Did Einstein Predict MVER?

How MVER relates to *insitu* %RH and probably more than you want to know
about the physical properties of water and water vapor.

Benny Dickens
Founder/CEO

Formulators
1790 S Boyd St Santa Ana, CA 92705

"Water - the ace of elements. Always in motion, ever-flowing (whether at stream rate or glacier speed), rhythmic, dynamic, ubiquitous, changing and working its changes, a mathematics wrong side out, a philosophy in reverse..." **Tom Robbins - Even Cowgirls Get the Blues**

Water is the most abundant molecule on Earth's surface - 70-75% is found as liquid, 1.6% below ground in aquifers and 0.001% in the air as vapor, clouds, and precipitation. Water is in a state of dynamic equilibrium between liquid and vapor at standard temperatures and pressures. At room temperature, water is nearly colorless, tasteless, and odorless. Many substances dissolve in water and as a result water is rarely clean. Water is the only common substance found naturally in all three states of matter - solid, liquid and gas.

To best treat the subject and understand the nature of water it is necessary to provide a definition of terms and general discussion of the physics related to water. Examples will be given high-lighting physical properties to observed field experiences, relating moisture and its effects on flooring installations.

Properties of Water and Water Vapor

Water is Polar

The chemical structure of water consists of two hydrogen atoms covalently bonded to a single oxygen atom. The reason that oxygen hydride (water) forms a liquid is that water is electronegative. Oxygen attracts electrons much more strongly than hydrogen, resulting in a net positive charge on the hydrogen atoms and a net negative charge on the oxygen atom. The presence of an opposing charge on each of these atoms gives a water molecule a net dipole moment. Electrical attraction between water molecules due to this dipole pulls individual molecules closer together, making it more difficult to separate the molecules and raising the boiling point. This attraction is known as hydrogen bonding.

Surface Tension

Water sticks to itself (cohesion) because it is polar. Surface tension develops from the cohesive force holding water to itself. Water exhibits adhesive properties as well due to its polarity. On an extremely clean/smooth glass surface water will form a thin, continuous film. This film formation results from the strong molecular forces between glass and water (adhesive forces). The attraction force between glass/water is stronger than the cohesive forces attracting water to itself.

Some examples of the effects of surface tension:

Beading of rain water on the surface of a waxed automobile. Water adheres weakly to wax and strongly to itself, so water clusters in drops. Surface tension gives them their near-spherical shape, because a sphere has the smallest possible surface area to volume ratio.

Formation of drops from a faucet first occurs when a mass of water accumulates at the faucet surface, adhering to the faucet it begins gaining additional mass to a point where the surface tension can no longer bind it to the faucet. It then separates and surface tension forms the drop into a sphere. If a stream of water runs from the faucet, the stream breaks up into drops during its fall. This is due to gravity stretching the stream and surface tension then pinching it into spheres.

Capillary action refers to the process of water moving up a narrow tube against the force of gravity. This occurs because water adheres to the sides of the tube and surface tension tends to straighten the surface making the surface rise with a ratchet effect. A cascading event begins with more and more water being pulled up through the tube by the strong cohesive/adhesive forces. The process is repeated as the water flows up the tube until there is enough water mass for gravity to counteract and stop the combined forces.

How does this relate to moisture in concrete? The polarity of water contributes to its surface tension properties. Water found within the concrete slab is not pure and can contain dissolved mineral salts which act to lower surface tension properties by disrupting the hydrogen bonding at the water surface. Lower surface tension can contribute to higher rates of MVER as we will learn later. Often the surface tension properties are still sufficient to create capillary activity. Capillary action a major positive force in the movement of water and its vapor through concrete, a semipermeable layer.

Density of Water and Water Vapor

For most substances, the solid phase is more dense than the liquid phase. A block of any pure solid will sink in a tub of that same pure liquid. By contrast, a block of common ice will float in a tub of water because solid water is less dense than liquid water. At room temperature, liquid water will become more dense with lowering temperature, just like other substances. However at 4 °C, just above freezing, water reaches its maximum density, and as water cools further toward its freezing point, liquid water expands, becoming less dense.

