Influence of Polymer Viscoelasticity in Reinforced Soil Structure Design

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ABSTRACT: The long-term stress-strain relationship, or structural response, of polymeric materials used for soil reinforcement is the single most important property needed for design. Polymers are viscoelastic materials and therefore do not have a single characteristic modulus. The structural response of a polymer ranges between elastic and viscous behavior and depends on its molecular structure and orientation, the magnitude and duration of applied stress or strain, and the ambient temperature. Therefore the modulus available under one set of conditions may not be available under a different set of conditions. This is important to the design engineer from the standpoint of both the temperature of the application (e.g., landfills) and the duration of the applied stress or strain (soil reinforcement in general). The purpose of this paper is to describe the relationships between structure and response so that the predictability of a polymer's response and the resulting limitations in its application can be understood.

1 INTRODUCTION

The long-term stress-strain relationship, or structural response, of polymeric materials used for soil reinforcement is the single most important property needed for design. Two polymers most commonly used in geogrid manufacture, polyethylene and polypropylene, have historically been vigorously marketed as having very high long-term tensile moduli relative to other polymers. These geogrids have even been claimed in some instances to have tensile moduli comparable to that of steel. However, polymers are viscoelastic materials and therefore do not have a single characteristic modulus. All other things being equal, the tensile modulus varies with the strain rate and temperature at which the material is tested.

Civil engineers involved in the design of reinforced soil structures are familiar with the concepts of creep and modulus, but most probably are not aware of the relationship between the two. Many project specifications encountered in practice emphasize product characteristics that are not relevant to the actual design. They are often merely copied from a manufacturer's literature. These types of design specifications often reflect the designers' lack of comfort with the range of reinforcement products available. If the designers do not understand the characteristics of the various polymers, then they will not be able to achieve the optimum reinforcement to cost ratio. They will specify characteristics that are unnecessary and fail to specify some that are necessary.

This paper discusses the various polymers commonly used in soil reinforcement products along with their molecular structure and the concept of polymer viscoelasticity. The paper then discusses each polymer's stress-strain, creep and temperature characteristics so that the engineer can approach reinforced soil designs from the perspective of viscoelastic performance.

2 MATERIAL CHARACTERIZATION

All materials used in civil engineering applications have a structure that falls somewhere in a range between fully crystalline and fully amorphous. For example, metals are completely crystalline materials while liquids are completely amorphous materials. Materials with a structure somewhere between these two extremes are partly crystalline and partly amorphous. Such a material is said to have a *two-phased structure*. A material with a structure anywhere within this range can be composed of molecular chains with length ranging from short to long, or can have a planar structure as do metals. The length of a molecular chain depends on the number of repeat units and is referred to as its *degree of polymerization*. However, materials composed of long chain molecules will not necessarily have a crystalline structure. Petroleum oils are examples of completely amorphous materials with very long chains, while water is a completely amorphous material with no chains.

Because metals are completely crystalline their stress-strain curves are linear over most of the elastic region, and the elastic limit is reached at a very high percentage of the ultimate strength. As the crystallinity of the material decreases, or the ambient temperature increases, the proportion of the ultimate strength for which the stress-strain relationship is elastic decreases. For a completely amorphous material, no elastic relationship exists between stresses and strains. The relationship is instead plastic, or viscous, with the viscosity decreasing with temperature.

The polymers used in the manufacture of soil reinforcement are materials that have a two phased structure. That is to say that they have crystalline regions as well as amorphous regions. Another viewpoint is that crystalline regions are highly ordered regions while amorphous regions are highly disordered regions. Their behavior under load and their response to temperature and moisture are functions of not only the crystalline proportion of their structure, but also the orientation of the molecules to the load axis, how tightly the molecules fit together in the cross section, degree of polymerization, the type and number of cross-links, or intermolecular, bonds, and the glass-rubber transition temperature.

Polyester (PET), polypropylene (PP), and polyethylene (HDPE) are the polymers used in the majority of soil reinforcement and stabilization applications. Although HDPE has been used in some landfill applications, it should not be used where it can be affected by the high temperatures generated by the decomposition of waste.

