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*Research Paper*

# WATER PERMEABILITY IN FIBER REINFORCED PLASTIC (FRP) WRAPPED CONCRETE BEAMS

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Fiber Reinforced Plastic (FRP) has become an efficient strengthening method for existing concrete structures. In addition to strength addition, FRP wrapping is likely add to the long-tern durability of concrete structures. This may occur due to the reduction of water and chemical permeability and eventual reinforcement corrosion and concrete deterioration in FRP wrapped concrete. A theoretical determination of the reduction of water permeability in FRP wrapped concrete was performed herein. Finite element analysis was utilized using the ANSYS software to analyze the progress of water and its circulation in FRP wrapped concrete. Finite element programs do not usually address the issue of permeability or diffusion. Therefore, diffusion of water in FRP-concrete was modeled by an analogy with thermal conduction. Analytical results showed that FRP wrapping is very useful in decreasing the water ingress in concrete members. The water penetration is largest near the concrete surface, but becomes uniform over time. The water penetrates mostly near the bond-free surfaces near the beam supports. The moisture contents in the FRP, epoxy and concrete varies significantly based on the location and time.

***Keywords:*** FRP, concrete durability, Corrosion, Water permeability, Chloride permeability, Finite element modeling

## INTRODUCTION

Deterioration, damage, and defects in concrete structures are the main causes for concrete repair. Studies show, over 500 million cubic yards of concrete are replaced every year in the US alone. These repairs are needed to improve and prolong service life of these structures. Fiber Reinforced Plastic (FRP) wrap is an effective product used for rehabilitation and strengthening of concrete structures. The conventional FRP system is a fabric saturated with an epoxy resin, which is "wrapped" in layers on the concrete surface. FRP wrapping has been the most widely used in applications where seismic actions pose a threat to the strength and deformation capacity of an existing structure. Because of its cost-effectiveness and superior performance in

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strength, self-weight, corrosion resistance, blast resistance and earthquake protection, FRP is widely used in retrofitting projects. FRP composites have been used only for a few years for strengthening structural members in reinforced concrete bridges. It has been found FRP composite strengthening as an efficient, reliable, and cost-effective means of rehabilitation. FRP wraps have several advantages including high strength, light weight, resistance to corrosion, low cost and flexibility (Saadatmanesh *et al*., 1997).

Studies on bond durability show that moisture plays an important role in the reliability of the bond between FRP and concrete. The interfacial adhesion between FRP and concrete is at risk of moisture attack. Therefore, further investigation of the progress and circulation of moisture in FRP-wrapped concrete structures is needed. The objective of this study was to perform a finite element analysis of FRP wrapped concrete using ANSYS software to analyze progression of water ingress and its circulation. Some other software programs, such as COMSOL Multiphysics, also allow water permeability modeling or diffusion. Diffusion of water in FRP can also be modeled by an analogy with thermal conduction through ANSYS.

Significant prior research has been conducted on the modeling of the moisture diffusion in porous material, composite, and polymer. However, very little research has been conducted on the moisture transportation in multilayered structures containing FRP composites, polymer adhesive and concrete. Y Weitsman investigated the water attack on epoxy and mild steel joints. The results indicated that the deprivation of joints could be defined as the attainment of a critical moisture status at the bond interface (Weitsman, 1977). T Nguyen directly measured the moisture status at the bond interface of an epoxy covered concrete specimen. The results indicated that a few water molecule layers were present in the epoxy and concrete interface after the specimens were exposed to water for certain duration (Nguyen *et al.,* 1998). Ouyang and Wan conducted an experimental study to investigate the relation between the bond interface region, relative humidity, and fracture energy of FRP and concrete bond joints. The results showed that interface region relative humidity was one of the primary factors that affected the bond fracture energy of FRP and concrete specimen in a moist environment. Highly uneven moisture distribution along adhesive thickness, especially for a relatively short period of exposure, was found. The moisture in the interface mainly came from the bond free area close to the FRP and the sides of the specimen (Ouyang *et al*., 2008).

## THEORETICAL BACKGROUND

In order to model water diffusion into FRP, an adaption of the heat flow equations had to be used. Fick's first and second laws for diffusion in one dimension is as follows:

$$F = -D\frac{\partial C}{\partial x} \quad ...(1)$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial^2 x} \quad ...(2)$$

where, $F$ = heat flux; $C$ = concentration of diffusion; $x$ = distance; $D$ = diffusion coefficient; $t$ = time.

The corresponding heat transfer equations are:

$$F = -k\frac{\partial \theta}{\partial x} \quad ...(3)$$

$$\frac{\partial \theta}{\partial t} = (\frac{k}{c\rho})\frac{\partial^2 \theta}{\partial^2 x} \quad ...(4)$$

where, $\theta$ = temperature; *k* = thermal conductivity; $\rho$ = density; *c* = specific heat per unit mass (Mrotek *et al.*, 2001).