How does this relate to moisture in concrete? Water will increase in density until it approaches 39.2°F. Moisture vapor readings by Calcium chloride (ASTM F-1869) loose reliability at lower temperatures due to the higher density of water and subsequent negative force applied to its migration or movement. Flooring installations made during winter months within the prerequisite MVER values will, in general, experience higher MVER in the summer.

Water the Universal Solvent

Water is a very strong solvent, referred to as the universal solvent, dissolving many types of substances. Substances that mix well and dissolve in water (e.g. salts) are "hydrophilic" (water-loving) substances, while those that do not mix well with water (e.g. fats and oils), are "hydrophobic" (water-fearing). The ability of a substance to dissolve in water is determined by whether or not the substance can match or better the strong cohesive forces that water molecules generate between each other. If a substance has properties that do not allow it to overcome this force then the molecules are "pushed out" from water and will not dissolve.

How does this relate to moisture in concrete? Liquid water will dissolve mineral salts during migration and deposit these salts at the surface of the concrete upon evaporation. This process is referred to as efflorescence. The salt deposits can elevate pH only if liquid water is available as a solvent. The degree of salt dissolution in water can change the diffusive properties of the slab and alter the measured MVER.

Water is Incompressible

If you fill a tube with water and place a piston on either end, you can not measurably push or compress the pistons together. This is why water is good for hydraulic systems because when squeezed it produces positive pressures (hydrostatic pressures).

A water hose will not explode from the water pressure behind it because this pressure does not build unless mechanical work is applied. If water were compressible (like air) then pressure applied will reduce the volume of the water allowing for more water and more pressure. Water does not act like a spring, but there is spring water.

In the opposite fashion to the above, if you pull the pistons away from one another, the water column resists the pistons movement. A suction develops on the water column - just like putting your finger on the end of a syringe and pulling back the plunger. Negative pressures (tensions) develop on the walls of the tube sucking and caving it in.

> **How does this relate to moisture in concrete?** A positive force exacted upon the liquid water below the slab is dependent on the height of the source volume, the resistance to the water emission, slab density and the atmospheric conditions that exist above. This exterior force can not build unless work is applied to it mechanically as in a pump or by increasing the exterior source height (such as could occur if a water tight subterranean slab were exposed to rising flood water). As a result hydrostatic pressures rarely cause installation failures. The actual cause is more complicated and related to temperature, porosity, resistance to diffusive forces (friction) and relative humidity as we will learn later.

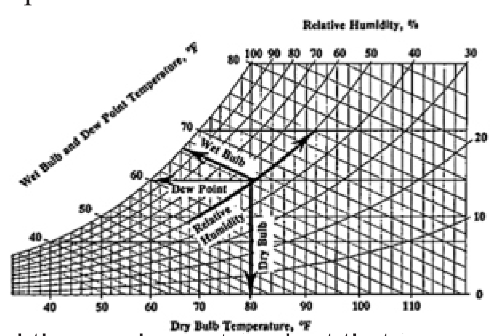
Fluid Mechanics

Fluid Dynamics

The sub-disipline of fluid mechanics dealing with fluids in motion offers a systematic approach to apply empirical laws of physics to flow measurement. The study of fluid dynamics involves the calculation of measurable properties of fluids such as velocity, pressure, density and temperature, as functions of space and time.

Psychrometrics

The term used to describe the field of engineering concerned with the determination of physical and thermodynamic properties of gas-vapor mixtures. The relationship between air temperature, moisture content



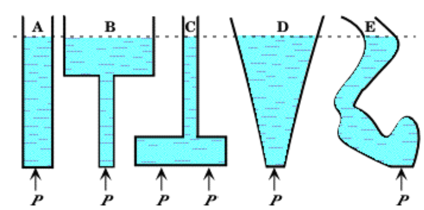
and humidity has been codified in a diagram called the psychrometric chart that is indispensable for understanding condensation. A psychrometer or hygrometer is used to measure the water vapor content in the atmosphere or humidity. The first crude device was invented by Leonardo Da Vinci in the late 1400's.