3 STRESS-STRAIN BEHAVIOR

3.1 Properties That Affect Polymer Strength

The structural response of a polymer is determined by the following properties:

- molecule / fiber orientation with respect to load axis and crystallinity
- degree of polymerization
  (each repeat unit can form a cross-link)
- intermolecular bonding - covalent, hydrogen, or van der Waals (secondary valence bonds)
- intra molecular bond angle ($F_e \alpha\ 1/x^6$)
- glass-rubber transition temperture, T_g

3.1.1 Molecule / fiber orientation

As the polymer chains grow in the molten material, they loop around one another like a pile of spaghetti noodles on a plate. In this state, the polymers polyethylene, polypropylene, and polyester are almost completely amorphous and the chains are unoriented.

Orientation of the chain molecules is accomplished by *drawing* after the polymer is extruded into fibers or sheets. Drawing increases the strength by orienting the molecules with respect to the axis of drawing and decreasing the cross section so that the molecules are closer to one another. The chains will stick together better if you can align the "spaghetti noodles" since they will then fit more closely together and increase the strength of the van der Waals bonds since the strength of the van der Waals interaction (or electrical attraction) force varies inversely with the sixth power of the molecular chain separation distance. The chains will also be more likely to develop hydrogen bond cross-linkages if they have the potential to do so. Thus drawing crystallizes the structure, although 100% crystallinity cannot be achieved. Drawing also increases the ultimate strength and modulus.

3.1.2 Degree of polymerization

Some folks talk about degree of polymerization (DP) as if it were the only property that matters. While the strength increases with degree of polymerization (since the longer the chains are the more likely your specimen will have continuous chains in it), there is a limiting chain length after which the molten polymer can no longer be extruded into fibers or sheets because the chains become so entangled that they cannot flow; i.e., their viscosity becomes too great. The natural cellulosic polymers such as cotton have a DP of about 5,000 to 10,000, far greater than PP, HDPE, or PET. If the latter three polymers had a DP this then they could not be extruded. The increasing viscosity of motor oils with decreasing temperature is a result of entanglement of the long chains due to their high degree of polymerization.

3.1.3 Cross-linking

The most important polymer property is *cross-linking*. Cross-linking is another name for inter-chain bonding. This is another benefit of long chains since every repeat unit has the *potential* to develop a cross-link. Notice the word *potential*. Just because a polymer has long chains doesn't mean it will form cross-links. It depends on the *types* of molecules in the chain. For example, HDPE doesn't form cross-links at all. That is one reason it has such high creep potential. The other reason is that its glass-rubber transition temperture is -100°C. Polyesters form fairly strong cross-links from strong van der Waals forces which is due mainly to the interaction of the large benzene rings. This is why it is so resistant to creep. Also its glass-rubber transition temperture is +75°C. It is cross-linking that causes strong elastic behavior with low creep.

However, it is a fallacy to assume elastic behavior for a viscoelastic material at any time, even for situations wherein the loads are rapidly applied and released. Asphalt cement concrete is a viscoelastic material and, even though traffic loads are usually very quickly applied and released, there is a cumulative strain that results over time.

Only the aramide (e.g. Kevlar®) family has cross-linking from strong covalent bonds as do epoxies and adhesives. The high strength of the aramids is due to the fact that they possess all the best of these characteristics: a completely crystalline linear structure fully oriented (parallel to the load axis) with high cross-linking.

Incidentally, the value of the vulcanization process of rubber is that it establishes cross-linkages.

3.1.4 The glass-rubber transition temperature

The glass-rubber transition temperature is the temperature at which a thermoplastic polymer changes from a glassy state to a rubber state if the temperature is increasing, or from a rubbery state to a glassy state if the temperature is decreasing.