From Equations (1) to (4), diffusion can be modeled by equating temperature to concentration and the diffusion coefficient to thermal diffusivity. If it is assumed that the moisture forms an ideal solution in the polymer, then relative humidity can be equated to the concentration in the polymer, i.e., temperature in heat transfer. Without loss of generality, $c\rho$ can be taken as 1.0 and *D* equivalent to *k* (Mrotek *et al.*, 2001).

If the water needs to be modeled with different solubility, it should be noted that diffusion is controlled by activity gradient. The relative humidity is only equal to the molar concentration when the activity coefficient is equal to one. Activity, *a*, is defined in Equation (5).

$$a = \frac{PH_2O}{P_{sat}} = H = \gamma * x' \quad ...(5)$$

where, $\gamma$ *= activity coefficient (constant); *x'* = mole fraction of water polymer; $PH_2O$= partial pressure of water; *H* = relative humidity; and $P_{sat}$= saturated vapor pressure. The activity can be related to the concentration of moisture, *C*, by Equations (6) and (7) (Mrotek *et al.,* 2001).

$$a = \gamma_{eff} C \quad ...(6)$$

$$\gamma_{eff} = \gamma * f \quad ...(7)$$

where, $\gamma_{eff}$= effective activity coefficient; and f = conversion factor between concentration in the polymer and vapor pressure in the surrounding air. The activity is equal to the relative humidity. Therefore, the relationship between the relative humidity and concentration of moisture can be expressed as in Equation (8).

$$H = \gamma_{eff} C \quad ...(8)$$

By combining Equations (1), (2) and (6), Equation (9) may be obtained:

$$D' = \frac{D}{\gamma_{eff}} \quad ...(9)$$

where, *D'* = Modified diffusion coefficient

The solubility of water in the polymer, $C_\infty$, is the concentration of moisture in equilibrium with 100% humidity in the surrounding air. From Equation (8),

$$C_\infty = \frac{1}{\gamma_{eff}} \quad ...(10)$$

Thus, different solubility can be accounted for by varying the effective activity coefficient. A polymer with high solubility will have a low coefficient. An equivalency between the diffusion and heat transfer parameter is needed to model different solubility in ANSYS. Table 1 shows the equivalency of diffusion and heat transfer. According to Ouyang and Wan, moisture potential can be included via Kelvin-Laplace equation in the form of relative humidity, as shown in Equation (11) (Ouyang *et al.*, 2008):

**Table 1: Diffusion and Heat Transfer Parameter Equivalency Table**

| Diffusion | Heat Transfer |
|---|---|
| RH | T |
| $\frac{D}{\gamma_{eff}}$ | k |
| D | $\frac{k}{c\rho}$ |
| | $\rho$ = 1 ( for convenience) |
| | $c = \frac{1}{\rho\gamma_{eff}}$ |

$$\varphi = \frac{RT}{W_u}\ln(H) \qquad ...(11)$$

where, $\phi$ = moisture potential; $T$ = temperature in Kelvin; $W_u$ = molecular weight of the water; $R$ = gas constant, and $H$ = relative humidity.

Polymer and composites are nonporous materials for which the moisture diffusion is controlled by the water activity gradient for a given temperature. The relative humidity can be considered equivalent to the water activity gradient for the nonporous materials. Equations (12), (13) and (14) can be derived in terms of relative humidity for concrete, epoxy and FRP, respectively:

$$\frac{\partial H}{\partial t} = \nabla\{D^c(H)x\nabla H\},$$

For concrete ...(12)

$$\frac{\partial H}{\partial t} = \nabla\{D^e(H)x\nabla H\},$$

For epoxy ...(13)

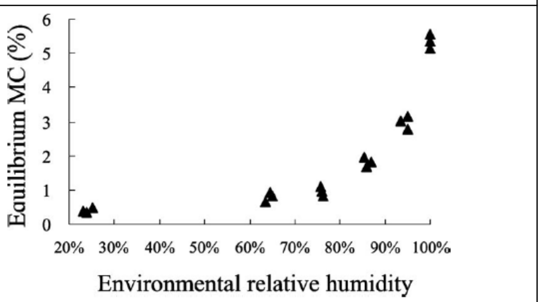
$$\frac{\partial H}{\partial t} = \nabla\{D^f(H)x\nabla H\},$$

For FRP sheet ...(14)

where, $D^c(H)$, $D^e(H)$ and $D^f(H)$ = moisture diffusivity of concrete, epoxy and FRP, respectively.

Ouyang and Wan showed that diffusivity of concrete is nearly constant for relative humidity greater than 90% and lower than 70% (Ouyang *et al.*, 2008). However, the diffusivity drastically decreases in between 70-90% relative humidity. As explained previously, diffusivity represents conductivity and relative humidity represents temperature in the ANSYS modeling. The diffusivity of epoxy normally decreases with the increase of relative humidity of epoxy, as seen from available test data. This trend is opposite to that in concrete. The environmental RH can be transferred to moisture content in the form of weight percentage in concrete through isotherm curves of concrete, as shown in Figure 1.