> **An example of physical observations that can be described through the study of psychrometrics:**
> **1. Why do jets leave a white trail in the sky?** Jets leave white trails, or contrails, in their wakes for the same reason you can sometimes see your breath. The hot, humid exhaust from jet engines mixes with the atmosphere, which at high altitude is of much lower vapor pressure and temperature than the exhaust gas. The water vapor contained in the jet exhaust will first condense and then freeze. This process forms a cloud very similar to the one your breath makes on a cold day.

2. **Water enters a typical drinking fountain through a large pipe at almost zero velocity and a pressure that's about 6 times atmospheric pressure (normal atmospheric pressure plus an additional 5 atmospheres). The water then passes through a nozzle and sprays up into the air. If the fountain did nothing to alter the water's total energy as it flows, how high would the water jet rise above the nozzle before coming to a stop and then descending?** The pressure of water in a vertical column rises by 1 atmosphere for every 10 meters of depth. Thus the pressure at the bottom of a 50-meter tall column of water is 6 atmospheres (1 atmosphere of pressure to support the atmosphere overhead and 5 more atmospheres of pressure to support the weight of the water above). The full-pressure jet will rise to 50 meters. To reduce the rise by a factor of 500 a regulator converts 99.8% of the water's total energy into thermal energy, leaving it with just enough energy to rise 10 centimeters above the nozzle before coming to a stop. Getting a drink of water can be complicated.

Fluid Statics (Hydrostatics) A sub-discipline of fluid mechanics is the science of fluids at rest under stable equilibrium. The use of fluid to do work is called hydraulics and the science of fluids in motion is fluid dynamics.

Question: If the height of the fluid's surface above the bottom of five different vessels is the same, in which vessel is the pressure of the fluid on the bottom of the vessel the greatest ? The volume of liquid in each vessel is not the same.



Answer: The pressure P is the same on the bottom of each vessel.

Sir Isaac Newton

A Newtonian fluid is described as a fluid that flows like water and continues to flow, regardless of the forces acting on it. For example, water is Newtonian because it continues to exemplify fluid properties no matter how fast it is stirred or mixed. Contrast this with a non-Newtonian fluid, in which stirring can leave a "hole" behind that gradually fills up over time (as seen in materials such as pudding or mash potatoes), or cause the fluid to become thinner, the drop in viscosity causing it to flow more (as is seen in non-drip paints, which brush on easily but become more viscous after application). For a Newtonian fluid, the viscosity, by definition, depends only on **temperature** and **pressure** (and also the chemical composition of the fluid if the fluid is not a pure substance), not on the forces acting upon it.

How does this relate to moisture in concrete? Water contained within the concrete slab migrates through capillary activity similar to a Newtonian fluid. This means seasonal temperature fluctuations and/or barometric pressure will have an effect on flow rates. Moisture vapor or water vapor is a consequence of the evaporation of liquid water. The rate of that evaporation is also dependent on temperature and relative humidity. At higher temperatures air can hold more water vapor. If the temperature increases quickly then the relative humidity will drop fueling the development of a moisture gradient within the slab. More about gradients later.

The Movement of Water

Diffusion and Bulk Flow

Bulk Flow is the movement of molecules in response to a pressure gradient. A good example is a faucet. When a faucet is turned on, water flows out. This occurs because the water in the tap is under pressure relative to the air outside the faucet. A toilet flushes due to the higher pressure in the tank/bowl versus lower pressure in the sewer system. Some molecular movements rely on bulk flow but require a mechanism to generate the pressure gradient or work. An example is the human heart; designed for the bulk flow of molecules through the circulatory system.

