ESTIMATION OF THE HYGRO-ELASTIC PROPERTIES OF A CARBON/EPOXY COMPOSITE TAKING INTO ACCOUNT HYGROMECHANICAL COUPLINGS

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OUTLINE

1. Scope and objectives
2. Materials and methods
3. Results and discussion
4. Perspectives and further studies

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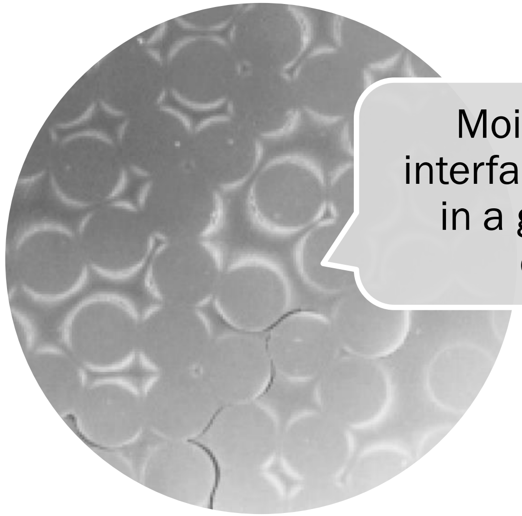
During their service life, composite materials are subjected to combined mechanical loads in humid environments…

Reversible plasticization of the material

"Differential swelling" of the hygroscopic constituents

Irreversible degradation of the composite & formation of micro-cracks



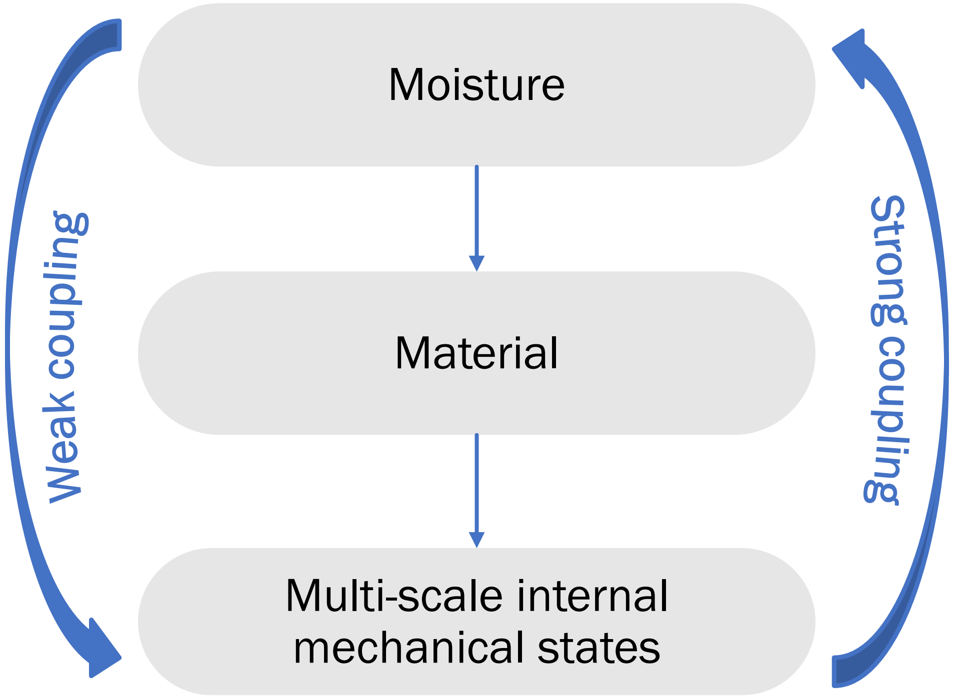
Moisture-induced interfacial micro-cracks in a graphite/epoxy composite

Weitsman and Elahi (2000)

Rising need to understand the hygromechanical behavior of composites by developing multi-scale numerical tools

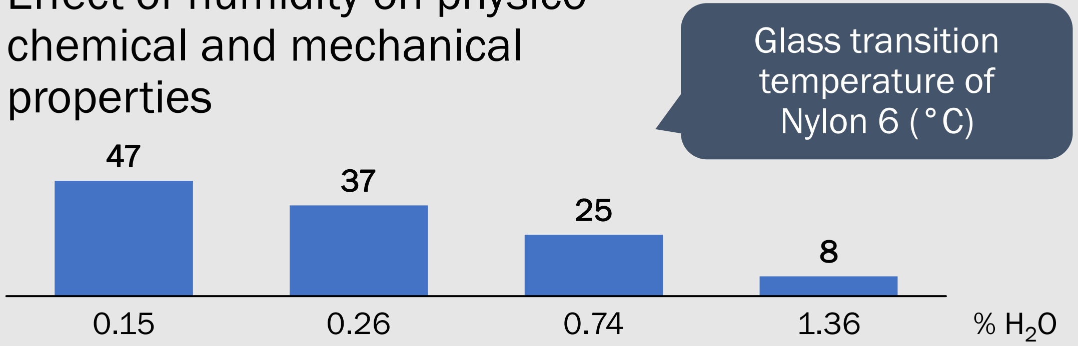
IMPORTANT RELATIONSHIPS BETWEEN WATER AND THE MECHANICAL BEHAVIOR OF POLYMER MATERIALS AND THEIR COMPOSITES PROVE THE EXISTENCE OF A HYGROMECHANICAL COUPLING...

Hygromechanical coupling



Weak coupling

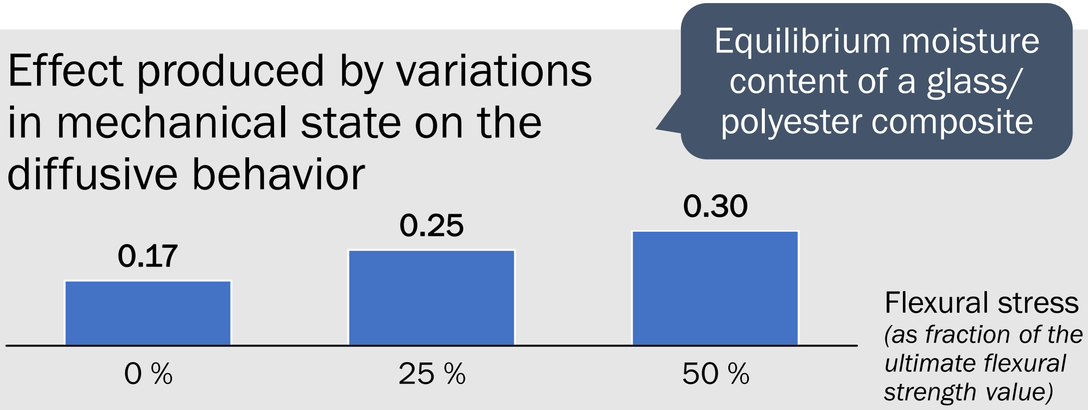
Effect of humidity on physico-chemical and mechanical properties



Jia et al. (2004)

Strong coupling

Effect produced by variations in mechanical state on the diffusive behavior



Autran et al. (2002)

Objective...