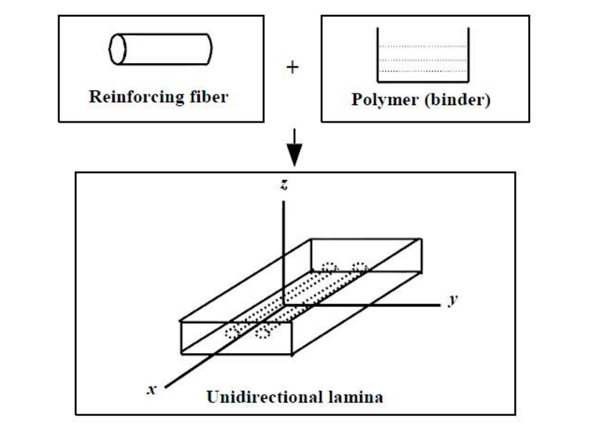
**Figure 1: Moisture Isotherm Curve of Concrete (Nguyen *et al.,* 1998)**




## Finite Element Modeling

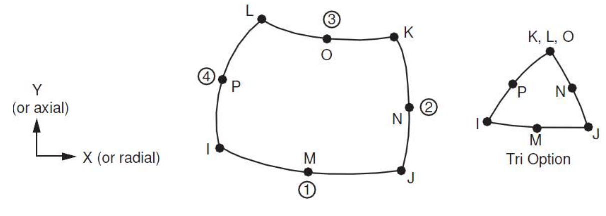
FRP composites consist of two constituents that are combined at the macroscopic level: the reinforcement, which is embedded in the second constituent, a continuous polymer called the matrix. The reinforcing material is in the form of fibers such as carbon and glass, which are typically stiffer and stronger than the matrix. The FRP composites are anisotropic in nature. As shown in Figure 2, the unidirectional laminas have three mutually orthogonal planes of material properties. The orthotropic material is also transversely isotropic. Thus, the properties in the *y* direction are the same as those in the *z* direction (Kachlakev, 2006).

**Figure 2: Diagram of FRP Composites (Saadatmanesh *et al.,* 1997)**




ANSYS PLANE77 was used here in to model the FRP sheet. The element has one degree of freedom, temperature, at each node. The 8-node orthotropic element has compatible temperature shapes and is well-suited to model curved boundaries like FRP wrapping. The thermal element is applicable for a 2-D steady-state or transient thermal analysis. The geometry, node locations, and the coordinates system for this element are shown in Figure 3. A triangular shaped element may be formed by defining the same node number for nodes K, L, and O. Orthotropic material directions correspond to the element coordinate directions. Specific heat and density are ignored for steady-state solutions. Heat generation rates may be input as element body loads at the nodes.

**Figure 3: PLANE77 Element Geometry (Weitsman, 1977)**




A vital step in finite element modeling is the selection of the mesh density. A convergence of results is obtained when a sufficient number of elements are used in a model. This is achieved when an increase in the mesh density has an insignificant effect on the results. In this finite element modeling, ANSYS smart mesh tool was used to mesh the model and achieve convergence. A nonlinear analysis approach was used herein. At the completion of each incremental solution, the stiffness matrix of the model was adjusted to reflect nonlinear changes in structural stiffness before proceeding to the next load increment. The program carried out a linear solution, using the out-of-balance loads, and checked for convergence. If the convergence criterion was not satisfied, the out-of-balance load vector was re-evaluated, the stiffness matrix was updated, and a new solution was attained. This iterative procedure continued until the model converged. For the nonlinear analysis, automatic time stepping in the ANSYS program predicted and controlled load step sizes. The maximum and minimum load step sizes were required for the automatic time stepping. Concrete was meshed with the finer size of 1 and the epoxy and FRP layers were meshed with a coarser mesh size of 6 (ANSYS, 1998).

## MODEL OF FRP WRAPPED BEAMS

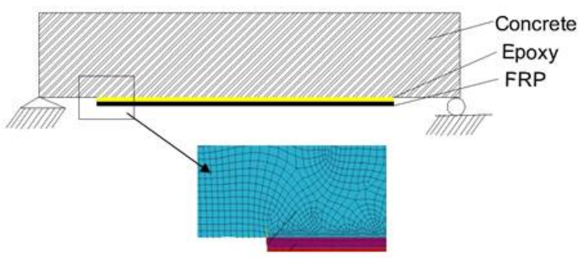
The analysis of an FRP wrapped concrete beam was considered herein as a two-dimensional problem. It was also assumed that the diffusivity is independent of the direction in the materials. Although diffusivity is dependent on the FRP fiber direction, both directions in the 2D model were perpendicular to the FRP fiber direction. Therefore, in the 2D model, only the diffusivity of FRP perpendicular to the fiber direction was needed. As discussed before, the analogy between thermal and diffusion analysis for input and output variables was used. Temperature represented relative humidity and thermal conductivity represented the diffusion coefficient.

