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EVAPORATIVE DRYING OF LIGHTWEIGHT INSULATING CONCRETE ROOF DECKS

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INTRODUCTION

Lightweight insulating concretes are a special type of concrete often used for roof decks, firewalls and floor fills or other areas where the structural properties of regular concrete are not required but the fire resistance and ease of placement of "liquid" concrete are advantageous. In addition to the ease of placement of lightweight insulating concrete, it also has, when dry, the property of providing some thermal insulation to a structure. One of the most popular and frequent uses for lightweight insulating concrete is for roof decks in non-residential or commercial construction.

Normal structural concrete weighs from 90 to 160 lbs. pcf when dry. A commonly accepted dry weight for lightweight insulating concrete ranges from 15 to 50 pcf. The most common dry density or weight per cubic foot that is seen on roof construction is in the range of 22 to 34 pcf. At these densities the 28-day compressive strength ranges from a low of 50 to a high of 220 psi.[1] One company which produces an aggregate for lightweight insulating concrete decks has specified a dry density range of 25 to 30 pcf and a minimum compressive strength of 125 psi for its product.[2]

Concretes are available in a wide range of weights and strengths. Normal weight concrete utilizes sand and gravel and is most commonly used for construction of structural concrete members. Normal weight concretes have a unit weight of approximately 145 pcf, and compressive strengths of approximately 2500 to 6000 psi are common. High strength normal weight concretes have been developed with strengths exceeding 15,000 psi.

Concretes in the 90 to 130 pcf range are known as structural lightweight aggregate concretes. These concretes have compressive strengths in the range of 2500 to over 9000 psi, depending on materials, mix design and other factors.

A second category of lightweight concretes is in the unit weight range of 50 to about 90 pcf. These are usually called fill concretes. Concretes in this weight range have not been widely used.

Concretes weighing 50 pcf or less are called insulating concretes. Current technology limits the compressive strengths of these concretes to about 600 psi.

Virtually all concretes associated with the construction industry have as a common binding medium a standard type of portland cement. Many types of concrete are made from portland cement. The Portland Cement Association lists at least 95 types of concrete which are made with portland cement and only 12 special types which do not use portland cement.[1]

The two types of lightweight insulating concrete seen most often are those which use an expanded lightweight aggregate such as perlite, vermiculite or expanded polystyrene beads, and those which mix the cement with a foam to form a uniform cellular structure of air voids. The latter is referred to as cellular concrete, the former as lightweight aggregate or insulating concrete.

During the period of 1965 to the present, one of the most popular types of lightweight insulating concrete used on roof decks has been that which incorporated vermiculite as an aggregate. Another frequently used concrete on roof decks was one which incorporated perlite as an aggregate. In recent years the cellular concrete has seen frequent use on roof decks. A comparison of the three types is listed below.

Type of Concrete	Ratio Cement to Aggregate By Volume	Oven Dry Density, pcf	Water to Cement Ratio By Weight	28-Day Compressive Strength, psi
Cellular (neat cement)	None (foam)	28	.57	130
Perlite aggregate	1:6	22 to 34	1.24	220
Vermiculite aggregate	1:6	23 to 29	1.60	130

TABLE I - COMPARISON OF LIGHTWEIGHT INSULATING CONCRETE TYPES[1]

Both perlite and vermiculite are minerals which, when heated, expand to many times their original volume and thus occupy a large volume at a low density. Being inorganic and occupying a large volume at low density, they become ideal materials for use as an aggregate in insulating lightweight concrete.

Vermiculite is really exfoliated mica. This is mica which, when heated, expands and produces a laminar structure which is flaky in character and very light in density. This becomes the aggregate in the lightweight insulating concrete products. When dry this concrete, because of its low density, has thermal insulating properties. However, because of the laminar structure of the aggregate, this concrete at time of placement has a very high water content. The vermiculite absorbs a substantial amount of the concrete mixing water. Note in Table I that the water/cement ratio for vermiculite concrete at mixing is 1.60 which is the highest of the three. Normal structural concrete has a water/cement ratio in the range of 0.50 to 0.60.

Perlite is a volcanic glass. Perlite aggregate is actually expanded perlite. The water/cement ratio of perlite concrete is generally less than that for vermiculite concrete.

Lightweight insulating concretes have a low viscosity and can be pumped long distances for placement as roof decks. It is this low viscosity which makes for good workability and easy placement and is largely a function of entrained air in the mix which may be in the range of 25% to 35% by volume as compared to structural concrete with 4% to 10% entrained air by volume.

Once placed and screeded to proper thickness and slope, the concrete in a roof deck must set and cure and dry in order to become a satisfactory deck or substrate which is to receive a roofing membrane. If the concrete is not dry at the time of application of the roof membrane, or does not dry shortly thereafter, a problem with the roof membrane may eventually ensue.

PURPOSE OF THIS PAPER

The object of this discussion of lightweight insulating concrete used in roof deck construction is to address some of the factors which determine whether the water stays in the concrete or does evaporate and what should be done to ensure that the water leaves the concrete. It has been established through practical experience that water which has not left the concrete in a reasonably short time has caused many of the conventional Built-up-Roofs used over the concrete from 1965 to 1980 to develop massive problems which eventually resulted in roof failure.(3)

This paper is directed toward the architectural designer or specification writer or person in the field who supervises and inspects construction. The paper is intended to bridge the gap between theory and practice and to be a helpful tool in enabling the designer, specifier, roofer, general contractor and owner to become more familiar with the basic problems to overcome in order to assure a successful deck and roof installation which will perform well for the time span expected.

Using the water/cement ratio of 1.60 as shown in Table I, consider one typical concrete mixture which is designed to become a roof deck. The most often used mix is a 1:6 mix which means that 1 volume of concrete is used with 6 volumes of aggregate. A typical mix formulation using vermiculite as an aggregate is as detailed below. Vermiculite has been chosen as an aggregate because it seems to have been most widely used during the period of 1965 to the present.

