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Research Article

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Viscoelastic and Viscoplastic Glucose Theory (VGT #2): Applying the Concept of Viscoelasticity and Viscoplasticity to Conduct a "Time-Dependent Glucose Analogy" Study of An Elastic Glucose Case Covering 4,056 meals <180 mg/dL Versus Plastic Glucose Case of 23 Meals >180 mg/dL Using Collected Postprandial Plasma Glucose Data from 4,079 Meals over 3.7-Year Period from 5/8/2018 to 1/10/2022 Based on GH-Method: Math-Physical Medicine (No. 579)

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Abstract

The author has studied strength of materials and theory of elasticity through his undergraduate courses at the University of Iowa. He also conducted research work to earn a master's degree in Biomechanics under Professor James Andrews. He remembers using the spring and dashpot models to simulate the behaviors of human joints, bones, muscles, and tendons to investigate the human-weapon interactions. Later, he went to MIT to pursue his PhD study under Professor Norman Jones, who taught him theory of plasticity and dynamic plastic behaviors of structure elements, and took additional graduate courses in the field of fluid dynamics and thermodynamics.

Since then, many advancements have been made in biomechanics in a few application areas, especially tissues of the human body which possess viscoelastic characteristics, such as bone, muscle, cartilage, tendon (connect bone to muscle), ligament (connect bone to bone), fascia, and skin. For example, the night splint dorsiflexes forefoot at the back of the foot increases plantar fascia tension to offer stress-relaxation for plantar fascia pain. This model of muscles and tendons connecting the lower leg and foot is a type of viscoelastic problem. However, when dealing with the human internal organs, it is not easy to conduct live experiments to obtain accurate measurements of material properties. Although blood itself is a viscous material, the viscosity factor may fall between water, honey, syrup, or gel. However, the author's research subject is "glucose", the sugar amount in blood carried by cells, ***not the blood itself.*** *It is nearly impossible to measure material geometry or certain engineering properties of glucose, for example, the viscosity of "glucose". Therefore, the best he could do is to apply the "concept of viscoelasticity and/or viscoplasticity" to construct an* ***analogy model of time-dependent glucose behaviors.***

The author's background includes mathematics, physics, and various engineering disciplines, not including biology and chemistry. As a result, he can only investigate the observed biomedical phenomena using his ready-learned math-physical tools. He has already conducted some investigations of glucose behaviors using elasticity theory and plasticity theory and written a few articles from his findings. ***In the elasticity and plasticity papers, he utilized the postprandial plasma glucose (PPG) value as the strain along with carbs/sugar amount and post-meal exercise level as the stress.***

In a recent email from Professor Norman Jones, he said that: "I have wondered if the use of viscoelastic/viscoplastic materials might be of some value to your studies. These phenomena embrace time-dependent behaviour and I know that you have emphasized the time-dependence of various behaviours in the body. Just a thought." His suggestion triggered the author's interest and desire to research the subject of glucose behaviors further using viscosity theory. This particular article is a follow-up to his paper No. 578 which studies certain generic characteristics of viscoelastic glucose behaviors. ***In this paper, he uses a relative glucose level (individual PPG - average PPG) as the strain and the strain rate (dε/dt) multiplied with***

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One special note is that he ceased taking any diabetes medications since 12/08/2015. *As a result, his research papers are* ***"medication-free".*** *Once medication enters the body, it takes over the control of glucose outputs, i.e. symptoms. In most of his studies using the CGM sensor collected glucose data after 12/08/2015, the raw data he has collected are completely "free from any biochemical influences". The only two influential forces or root-causes are the natural health of his organs (liver and pancreatic beta cells) and his lifestyle management (specifically, diet and exercise).*

Elastic Glucose vs. Plastic Glucose

The author has spent a considerable amount of research time during 2020 and 2021 to write 39 papers about his developed ***linear elastic glucose theory (LEGT).*** *This LEGT can be expressed through the following linear elastic glucose equation:*

Predicted PPG
= FPG * GH.f + (carbs&sugar grams) * GH.e + (post-meal walking k-steps * GH.w)

Where:

GH.f-Modulus *can estimate the starting PPG of a meal at 0-minute using FPG value during sleep;*

GH.e-Modulus *can estimate the peak PPG level at 60-minutes after a meal using carbs&sugar grams;*

