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Technical Note

Measurement of 'Strain Hardening Modulus' of geomembranes – with or without extensometer?

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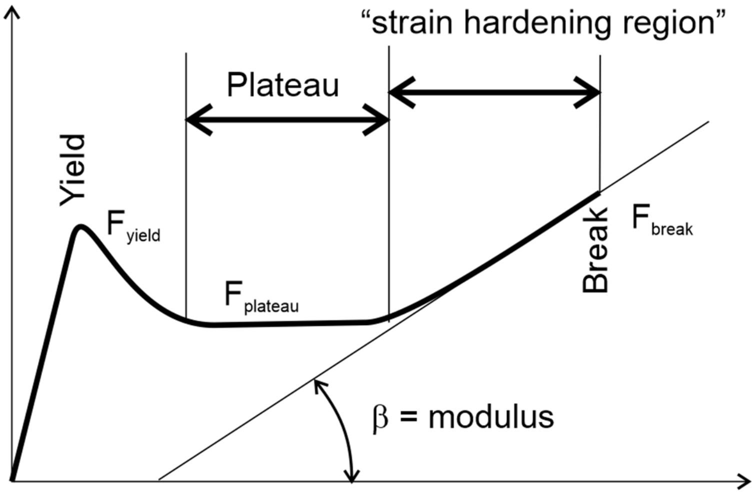
In this technical note, we are analyzing the methodology used to measure strain-hardening properties of geomembranes, when tested without extensometer.

MECHANISMS CONTROLLING THE TENSILE PROPERTIES OF HDPE GEOMEMBRANES

A D6693 tensile test can be described as follow:



Where:

- F_{yield} = Force (in N) needed to initiate yielding of the polymer on a specimen with a thickness T and a width W, and σ_{yield} the corresponding force per unit width.
- $F_{plateau}$ = Force (in N) mobilized for necking to take place, i.e., to continue stretching the polymer (in the narrow section) once the yield point has been reached once, and $\sigma_{plateau}$ the corresponding force per unit width. This reflects the 'plateau' region on the force / strain curve.
- F_{break} = Force (in N) required to break the specimen, and σ_{break} the corresponding force per unit width.

To initiate yield, a force F equal to F_{yield} is required. However, once the yielding process is initiated, a smaller force is sufficient to continue necking, as long as the width of the specimen does not change. This is the 'plateau' and the required force is '$F_{plateau}$' which is equal to $\sigma_{plateau}$ x W_N, where $\sigma_{plateau}$ is normalized to the thickness and expressed in N/m. $F_{plateau}$ is constant and the width of the specimen is constant, which confirms that '$\sigma_{plateau}$' is an intrinsic property of the polymer.

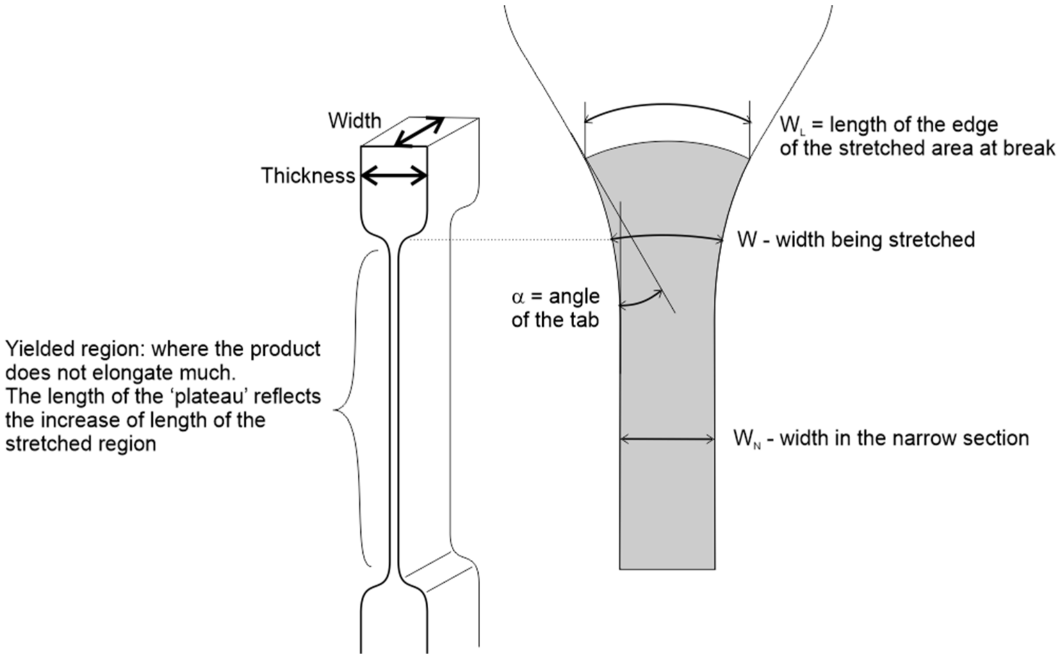
When all the narrow section of the specimen has entirely yielded, necking enters the tabs of the specimen, where the width increases. Therefore, the width of material actively necking starts to increase. Indeed, the measured force F increases, and is no longer '$F_{plateau}$'.

