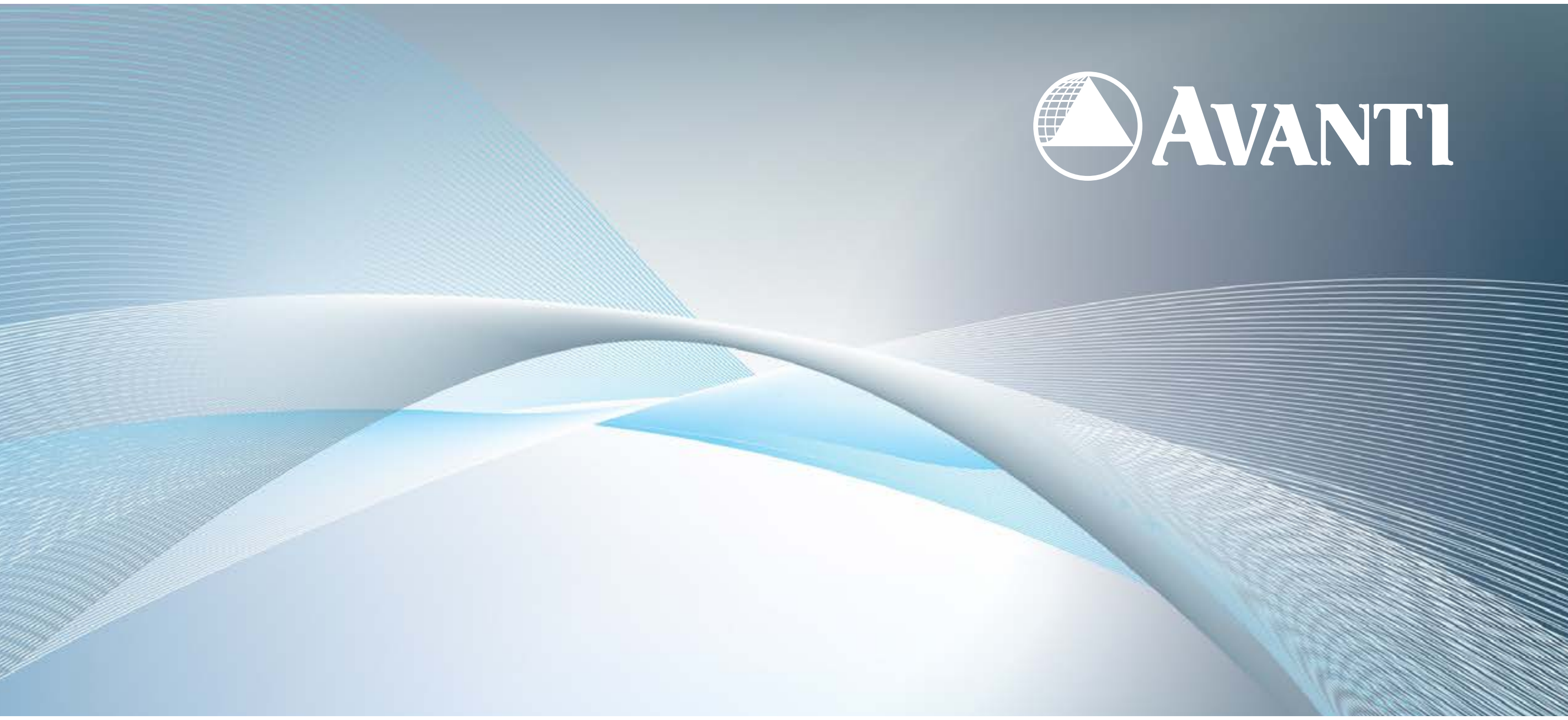
WHITE PAPER

NEW SCIENTIFIC EVIDENCE FROM FIELD TESTING & LABORATORY ANALYSIS:

ZERO SHRINKAGE OF AV-100® CHEMICAL GROUT DUE TO CONSISTENT RELATIVE HUMIDITY IN SOILS



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ZERO SHRINKAGE OF AV-100® CHEMICAL GROUT DUE TO CONSISTENT RELATIVE HUMIDITY IN SOILS

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Doug Cobos is a Senior Research Scientist and the Director of Environmental Research at METER Group, Inc. (formerly Decagon Devices), where the testing described in this white paper was performed. He is also President of Cobos Testing Labs, LLC, which focuses on characterization of thermal properties for soil and concrete for buried power cable installations. Cobos also holds an adjunct appointment in the Department of Crop and Soil Sciences at Washington State University where he teaches Environmental Biophysics. His advanced degrees are from Texas A&M University and the University of Minnesota in Soil Science. Cobos was also the Lead Engineer for the Thermal and Electrical Conductivity Probe (TECP) that was designed by Decagon and flew to Mars aboard NASA's 2008 Phoenix Scout Lander, successfully measuring a variety of Martian soil and atmospheric properties. His current research is focused on instrumentation development for use in soil and plant research.

