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Water Permeability vs Waterproof

by Patrick F. McGrath, Ph.D.

Xypex Chemical Corporation, Richmond, B.C., Canada

The paper presents a general overview of the reasons for reducing the permeability of concrete structures. The various mechanisms by which water, and aggressive ions move into or through concrete are reviewed. Basic categories of barrier systems are defined and expanded.

1.0 INTRODUCTION

There is a great deal of misunderstanding of the terms water permeability and waterproof. Water permeability is a most commonly thought of when discussing "high performance concrete". Waterproof is a term often used when describing the ability of a structure to hold in or hold out water. Both strength and durability are closely linked to low permeability. However, the problem of creating durable structures fit for their designed purpose requires a broader understanding of what exactly is meant by low permeability concrete and waterproof concrete.

1.1 Classification of Systems

The basic categories outlined in ACI 515.1R-79 "A Guide to the Use of Waterproofing, Dampproofing, Protective and Decorative Barrier Systems for Concrete" [ref 1] are useful to organise the thinking process. These categories are as follows along with the definitions provided in the guide:

a) <u>Waterproofing Barrier Systems:</u> Prevent the passage of water under hydrostatic pressure.

b) <u>Dampproofing Barrier Systems:</u> Resist the passage of water in the absence of hydrostatic pressure.

c) <u>Protective Barrier Systems:</u> Protect concrete from degradation by chemicals and subsequent loss of structural integrity, or prevent staining of concrete, or protect liquids from being contaminated by concrete.

d) <u>Decorative Barrier Systems:</u> Stabilise or change the appearance or colour of a concrete surface for aesthetic reasons.

These categories can be used to form a basis on which to conceptualise the application to which a design must fit.

The ACI guide is careful in selecting the term "barrier system", apparently, to include many varied forms of systems including roofing products, coatings, sealers, liners, etc. The word system was likely chosen since the overall performance may come from a system of different components. The standard does not preclude the an admixture to obtain the required performance.

It is likely there will be substantial overlap within these categories. For instance a permeability reducing admixture may both waterproof a structure (prevent leakage) and enhance durability by limiting water and other chemicals to ingress.

1.2 Size Scales to Remember

It seems common for people to confuse size scales with respect to movement of water and other elements through concrete. In order to better define and delineate this movement let us review the size scales through which movement occurs.

- *Capillary Pore Scale:* At the smallest scale water may move into concrete through interconnected capillary porosity. Capillary pores are essentially a residue of the originally water filled spaces in the fresh concrete. This scale is important with respect to durability (protection) of concrete as it is the path by which water and other aggressive ions penetrate into the concrete matrix, resulting in such durability problems as reinforcing steel corrosion.

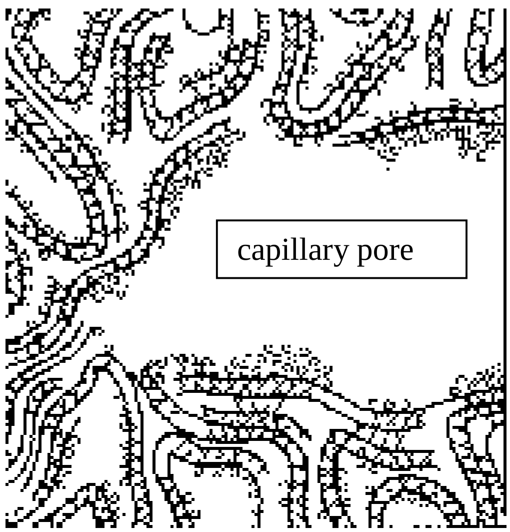

Figure 1: Capillary Pore in hydrated cement paste (from Ref 7 based on Ref 8)

- *Micro-crack and Transition Zone Scale*: Somewhat larger but of similar magnitude to capillary pores are micro-cracks and transition zones. Micro-cracks may be formed due to internal thermal and shrinkage forces or stress due to external loads. The transition zone is a weak permeable layer that occurs around aggregate particles. This scale is also of importance with respect to movement of water and other aggressive chemicals within the concrete matrix and thus is important from a durability standpoint as well.