GH.w-Modulus *can estimate the decreased PPG level at 180-minutes after a meal using post-meal walking k-steps.*

The above-described linear elastic equation can be applied to the ***4,056 meals with "elastic glucose" behaviors (99.5% of total).*** *A synthesized PPG waveform, by combining all of the 4,056 elastic PPG curves together, has the following described biophysical behavior pattern.*

It starts from 123 mg/dL at 0-minute, where his PPG value increased due to the consumption of ***13.5 grams of carbs/sugar*** *for energy input (low energy input or low stress) and reaches a PPG peak level of 133 mg/dL at 60-minutes, before starting to decline due to post-meal walking exercise, which burns off the energy to finally return to its ending-PPG level of 122 mg/dL at 180-minutes.* ***This end-glucose value returning to its initial-glucose position, after burning off energy influx, is called "elastic".***

On the contrary, another scenario of the glucose behavior can be explained using his ***23 meals with "plastic glucose" behaviors (0.5% of total).*** *A synthesized PPG curve, by combining all of the 23 plastic PPG curves (>180 mg/dL) together, has the following* ***different biophysical behavior pattern****. It starts from 142 mg/dL at 0-minute, where his PPG value increases due to the consumption of* ***85.7 grams of carbs&sugar*** *amount for energy input (high energy input or high stress) and then reaches to the first PPG peak level of 187 mg/dL at 60-minutes, but it continuously climbs* ***with a lower slope rate (43% of the earlier elastic phase)*** *due to the excessive carbs&sugar intake amount, until it reaches to its second peak PPG level of 207 mg/dL at 120-minutes. At this instant, the effect from his post-meal walking exercise finally kicks in to burn off the energy intake until it decreases to the end-glucose level of 191 mg/dL at 180-minutes.* ***This end-glucose value of 191 mg/dL is still 49 mg/dL higher than its initial-glucose position of 142 mg/dL. This type of "permanent deformation" or "residual glucose" value of 49 mg/dL is called "plastic" or "elasto-plastic".***

In his plastic glucose study of nonlinear plastic glucose theory (NPGT), he has developed the following simplified plastic glucose equation:

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To offer a simple explanation to readers who do not have a physics or engineering background, the author includes a brief excerpt from Wikipedia regarding the description of basic concepts for viscoelasticity theory and viscoplasticity theory from the disciplines of engineering and physics in the Method section.

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But, the medicine field is still quite different from the engineering field, where the engineering materials such as steel, copper, concrete, and aluminum are ***inorganic*** *in most cases. These material properties do not change significantly over their expected lifespans. However, in medicine, the body with its organs and cells are* ***organic*** *and go through many distinct stages over their natural lifespans, such as birth, splitting, growth, mutation, development, repair, sickness, and death. Therefore,* ***the biomedical properties are "moving targets" which vary with the individual person, severity of diabetes, and selected different time-windows.*** *In another word,* ***they are both time-dependent and specimen-dependent.*** *Because of these fundamental characteristics, calculations of cross-section of subject, bending moment of resistance, or the shape-factors in solid mechanics are not applicable in this biomedical elasticity/plasticity or viscoelasticity/viscoplasticity study. The most important part, in the author's opinion, is that by applying the concept of plasticity theory or viscoelasticity theory on understanding the biomedical phenomena is extremely useful for exploring deep insights for predicting abnormal glucose behaviors (or severe Diabetes) in order to help the 100+ million diabetes patients or 1.3% of the world population of 7.9 billion who are currently suffering from hyperglycemia (i.e., high glucose level > 180 mg/dL).*

Energy Theory

After declaring the analogy of elasticity and plasticity theories, the energy theory in physics must be brought into context. The human body and organs are composed of different organic cells that require energy infusion from glucose carried by red blood cells and energy consumption from labor-work or exercise. By the way, there are approximately 70% of energy inputs are consumed by brain functions. When the residual energy resulting from a plastic glucose scenario is stored in the body, it will cause damage to many internal organs. ***According to physics principle, energies associated with the residual glucose waves are proportional to the square of the residual glucose amplitude. The residual energies from elevated glucoses are then circulating inside the body via red blood-cells inside blood vessels which then impact all of the internal organs to cause different degrees of damage and develop into different diabetic complications.*** *The author has applied Fast Fourier Transform (FFT) operations to convert the glucose wave from a time-domain into a frequency-domain. The y-axis amplitude values in the frequency-domain indicate the proportional energy levels associated with each different frequency component of glucose occurrence.*

Currently, many people live a sedentary lifestyle and lack sufficient exercise to burn off the energy influx which causes them to become overweight or obese. Being overweight and/or having obesity can lead to chronic diseases, including diabetes. In addition, many types of processed food add unnecessary ingredients and harmful chemical components that are toxic to the bodies, which lead to the development of many other deadly diseases, such as cancer. For example, there are ~85% of worldwide diabetes patients, who are overweight, and ~75% of them have cardiac issues or require surgeries due to diabetes conditions.