Mix is 1:6; 1 part cement, 6 parts aggregate by volume.

7.5 bags of vermiculite aggregate X 4 ft^3/bag = 30 ft^3
(one bag is 4 ft^3; weight is 6 - 10 pcf; assume 7 pcf)(4)

5 bags cement X 1 ft^3/bag = 5 ft^3
(5 X 94 lbs./bag = 470 lbs. cement) 30 ft^3

Water/cement ratio is 1.6; so water = 470 lbs. X 1.6 = 752 lbs. = 90 gallons

NOTE: The volume of the mix does not change significantly when water and cement are added to the vermiculite aggregate, as the water and the very fine particles of cement fill the voids between the exfoliated vermiculite. This action is similar when perlite is the aggregate. In cellular concrete no aggregate is used and the volume is a function of the foam which produces the cellular structure.

Water Constants

7.48 gals. = 1 ft^3 water
62.4 lbs. = 1 ft^3 water
8.34 lbs. = 1 gal. water
lbs. water X .1198 = gals. water

30 ft^3 can be poured 3 inches thick and cover 120 sq. ft. of deck.

$\frac{90 \text{ gals.}}{120 \text{ sq. ft.}}$ = .75 gals./$ft.^2$ initial water.

If water of hydration is .20 X wt. of cement, then water that chemically unites with cement is .20 X 470 lbs. = 94 lbs. combined water.

752 lbs. water minus 94 lbs. = 658 lbs. of water to evaporate.

658 lbs. X .1198 = 79 gals. free water (see water constants above)

$\frac{79 \text{ gals.}}{120 \text{ sq. ft.}}$ = .65 gals./sq. ft. free water

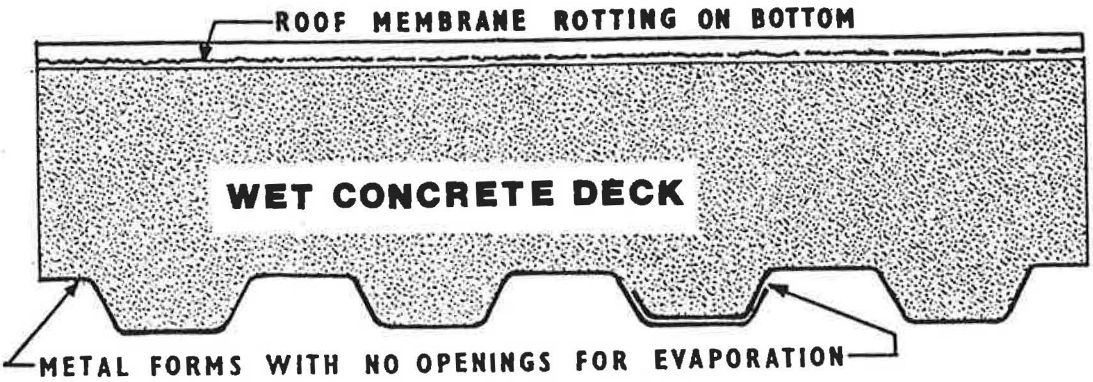
In summary, there is approximately .65 gals./ft^2 of water in the newly set concrete which must be made to escape somehow in order for the concrete to reach its optimum value of thermal insulation. Assuming the concrete will have a dry density of 25 pcf, it will weigh 25 ÷ 4 = 6.25 lbs./ft^2 when dry if cut into 3-inch thick slabs each 1 ft^2 in area. The free water in each wet slab is .65 gals. X 8.346 lbs./gal. = 5.42 lbs. ft^2. At this point in time (before drying) the concrete contains $\frac{5.42 \text{ lbs. water}}{6.25 \text{ lbs. dry wt.}}$ or 87% water by weight.

The wet density at time of placing is approximately equal to 470 lbs. cement + 752 lbs. water + (7 X 4 X 7.5)lbs. aggregate = 1432 lbs.; thus, $\frac{1432 \text{ lbs.}}{30 \text{ ft}^3}$ = 47.4 pcf.

Dry density is equal to 94 lbs. combined water + 470 lbs. cement + 210 lbs. aggregate; thus, $\frac{774 \text{ lbs.}}{30 \text{ ft}^3}$ = 25.8 pcf

These numbers correspond closely to recent catalogs of one of the major suppliers of vermiculite aggregate[2] and are consistent with Portland Cement Association literature.[1]

THE PROBLEM OF GETTING THE CONCRETE TO DRY



THE PROBLEM

FIGURE 1.

In the period starting in the 1960s, lightweight concrete was most frequently placed over a light gage corrugated metal support as shown in Figure 1. The overlapping side joints in the corrugated metal were the only avenue for water to escape into the interior atmosphere of the building. Obviously, the initial new bituminous roof membrane did not allow the water to move into the outside atmosphere. As a result, the free water remained in the concrete for extended periods of time - sometimes as long as 8 to 10 years.

Figures 2, 3 and 4 show examples of roof membrane deterioration when exposed to water in a concrete deck for extended periods of time. Figure 2 shows a four-ply organic felt and asphalt roof which had been over a wet lightweight concrete deck in Iowa for almost 10 years while leaks developed and increased. A sample of the membrane was taken to the laboratory and the asphalt was extracted from the membrane by washing with solvent. The results show the bottom ply as rotted while the ply directly above it was slightly deteriorated; the two top plies were in near original condition. When the sample was removed from an area where no leaks had occurred, a sample of the lightweight insulating concrete was also removed. The concrete was found to contain 84% of its weight in water. This is water that was trapped during construction because the supporting steel did not vent.

Figure 3 shows a 3-ply coated organic asphalt roof taken from a school in Virginia. The roof was about 9 years old when the sample was taken. The membrane over the lightweight insulating concrete was severely rotted from the bottom up, with a 74% water content in the lightweight insulating concrete. The identical membrane was used over a wood fiber cement deck on the school gym and had no deterioration in the same time span.