Diffusion The net, random movement of individual molecules from one area to another. Water will move from high concentration to low concentration following a concentration gradient. The molecules move from an area of high free energy (higher concentration) to one of low free energy (lower concentration). The net movement stops when a dynamic equilibrium is achieved.

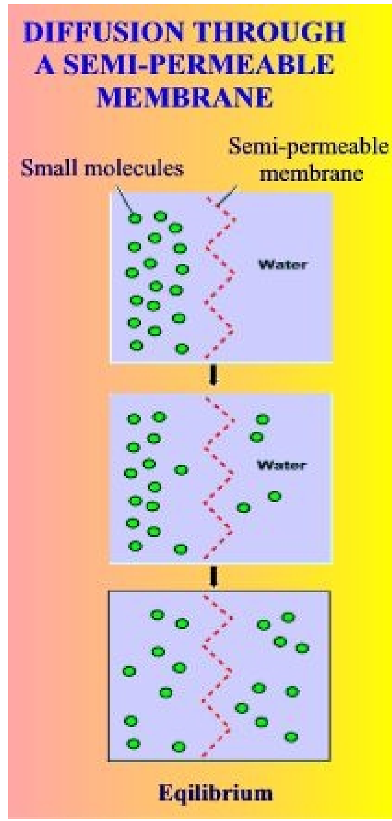
Imagine opening a bottle of perfume containing volatile oils in a very, very still room. Initially, the oils are concentrated in a corner of the room with the bottle. As the molecules move randomly (in all directions) they eventually appear throughout the room over time. Ultimately the oils will reach a point (dynamic equilibrium) at which they are evenly distributed throughout the room. At this point the molecules are still moving. They continue to move randomly in every direction. The only difference is that the net change in overall distribution of the perfume in the room does not occur.

How does this relate to moisture in concrete? Imagine the same room sited above is divided by a partition with holes (analogous to a concrete slab). If we place a drop of perfume on one side of the partition and then count at intervals the number of oil molecules on either side of the partition we will observe that the number of molecules on one side will decrease while the other will increase until they reach dynamic equilibrium. At equilibrium the molecules continue to move randomly, back and forth from one side of the partition to the other. At this point the number of molecules on either side of the partition at any given time is simply chance. The number fluctuates about a midpoint, the equilibrium concentration.

This is the type of event that occurs within the concrete slab prior to a resilient flooring installation. The open slab develops a concentration/pressure gradient catalyzed by temperature fluctuation and evaporative effects at the slab surface. The movement of moisture from the slab is held back by the density of the slab and forces that can simply be attributed to friction. When the resilient flooring is installed the evaporative effect is removed and the moisture moves toward dynamic equilibrium. The *insitu* %RH (*insitu* is Latin for "within") measured for a concrete slab per ASTM 2170 is a value of the percent relative humidity when the moisture gradient achieves equilibrium. A measurement at 40% depth of slab giving 85% *insitu* RH will more than likely be the value at the slab surface when the dynamic drive is eliminated with the resilient flooring installation.

Factors Influencing Diffusion

Concentration Gradient As previously stated, solutes (molecules dissolved in a solvent) move from an area of high concentration to one of lower concentration; in other words, in response to a concentration gradient. Water and water vapor or moisture will migrate from an area that is wet to an area that is dry in a similar fashion.



Chemical Potential is a term related to thermodynamics and chemistry, first described by the American physicist Willard Gibbs. Gibbs noted that any given element or combination (molecule), can be considered a substance. As such, Gibbs introduced the term chemical potential to describe the change in the state of a substance in relation to its surroundings. In other words it can be used relativistically, to measure the tendency of a particle or particles to diffuse. Therefore, particles tend to diffuse from a region of high chemical potential to regions of low chemical potential. If a system with two species are found at equilibrium, the chemical potential of the two species must be equal. Otherwise, any increase in one chemical potential would result in an irreversible net release of energy (heat) of the system.