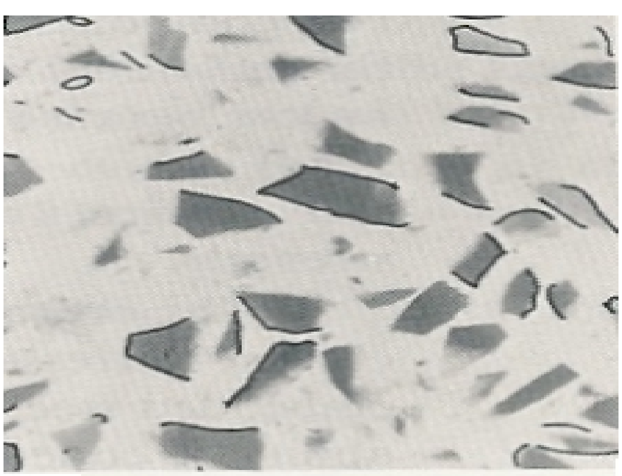

Figure 2: Microcracks around aggregate particles after 60 days of sustained load at 65% of the 28 d compressive strength (Ref 9)

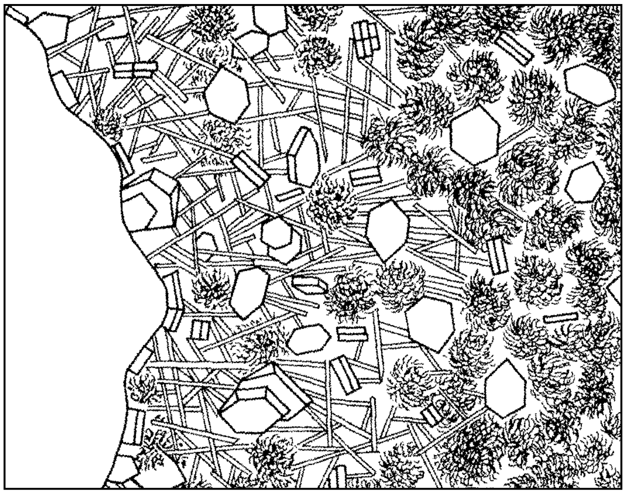

Figure 3: Illustration of the transition zone (Ref 7)

- *Macro Scale:* On the largest scale water or chemicals may move through cracks, rock pockets, construction joints and other large defects or joints in the concrete structure. This scale of flow is of primary importance with respect to "waterproofing" and involves keeping water out or in.

The approximate sizes of each of these features is shown in Figure 4. It can be seen the the variation of the size scales is tremendous. The point to be understood is that with such a great variation in sizes a waterproofing or permeability reducing treatment may not be appropriate for all size scales. For instance silica fume greatly reduces the connectivity of the capillary porosity and also reduces transition zone thickness but, if not used with care, may increase micro and macro cracking.

A combination of treatments may be necessary however, an ideal water permeability reducing admixture would be able to reduce water flow and water ingress over the full range of porosity and defect sizes. Furthermore it would need to either self-heal or span cracks that form after the time of construction.

2.0 MECHANISM OF TRANSPORT

One of the primary roles of all systems (even decorative coatings) is the control of the movement of water and aggressive chemicals, whether this is by keeping water in, out, off, or even letting it through. A review is, therefore, in order of the scientific terms used to define these movements.

Foremost is an understanding of the difference between porosity and permeability. Porosity is the amount of holes and permeability is how well the holes are connected. More specifically, the porosity is the volume of voids expressed as a percentage of the total volume of a material.

2.1 Water Flow and Water Permeability

Permeability is a broader term than porosity. The ability of liquid water, under pressure, to flow through porous materials is permeability and is described by the permeability coefficient. This coefficient is commonly referred to as the D'Arcy's coefficient. The equation used to calculate the D'Arcy's coefficient is as follows:

$$Q = \frac{K \cdot A \cdot \Delta h}{l}$$

where: K = water permeability or D'Arcy's coefficient (m/s)
Q = flow rate through the sample (m^3/s)
A = cross section area of sample (m^2)
Δh = water pressure differential across the samples (m)
l = sample length (m)

This equation applies (more or less) for the case where the concrete is saturated (all the pores are filled with water) and there is liquid water on both the up-steam and down-stream side.

Water permeability of the concrete matrix is a useful indicator of the quality of the concrete for durability reasons. The lower the D'Arcy's coefficient, the higher the quality of the material. A concrete with a low water permeability may be relatively durable but may still require a waterproofer, e.g., to prevent leakage through cracks.

2.2 Vapour Flow and Relative Humidity

Unfortunately, concrete is rarely saturated and a more complex description of the state of water and water flow is required. Relative humidity is a term used to describe the amount of water contained in air. This water is held in air as a dissolved gas. Relative humidity is really a term that defines the concentration of water in air. At 0% rh there is no water in the air and at 100% rh the air can take up no more water and condensation will occur.