Executive Summary

An investigation was launched to determine how relative humidity varies within the soil environment. Soil undergoes a two-stage process of drying to create a shallow layer of dry soil and a deeper layer of moist, near 100% relative humidity soil below. The vegetative rooting zone extends the surface-coupled layer to deeper depths, but a thermodynamic analysis demonstrates that the drying in the rooting zone is generally limited to 99% relative humidity. A 96% relative humidity floor was calculated based on the lowest recorded soil water potential, inferring that any soil with vegetation will have a relative humidity greater than 95%. Field testing was conducted at Riverside, California, one of the top three driest cities in America, to monitor relative humidity at varying soil depths of 2, 4, 7, 10 and 14 feet for 4 months. Soil samples were taken at 2, 4, 7, 10, 14, and 20 feet to test soil texture, water content and relative humidity and find a correlation between soil depth and the three tested properties. Water content was found to be higher at depths of 2 and 4 feet in a sandy loam soil texture. Relative humidity was found to be independent of soil depth, soil texture and water content, ranging from 99.84% to 99.99%. AV-100 chemical grout samples were tested in an environment that mimicked soil conditions of the field testing to determine if relative humidity significantly contributed to dehydration and comprised the integrity of the grout's sealing capabilities. The 12 week period of testing showed an average water loss of 0.02%.

Relative humidity (RH) is an unintuitive parameter, the misunderstanding of which has led to the large scale failure of underground storage tanks and contributed to Superfund level subsurface contamination (e.g. radioactive waste leaking from underground storage tanks at the Hanford Site). The theoretical analysis and empirical results presented in this paper demonstrate that high soil RH maintains the integrity of AV-100 chemical grout.

Vapor Phase Transport Theory and Quantification of RH within Vegetation Root Zones

Take a non-vegetated soil profile that has been moistened by rainfall and is now drying. Evaporation occurs at the soil surface, with water from deeper in the soil profile replenishing the water evaporated from the surface through liquid phase hydraulic transport (Stage 1 drying). At the point where soil water can no longer be conducted to the surface efficiently enough to satisfy the surface evaporation, a dry surface layer rapidly develops through which vapor phase transport dominates (Stage 2 drying). Vapor phase transport of water, evaporated deeper in the soil profile through the dry surface soil layer, is highly inefficient. This leads to a dramatic decrease in the overall evaporation rate. As the dry surface layer becomes thicker with continued drying, the evaporation rate slows accordingly, eventually falling to nearly negligible levels once the dry surface layer reaches around a meter in depth. This scenario results in a soil environment depicted in Figure 1 with moist, nearly 100% RH soil in the deeper layers, and dry soil at low RH, controlled predominantly by the atmosphere, in the surface layer. This condition can exist indefinitely, even in desert environments. In a comprehensive characterization of the Yucca Mountain

Nuclear Waste Repository in the Nevada desert, analysis of 28 boreholes to 800 m depth showed a minimum mean RH of 99.0% RH, with most boreholes much higher than that (Flint, 1998 Table 7).

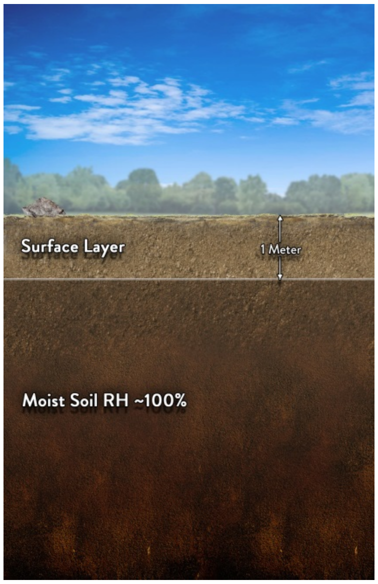

Figure 1. Soil RH regime in the bare soil scenario presented above. Under fully dried conditions, a shallow dry layer develops while moist soil near 100% relative humidity persists at depth indefinitely.