No matter how well the polymer is crystallized or cross-linked, or how high its DP, if its service temperature is above its glass-rubber transition temperature then its strength properties will be adversely affected. The effect of the glass-rubber transition temperature can be visualized by considering as an analogy a phenomenon with which some of us who have experienced ice storms are familiar. During an ice storm, ice and sleet can build up on the hood of a car to a depth of a couple of inches. When the temperature of the ice is well below freezing the mechanical properties of the ice are that of a glassy material. As the temperature of the ice layer approaches its melting temperature, it goes through a glass-rubber transition although it has not gone through a phase change. In fact, it *has* to go through this transition before it melts since then it has the mechanical properties of the fluid which it has become. This transition may be more accurately termed a glass-plastic transition for ice, but the point is that it becomes ductile, whereas it was brittle in its glassy state. As the ice melts, it may start to slide over the front of the car hood where it bends downward without breaking before it slides off, thereby manifesting its ductility.

The reason for this ductility is that the bonds have loosened due to the increasing temperature. The same thing happens to polymers as they pass their glass-rubber transition temperatures. The glass-rubber transition temperature for polyester is about 75°C while that for polypropylene and polyethylene is about -100°C. Therefore polyester has a service temperature *below* its glass-rubber transition temperature while polypropylene and polyethylene have service temperatures *above* their glass-rubber transition temperatures. This is why even though these two materials may have "high molecular weight" and crystallinity, they have worse mechanical properties than polyester including very high creep susceptibility.

The stress-strain curve of PET has a much larger elastic region than the other two polymers and correspondingly much less creep. The creep that does occur is mostly elastic creep whereas the creep manifested by the others is mostly plastic, or permanent, creep. This shows the significance of cross-linking and the glass-rubber transition temperature since PP and HDPE are usually more crystalline than PET, but have much less cross-linking and have service temperatures far above their glass-rubber transition temperatures.

In fact, the shape of the creep curve is influenced by the ambient temperature relative to the glass-rubber transition temperature. This is why PP and HDPE exhibit a highly nonlinear creep curve with tertiary creep whereas PET does not.

3.2 The influence of test speed

The more cross-linking a polymer has, the less sensitive is its ultimate strength and strain at break to the rate of elongation during tensile testing and the more it exhibits Hookean behavior.

Obviously, the more viscous the polymer, the greater its creep potential. Not so obviously, the more viscous the material, the greater is the sensitivity of its stress-strain characteristics to the rate of strain during testing. In order to visualize this, the rheological model must be considered.

A simplified rheological model for viscoelastic materials is a Hookean spring in series with a dashpot. The more cross-linking a polymer has, the higher the spring constant and the more viscous the fluid in the dashpot. Inversely, the less cross-linked the polymer, the lower the spring constant and the viscosity of the dashpot fluid.

If the stress-strain test is conducted quickly, the lagging viscous strain component is suppressed, and the ultimate strength is higher, and the strain at break is lower, than if the test had been conducted at a slower strain rate. Therefore, the modulus varies with strain rate, with the variance dependent upon whether the material is more viscous or more elastic.

As an example of the severity of the potential variability of modulus with strain, Figure 1 (van Zanten, 1986) shows the ultimate strength of HDPE obtained at a strain rate of 10% per minute is only about 76% of that obtained at a strain rate of 100% per minute, while that obtained at a strain rate of 1% per minute is only about 45% of that obtained at a strain rate of 100% per minute. Therefore, a polymer reinforcement has no particular modulus, much less an elastic modulus. Note that ASTM D-4595 recommends a strain rate of 10% per minute ± 3%.

Figure 2 shows a series of stress-strain curves for Tensar SR2 (Cheok, 1985). The decrease in ultimate strength with corresponding increase in strain at break as a function of decreasing strain rate is obvious. The modulus at any point on such a stress-strain curve is referred to as an apparent modulus (ASTM D 638-91).

Note that the modulus and ultimate strength values given on the geogrid specification sheets of some manufacturers are obtained from tests conducted per Geosynthetic Research Institute's GG-1 which does not specify a strain rate. Due to the sensitivity of polypropylene and polyethylene to strain rate, engineers should specify the strain rate at which the design strength is obtained.

Furthermore, engineers should ensure that the polymer chosen will actually provide the required strengths at the strain rate at which the reinforcement will be loaded in situ.