Develop a numerical tool that will:

- Combine the weak and strong hygromechanical coupling phenomena in a carbon/epoxy composite
- Predict the evolution of the properties and the mechanical states

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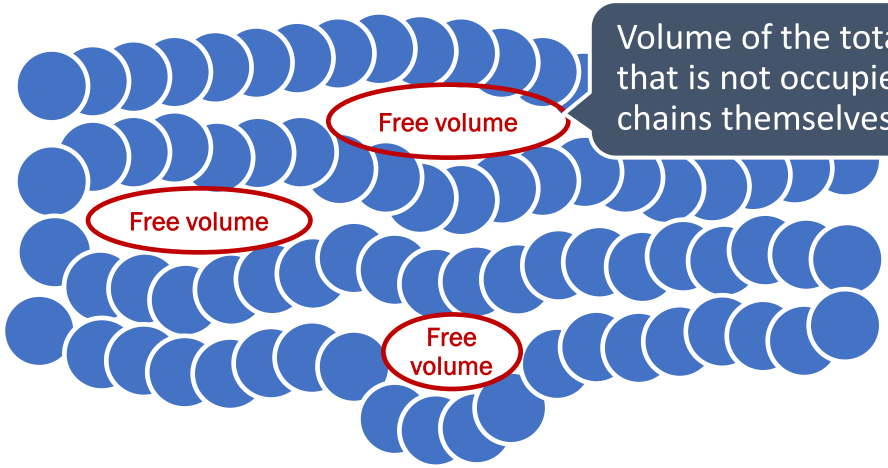
THE STRONG COUPLING IS REPRESENTED BY THE **FREE VOLUME THEORY**, THAT ATTRIBUTES THE VARIATION OF THE DIFFUSION PARAMETERS TO A CHANGE IN THE FREE VOLUME…

Free volume variation

$$\ln \frac{D_\varepsilon^m}{D_0^m} = \frac{a}{v^m} \mathrm{Tr}(\varepsilon^m) \frac{1}{v_{f0}^m \left[v_{f0}^m + \mathrm{Tr}(\varepsilon^m)\right]}$$

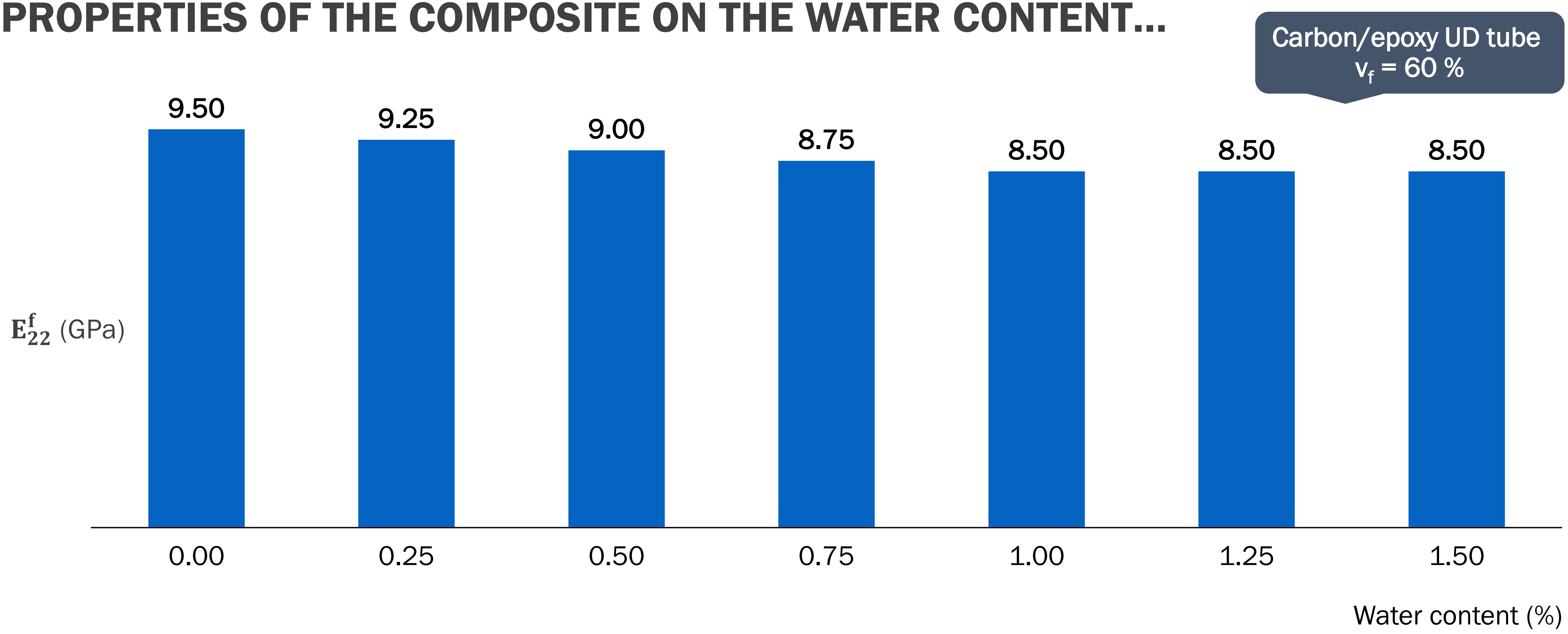
$$M_\varepsilon^m = M_0^m + \mathrm{Tr}(\varepsilon^m) \times \frac{\rho^w}{\rho^m}$$



Volume of the total material, that is not occupied by polymer chains themselves

- D_0^m and D_ε^m: diffusion coefficients for the strain-free matrix and the strained matrix, respectively
- M_0^m and M_ε^m: maximum absorption capacities for the strain-free matrix and the strained matrix, respectively
- a: adjustment parameter *(from literature)*
- v^m: volume fraction of matrix in the composite
- $\mathrm{Tr}(\varepsilon^m)$: trace of the strain tensor experienced by the matrix
- v_{f0}^m: free volume fraction of the strain-free matrix
- ρ^w: water density
- ρ^m: matrix density

THE WEAK COUPLING IS DEFINED AS THE DEPENDENCE OF THE HYGROELASTIC PROPERTIES OF THE COMPOSITE ON THE WATER CONTENT…



Patel et al. (2002)

THE MORI-TANAKA HOMOGENIZATION APPROACH WILL BE USED TO DETERMINE THE HYGRO-ELASTIC PROPERTIES OF THE HYDROPHOBIC CARBON FIBERS AND THE EPOXY MATRIX VERSUS WATER CONTENT...

$$\mathrm{L}^{\mathrm{I}} = \left\langle \mathrm{T}^{\mathrm{i}} : \left\langle \mathrm{L}^{\mathrm{i}} : \mathrm{T}^{\mathrm{i}} \right\rangle_{\mathrm{i=f,m}}^{-1} \right\rangle_{\mathrm{i=f,m}}^{-1}$$

The brackets <> stand for volume weighed averages

$$\beta^{\mathrm{I}} = \frac{1}{\Delta \mathrm{C}^{\mathrm{I}}} \left\langle \left(\mathrm{L}^{\mathrm{i}} : \mathrm{T}^{\mathrm{i}} : \left\langle \mathrm{L}^{\mathrm{i}} : \mathrm{T}^{\mathrm{i}} \right\rangle_{\mathrm{i=f,m}}^{-1} \right)^{\mathrm{T}} : \beta^{\mathrm{i}} \Delta \mathrm{C}^{\mathrm{i}} \right\rangle_{\mathrm{i=f,m}}$$