However, as air heats up, it can hold more water. Therefore a relative humidity measurement must be accompanied by a temperature. A more convenient term is "vapour pressure". This is the pressure exerted by the molecules of water vapour and is proportional to the amount of water in the air. In simplified terms, it is the concentration of water molecules in the air. A good description of the processes can be found in reference 2.

A considerable amount of water can be transported through concrete in the vapour or gaseous state. The direction of flow will be from high vapour pressure to low vapour pressure by the process of diffusion. Diffusion is simply described as flow of species (gas, dissolved ions etc) from a location of high concentration to low concentration (or more precisely from high chemical potential to low chemical potential).

It is important to note that water vapour does not necessarily move from high relative humidity to low relative humidity as illustrated by the following example of the typical exterior concrete building wall (Figure 5) Vapour flows from the higher vapour pressure to the lower.

The actual flow of moisture in an exterior concrete building wall is much more complex owing to the effect of wetting and drying and heating and cooling cycles. These produce flow direction reversals. For instance rain on the outside surface would immediately raise the external vapour pressure to saturation and flow may move from vapour to liquid transport or some combination thereof. Partially saturated flow is described in more detail in the next section.

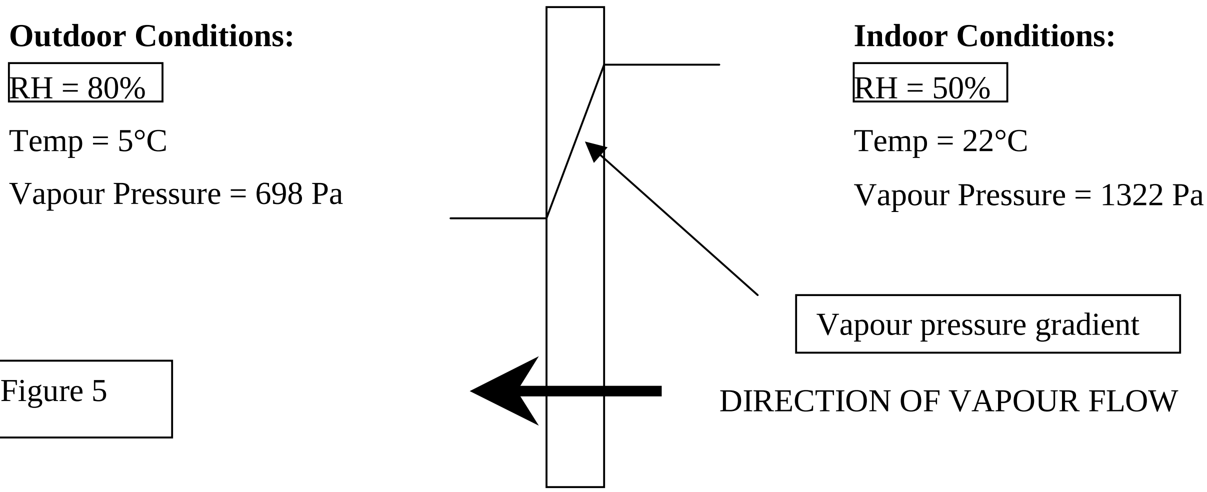

Figure 5

Understanding vapour flow is essential when applying waterproofing treatment where an unbalanced vapour pressure gradient exists. Some examples of this are as follows:

- applying a low vapour permeable membrane such as a traffic deck coating over a damp concrete surface (even if the very top surface is dry) on a warm day will result in pressure vapour pressure build-up and pin-holing or blistering,
- applying a coating or sealant to the outside of a building wall may trap moisture into the wall if the sealant is not sufficiently vapour permeable,
- applying low vapour permeable flooring over a slab-on-grade which has a high subsurface moisture content may result in delamination of the flooring.

As a general rule of thumb a low vapour permeable sealant or coating should not be placed on the downstream face. Either the vapour pressure or water pressure will act to damage and blister the membrane. Some types of coatings and water permeability reducing admixtures will allow considerable vapour movement thus allowing them to be placed successfully on the downstream side. Chief among these are cement based waterproof coatings and water permeability reducing admixtures.

2.3 Sorptivity or Unsaturated Water Flow

As the concrete starts to dry, the water retreats into smaller and smaller capillary pores. Attractive forces between the water surface and the surface of the solid occur and the water film becomes curved. As a result the water in the pores goes into a state of negative pressure or suction. This is commonly referred to a capillary suction and is one reason why materials suck up water when dry.