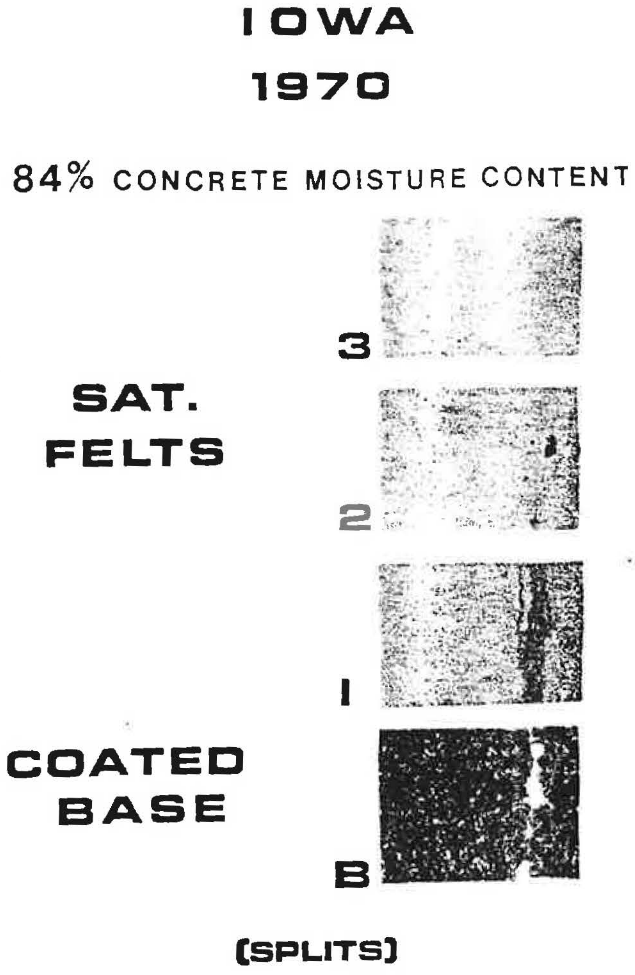


FIGURE 2.

ROTTING ROOFING FELTS
SHOWN BY ASPHALT EXTRACTION

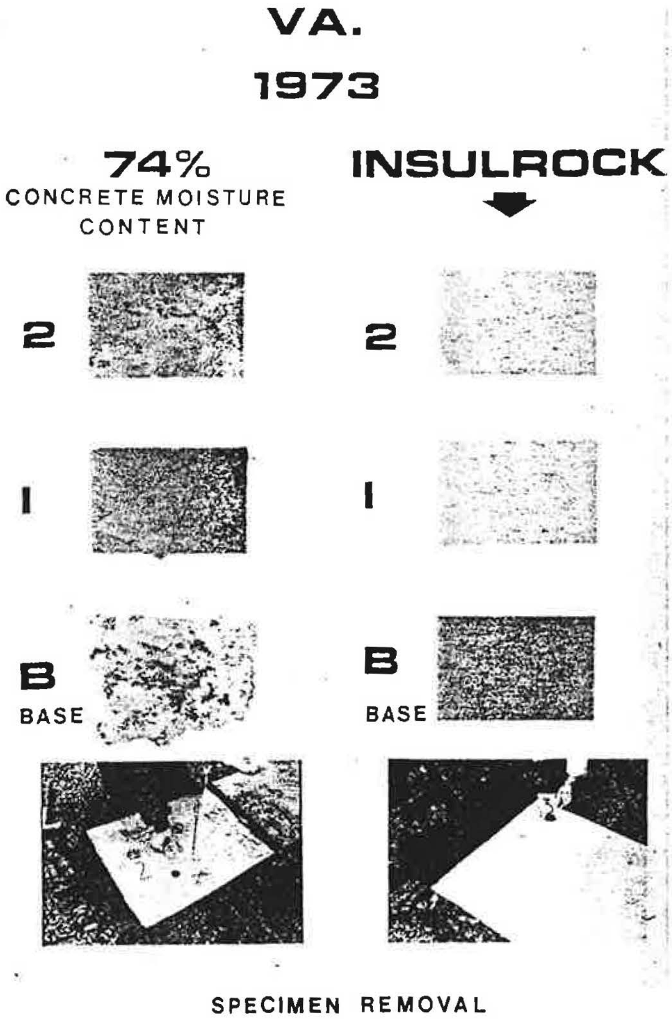
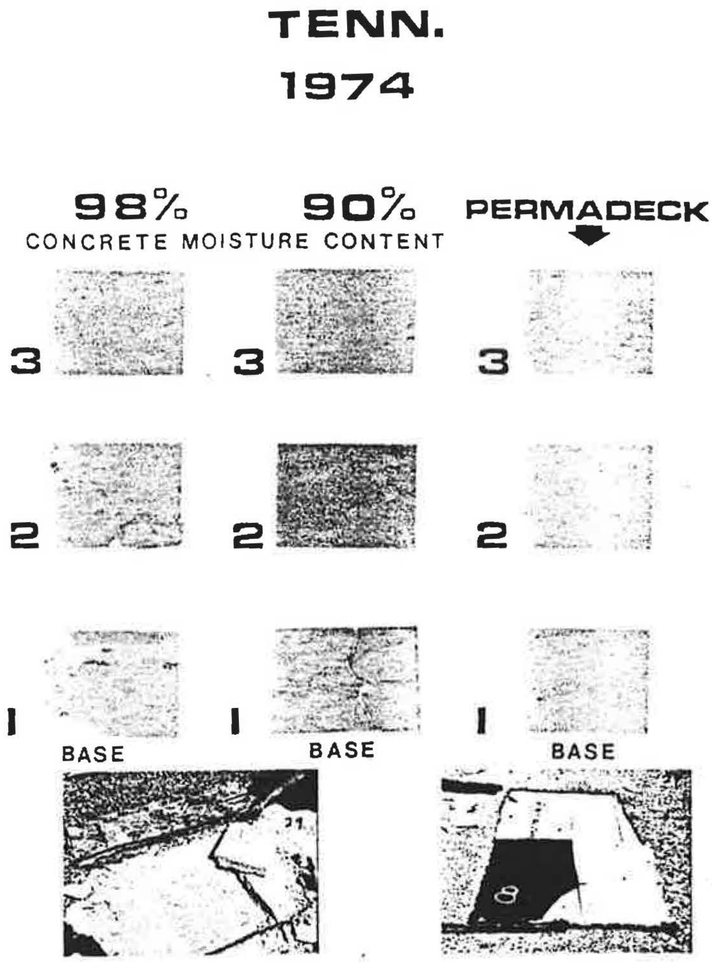