As indicated on the figure above, this segment of the stress-strain curve is usually described as the 'strain hardening' region.

In is important to analyze the stress state of both the narrow section, and the two ends, or 'tabs', where the test specimen has a triangular shape to progressively reduce the stress per unit width.

- <u>In the narrow section</u>: once the test has entered the 'strain hardening region' (on the stress-strain curve), the applied force increases, therefore the narrow section (which has a constant width) is exposed to a force per unit width 'F/W_N' which increases as well, and may therefore elongate, to a rhythm that would reflect the true 'strain hardening modulus' of the material.
- <u>In the tabs</u>: while F/W_N increases, the force per unit width required to continue necking, '$\sigma_{plateau}$', remains constant. The increase of the applied force 'F' therefore reflects an increase of the width of material actively necking, as the yielded region progresses within the tabs.

The applied force 'F' continues to increase until the force applied in the narrow section is equal to the breaking strength of the (yielded) material.



Considering that the unyielded region, in the tabs, cannot be exposed to a stress greater than the stress needed to continue necking the polymer $\sigma_{plateau}$, the stress at break σ_{break} is related to $\sigma_{plateau}$ by the following equation:

$$\boldsymbol{\sigma_{break} \times W_N = \sigma_{plateau} \times W_L}$$

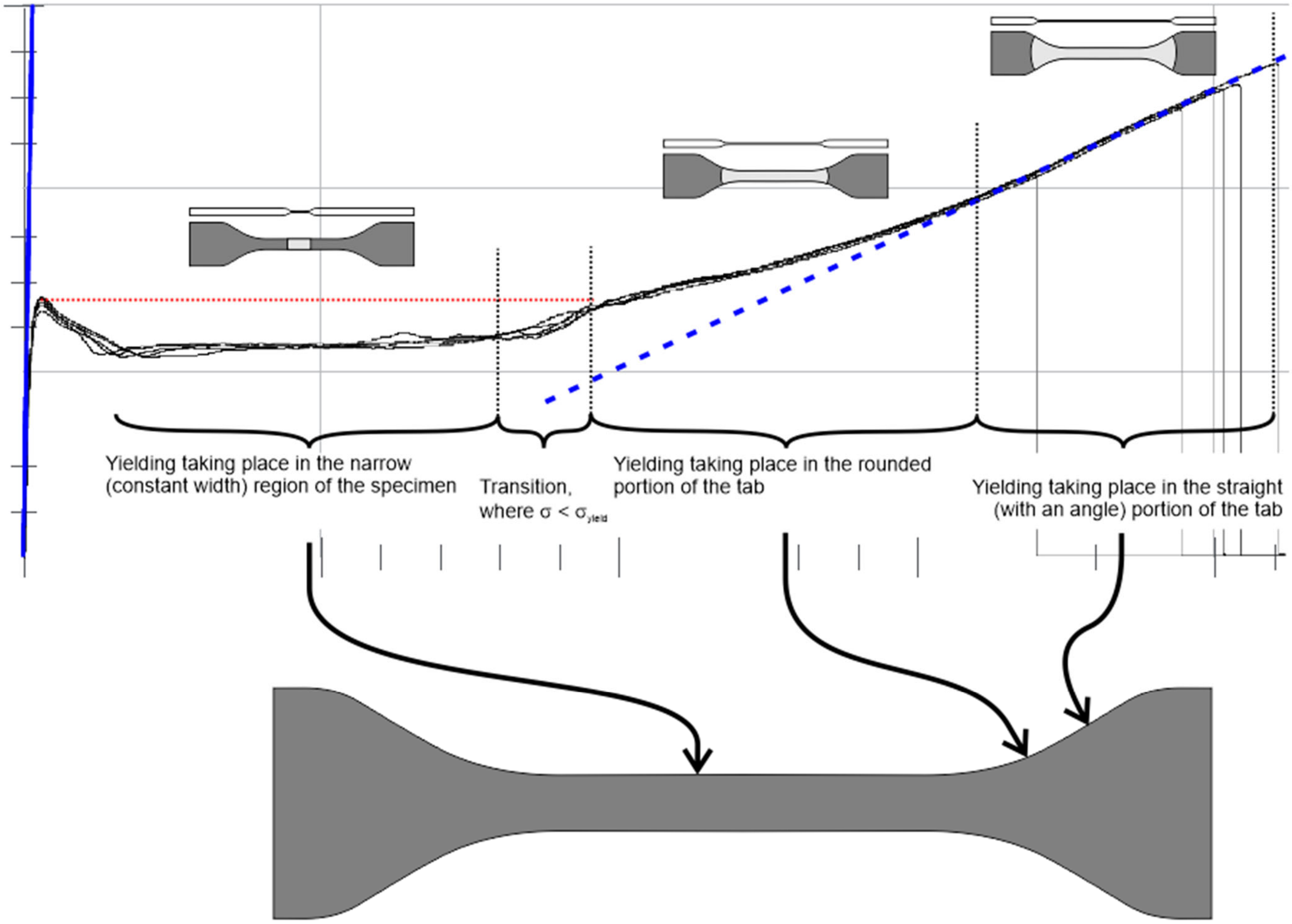
Where W_N is the width of the specimen in the narrow section, and W_L the width of the specimen in the region actively necking, at the instant the break occurs.