Properties	E_{11}^{f} (GPa)	E_{22}^{f} (GPa)	G_{12}^{f} (GPa)	G_{23}^{f} (GPa)	υ_{12}^{f}
Mori-Tanaka	205.2	12.17	15.18	3.92	0.432
Typical values	232	15	15	5.02	0.279

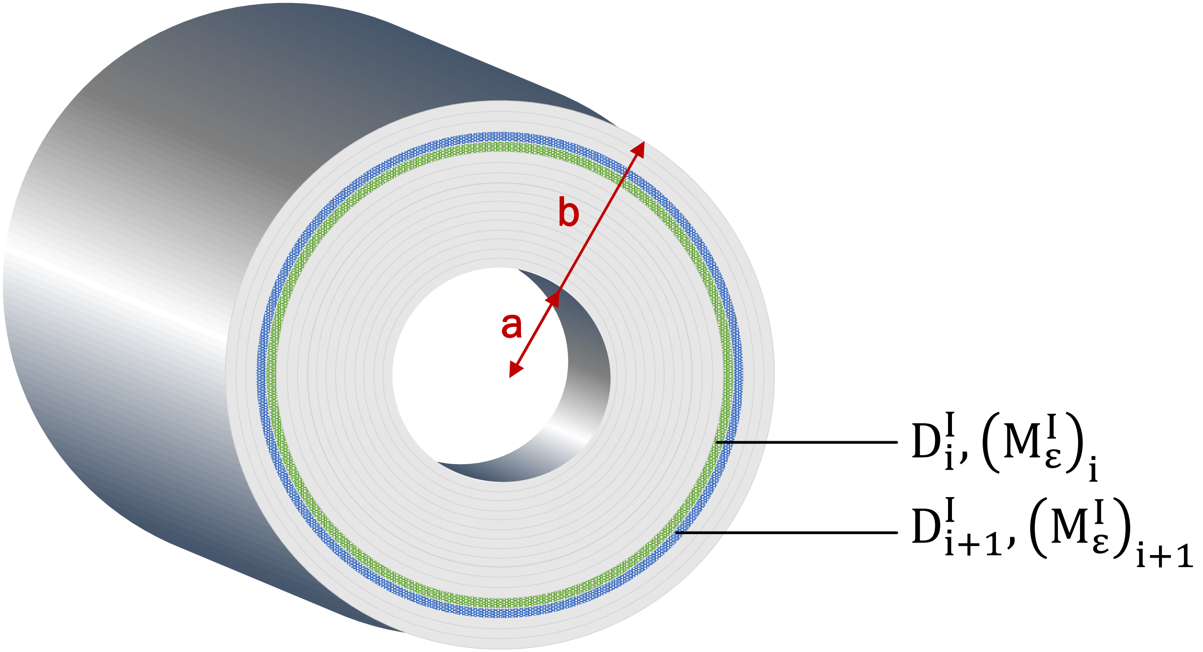
- L^{I}: stiffness tensor of the composite
- L^{f} and L^{m}: stiffness tensors of the fiber and matrix, respectively
- β^{I}: coefficient of hygroscopic expansion tensor of the composite
- β^{f} and β^{m}: coefficient of hygroscopic expansion tensors of the fiber and matrix, respectively
- T^{f}: elastic strains localization tensor ($\mathrm{T}^{\mathrm{m}} = 0$)
- $\Delta\mathrm{C}^{\mathrm{I}}$: moisture content in the composite
- $\Delta\mathrm{C}^{\mathrm{m}}$: moisture content in the matrix ($\Delta\mathrm{C}^{\mathrm{f}} = 0$)

FICK'S PROBLEM WILL BE SOLVED TO DETERMINE THE MACROSCOPIC WATER CONTENT PROFILE BY USING FINITES DIFFERENCES WITH AN EXPLICIT SCHEME...

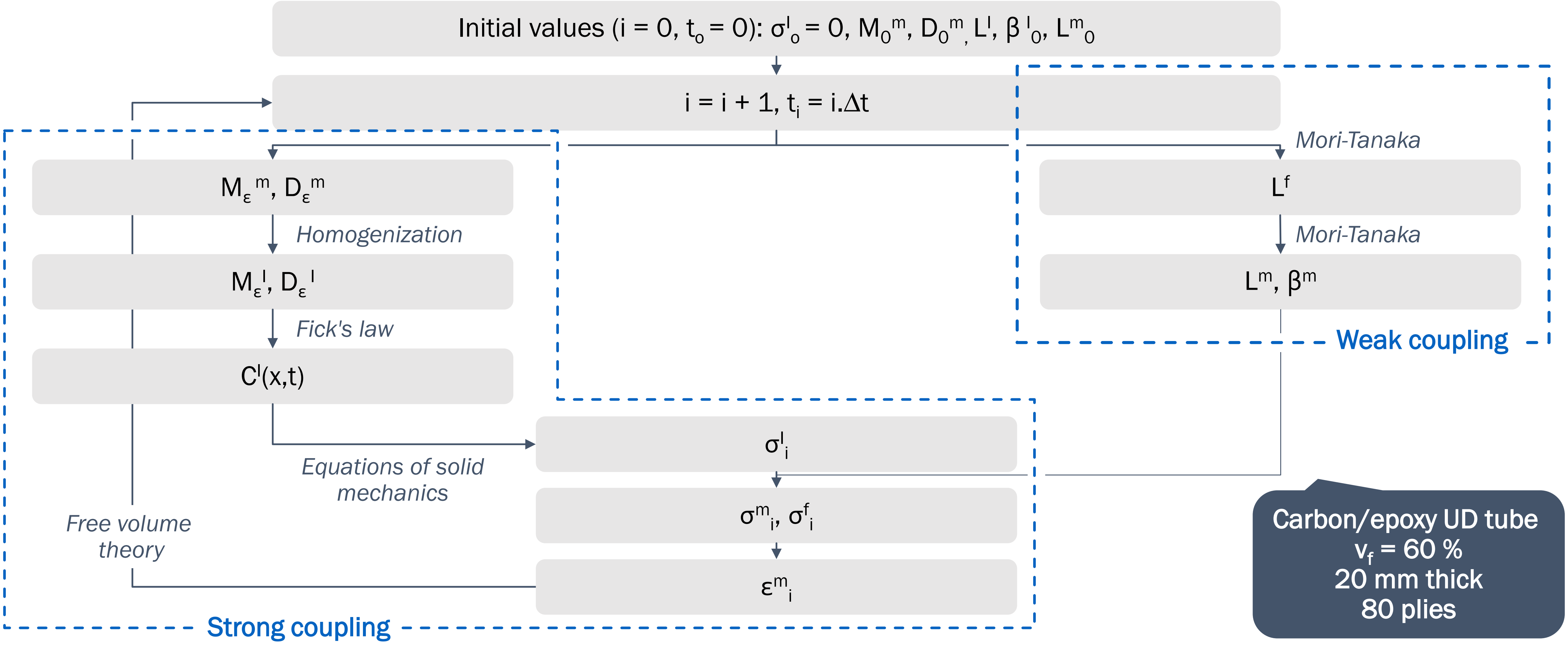
$$\frac{\delta C_i}{\delta t} = D_i^I(t)\left[\frac{\delta^2 C_i}{\delta r^2} + \frac{1}{r}\frac{\delta C_i}{\delta r}\right] \quad a < r < b, t > 0, i = 1 \text{ to } n$$

$$\begin{cases} C_i(r_i,t) = \dfrac{\left(M_\varepsilon^I\right)_{i+1}}{\left(M_\varepsilon^I\right)_i} C_{i+1}(r_i,t) \\ D_i^I(t)\dfrac{\delta C_i(r_i,t)}{\delta r} = D_{i+1}^I(t)\dfrac{\delta C_{i+1}(r_i,t)}{\delta r} \\ C(a,t) = M_\infty^I(a,t) = 1.5\ \% \\ C(b,t) = M_\infty^I(b,t) = 1.5\ \% \\ D_o^I = 3.4 \times 10^{-8}\ \mathrm{mm}^2/\mathrm{s} \\ C(r,0) = 0 \end{cases}$$