FIGURE 3.

ROTTING ROOFING FELTS
SHOWN BY ASPHALT EXTRACTION

Figure 4 shows a similar roof taken from a school in Tennessee. The two extracted samples of membrane taken from the lightweight insulating concrete were rotted from the bottom up, while the extracted sample from the wood fiber cement deck on the gym showed no deterioration after 8 years of service. It is obvious that the retained moisture in the concrete, averaging over 90%, was the cause of the rotting.



SPECIMEN REMOVAL

FIGURE 4.

ROTTING ROOFING FELTS
SHOWN BY ASPHALT EXTRACTION

Ideally, it would be most effective to allow the concrete to dry into the atmosphere before applying the roof but even this would take an extended period in ideal weather. In actual practice, the habit has been to apply the roof membrane to the deck as soon as the deck has set and becomes surface dry. This is usually done by the roofer, under pressure from the general contractor, within three to five days after the concrete has been placed. Thus, the major original free water is encapsulated between the steel forms below and the bituminous membrane above. In some instances the concrete is placed over another substrate such as structural concrete, prestressed structural tees, or concrete planks. In these latter cases there is very little more opportunity for the water to escape than in the case of the corrugated steel form supports.

MOISTURE MOVEMENT AND EVAPORATION IN LIGHTWEIGHT INSULATING CONCRETE DECKS

The behavior of moisture in lightweight insulating concrete conforms to the observable and known behavior of moisture in other construction. In summer the heat from solar radiation warms the top side of the concrete slab and drives the moisture downward into the lower areas of the concrete. In winter in the northern two-thirds of the United States the cold outer temperatures and warm inside temperatures reverse this process and concentrate the moisture in the top of the slab.

Laboratory tests have confirmed the movement of moisture in lightweight concrete under a temperature gradient of 50°F (100°F bottom surface and 50°F top surface). Slices of concrete from top to bottom were taken from a composite moist lightweight concrete deck made up of 1 inch of concrete over 1 inch of styrofoam bead board. These tests showed that the higher the average composite moisture, the more pronounced the moisture distribution. In one case the concrete and bead board had a composite moisture conof 67%. The top slice of concrete has a moisture content of 81%. One inch below the top, the moisture content of the concrete was measured at 30%. The bottom slice of 1-inch bead board had a moisture content of 12%. The density of the concrete was 23 pcf.

It became known in the Lightweight Concrete Industry by the early part of the 1970 decade that a lightweight concrete deck must be placed over an open supporting form if any degree of drying could be expected to take place. One spokesman for the Industry indicated in 1972 and 1973 that the optimum open area in supports was at least 3%.(5) Steel deck manufacturers quickly provided corrugated steel panels with slots in the flutes which provided 1.5% to 3% open area. In recent years the 3% open area slots have been reduced to 1.5% open area. It is believed that the reduction in open area came about because of run through of the liquid concrete and resulting contamination of items under the deck as it was placed and poured. In any case the common type of supporting steel panels available today are made of 28 gage steel and provide an open area of 1.5% through slots in the flutes.

Given this open area of 1.5% on the bottom side of the concrete slab, it is now possible to expect some degree of drying downward into the building interior. This assumes that the building interior will have a very low vapor pressure in order to remove the water through the openings. The only way for the water to leave is by evaporation into the interior. One manufacturer, W. R. Grace & Company,(6) suggests that any interior building atmosphere which has a relative humidity constantly exceeding 60% may not be acceptable for a lightweight concrete roof deck. Obviously, there may be a possibility that the vapor pressure gradient between the bottom of the deck and the interior would be too small to allow drying or might reverse itself and push water into the deck from a highly humid interior. It should be noted that most commercial and industrial buildings seldom have relative humidities as high as 60%.

It is commonly accepted that water vapor moves from the warm side of a construction toward the cold side if any avenues of movement are available. In the case of the lightweight insulating concrete deck, as stated above, the free water moves seasonally up and down in the concrete as a function of the season. The avenues of movement are based on the cellular structure of the portland cement paste itself and the aggregate - in this case, vermiculite. The free water is contained within the laminar structure of the aggregate but it can move within the interconnecting particles of aggregate. Unfortunately, the vermiculite is one of the better examples of an expanded mineral which can hold large quantities of liquid. In fact, one producer of expanded vermiculite promotes it as a vehicle which "can absorb large quantities of liquid chemicals in its internal pores" which makes it possible to transport high weights of active chemicals by moving the granular vemiculite when loaded with the chemicals.(7)

This affinity for holding liquids makes more difficult the elimination of free water from the concrete using vermiculite as an aggregate. This is true to a lesser degree in the case of perlite aggregate concrete and appreciably different with cellular or "foam" concrete.

The only major avenue available for removal of excess water and perhaps the only real avenue is evaporation into the interior of the building through permeability of the material which supports the lightweight concrete. Powell and Robinson of the NBS in Building Science Series 37(8) described the importance of permeability of the supporting structure for insulating concrete. Those initially wet specimens of insulating concretes tested over supporting structures with high porosity tended to reach a stable value of conductance and moisture content not greatly different from that of initially dry specimens exposed to the same cycles of winter and summer conditions. Those wet specimens placed over dense supports of low porosity and permeability lost moisture slowly.