The most common means of modelling the unsaturated flow through porous materials is to adapt the simple D'Arcy's equation. Both the D'Arcy's coefficient and the pressure gradient are a function of moisture content. A mathematical substitution leaves the equation looking much like a diffusion equation (although the flow is not a true diffusion process) and a "capillary diffusivity" or "hydraulic diffusivity" coefficient is thereby defined. This type of analysis is commonly used in oil field hydraulics and environmental engineering. However, in concrete the pore size is much smaller than in soils and several parameters are very difficult to measure.

The capillary diffusivity can be measured by monitoring the movement of the wetting front [ref 3] but is not simple to carry out. A simplified means to describe the water absorption of concrete utilises the fact that the amount of water absorbed per unit surface area, (i) increases as the square root of time (t) [ref 4]:

$$i = S \cdot t^{1/2}$$

The term S or sorptivity coefficient is easily measured in a simple lab test and gives a good indication of the quality of the concrete cover and its ability to absorb water.

2.4 Combined Liquid and Vapour Flow

If the concrete is only partially saturated then both liquid filled and empty pores exist. Two types of flow can occur: vapour flow through the empty pores and liquid flow through the partially filled pores [ref 5]. In fact this is a very common situation that occurs, for instance, in a basement wall which has liquid water on the outside and dry basement air on the inside (Figure 6). Near the outside of the wall the water flow may be nearly saturated and flow occurs almost entirely in the liquid phase. Evaporation occurs within the wall and near the basement wall surface nearly all the flow will be occurring by vapour diffusion.

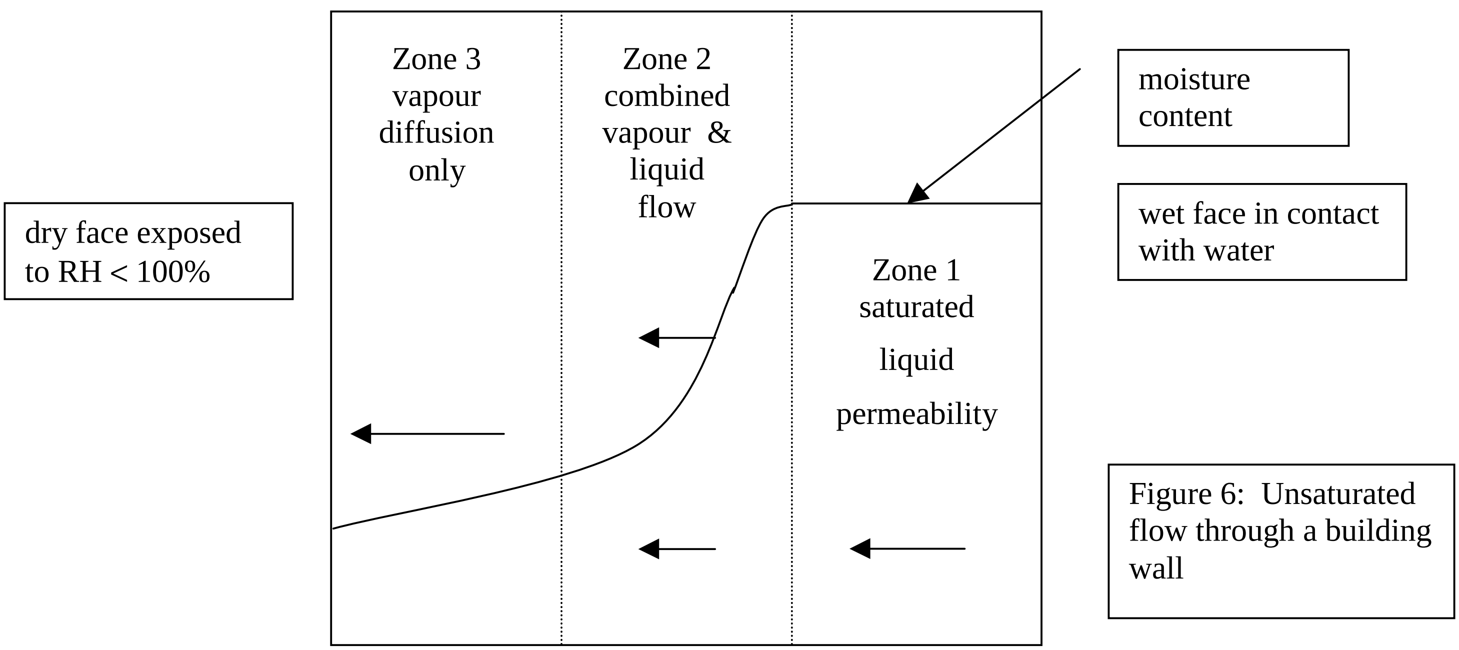

Figure 6: Unsaturated flow through a building wall

In the above example, the wall is "dry" on the downstream face and "wet" on the upstream face. There will be no wet spots on the downstream face and the wall by most definitions will be considered "waterproof". If the wetting front (sharp break in the curve) is pushed to the dry face of the wall a wet spot will occur. There are three basic parameters that control if the wetting front will pass all the way through the wall:

- the amount of water pressure on the upstream face
- the quality of the concrete as expressed by the permeability of vapour diffusivity,
- and the vapour pressure (or relative humidity) at the downstream side.