Fick's Law is an equation that relates the rate of diffusion to the concentration gradient or chemical potential (C1 – C2) and resistance (r). The diffusion rate (D), can be expressed in this simplified version of Fick's equation as:

$$D = (C1 - C2) / r$$

Here are some important points that Fick's Law provides in relation to the movement of water and water vapor (moisture):

1. The rate of diffusion is directly proportional to the concentration gradient. The greater the difference in concentration between two areas, the greater the rate of diffusion (MVER). Thus, when the gradient is zero, diffusion will not occur, diffusion will only occur so long as the concentration gradient exists.

2. The rate of diffusion is indirectly proportional to resistance. The greater the resistance (frictional forces) to diffusion, the lower the rate of diffusion. Resistance refers to anything that reduces the rate of diffusion, such as the partition in our perfume example earlier or a concrete slab. Increasing the width of the slab will increase resistance. Increasing the density of the slab or decreasing the number of holes (capillaries) in the slab will increase resistance. Increasing the viscosity or size of the particle will increase resistance. In the case of water, increasing the dissolved solids can increase resistance.

3. The rate of diffusion is inversely proportional to distance traveled (also a function of resistance). The wider the partition the water or water vapor must travel the greater the resistance

to the diffusive flow.

Kinetic Motion According to kinetic theory, particles like atoms and molecules are always in motion at temperatures above absolute zero (0 K = -273 C).

Temperature is directly proportional to the rate of diffusion (D). Increasing the temperature, increases the rate of molecular movement which will drive faster diffusion.

Pressure is directly proportional to the rate of diffusion (D). Increasing the pressure, increases the speed of molecules driving diffusion. If we reduce the pressure on the low free energy side (low concentration) of the partition in relation to the other, we can affect a net gain in the diffusion rate. The latter is how a diaphragm pump works or the human heart. A vacuum force of lower pressure on one side of the chamber facilitates the movement of fluid into it and a high pressure force is applied to the other side pushing the fluid out.

Solvation Solute particles decrease the free energy of a solvent or in other words, increase the effective volume of a particle. The critical factor is the number of particles or concentration, not charge or particle size. By increasing volume we increase the frictional force acting on the particle during diffusion. This is particularly important in the movement of water. Water will move from an area of higher mole fraction (solute concentration) or higher free energy to an area of lower mole fraction or lower free energy (less concentrated). This means that pure water will tend to move toward water containing a dissolved salt.

Einstein's Relation is a previously unexpected connection revealed by Einstein as part of his PhD thesis published in 1905 on the motion of particles:

$$\mathbf{D = k_B T/f}$$

This equation relates a measurable value, the diffusion coefficient **D**, to a molecular property **f**, the frictional coefficient. The frictional force is characterized by the velocity a molecule has when diffusion occurs. The movement of water and water vapor through a partition like a concrete slab is predictable, is measurable and can be calculated as Einstein derived, the speed or velocity the water has is dependent on the frictional forces acting on it.

How does this relate to moisture in concrete? When MVER data is collected we obtain a velocity associated with the movement of water vapor through a concrete slab. Forces related to friction effect this velocity. We can demonstrate the effect of these physical phenomena by artificially altering frictional forces in concrete slabs in the lab:

1. Concrete created with an open or "loose" lattice structure can be made by increasing the water to cement ratio leaving voids from the excess water.

2. Increasing the content of larger aggregate allows for channeling of moisture, reducing the frictional forces acting on it and increasing the potential for higher rates of emission. This latter example also demonstrates the effect of surface area and its relation to water flow.

Increased surface area with smaller aggregate will increase the boundary effect on water flow. This results in increased turbulence having a net negative effect on the flow rate.

3. A common misconception is that MVER will migrate or hop about the floor. Without a driving force providing the chemical potential, lateral movement of elevated moisture is impossible. If a floor is mapped out based on elevated moisture and conditions remaining static (no flooding, broken pipes, saw cutting for drains, etc.) chances are 10 years from now those same areas will remain a problem. The reason those areas were problematic in the first place can be understood considering reduced frictional forces providing a greater velocity to the diffusive event as measured by MVER. %RH can be high or low in these areas independent of the measured velocity. %RH is only the water behind the dam not the flow rate from the release gate.