In one specimen of lightweight insulating concrete placed over a glass fiber formboard which was quite permeable and of low thermal conductivity, Powell and Robinson stated that "Due to its comparatively high thermal conductivity the entire depth (3 inches) of the insulating concrete top layer was raised substantially in temperature during the solar heating part of the daily exposure cycle. The concomitant increased water vapor pressure in the moist permeable concrete promoted vapor escape through the permeable deck material (1" glass fiber formboard) and thus effected rapid drying of the specimen." In this case, the specimen was a 3-inch thick perlite insulating concrete placed over 1-inch glass fiber formboard. An obvious analogy to the glass fiber formboard in this experiment is the 3% or 1.5% open area of a corrugated steel supporting structure which receives and supports the lightweight insulating concrete pour. While the 1.5% open area may be a poor substitute for the formboard, it certainly is superior to the steel deck with no openings.

A numerical example of the mechanics of the evaporative process would be helpful in defining the requirements for drying of a lightweight insulating concrete deck. Powell and Robinson used as summer temperatures of the top surface of the above concrete a range of 75°F to 138°F and interior conditions of 75°F and 49% relative humidity. They further state that the entire depth of the concrete was raised substantially in temperature during the solar heating part of the cycle. If we assume the temperature of the top of the deck was a 138°F, we can estimate the bottom of the deck to be 100°F at that point in time. Thus, the water vapor on the bottom surface of the concrete is in a saturation state at 100°F.(9) Using Powell and Robinson's indoor temperature and relative humidity of 75 F and 49% RH, we can read the two vapor pressures as follows from Standard Steam Tables. (This ignores R value of formboard.)

1. Vapor pressure at bottom of concrete at saturation = .950 psia

2. Vapor pressure of inside air at 75°F and 49% RH equal .49 X .430 psia = .210 psia

Vapor pressure gradient = .740 psia

This is a very large vapor pressure gradient, and while it exists water will leave the bottom of the concrete and evaporate into the air inside the building.

Obviously, the temperature of the concrete in this example is a function of solar heat absorbed by the roof surface and will vary constantly; thus, the vapor pressure gradient will vary constantly subject to exterior and interior temperature and humidity variations. Drying will occur, however, as long as the vapor pressure gradient exists and there is an avenue of vapor escape from the concrete.

The obvious question to be asked by anyone contemplating a design utilizing lightweight insulating concrete is, "How long will it take to dry, and how dry will it get?" If no avenue of escape to the interior is provided, the answer is almost assuredly that it will never dry. If an adequate open area to the interior is provided, it will no doubt dry but calculations to predict when and how dry it will become are complex. Each building will have its own particular environment, both inside and outside, so the drying factors will be different for each building.

Test cuts have found some decks to have moisture contents as low as 3% after long term drying but it is not realistic to expect all decks to reach this low a moisture content. Indeed, it is not necessary for a deck to dry down to 3% to be acceptable as a functional component of a roof. The term "Equilibrium Moisture Content" has been used in relation to lightweight concrete decks. Equilibrium moisture content is defined as that moisture content at which the concrete is neither gaining nor losing moisture; it can be different for each building. In fact, Powell and Robinson have shown that moisture content varies with seasonal cycles. From a practical consideration, a moisture content of 10% to 15% is probably realistic as an estimated equilibrium moisture content for insulating concrete. This amount of moisture may reduce the theoretical thermal resistance to a minor degree but is probably low enough to represent minimum hazard to roof membranes. The Forest Products Laboratory sponsored by the U. S. Department of Agriculture has published an Equilibrium Moisture Content for wood in an environment of 70°F and 65% RH as 12%. This laboratory also suggests that at time of installation exterior woods average 12% moisture content in most areas of the United States.(10) Using wood as a guideline for equilibrium moisture content, the figure of 10% - 15% seems realistic for lightweight concrete roof decks.

More lightweight concrete decks are being specified at present in combination with a rigid styrofoam beadboard embedded in the concrete. The beadboard is generally placed at the bottom of the concrete fill and closer to the supporting steel deck. The beadboard is used to increase the overall thermal resistance of the assembly but it reduces the drying capability in at least two ways: it has about six times less permeability than the concrete itself, thus reducing vapor flow downward; and by virtue of its higher thermal resistance, compared to the concrete, it reduces the temperature at the interface of the concrete with the interior air. This reduces the temperature gradient which causes drying. As with monolithic lightweight concrete decks, it is imperative that the supporting element of this construction have as much porosity as possible. Figure 5 shows typical slotted steel corrugated supports which must be incorporated in this assembly.

FIGURE 5.

Photos of steel Tensilform/Tensilvent by Wheeling Corrugating Company Division of Wheeling-Pittsburg Steel Company