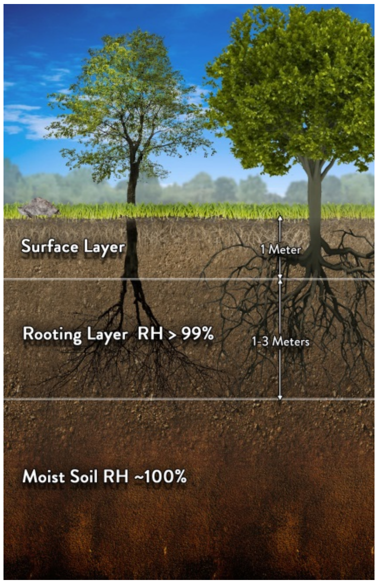

Figure 2. Soil RH regime in the vegetated scenario presented below. The presence of roots extends the depth of water extraction, but plant-available water is limited to >99% relative humidity.

The introduction of vegetation can significantly alter the scenario presented above. Many woody shrubs and trees develop root zones that extend well below the typical dry zone that develops at the soil surface. These roots extract water from the deeper layers (see Figure 2). In this scenario, the RH of the deeper soil in the rooting zone is controlled by the plant's ability to extract water from the soil. The availability of water in soil to plants is governed by the potential energy of the water or *soil water potential*. The lower limit of soil water potential at which plants can still effectively extract water is the Permanent Wilting Point, generally taken to be -1.5 MPa. However, desert species have been shown to extract water down to -3.1 MPa (Chen et al., 2008) with a range of -1.8 to -6.1 MPa reported by Sperry et al., 2002. These potential energy values can be directly converted to RH using the well-known Kelvin equation from thermodynamics (Adamson, 1990).

$$RH = e^{\left(\frac{\Psi M_w}{\rho_w R T}\right)}$$

Where RH is soil relative humidity, Ψ is soil water potential, M_w is the molecular mass of water, ρ_w is density of water, R is the universal gas constant, and T is Kelvin temperature. Using the Kelvin equation to convert the soil water potential, at -1.5 MPa Permanent Wilting Point, translates to 99% RH, and even the lowest value of soil water potential recorded under desert shrubs by Sperry et al. translates to 96% RH.

These high RH values are somewhat counterintuitive to most people. Soil at permanent wilting point looks and feels quite dry. A sandy soil at this dryness state would pour like table salt, and a clay soil at this dryness state would be “hard as a rock”. The plant community would also agree that the soil is dry, as water is held at such a low potential energy state as not to be accessible to them. However, from a RH standpoint, even this “dry” soil is still quite moist. And this high RH state will persist indefinitely in the deeper soil layers, as there are no effective transport processes available to conduct this deep soil water to the atmosphere.

Several important facts should be apparent from the theory and calculations presented above.

1) Surface soil RH is dynamic, and is controlled by cyclical wetting events and atmospheric drying.
2) Deep soil RH in non-vegetated areas persists at a high RH state due to inefficient water transport mechanisms through the dry surface layer.
3) Deep soil RH under vegetation is controlled by biophysical interactions with the plant community. However, even this soil persists at a high RH state due to the lack of ability of plants to extract water below ~96% RH.

The practical implication of this analysis is that any deep soil engineering project needs to be engineered for continuous exposure to >95% RH conditions.

Field Testing in Extremely Arid Conditions

To validate the persistence of high RH conditions in arid soil, a field monitoring campaign was undertaken in Riverside, CA during the summer of 2017. Riverside was chosen as the monitoring location due to its status as one of the three driest large American cities, and its high evaporative demand resulting from low atmospheric humidity, high solar radiation load, and high temperatures. A field was selected on the University of California Riverside (UCR) experiment station (33.972983, -117.341559) with characteristics favorable for maximum surface evaporation. The field had been out of crop rotation and had stood fallow, receiving no irrigation for at least five years, according to UCR and United States Department of Agriculture (USDA) records. Vegetative cover ranged from small woody-stemmed weeds and grasses to bare ground resulting from occasional weed control measures by UCR and USDA staff.