This relation can be generalized to a relation between the applied force per unit width σ, the force required to continue necking the material $\sigma_{plateau}$, the thickness of the narrow section W_N, and the width actively necking at anytime W. The equation becomes:

$$\sigma \times W_N = \sigma_{plateau} \times W$$

It is interesting to see that when $W = W_N$, then $\sigma = \sigma_{plateau}$. This indeed reflects that necking is taking place in the narrow section, after the yield point.

On some stress-strain curves (i.e., slightly steeper modulus), a transition is visible, where σ increases from $\sigma_{plateau}$ to σ_{yield}. This reflects a situation where the portion of the specimen which is NOT yielded experiences some elongation, simultaneously to the mechanism described above.



IMPLICATIONS FOR THE STRAIN HARDENING TEST

W_N and $\sigma_{plateau}$ are constant values, defined by the specimen shape (W_N) or the polymer ($\sigma_{plateau}$). Therefore, the rate of increase of the force per unit width σ depends on the rate of increase of the width of material being stretched 'W'. Therefore, it depends on the angle of the edge of the test specimen 'α', described on the figure above. Of course, the rate of elongation of the material (i.e., the strain hardening modulus, the property we are trying to measure) is also affected by the increase of the stress σ, but to an extend which is typically unknown, and which is material-specific: it will depend on the thickness of the material and its mechanical properties before and after yield.

The phase of the test where the force increases with elongation, immediately before break, is the region where we want to measure the ‘strain hardening modulus’. Therefore, the measurement of ‘strain hardening modulus’, without an extensometer, is directly affected by the geometry of the test specimen - i.e., by the rhythm at which the width of the necking line increases. The larger the angle ‘α’ on the tab of the test specimen, the larger will be the measured modulus. Therefore, this value does not reflect the true strain hardening modulus, as if it was measured with an extensometer.

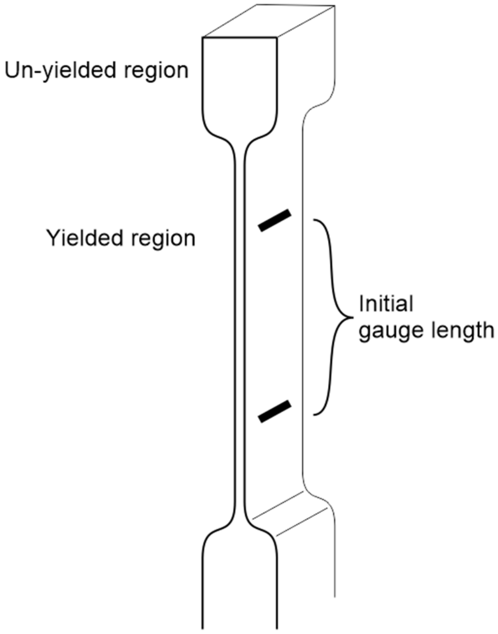
In other words:

the significance of a ‘strain-hardening modulus’ measured using the crosshead displacement of the tensile tester, instead of an extensometer, may be vastly overstated as it is (primarily?) influenced by the geometry of the test specimen, and in particular by the angle of the edges of the tabs with the axis of the specimen.

PATH FORWARD

A potential solution for measuring a ‘real’ strain hardening modulus could be use an extensometer installed in the narrow section of the test specimen, after it has yielded. Doing so will exclude any ‘noise’ caused by a change of thickness (occurring while the material is necking) and influence of the precision of the initial gauge length. With current tensile testers (equipped with an extensometer), this would require running the test in two successive steps:

1. Stretch the specimens to yield them over a length significantly longer than the gauge length of the extensometer, but without breaking them, e.g., reaching approximately 250% elongation (a value sometimes used to specify $\sigma_{plateau}$ as an intrinsic property of a PE geomembrane).
2. Stop the test, install the extensometer in the yielded region.
3. Start the ‘real’ test with the extensometer installed on the stretched portion of the specimen.



The modulus of the post-yield region of the test can then be defined as the strain-hardening modulus of the polymer.

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