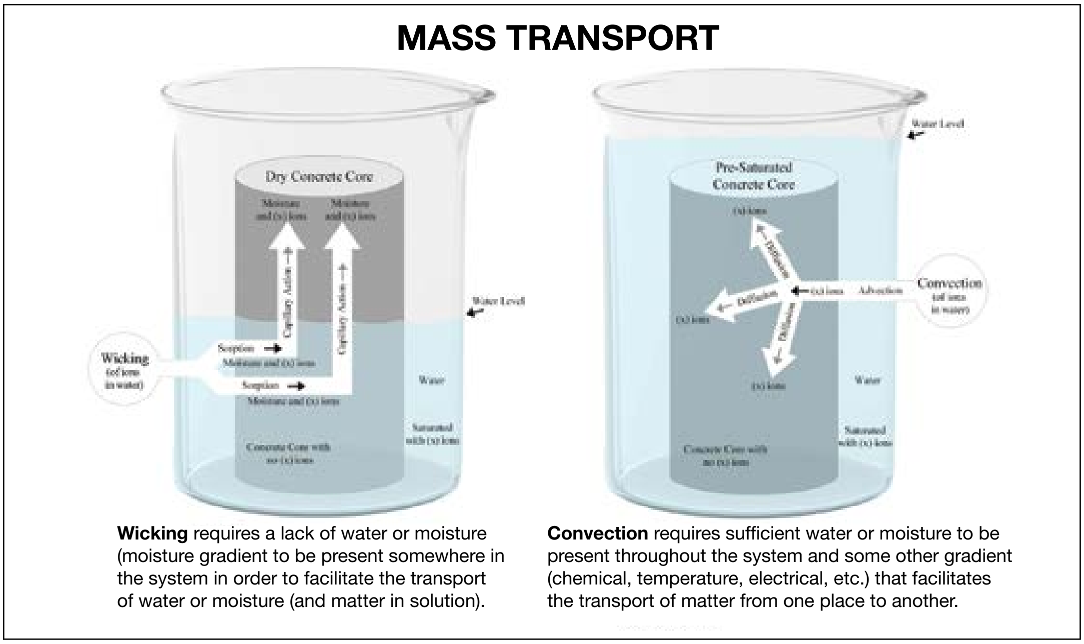

Fig. 2: Deterioration—transport mechanisms

Capillary action is the transport of water or moisture and material in solution by the forces of capillary motion and capillary rise. In general, this is the ability of water or moisture and material in solution to transport through narrow passages without the assistance of gravity or bulk motion. In Fig. 2, an 8 in. (200 mm) dry concrete cylinder is placed in a bucket with 4 in. (100 mm) of standing water; the water is wicked into the cementitious matrix. This is mainly due to sorptivity. The water or moisture and material in solution, however, continue to slowly climb upward against gravity; this upward permeation is mainly due to capillary action.

Combined Mechanisms

Not all attacks on concrete or shotcrete include mass transport as a contributing factor. While physical gradients, chemical gradients, electrical gradients, and combinations of these were placed within the overall sphere of mass transport deterioration mechanisms (refer to Fig. 1), this may not always be technically correct. For example, freezing and thawing could be considered solely a physical deterioration, and a sphere could be added to the diagram that is outside of (but still linked with) the mass transport sphere. However, for cementitious materials exposed to water or moisture contact, mass transport mechanisms often initiate, facilitate, and govern the rate at which deterioration proceeds. In other words, if there was no water or moisture present, there would be no mass transport mechanism, and there would be no deterioration.

Physicochemical

Deterioration caused by the physical action of erosion, weathering, or decomposition does not require a mass transport mechanism to proceed. However, a cementitious material placed in a water-contact environment or exposed to cycles of wetting and drying can experience a physicochemical attack. The combination of physical attack (abrasion, weathering, and so on) and chemical attack (leaching, dissolution, dissolving, or formation of concentrated areas of salts or alkalis) is facilitated by mass transport mechanisms. With salt weathering, for example, there is mass transport of salts into a cementitious matrix, but the attack may be considered strictly a physical attack as it results from the precipitation of salts within the matrix without necessarily the dissolution of the cementitious components to drive the degradation. In either instance, a mass transport mechanism facilitates the attack. The attack is considered a "physical salt attack" form of deterioration, made possible by a physicochemical transport mechanism.

Electrochemical

Electrochemical transport is a migration of electrons or ions through solution. This mechanism plays an important role in maintaining (protecting) or breaking down (destroying) the passivity layer on and around all embedded steel reinforcement. Except for the electrochemical migration associated with steel reinforcement, electrochemical gradients within cementitious materials typically cause migration of material in solution on the scale of millimeters.

Other Terms and Definitions

- Decompose—break down into components, or to separate into constituents or elements
- Deteriorate—to decompose, decay, breakdown, or crumble
- Dissolution—to extract chemically or preferentially remove material into a solution
- Dissolve—to disintegrate a material chemically into a solution, or to break apart
- Etch—to physically or chemically carve or engrave into the surface of a material
- Leach—the loss of mineral and organic solutes due to percolation from a material
- Migration—a motion of material in solution, distinct from diffusion, due to an electrical-applied force or electrical gradient

Jonathan E. Dongell *is current Director of Research & Development, Pebble Technologies, Scottsdale, AZ. Dongell has worked in concrete construction and with cementitious materials spanning over 30 years. His roles have included technician, superintendent, manager, contractor, and President. He was Past President, Whitestone Cement Company, Scottsdale, AZ (1998-2005) and Universal White Cement Co, Inc., Glendale, AZ (1992-1998). He is a member and past Chair of ACI Committee 524, Plastering, and is a member of ACI Committees 201, Durability of Concrete; 225, Hydraulic Cements; 232, Fly Ash in Concrete; 308, Curing Concrete; 350, Environmental Engineering Concrete Structures; and 555, Concrete with Recycled Materials. Dongell also serves on the ACI Concrete Research Council (CRC) and the ASA Pool & Recreational Shotcrete Committee. He is a voting member of ASTM International main committees and several subcommittees, including C4.01, Cement, Lime, Gypsum, and C4.02, Concrete and Aggregates. Dongell is the author of several books, including* The Durability of Cementitious Materials in a Water Contact Environment. *He is an inventor and holds three patents on cementitious materials. Dongell is a designated expert witness in the fields of cement, concrete, stucco/plaster, and water chemistry. He was the recipient of the Del Bloem Distinguished Service Award in 2008.*