Monitoring instrumentation was installed on July 14, 2017. A standard drill rig was used to produce a borehole to a depth of 20 ft (Image 1). Split spoon soil samples were collected at depths of 2, 4, 7, 10, 14, and 20 ft. and immediately sealed in double-layer bags for subsequent laboratory analysis. Soil temperature and RH sensors (model VP4, METER Group, Inc., Pullman, WA) were then lowered into the borehole at depths of 2, 4, 7, 10, and 14 ft. and the hole was backfilled with native soil from the borehole. The temperature and RH sensors were read every minute, and averages were recorded every six hours by a data logger (model Em50G solar, METER Group, Inc., Pullman, WA), and uploaded to the cloud via cellular network daily (Image 2).

Image 1. Standard drill rig used to produce borehole to depth of 20 ft.

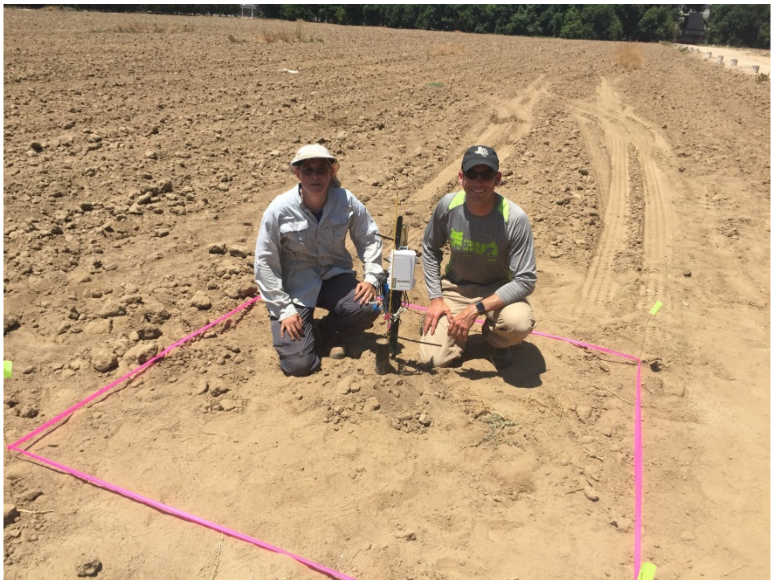

Image 2. Installed model Em50G solar data logger in arid dry environment.

Weather conditions in the months previous to and during the field installation were hot and dry as is typical for this location (Figure 3).