The combined liquid and vapour transport is much more common than would be expected. Wetting and drying of normal concrete, although bi-directional operates in this manner. An example where this scenario is important is the basement wall efflorescence problem In a basement wall, or other similar situation, dissolved salts from the soil migrate along with the liquid water phase. These salts normally precipitate within the thickness of the wall. However, if the wetting front approaches the downstream face, then efflorescence will build up on the surface.

2.5 Diffusion of Chlorides and other Aggressive Chemicals

The ingress of aggressive ions dissolved in water is one of the most important concepts to understand with respect to the durability. Dissolved ions move into concrete by diffusion or are dragged in by D'Arcian flow. In diffusion, a high concentration of ions will move to areas of low concentration much like how smoke or perfume will move to fill a room. At a further distance the concentration becomes less and less. This is the case for the diffusion of chloride into concrete, which is largely responsible for reinforcing steel corrosion. The basis diffusion equation is as follows:

$$J = -D\frac{dC}{dx}$$

where: D = diffusion coefficient (m^2/s)
J = flux (ion flow rate) into the material (mol/m^2s)
C = concentration of ions (mol/m^3)
x = distance in the direction of flow (m)

The equation is an oversimplification. Useful related parameters can be obtained by laboratory testing [ref 6] and can be used in concrete specifications. The important things to note about the diffusion coefficient are:

- D is a property of the concrete quality; higher quality concrete will have lower D values,
- concentration reduces at greater distance into the concrete,
- higher surface concentration will result in higher flow rates.

Diffusion of gasses may also occur. It has already been mentioned that water vapour moves by diffusion. Other gasses too may be of concern, for example, atmospheric carbon dioxide that can cause carbonation damage. In some regions, radon or methane gas may be present in soil and may diffuse into occupied space causing health hazards.

Diffusion is not the only means by which dissolved ions such as chloride can move into concrete. Salts may be dragged along with water during liquid flow. This occurs when water flows through cracks or during wetting (sorption) of concrete. Salts are also dragged along with liquid flow in the case of the basement wall efflorescence example.

The understanding of diffusion is important to concrete for the following reasons:

- Diffusion of aggressive chemicals, particularly chloride ion, is the leading cause of failure of concrete structures world-wide. The application of a coating (and to a lesser extent a sealer) greatly reduces diffusion and is a primary defence against durability problems.
- Vapour moves by diffusion as mentioned above. Even seemingly dry concrete may have significant vapour flow by diffusion.
- The diffusion coefficient is a fundamental property of concrete and an approximate measurement can be easily obtained in the laboratory; this may be used to assist in the decision as to whether a durability enhancing treatment is required or if the concrete can be left bare.

3.0 THE IDEAL WATER PERMEABILITY REDUCING ADMIXTURE

The ideal waterproofing material would have the following properties:

- create waterproof concrete without the need for addition membranes or perhaps supplemented with additional protection is certain instances,
- result in a concrete that is durable to environmental degradation, primarily through reduction in permeability, diffusivity and sorptivity on the various size scales mentioned but perhaps also providing supplemental chemical protection,
- result in no major side effects to the concrete, i.e. will not seriously affect concrete properties in a negative manner,
- have the ability to self-heal cracks, (although sealing of larger dynamic cracks may be impractical) and ideally reducing the amount cracking and other defects,
- be able to transmit vapour where required
- be practical, in that it is not overly expensive either from an initial capital cost or a life cycle cost perspective,
- permanent – ideally, the treatment would not need to be repeated in the future.

In order to result in a material that has no major side effects concrete mix designers choose the proportions of ingredients such that the desired hardened concrete properties are obtained while still making a material that feels and handles like concrete. Ideally a special “water permeability reducing” mix design should not make concrete more difficult to manufacture successfully. Over complex production requirements make the product vulnerable to failure. In a perfect world, the special mix would handle just like “normal” concrete.

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