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Time-dependent strain (glucose) and time-dependent stress (viscosity * glucose rate):

The Hooke's law of linear elasticity is expressed as:

Strain (ε: epsilon)
= Stress (σ: sigma) / Young's modulus (E)

For biomedical glucose application, his developed LEGT is expressed as:

PPG (strain) = carbs/sugar (stress) * GH.p-Modulus (a positive number) + post-meal walking k-steps * GH.w-Modulus

(a negative number)

Where GH.p-Modulus is reciprocal of Young's modulus E.

In this article, in order to construct an "ellipse-like" diagram in the stress-strain space domain covering the positive and negative sides of the space, he has modified his definition of strain as follows:

Strain
= (PPG value at certain time instant) - (averaged PPG value)

In summary, in this viscoelastic and viscoplastic study, he defines his strain and stress as follows:

strain = ε
= (individual PPG - averaged PPG)

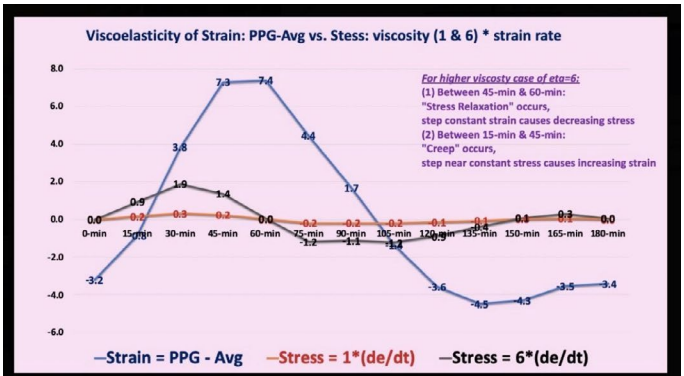
Stress = σ
= η * (dε/dt)
= viscosity factor * (d-strain/d-time)
= η * (PPG at next time instant - PPG at current time instant) / 15

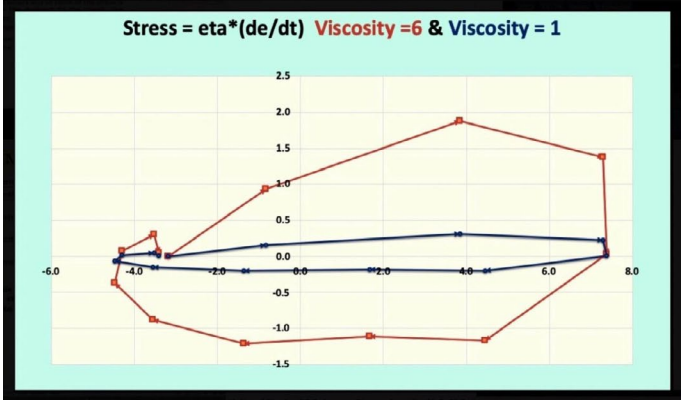
Where 15 indicates the 15-minute timespan of his CGM sensor Glucose measurement.

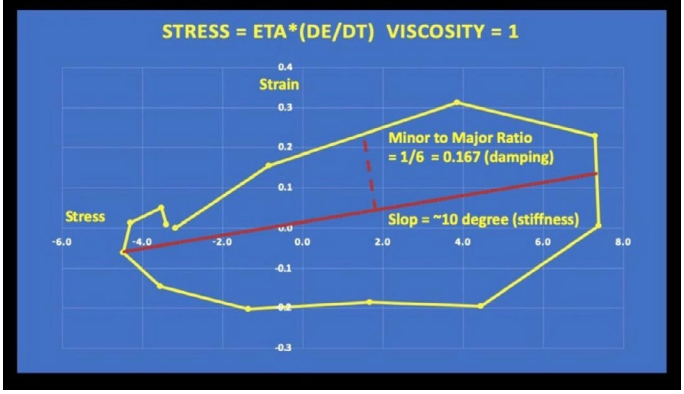
He then uses 13.5 grams as the viscosity of viscoelastic case (<180 mg/dL) and 85.7 grams as the viscosity of viscoplastic case (>180 mg/dL). The strain rate or PPG change rate has included the exercise effect on PPG level.