The environmental RH is typically different at various times during a day. The average environmental RH in the cities of Houston and Corpus Christi, Texas, USA, is about 90% in the morning. The average daily environmental RH of Dallas, Texas, U.S.A., is 64%. Therefore, the model beams were exposed to two different environmental RH: 100% and 64%.

A simply supported beam wrapped with FRP normally has a small bond free area next to the support (Figure 4). The bond free area is due to the difficulty in FRP wrapping created by the supports.

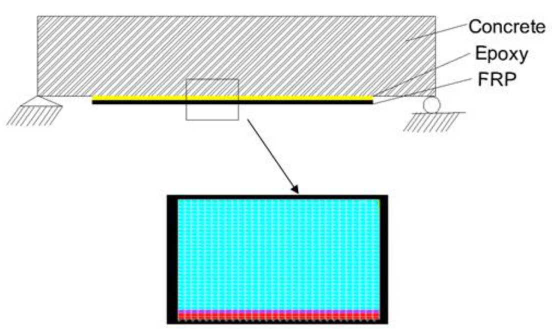
This is vulnerable to moisture attack. A small area, as shown in Figure 4, was analyzed herein to determine moisture movement. Analysis was focused on the water permeability of the FRP matrix. The dimensions of the model used were: concrete 38 mm x 38 mm, FRP thickness of 2 mm, and epoxy adhesive thickness of 1.2 mm. The model beam was also analyzed for 10 years of exposure time frame, assuming a constant diffusion coefficient.

**Figure 4: Bond Free Areas Near Support in FRP Wrapped Simply Supported Beam**




The area of the middle part of the beam, as shown in Figure 5, was also analyzed to see the moisture movement. The moisture movement in the bond-free section and the middle section of the beam were compared.

**Figure 5: Bonded Areas at the Middle Section of FRP-Wrapped Simply Supported Beam**




The diffusion coefficient of the selected FRP was obtained from a published inspection report (Xian, 2008) while those for epoxy and concrete were taken from a previous research paper by (Ouyang *et al.*, 2008). Table 2 shows the values used in this finite element analysis for a 7-56 day time interval.

As discussed previously, the diffusion coefficient of concrete and epoxy vary with time. The FRP diffusion coefficient does not depend on temperature. The analogy between thermal and diffusion analysis for input and output variables were used. Temperature represented relative humidity and thermal conductivity represented the diffusion coefficient. Some of the assumptions and corresponding justifications are given in Table 3.

## RESULTS AND DISCUSSION

Figure 6 presents the material RH contour in a bond free area in the beam near the supports. The largest material RH was at the edge parts of the FRP and concrete. It decreased closer to the middle of the model,

**Table 2: Diffusion Coefficient with Relative Humidity**

| Material | Diffusion Coefficient($m^2/s$) | Relative Humidity(%) | Days |
|---|---|---|---|
| Concrete | $0.05 \times 10^{-12}$ | 40 | 7 |
| Concrete | $0.05 \times 10^{-12}$ | 45 | 14 |
| Concrete | $0.133 \times 10^{-12}$ | 68 | 28 |
| Concrete | $0.5 \times 10^{-12}$ | 80 | 56 |
| Epoxy | $10.32 \times 10^{-14}$ | 40 | 7 |
| Epoxy | $10.00 \times 10^{-14}$ | 45 | 14 |
| Epoxy | $6.34 \times 10^{-14}$ | 68 | 28 |
| Epoxy | $4.64 \times 10^{-14}$ | 80 | 56 |
| FRP | $3.0 \times 10^{-15}$ * | - | - |

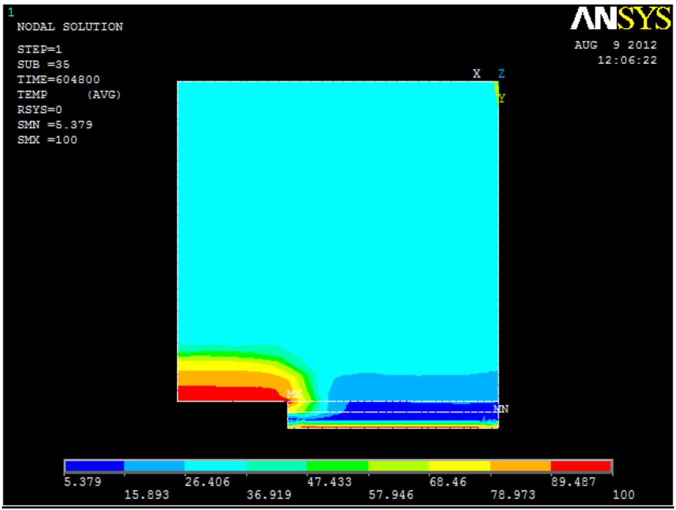
**Note:** *Obtained from an inspection report.