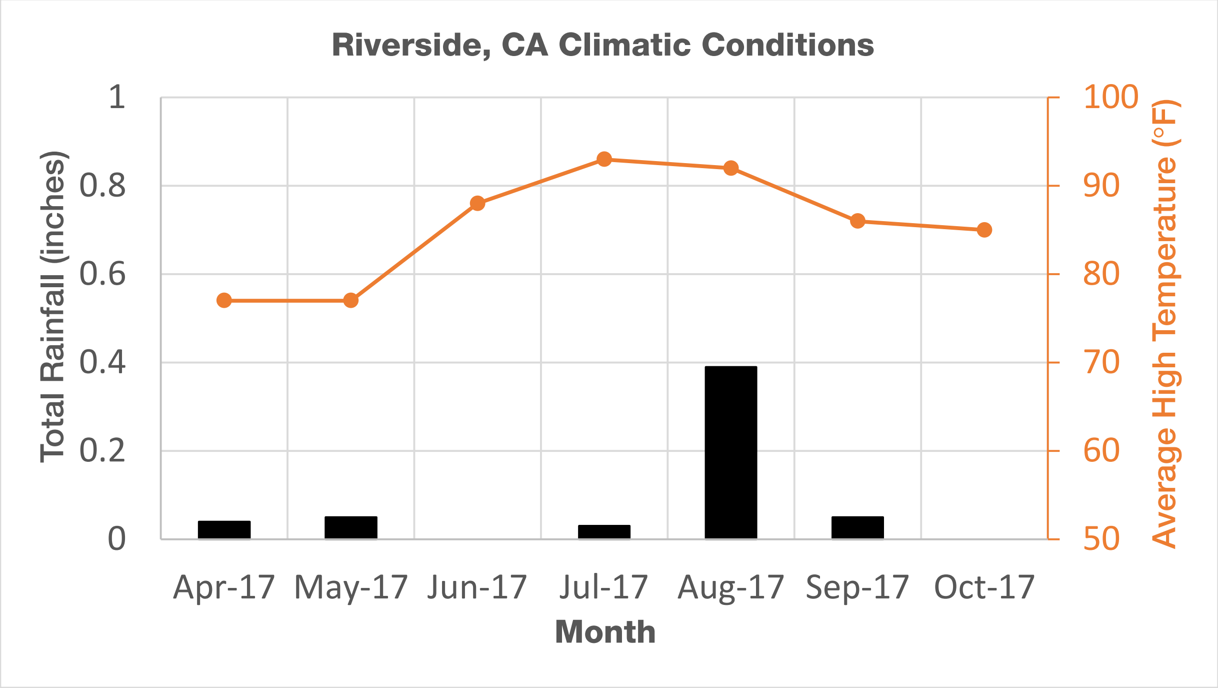

Figure 3. Total precipitation and average high temperatures for Riverside, CA from April to October 2017. Conditions in the three months previous to sensor installation are included because they control the moisture state of the soil at the time of installation. Source: UC Cooperative Extension

The soil samples collected during sensor installation were returned to the laboratory for analysis of soil texture (NRCS methodology), water content (oven drying), and RH (WP4C, METER Group, Pullman, WA). The WP4C instrument used for the laboratory RH analysis is one of the most accurate instruments available for measuring in the high RH range, with accuracy of approximately 0.01% RH. Three sub-samples of each soil sampling depth were analyzed for RH. Laboratory testing results are below in Table 1. Laboratory characterization of the split spoon samples showed low water content levels characteristic of a well-drained, coarse textured soil, ranging from 2.4% to 8.8% gravimetric water content (Table 1). Soil water content levels were correlated to soil texture, as expected. Soil RH measurements were all above 99.8% (Table 1) and showed no discernable trend with depth or soil texture, despite Riverside's dry climate and a total of 0.01" of rainfall in the 2.5 months leading up to soil sampling.

Depth (ft.)	Soil Texture (NRCS Classification)	Water Content (% dry mass)	RH (%)	Standard Deviation of RH (%)
2	Sandy Loam	7.7%	99.89%	0.0007
4	Sandy Loam	8.8%	99.84%	0.0012
7	Sand	3.3%	99.99%	0.0001
10	Sand	2.4%	99.89%	0.0010
14	Loamy Sand	3.7%	99.92%	0.0007
19	Sand	2.6%	99.91%	0.0006

Table 1. Soil texture, water content, and RH resulting from laboratory analysis of Riverside, CA field site samples.

The soil RH monitoring installation showed that high RH conditions persisted at the site throughout the monitoring campaign (Figure 4). After initial sensor equilibration, measured RH values hovered at approximately 105%. Values above 100% RH are clearly not possible, and are an artifact of accuracy limitations of the capacitance type sensors deployed at the site. Manufacturer's specifications show expected accuracy of ± 5% RH at 100% RH, so these artificially high measured RH values simply indicate true RH values of very near 100%, as were confirmed by the more accurate laboratory testing shown in Table 1. Some drying at the surface level was experienced toward the end of the measurement period, with the surface sensor briefly dropping down as low as 98.3% RH. This type of surface drying is expected as explained earlier in the theoretical analysis of soil RH.