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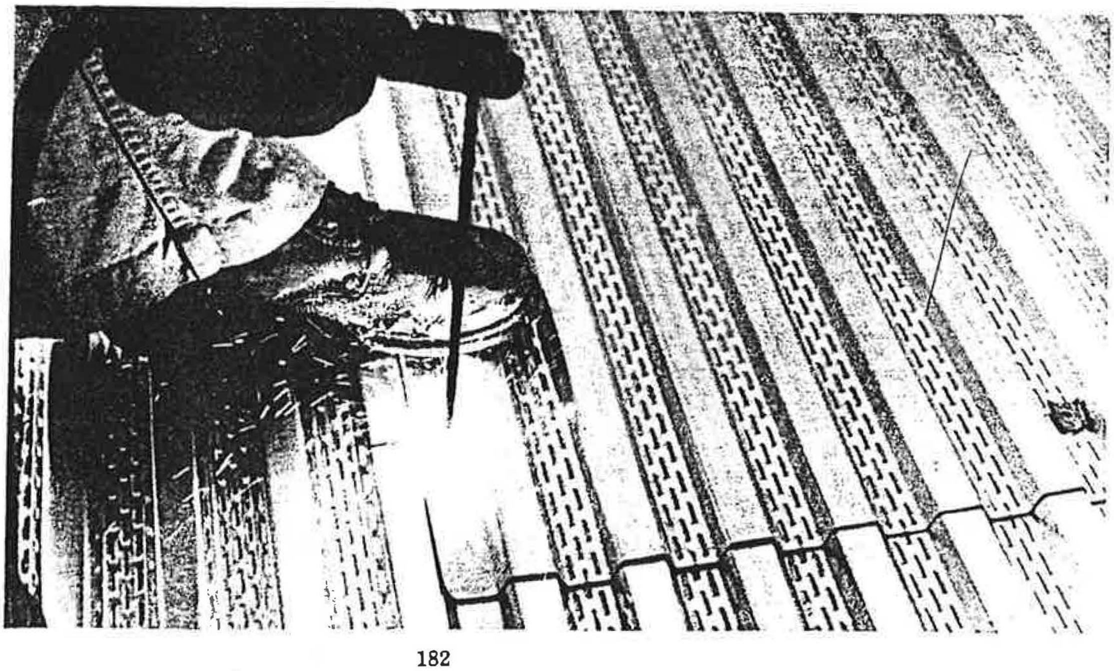
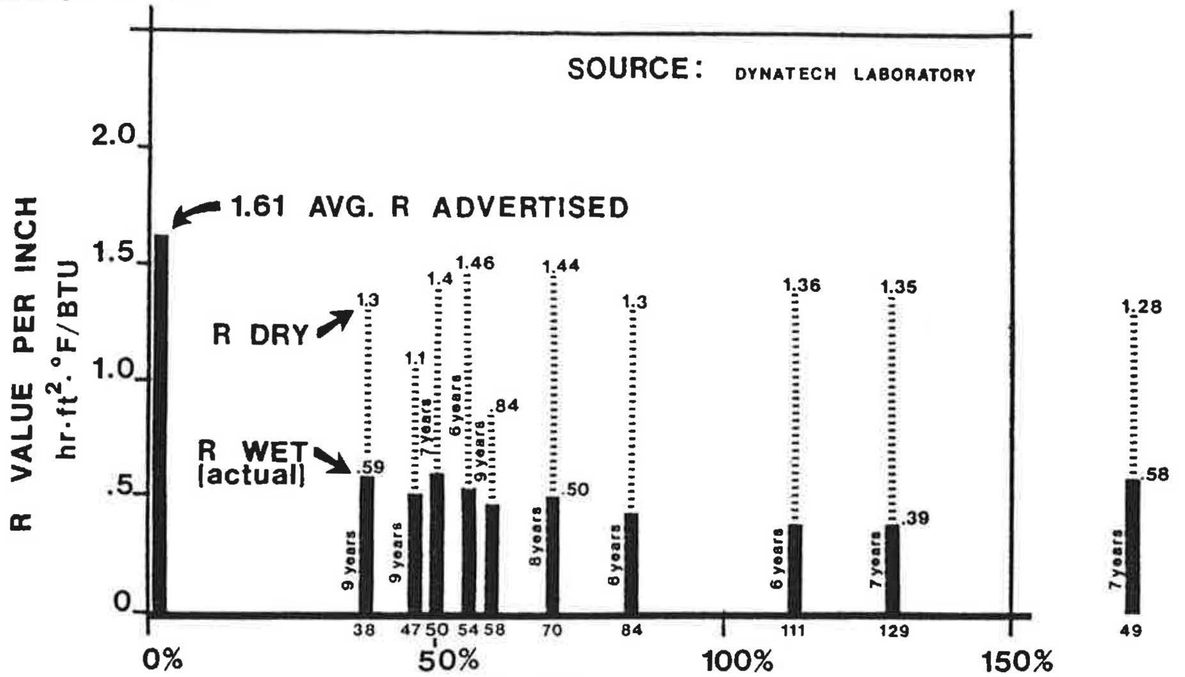


Figure 6 represents the R value or thermal resistance of monolithic lightweight concrete decks sampled from 10 different roofs which had failed as described above. None had any degree of open area under the concrete. The age of each roof is given from the time of construction to the time the sample was taken, and the roof was replaced soon after sampling. In each instance the sample of the deck was taken from an area of the building which had exhibited no history of leakage. The R value was measured in the wet condition and again after the deck had been oven dried. In no case did a dry R value reach the advertised value of approximately 1.61 per inch.(11)



R VALUES
VS.
PERCENT OF MOISTURE IN DECK
FROM TEN MEASURED SAMPLES

NOTES
- SOLID BARS SHOW R VALUE OF CONCRETE DECK AS REMOVED FROM ROOF WITH MOISTURE RETAINED
- MOISTURE PERCENT SHOWN AT FOOT OF BARS
- AGE OF DECKS SHOWN AT SIDE OF BARS
- DOTTED BARS SHOW R VALUE OF EACH DECK AFTER OVEN DRYING. COMPARE WITH ADVERTISED R VALUE OF 1.61