**Table 3: Assumptions and Justifications**

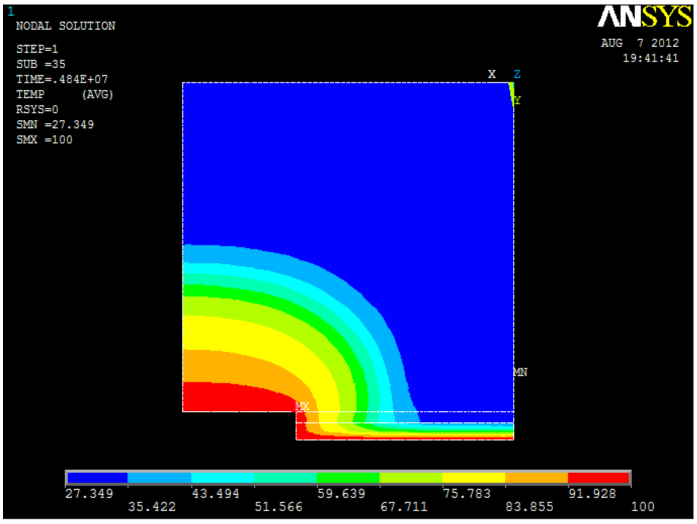
| Assumptions | Justification |
|---|---|
| Moisture flux in longitudinal direction =0 moisture transport. | Under isothermal condition, there is no heat flux affecting the |
| Initial uniform pore RH of concrete = 30% | To treat the concrete as mature specimen. |
| Initial RH of FRP and epoxy = 0% | Epoxy and FRP initially dry. |
| Surrounding environmental RH (1) = 100% to speed up the moisture uptake. | Morning environmental RH of Houston area is above 90% and |
| Surrounding environmental RH (2) = 64% | Average yearly environmental RH of Dallas is 64%. |
| Density =1Specific heat per unit mass = 1 taken care of when finding diffusion coefficient[4]. | Already taken care of when finding diffusion coefficient[4]. Already |

**Figure 6: Moisture Contours for Bond Free Areas near Support of Beam**

**(a) 7 Days**




**(b) 56 Days**



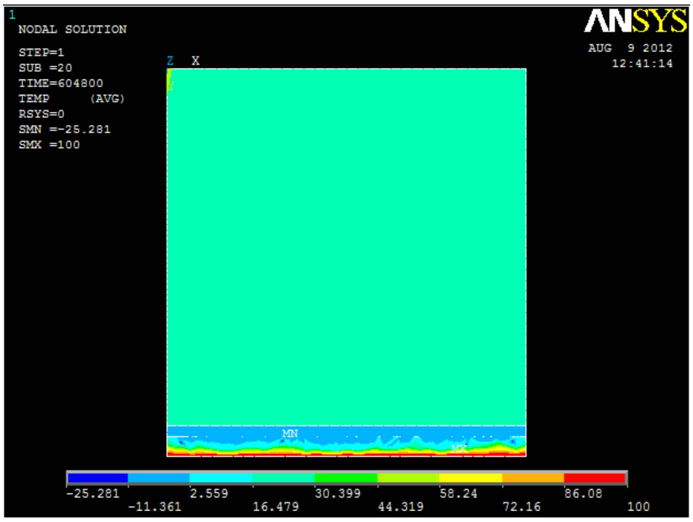

which is expected. The differences in the pattern of material RH show that moisture moved inside the beam with time. More RH variation in epoxy can be noticed in Figure 6b. This could have resulted from the diffusion coefficient of epoxy, which decreases with increased time.

Figure 7 presents the material RH contours in the bonded area at the middle of the simply supported beam. The largest material RH still occurred at the edge part of the FRP and concrete. There is a large difference in relative humidity of concrete, epoxy and FRP.

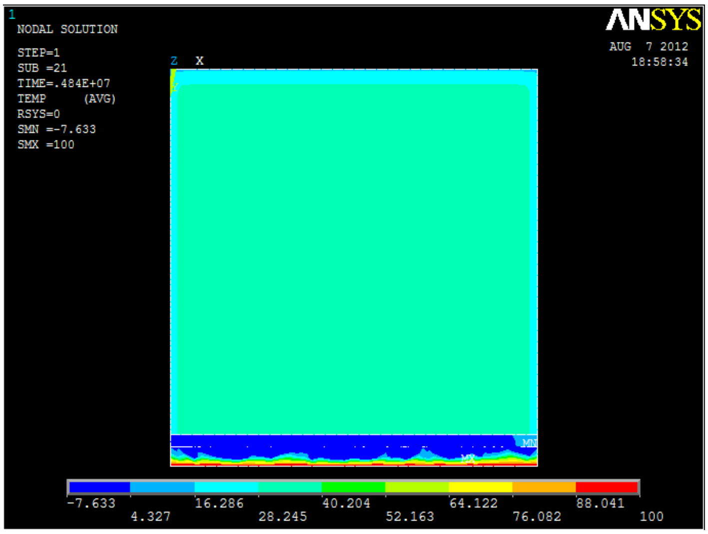
Figure 8 shows the graphs of moisture movement up to 56 days when the model is exposed to 100% environmental RH. As per Figure 8a, the material RH of concrete at 56 days is 76.6%. Values at 15 mm have a higher