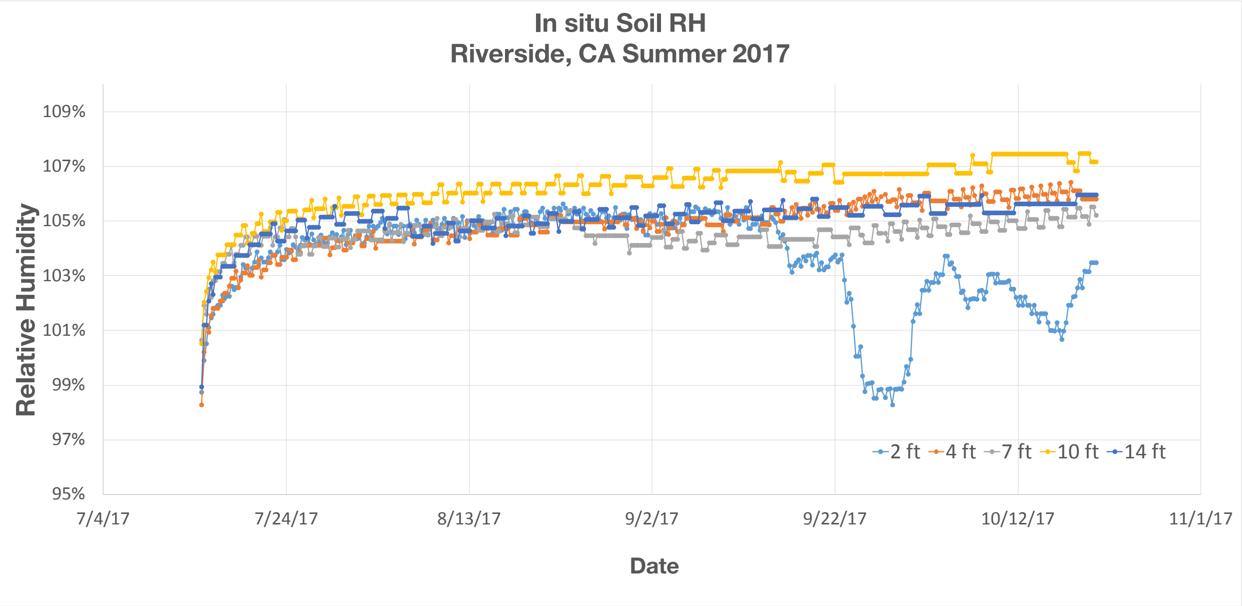

Figure 4. Soil RH at five depths at Riverside, CA field site over the Summer and early Fall of 2017. 105% RH measurements are artifacts of the limitations of the sensors used and simply indicate RH near 100%. Near 100% RH conditions persist throughout the period except for some drying at the 2 ft. depth near the end of the measurement period.

The results of the field campaign presented here corroborate the theoretical analysis presented in the first section. Even in highly arid locations, the RH of soil below the shallowest surface layer is maintained at very close to 100% RH. The practical implication of this analysis is that any deep soil engineering project needs to be engineered for continuous exposure to RH conditions that remain near 100%.

The Effect of Soil RH on AV-100 Chemical Grout

AV-100 chemical grout is often used in the soil environment as a sealing agent to prevent water infiltration into engineered structures or leakage from water-carrying vessels. These grout formulations shrink when dehydrated, and could potentially lose their sealing capabilities if desiccated. It has been established earlier in this study that the soil environment remains near saturation (100% RH), even in arid environments. Laboratory analysis was undertaken to determine if fully-hydrated grout loses water under high RH conditions similar to those found in the soil.

To establish high RH conditions similar to those found in the soil environment, deionized water was sealed in airtight containers and allowed to saturate the headspace. Four 3 cm lengths of PVC pipe were placed in the water on the bottom of the container to act as standoffs. A stiff wire screen was placed on top of the standoffs to act as a platform to keep the grout samples from coming into contact with the liquid water, but still allow water vapor to diffuse throughout the container and bring the headspace to high RH (See Image 3). Vacuum grease was applied to the gasket of each container to ensure a full airtight seal.

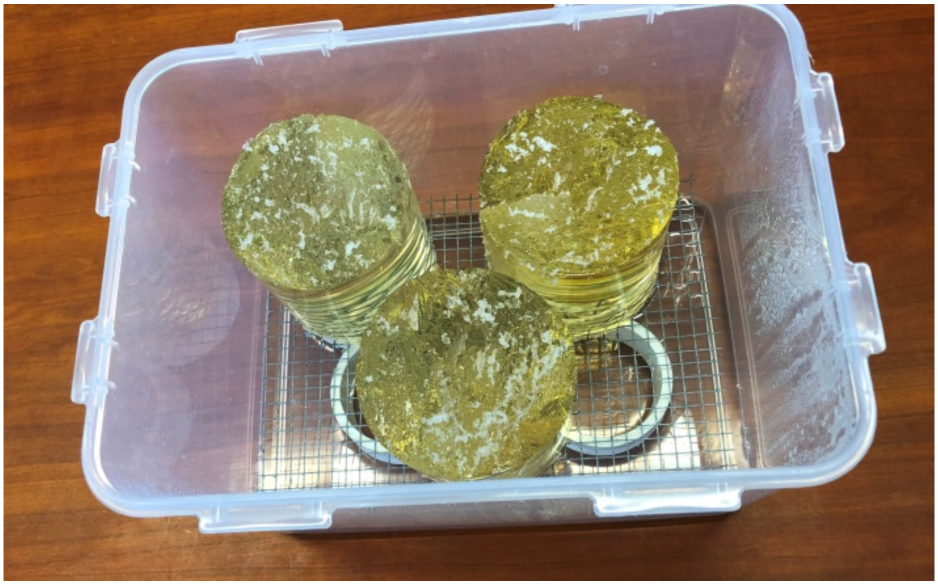

Image 3. Test chamber used in the laboratory experiment. A shallow layer of liquid water in the bottom of the container maintained 100% RH conditions in the headspace surrounding the grout once the lid was sealed in place. PVC standoffs and screen prevented grout contact with liquid water.