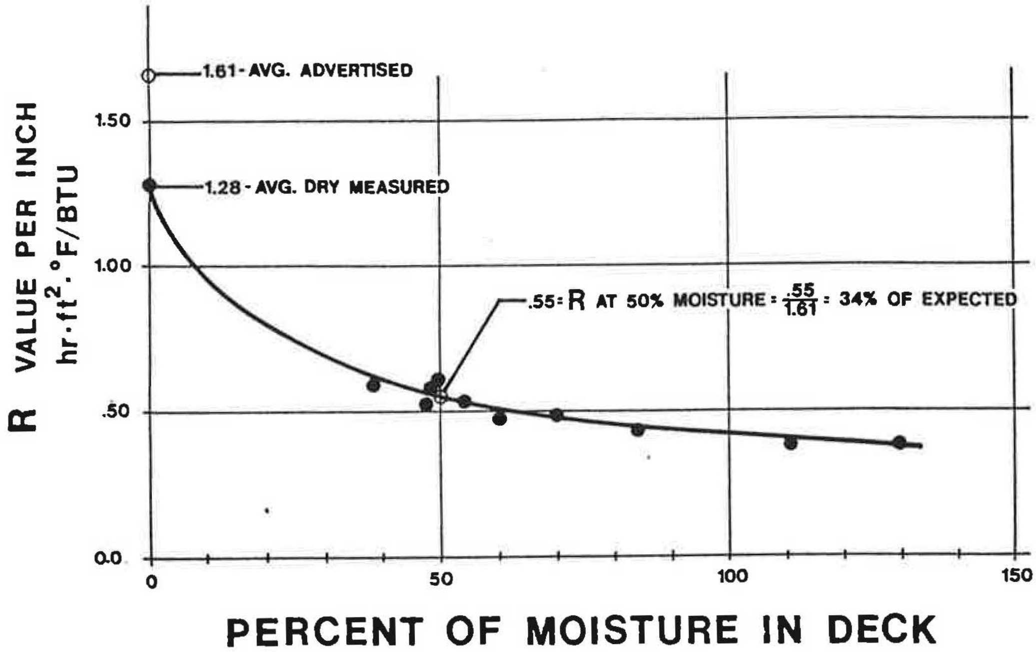
FIGURE 6.

Figure 7 is a curve plotted to show dry R values in Figure 6 for the ten sample decks tested.(12)

Figure 8 shows graphically the shrinkage character of lightweight vermiculite concrete. Three separate decks were sampled - from Florida, Ohio and South Dakota. The densities were different for each deck but in the range of 23 - 30 lbs. per cubic foot. Note that there is minimal shrinkage until the moisture content approaches 20%, at which point it rapidly increases. For decks where indications or design conditions anticipate an equilibrium moisture content below 10%, consideration should be given to adding a shrinkage reinforcing to the deck. Decks with very low moisture content have split and have, in some cases, caused a split in the roof membrane.(13)

CONCLUSIONS AND SUMMARY

Lack of attention by the designer and specifier in properly preparing a specification for the use of a lightweight concrete deck, either monolithic or as a composite with polystyrene beadboard, will doubtless lead to some long term problems in the roof membrane or in the expected thermal performance, or both.



ACTUAL R VALUE PER INCH
OF
LIGHT WEIGHT CONCRETE
IN
RELATION TO MOISTURE CONTENT
(BASED ON 10 TEST CASES
TAKEN FROM ROOFS)

FIGURE 7.

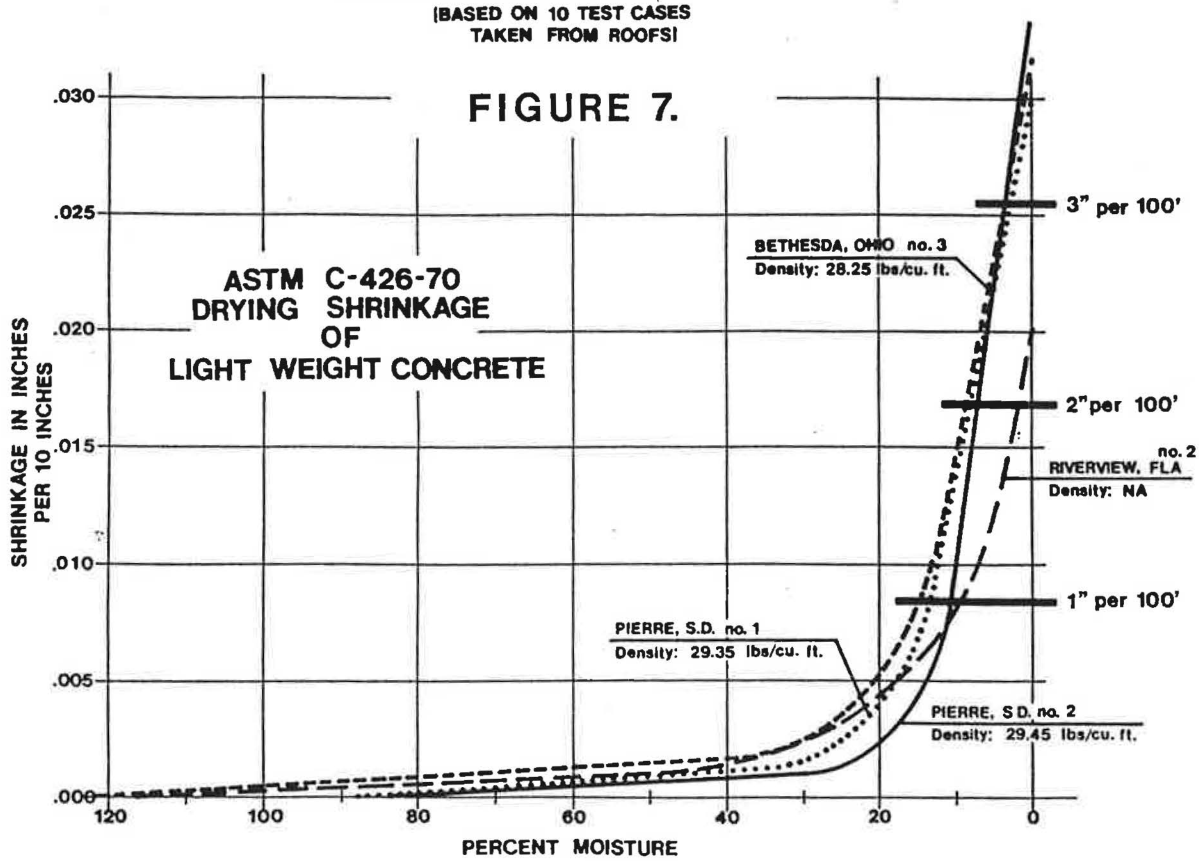


FIGURE 8.