Loos and Springer (1979)



THIS FLOWCHART PRESENTS THE ALGORITHM USED TO SOLVE THE COUPLED HYGRO-MECHANICAL PROBLEM…



Carbon/epoxy UD tube
$v_f = 60$ %
20 mm thick
80 plies

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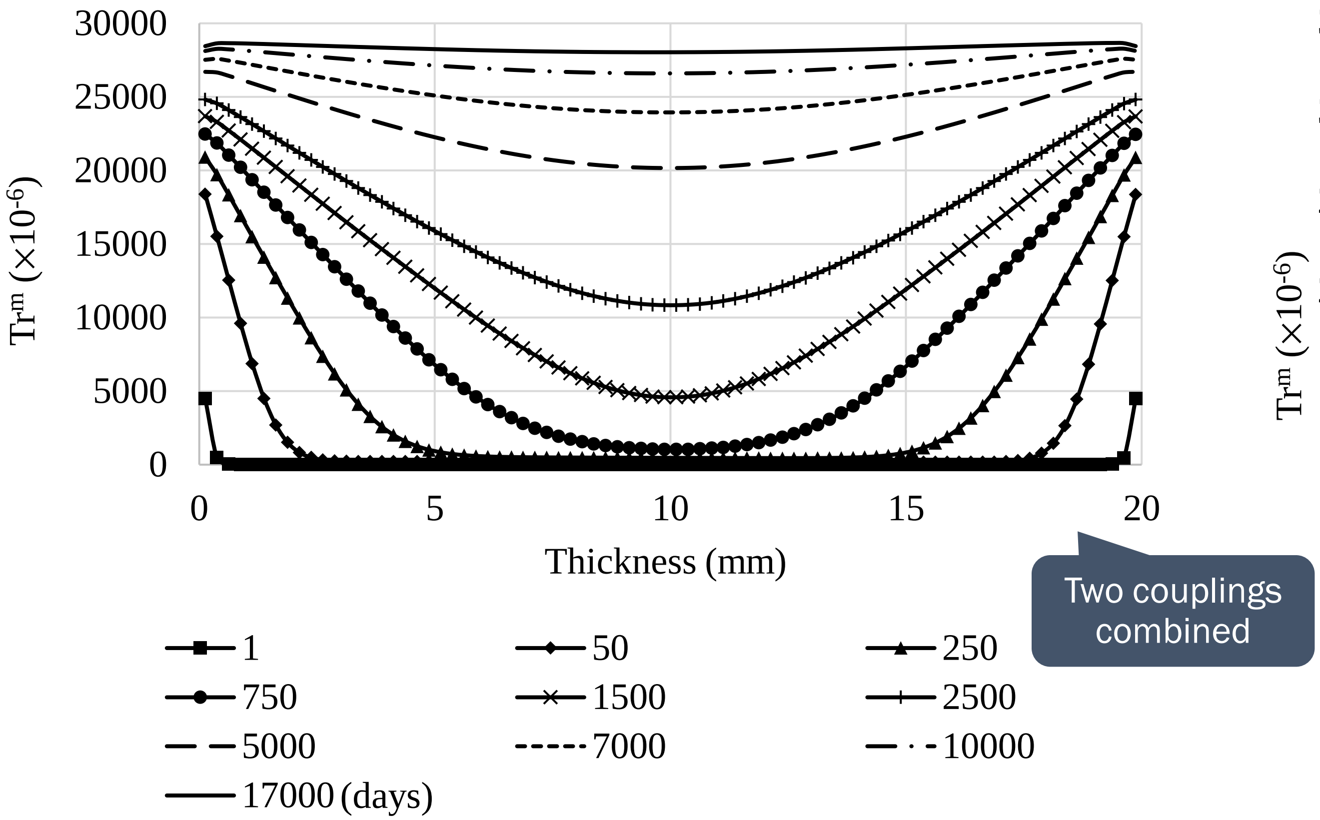
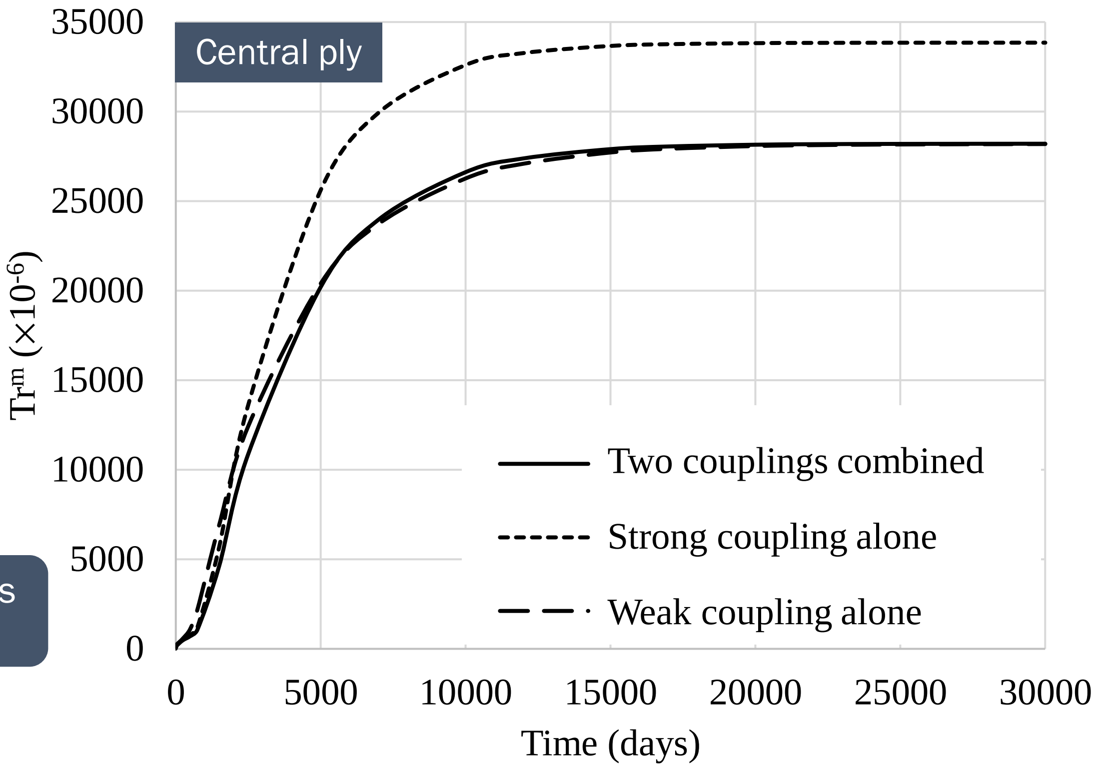
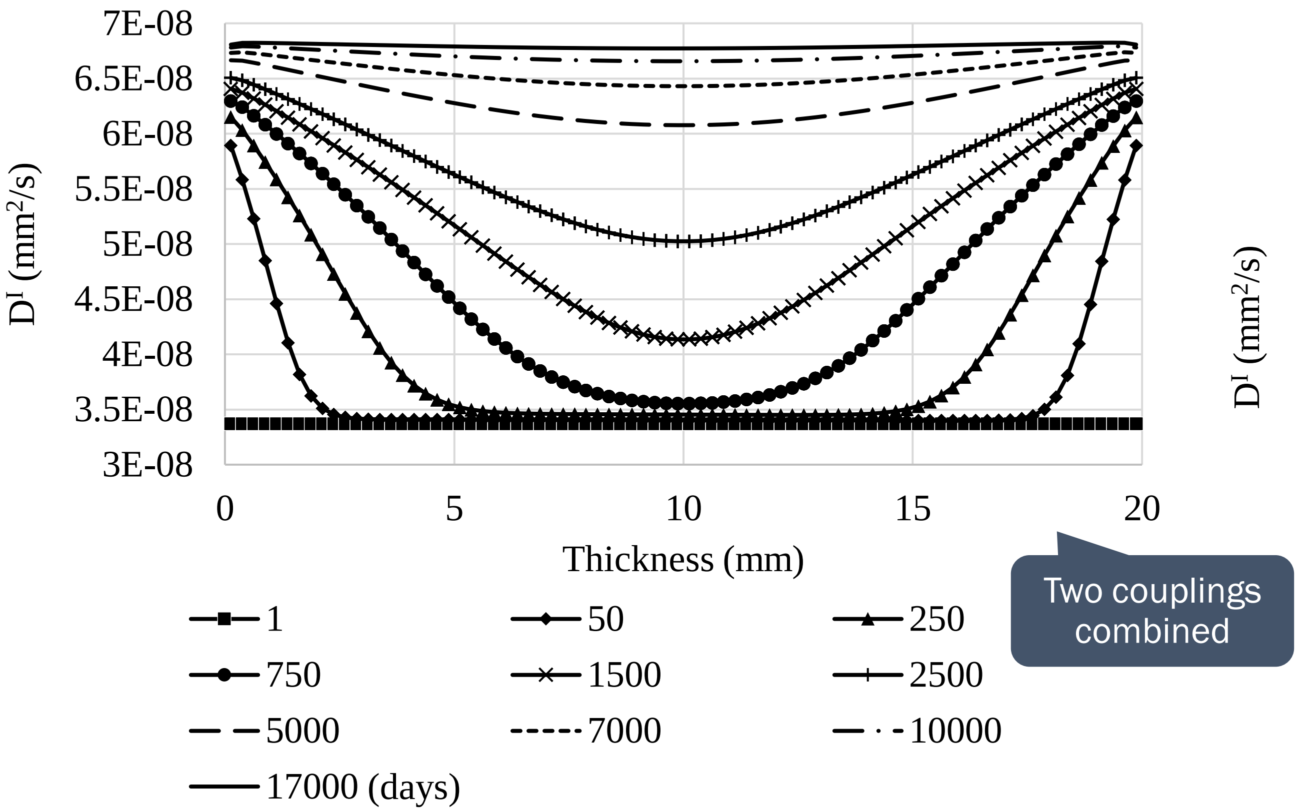
TRACE OF THE STRAIN TENSOR UNDERGONE BY THE MATRIX