Einstein was able to demonstrate that forces acting at the molecular level are predictable and more importantly can be related to observable systems on a larger scale. Einstein tied our empirical data to the physical laws of fluid motion.

Definitions for Different Types of Fluid Movement

Emission - In concrete, describes the movement of moisture (liquid water and /or water vapor) through a concrete slab.
Transpiration - Plants take in water in their root systems and release it into the atmosphere through their leaves.
Evaporation - Liquid water is converted to its vapor phase from the ground or from a body of water and mixes with the atmosphere.
Osmosis - A specialized case of diffusion in which a solvent, like water moves across a membrane into a solution of high concentration. Reverse osmosis involves the application of force to push a solution of high concentration across a membrane effectively separating solute from solvent.
Dialysis - Another specialized case of diffusion; is the diffusion of solute across a semi-permeable membrane. Example - consider blood containing a high level of dissolved sugar. If the sugar (solute) flows out of the blood across a permeable membrane, it is an example of dialysis. If the blood (solvent) flows across the membrane leaving the sugar behind it is osmosis.

%RH and its Relation to Water Vapor Emission (MVER)

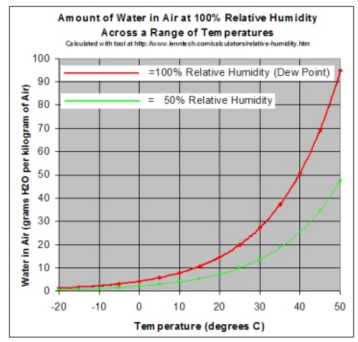
Definition Relative humidity is defined as the ratio of the partial pressure of water vapor in a gaseous mixture of air/water to the saturated vapor pressure of water at a given temperature. Relative humidity is expressed as a percentage and is calculated in the following manner:

$$\%RH = p(H2O)/p^*(H2O) \times 100\%$$

where:
%RH is the % relative humidity of the gas mixture being considered;
***p*(H2O)** is the partial pressure (the concentration) of water vapor in the gas mixture; and
***p**(H2O)** is the saturation vapor pressure (highest possible concentration) of water at the temperature of the gas mixture.

Often the concept of air holding water vapor is used in the description of relative humidity. Relative humidity is wholly understood in terms of the physical properties of water alone and is the ratio of the amount of water vapor in air to the maximum amount of water vapor that could be present if the vapor were at its saturation conditions. This maximum amount is dependent on the temperature at the time of measurement.

Air is referred to as saturated when the vapor pressure of water is at the equilibrium vapor pressure for water vapor. This equilibrium is dependent on the given temperature of the air and water vapor mixture; liquid water (and ice, at the appropriate temperature) will fail to evaporate when exposed to saturated air. This is the explanation for the appearance of dew or fog. Fog consists of very minute droplets of liquid water, primarily held aloft by isostatic motion, unavailable to evaporative effects as a result of the air containing the maximum water vapor possible at the given temperature.



For a given dewpoint (point of maximum water vapor content or saturation), the relative humidity will change inversely, albeit nonlinearly, with the temperature. This is because the partial pressure of water increases with temperature – the operative principle behind everything from hair dryers to dehumidifiers. In other words the higher the temperature the more water can evaporate and be held in its vapor state.

Because of the increased potential for higher water vapor content at higher air temperatures, the content of water vapor in air at sea level can get as high as 3% by mass at 86°F compared to no more than about 0.5% by mass at 32°F. This explains the low levels of humidity in heated structures during winter, indicated by dry skin, itchy eyes, and persistence of static electric charges. Even with saturation (100% humidity) outdoors, heating of infiltrated outside air raises its capacity to hold moisture, resulting in a lower indoor relative humidity and increased evaporation rates from moist surfaces like skin or concrete.