**Figure 7: Moisture Contours for Bonded Areas Near Middle of Beam**

(a) 7 Days




(b) 56 Days

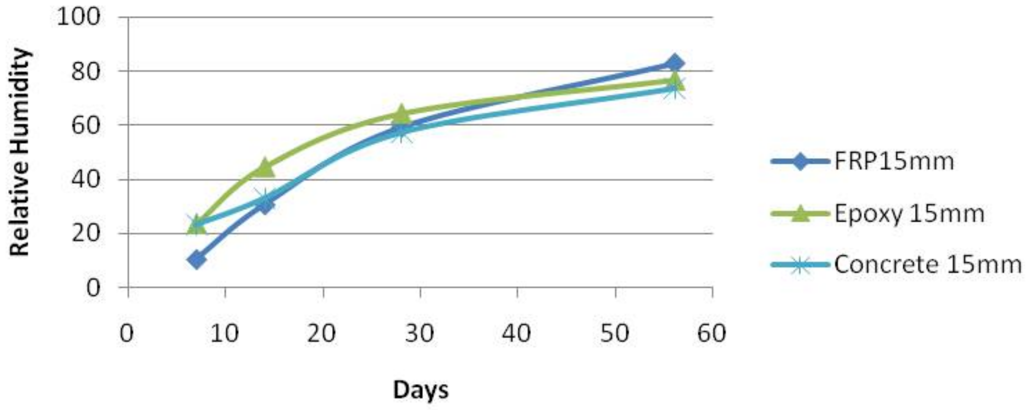



material RH as compared to the values at 30 mm. It demonstrates that material RH decreases away from the FRP edge.

Figure 9 shows the moisture movement up to 56 days at a middle section of the FRP-wrapped beam. This epoxy graph is plotted at the inner surface of the 2 mm FRP, and at 38 mm transverse direction for concrete. The relative humidity is 1.9% from the finite element analysis at 56 days. This shows that water movement is less in this region of the beam when compared to the bond free area near the support. The concrete relative humidity stays the same as the initial condition. As described before, concrete was modeled with 30% RH initial condition. The RH of concrete at 38 mm in transverse direction from the edge of the beam remained at 30% after 56 days,

**Figure 8: Time Dependent Moisture Contours for 100% Environmental RH at Bond-free Area**

(a) at 15 mm from FRP Edge




(b) at 30 mm from FRP Edge

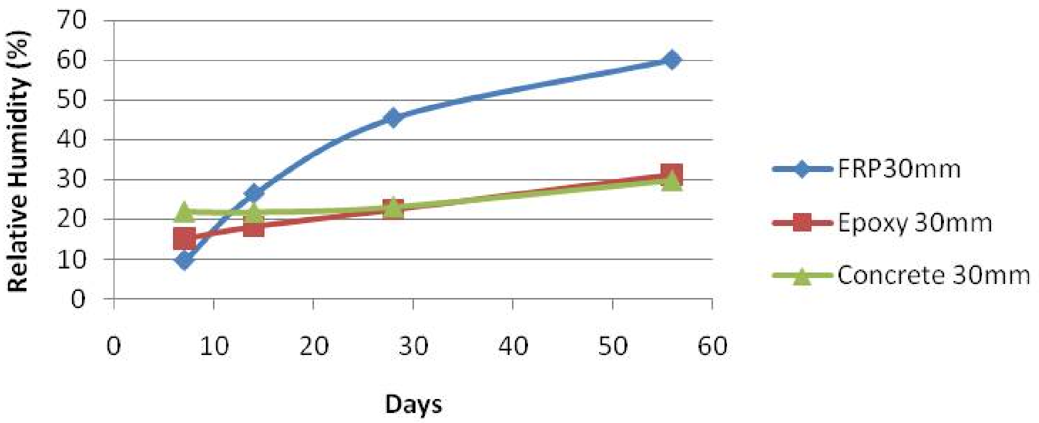
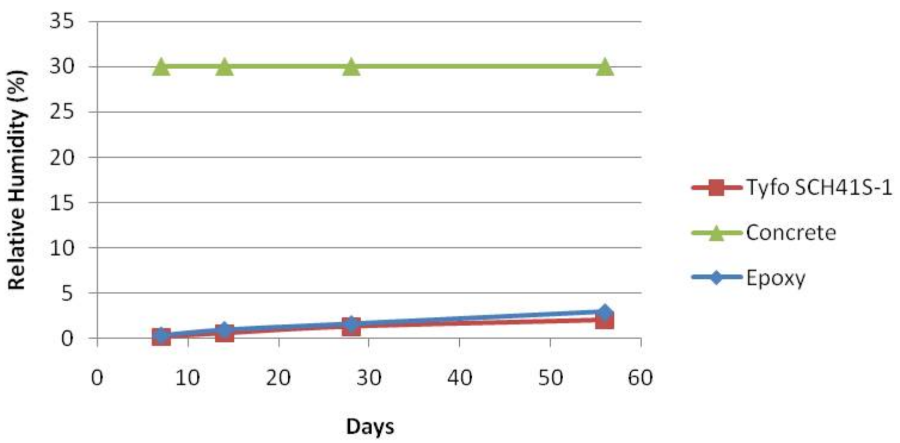



**Figure 9: Time Dependent Moisture Contours for 100% Environmental RH at Middle Section of the Beam**



which means that there is minimal risk of moisture attack for concrete.