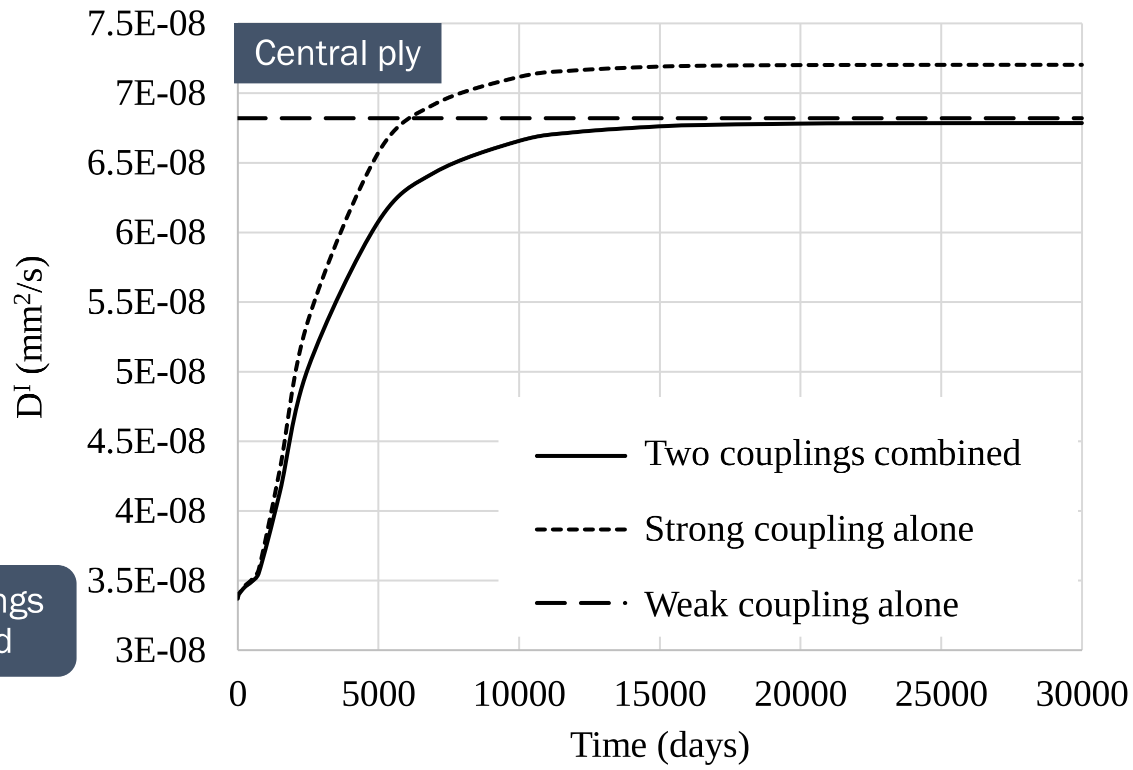




The plasticization of the material during the diffusion phenomenon strongly influence the strong coupling.