> **How does this relate to moisture in concrete?** A prerequisite for ASTM 1869 is that the test for MVER using Calcium chloride be conducted with all windows installed, HVAC units operational, the surface temperature of the concrete at 65 - 85°F and atmospheric relative humidity at 40 - 60%. If these conditions are followed in the dead of a northeast winter chances are the indoor relative humidity will be very low increasing the evaporative effect of moisture and imparting a positive force to the concentration gradient found within the slab as discussed earlier. This could result in higher recorded MVER.

During the hot days of summer in humid climates a great deal of liquid water condenses from air cooled in air conditioners. Warmer air is cooled below its dewpoint and the excess water vapor condenses like on the outside of a cup containing an ice-cold drink. In dry climates of the southwest evaporative coolers are used. The evaporation of water drawn through a moist pad cools the dry air flowing through it. The evaporation of the liquid water results in a loss of heat and a net reduction in free energy.

A useful rule of thumb is that the maximum absolute humidity will double for every 20°F increase in temperature or in other words relative humidity RH will drop by a factor of 2 for each 20°F increase in temperature, assuming we keep the same total moisture content.

Examples:

- In the range of normal temperatures, air at 70°F and 50% relative humidity will become saturated if cooled to 50°F, its dewpoint.
- If we start with an air temperature of 40°F at 80% relative humidity warmed to 70°F will have a relative humidity of only 10% and feel dry.
- If we change the starting point temperature from 40°F to 60°F and relative humidity from 80% to 40%, then raise to 70 °F, relative humidity falls only a quarter, from 40% to 30% - not to 10%.

Water vapor is a lighter gas than air at the same temperature, so humid air will tend to rise by natural convection. This is a mechanism behind thunderstorms and other weather phenomena. Relative humidity is often mentioned in weather forecasts and reports, as an indicator of the likelihood of precipitation, dew, or fog.

How does this relate to moisture in concrete? %RH recorded within the slab can fluctuate with changes in temperature. Not only temperature within the slab but also temperatures measured indoors. As slab temperatures increase the air contained in the slab will have an increased ability to hold more water vapor. Thus temperature increases can be a positive contributor to MVER rates as record by Calcium chloride. The higher the *insitu* %RH the more moisture is available to feed the dynamic movement of water vapor through the slab.

Conclusion and General Comments on the Flooring Industry

"The foreknowledge required to be in complete control of events is gained from complete information..." **Sun Tzu - 5th Century BC**

To effectively identify moisture emission we begin by collecting data. The data provides a glimpse as to the quantity of moisture and the dynamic processes acting within the slab that results in elevated MVER and *insitu* %RH. The more data collected, the more professional the collection, the more thorough the analysis; the better the recommendation for proper mitigation. Just like a doctor treating a patient during a physical. With each additional test result the prognosis or predicted condition evolves to a diagnosis. With a diagnosis the doctor prescribes a protocol to remedy the condition.

Prognosis- prediction based on circumstantial evidence of a physical condition.
Diagnosis- conclusive determination of a physical condition from testing and evaluation.

The measurement of MVER and *insitu* %RH has some real science behind it. The estimated cost of a floor failure exceeds twice the installation. For a typical 50,000sf commercial/retail installation at $2.50/sf this means the potential loss could exceed $500,000. More than enough to put a small flooring contractor out of business. This begs the question as to who should be responsible for collecting the data, providing the analysis and determining the proper mitigation technique to be employed. Does the typical flooring contractor need this liability? If a third party, independent testing facility is used should they be the one to provide the recommended chemistry? Or does a coordinated effort on the part of contractor, testing service and manufacturer (flooring or adhesive) best serve the retailer/owners interest? Whatever the case the data collected must be interpreted correctly.

Moisture mitigation is complex. An evolution toward reliance on field data prior to installation is necessary to avoid the inflating cost of liability and loss. Data must direct the solution.