Figure 10 shows that concrete RH is 40.17% at the 15 mm location when the model was exposed to 64% environmental RH. From isothermal curve, 40.17% RH is equal to 0.5% equilibrium moisture content in concrete. Comparing the material RH from Figures 8 and 10, it may be inferred that higher environmental RH increased the material RH.

A comparison of moisture contents in a control beam without FRP and one with FRP is made in Figure 11. This clearly shows that the beam with FRP and epoxy layer had very little or no moisture intrusion. The material RH of concrete is 73% in the beam without epoxy and FRP. From isotherm curve, 73% RH is equal to 1.1% equilibrium moisture content in concrete. This demonstrates that the FRP and epoxy plays a significant role as a moisture barrier, resulting in possible reduction of steel corrosion and concrete deterioration.

To gauge long term affects, the results for 10 years with 64% environmental RH,

**Figure 10: Time Dependent Moisture Contours for 64% Environmental RH at Bond-Free Area**

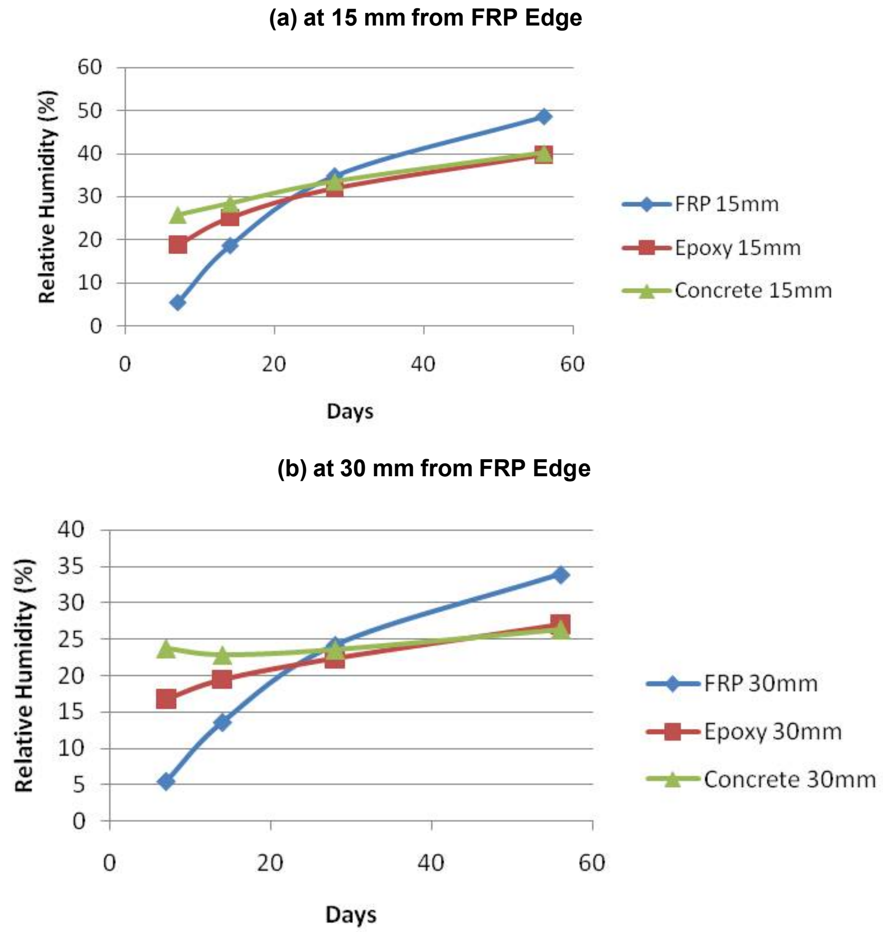


**Figure 11: Moisture Contours in Control Beam and FRP Wrapped Beam, 64% Environmental RH**

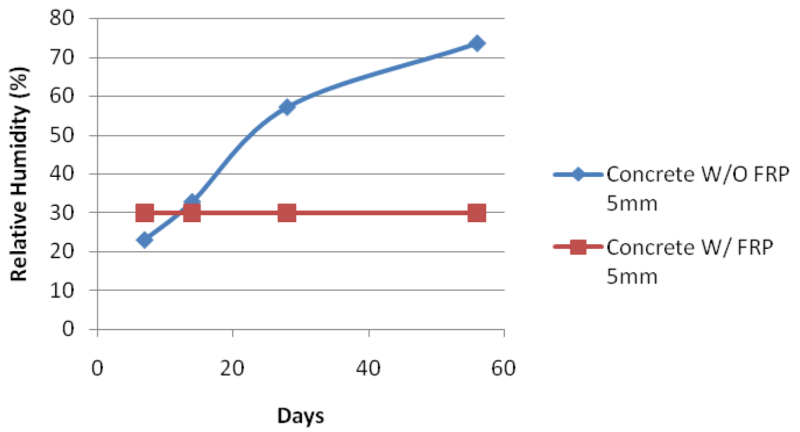
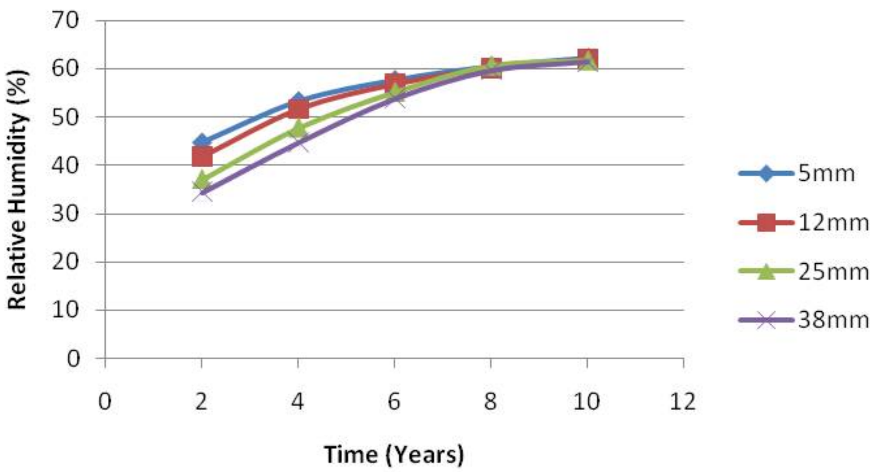



**Figure 12: Moisture Contours in Concrete for 10 Years with 64% Environmental RH**




assuming a 56 day diffusion coefficient as valid, were plotted in Figure 12. This graph was plotted for concrete at 38 mm horizontal distance and at 5 mm, 12 mm, 25 mm and 38 mm vertical distance from the edge of the beam. This graph shows that the material RH decreases with increased vertical distance from the edge of the beam, but converged after 8 years of service at about 60%.

## CONCLUSION

The following conclusions may be made based on the results from this study:

1. FRP wrapping is useful in decreasing the ingress of water in concrete members. Moisture content in concrete beam without FRP wrapping is higher as compared to the concrete with FRP and epoxy layers. For short term, the moisture ingress in concrete with FRP is negligible, while the moisture intrusion in concrete without FRP can be significant (as high as 50% gain over two months).