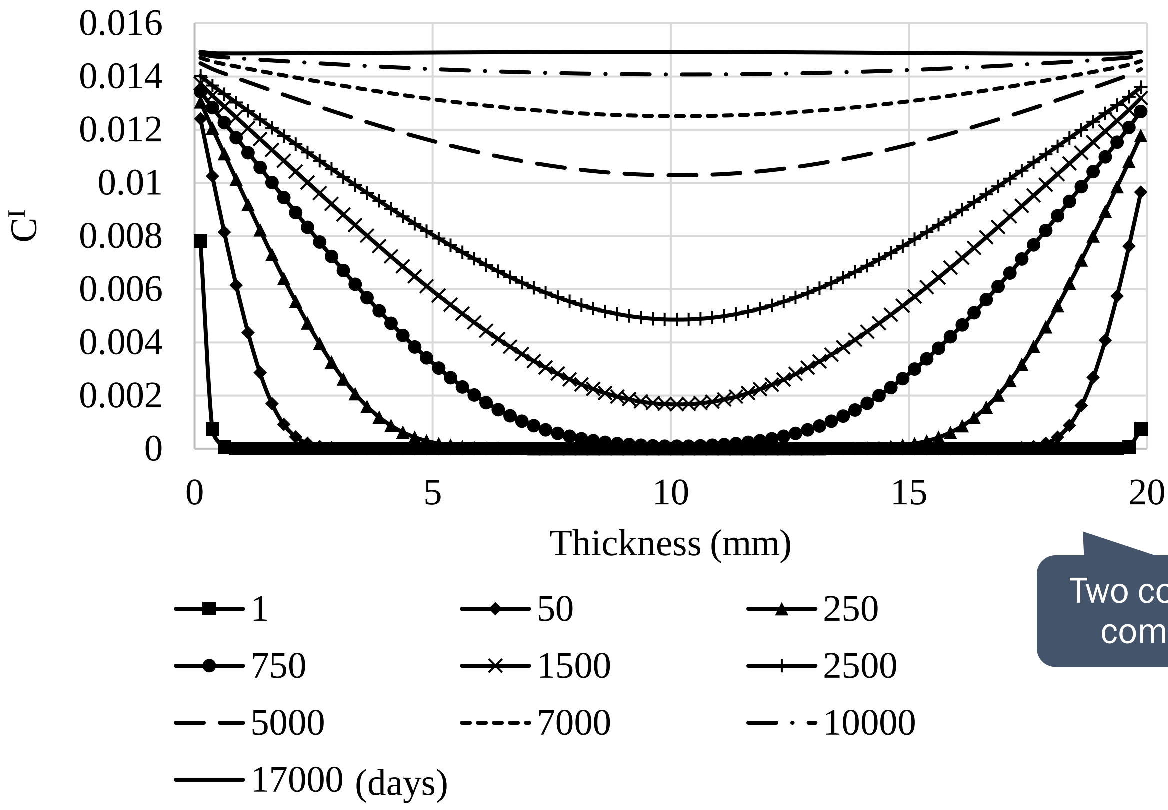
COEFFICIENT OF DIFFUSION OF THE COMPOSITE



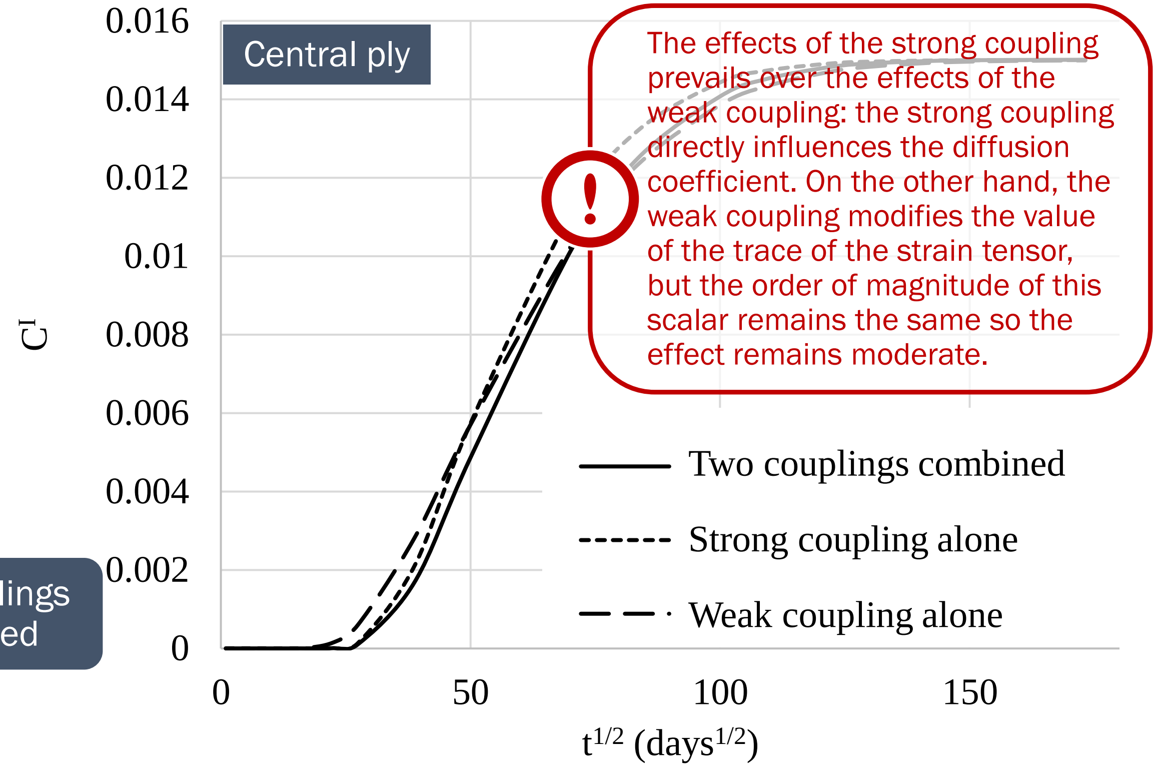


The increase in the diffusion coefficient during the absorption phenomenon is directly related to the evolution of the trace of the strain tensor.