Triplicate fully-hydrated grout samples of approximately 350 g were weighed and placed on the screen in each container before the lid was placed on the container and sealed. Great care was used to minimize grout exposure to ambient conditions while weighing and transferring to the high RH containers. No sample was exposed to ambient conditions for more than 20 seconds. Six high RH containers were prepared as described above, each with three grout samples.

After preparation, the containers were placed in a temperature-stable environment until the pre-determined equilibration time was reached. To understand the potential water loss behavior over time, one container was opened and the three samples quickly removed and weighed after 1, 2, 3, 4, 8, and 12 weeks.

There was no significant water loss measured on any of the 18 samples. The total water exchange ranged from 0.19% water loss to 0.13% water *gain*, with an average of 0.02% water loss. There was no water loss/gain trend over time (Figure 5).

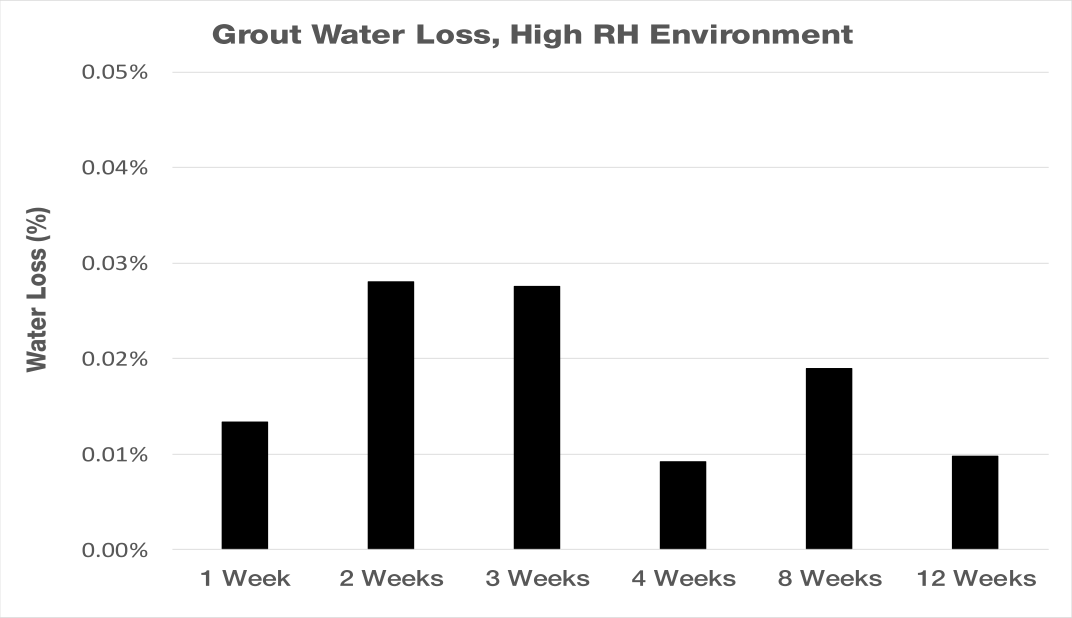

Figure 5. Water loss from fully-hydrated grout exposed to saturated conditions. Each bar represents the average of three samples. There is no water loss trend over time, and the average water loss is a negligible 0.02 %.

From the results presented, it is clear that AV-100 chemical grout will not experience significant shrinkage under high RH conditions. The theoretical analysis and literature review demonstrate that the RH remains very near 100% below a dry soil layer and where vegetation root growth is available. The field testing conducted confirms that soil beyond the shallow surface layer is always at high RH, even in one of the driest cities in the US. Based on thermodynamic analysis, field testing, and laboratory testing, AV-100 chemical grout installed below the shallow surface layer will not shrink from desiccation.

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