Lightweight concrete decks are difficult to use in the northern two-thirds of the United States. not virtually dry by the first winter, there is a definite potential for freeze damage to the top sur-:e, with potential for loss of attachment and some potential loss of structural properties. This means ıt placing of these decks in the north must be done in late Spring or early summer. The obvious con-:raints on construction schedules emerge as serious consideration for the use of these decks in the north.

It is imperative that a realistic evaluation of expected vapor pressure gradients be made, with ıe allowance for error, in order to have a deck that has a chance to dry. The placement of wet concrete :ks over structures such as swimming pools, textile mills or other high humidity areas seems impractical best. The better choices for interiors are air conditioned interiors with no suspended ceiling below ; roof deck or plenums which are used to carry air conditioned air - even return air. Plenums containing ad air with no circulation are to be avoided under wet concrete decks. Warm, dead air in closed plenums n reach high relative humidities and restrict evaporation of the deck.

Some deck manufacturers promote the concept of venting the lightweight deck in a horizontal plane omitting any openings on the underside. These specifications call for placing a composite or monolithic ck over structural concrete or structural concrete tees or even over an old gravel roof. The possibil-ies of drying this deck appear remote, either by horizontal venting or by top venting through the roof mbrane. These systems need further investigation. The concept of top venting has been largely discredited being ineffective by several authorities in recent years.[8][14]

One last reminder is the consideration that the deck applicator be adequately supervised as he .aces and screeds the wet deck. Many architects use lightweight fills as an easy and inexpensive way to ıild slope into a dead flat structure. In any case, whether the deck is just to provide slope or to in-ılate and provide slope, it is imperative that the actual screeding be checked to assure that the slope is :tually built in properly. Many decks are screeded and left finished with low spots built in due to the ıck of care on the applicator's part. These low spots are areas for ponding water, and ponding water de-:roys roof membranes. There is no guarantee of good screeding and sloping unless there is supervision and ıspection of the work.

Finally, the designer should require a certificate from the deck material supplier that the deck ıets his standards and requirements. An added precaution is to require a Roof Bond or Warranty from the ɔofing material manufacturer; and if the construction budget can afford it, it is most desirable to have a ılltime knowledgeable inspector on the job for both the deck and the roof application.

EVAPORATIVE DRYING OF
LIGHTWEIGHT INSULATING CONCRETE ROOF DECKS

REFERENCES/BIBLIOGRAPHY

1. Portland Cement Association, "Design & Control of Concrete Mixtures" - Twelfth Edition, pages 128 - 131, 1979.

2. W. R. Grace Manual, Grace Construction Products Division, "Zonolite Roof Deck Insulation" 7.15 GE, Page 9. Printed in U.S.A. 1981.

3. S. A. Funk, Celotex Corporation, "Suggested Repair Specifications for Built-up Roofs Over Wet Lightweight Concrete Decks" - Proceeding of the Second International Symposium on Roofing Technology - Co-sponsored by the National Roofing Contractors Association, U. S. National Bureau of Standards and International Union of Testing and Research Laboratories for Materials & Structures, Gaithersburg, Md., Sept. 1985.

4. Frank R. Walker Company, publisher, Chicago, "The Building Estimator's Reference Book" nineteenth edition, pages 417 - 427.

5. John L. Wright, W. R. Grace & Company - Technical Presentation with Slides, "Poured Lightweight Decks" - Midwest Roofers Annual Convention, Colorado Springs, Colorado, November 8, 1972 and Presentation and Discussion with Slides, "Wet Decks Over Vermiculite Fills" - National Roofing Contractors Association Meeting at the National Bureau of Standards, March 21, 1973.

6. W. R. Grace & Company, Construction Products Division, "Zonolite Roof Insulation" - 1987 Sweet's Catalog No. 07220/GRA and earlier catalogs.

7. M. J. Horsch, Construction Consultants, Inc. Paper entitled, "Some Important Properties of Vermiculite and Vermiculite Concrete" Detroit, Michigan, September 17, 1980.

8. F. J. Powell and H. E. Robinson, "The Effect of Moisture on the Heat Transfer Performance of Insulated Flat-Roof Constructions" - National Bureau of Standards, Building Science Series 37, 1971.

9. ASHRAE Handbook, Chapter 3, "Mass Transfer" - 1977 Fundamentals Fourth Printing 1980, Page 3.1. Partial Pressure at a Wet Interface is the Saturated Vapor Pressure at Temperature T.

10. U. S. Department of Agriculture, Forest Products Laboratory, Wood Handbook Chapters 3 & 14, Handbook No. 72 1974.

11. DYNATECH R/D Company, Cambridge, MA. "The Apparent Thermal Conductivity of a Specimen of an Insulating Concrete Material. Prepared from ten lightweight concrete deck samples taken from ten different buildings by the Celotex Corporation in the period 1980 to 1982. R value data reported on each deck sample as taken containing water and after oven drying.

12. Same source and data reported by the Dynatech R/D Company in ref. (11) but drawn as a curve rather than bar graph. By determining moisture content of the concrete an approximate R value can be read directly from the curve.

13. Shrinkage curves showing effects of moisture loss on three lightweight concrete deck samples taken from actual decks in the field. Tests conducted for Celotex and results computed by Pittsburgh Testing Laboratory, Tampa, Florida in 1982.

14. W. Tobiasson, "Venting of Built-up Roofing Systems" from proceeding of 6th Conference on Roofing Technology pages 16 - 21. NBS & NRCA, 1981. Available from NRCA, Oak Park, Illinois. Also from CRREL, Hanover, N. H.