MOISTURE CONTENT IN THE COMPOSITE



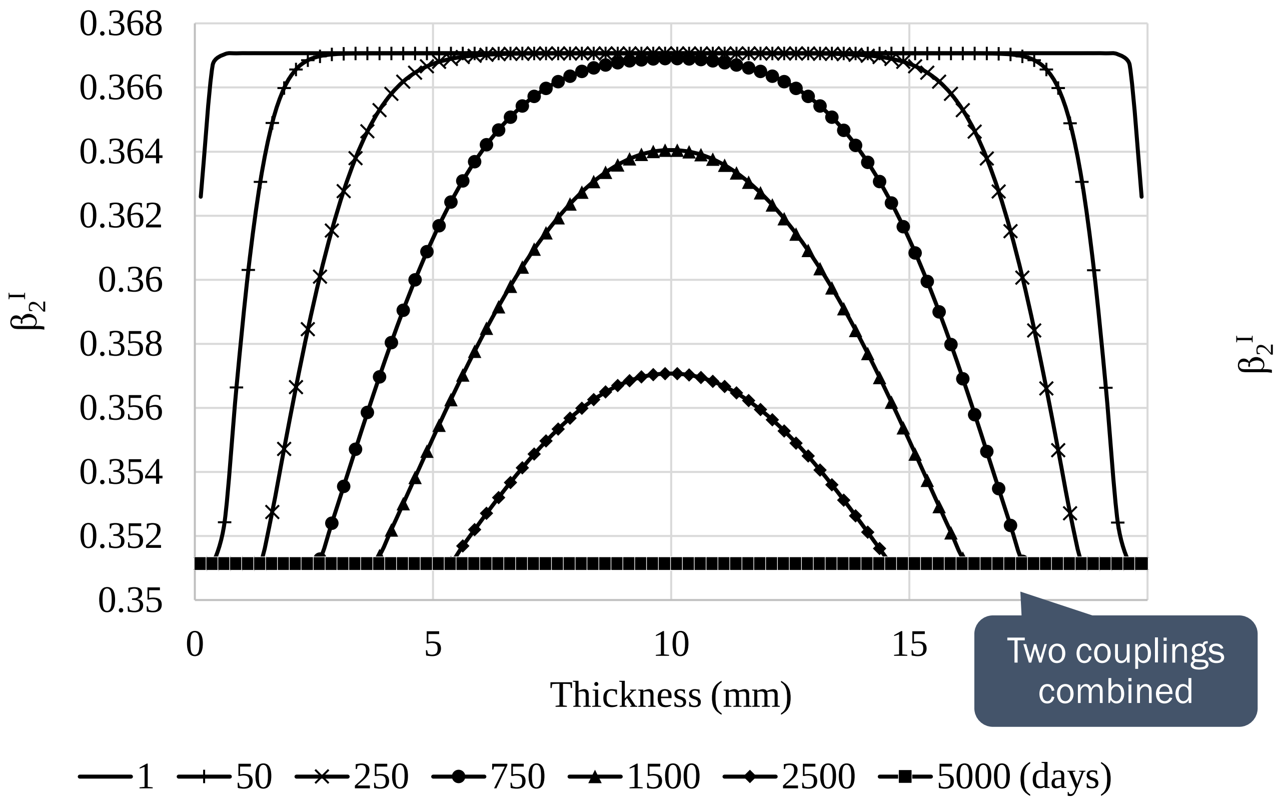
Two couplings combined

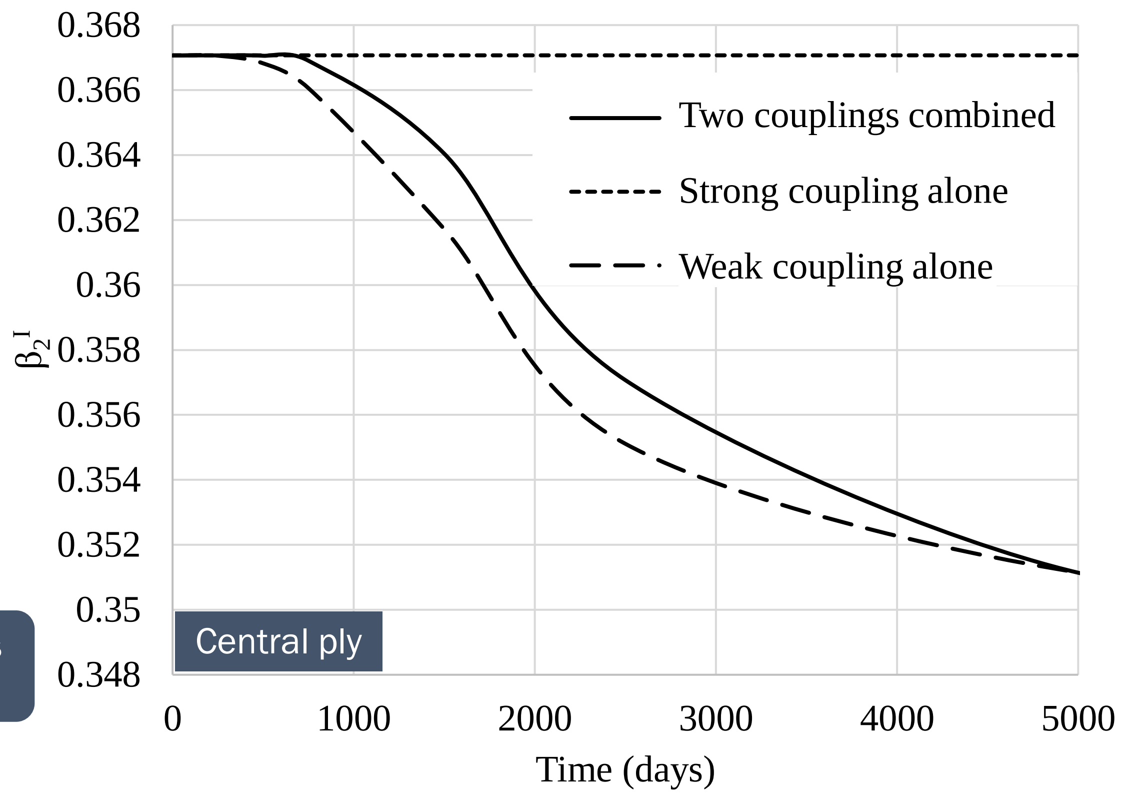


The effects of the strong coupling prevails over the effects of the weak coupling: the strong coupling directly influences the diffusion coefficient. On the other hand, the weak coupling modifies the value of the trace of the strain tensor, but the order of magnitude of this scalar remains the same so the effect remains moderate.

The strong coupling accelerated moisture diffusion by 32 % and weak coupling slowed it down by 12 % (inconsistency with experimental results).