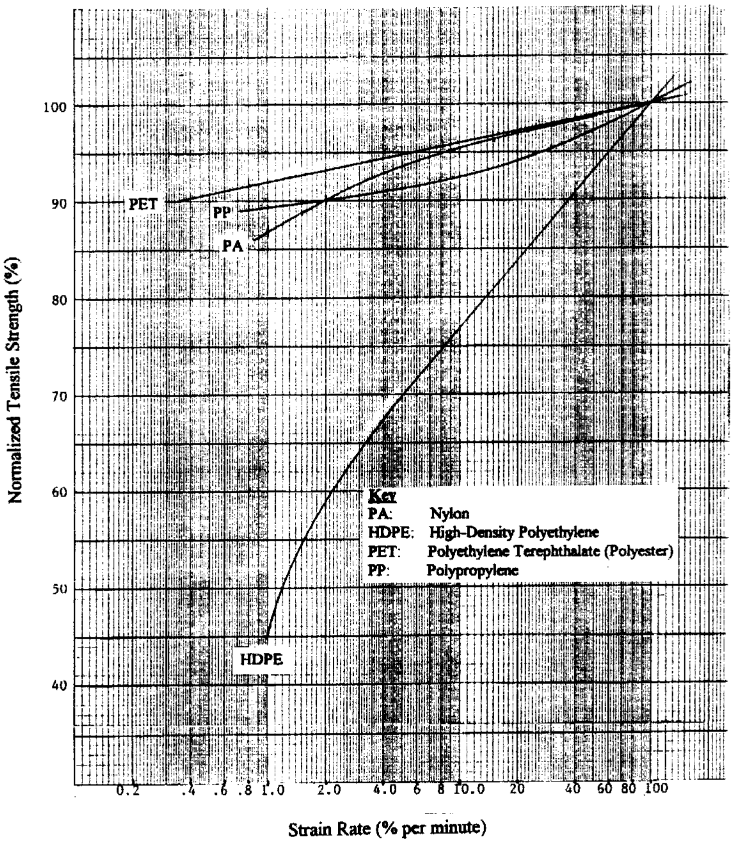

Fig. 1 Variation of tensile strength with strain rate (from van Zanten, 1986)

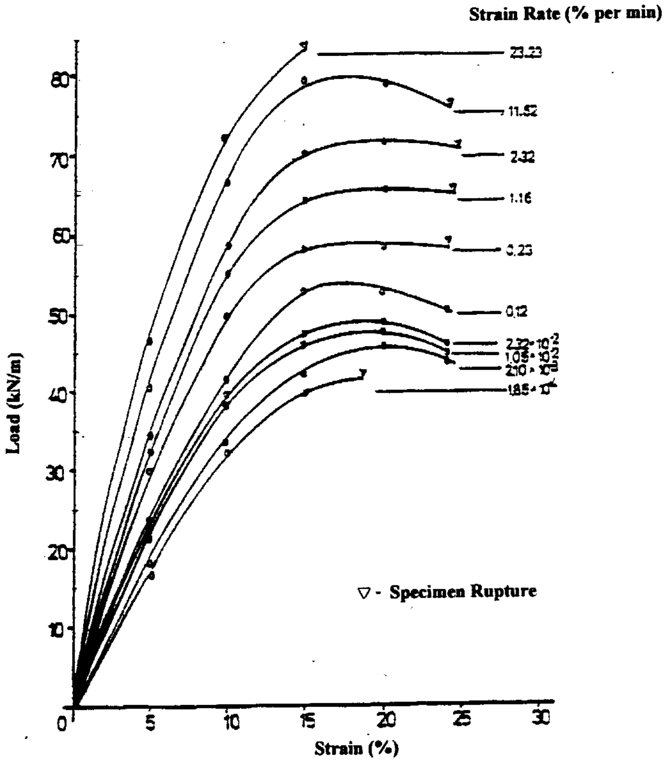

Fig. 2 Influence of strain rate on the load-strain behavior of Tensar SR2 at 20°C (Cheok, 1985)

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