2. The water ingress is maximumin concrete near the surface and decreases by about

10% at about 38 mm from the surface. Over long term (8-10 years), the water saturation inside the beam becomes independent of the distance from the surface to about 60%, or 30% increase with time.

3. Moisture ingress in a FRP wrapped simply supported beam is mainly due to intrusion at the bond free area near the supports. Water movement in FRP and concrete is higher in the FRP bond-free area than in the bonded area of the beam.
4. The water movement inside the FRP, epoxy and concrete tend to increase with increasing exposure time to saturated outside water exposure. This tendency is more pronounced at the bond free area near supports. The time dependency is larger in the FRP layer than in the epoxy and the underlying concrete. The water movement increase with time is not significant in the bonded area.
5. It was found that lower external water presence resulted in smaller water ingress inside the beam, as compared to the saturated condition.
6. Moisture moves from FRP terminating area and travels longitudinally towards middle of the beam with time.

## ACKNOWLEDGMENT

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## Symbols

$\gamma^*$ =Activity coefficient

$\gamma_{eff}$ = Effective activity coefficient

$\rho$ = Density

$\theta$ = Temperature in celsius

$\varphi$ = Moisture potential

$c$ = Specific heat per unit mass

$C$ = Concentration of diffusion or moisture

$C_{\infty}$ = Concentration of moisture in equilibrium with 100% humidity in the surrounding air

D = Diffusion coefficient

$D^2$ = Modified diffusion coefficient

$D^c(H)$ = Moisture diffusivity of concrete

$D^e(H)$ = Moisture diffusivity of epoxy

$D^f(H)$ = Moisture diffusivity of FRP sheet

$f$ = Conversion factor between concentration in the polymer and vapor pressure in the surrounding air

$F$ = Heat flux

$H$ = Relative humidity

$k$ = Thermal conductivity

$PH_2O$ = Partial pressure of water

$P_{sat}$ = Saturated vapor pressure

$R$ = Gas constant

$RH$ = Relative humidity

$t$ = Time

$T$ = Temperature in Kelvin

$W_u$= Molecular weight of the water

$x$ = Distance

$x'$ = Mole fraction of water polymer