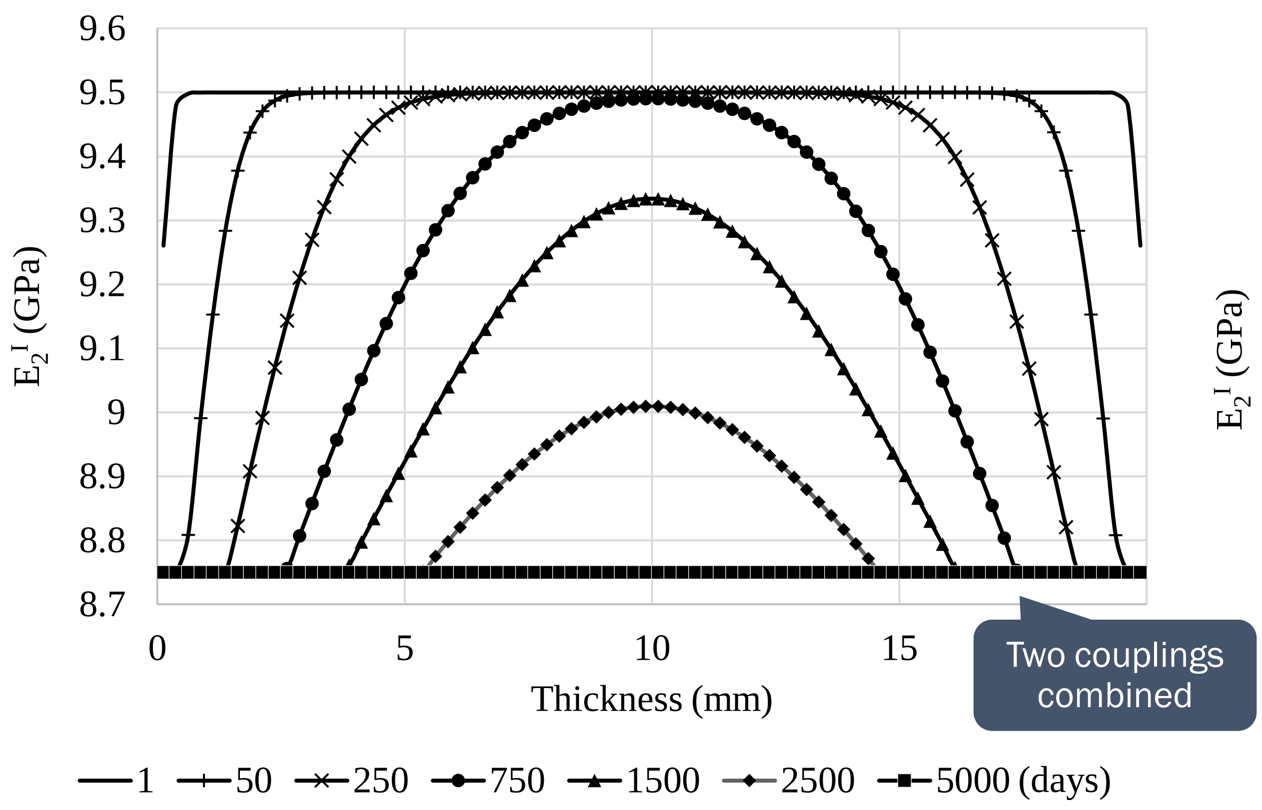
COEFFICIENT OF HYGROSCOPIC EXPANSION OF THE COMPOSITE

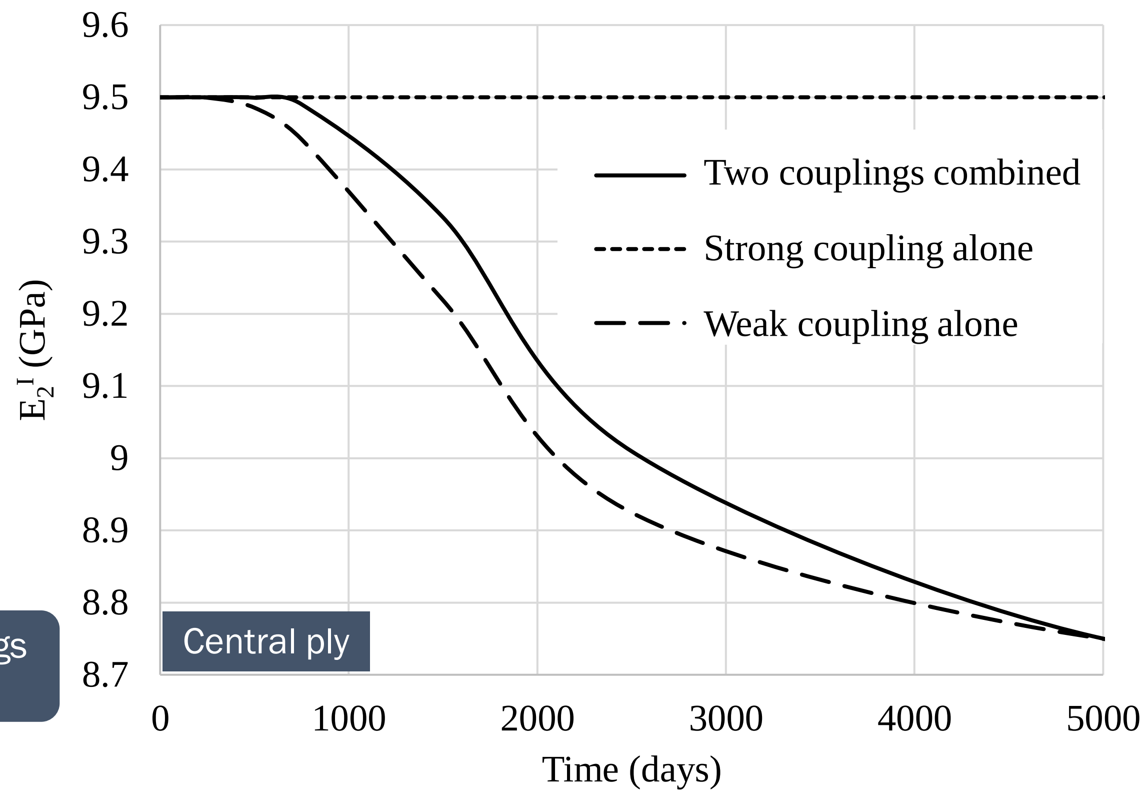




The results do not fully agree with the experimental data obtained. It has been observed that the transverse hygroscopic expansion coefficient significantly increases with moisture content.

TRANSVERSE YOUNG'S MODULUS OF THE COMPOSITE

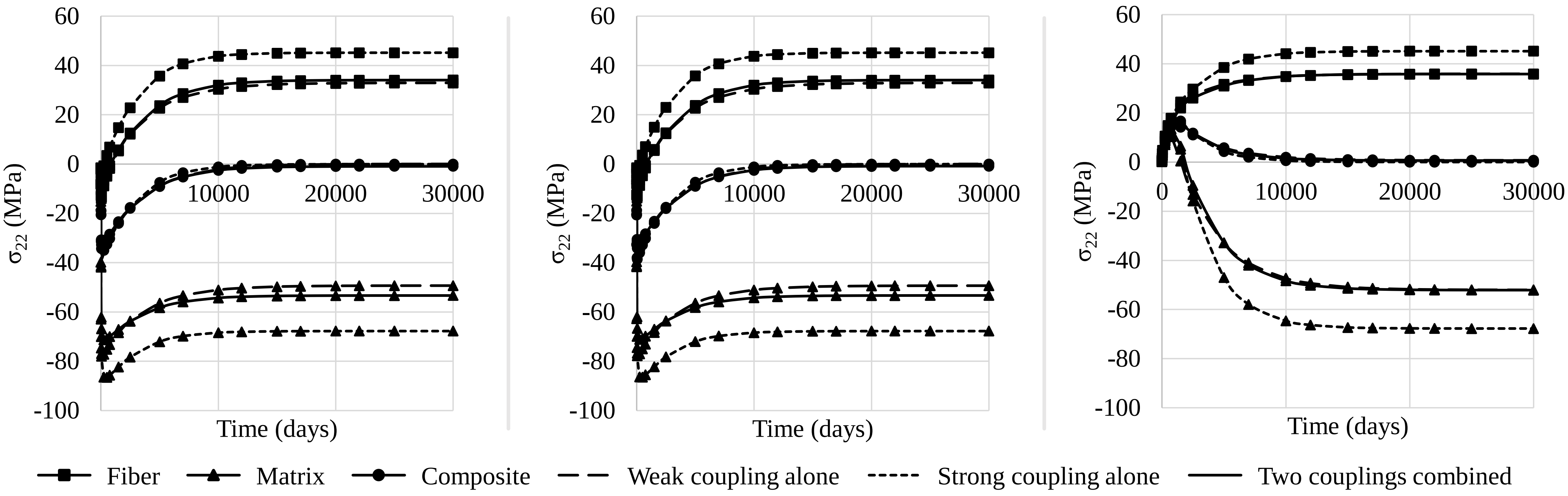




Moisture enters more quickly when taking into account the weak coupling alone and since the transverse Young's modulus depends mainly on the water content, as expected.

MULTI-SCALE TRANSVERSE STRESS STATE

Outer ply	Inner ply	Central ply



Transverse stresses are strongly affected by the different coupling configurations. When the stiffness reduction due to water absorption is neglected, transverse stresses are overestimated.

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Perspectives and further studies…

- The model is being extended to biobased composites, where water absorption in the fibers should not be neglected.
- Weak coupling should be considered to apply to the hygroscopic coefficient of expansion of the polymer matrix, in order to achieve more accurate results.
- Experimental results are not consistent with the free volume theory. Instead, water transport should be linked to water-polymer affinity which itself depends on the chemical composition of the polymer.

THANK YOU FOR YOUR ATTENTION