The objective of this article is to explore and validate certain basic characteristics of viscoelasticity and viscoplasticity using the author's own collected elastic and plastic glucoses over a long period of 3.7 years from 5/8/2018 to 1/10/2022. The discovered characteristics include stress relaxation, creep, hysteresis loop, material stiffness, and damping effect ***based on time-dependent stress and strain*** *which are different from previous research findings using* ***LEGT*** *and* ***NPGT.*** *Actually, the hysteresis loop areas of energy loss through heat have some connection with both energy theory and thermodynamics principles.*

In summary, the following three concluding remarks have described the findings of this research paper:
(1) From the time-domain diagram of the elastic glucose and plastic glucose waveforms, we can observe the differences between the two curves. The end-glucose at 180-minutes and initial glucose at 0-minute of the elastic case are identical at 123 mg/dL. However, the end-glucose at 180-minutes of 191 mg/dL has a "residual glucose" of 49 mg/dL in comparison with the initial glucose at 0-minute of 142 mg/dL of the plastic case.
(2) From the space-domain diagrams of the viscoelastic and viscoplastic cases, there is a vast difference. ***The viscoelasticity stress-strain curve is a "closed" hysteresis loop which means the glucose value bounces back to its original level. However, the viscoplastic stress-strain curve has a big "opening hole" which represents the 49 mg/dL of "residual glucose" gap.*** *Incidentally, if we superimpose these two curves together, the viscoelastic loop will occupy a much smaller space (about 1/6 size) in the center portion of the viscoplastic open loop. This space area difference is caused by the two viscosity factors (13.5/85.7 = 1/6) and the two different datasets of strain rates (smaller elastic rate vs. larger plastic rate). This area difference indicates that the viscoplastic case has more energy loss than the viscoelastic case. It is interesting to find out that the initial portion (left portion) of the viscoplastic stress-strain curve has shown a similar pattern as the "strain hardening effect".*
(3) The author has also plotted the space-domain diagram of stress vs. strain (X vs. Y) in a reverse way of ***strain vs. stress*** *(X vs. Y). Although they look different when compared closely, but both diagrams still preserve the basic characters of both viscoelasticity and viscoplasticity.*







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Methods

Elasticity, Plasticity, Viscoelasticity and Viscoplasticity

The Difference Between Elastic Materials and Viscoelastic Materials

(from "Soborthans, innovating shock and vibration solutions")

What are Elastic Materials?

Elasticity is the tendency of solid materials to return to their original shape after forces are applied on them. When the forces are removed, the object will return to its initial shape and size if the material is elastic.

What are Viscous Materials?

Viscosity is a measure of a fluid's resistance to flow. A fluid with large viscosity resists motion. A fluid with low viscosity flows. For example, water flows more easily than syrup because it has a lower viscosity. High viscosity materials might include honey, syrups, or gels – generally things that resist flow. Water is a low viscosity material, as it flows readily. Viscous materials are thick or sticky or adhesive. Since heating reduces viscosity, these materials don't flow easily. For example, warm syrup flows more easily than cold.

What is Viscoelastic?

Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Synthetic polymers, wood, and human tissue, as well as metals at high temperature, display significant viscoelastic effects. In some applications, even a small viscoelastic response can be significant.

Elastic Behavior Versus Viscoelastic Behavior

The difference between elastic materials and viscoelastic materials is that viscoelastic materials have a viscosity factor and the elastic ones don't. Because viscoelastic materials have the viscosity factor, they have a strain rate dependent on time. Purely elastic materials do not dissipate energy (heat) when a load is applied, then removed; however, a viscoelastic substance does.

The following brief introductions are excerpts from Wikipedia:

"Elasticity (Physics)

Physical property when materials or objects return to original shape after deformation

In physics and materials science, ***elasticity*** *is the ability of a body to resist a distorting influence and to return to its original size and shape when that influence or force is removed. Solid objects will deform when adequate loads are applied to them; if the material is elastic, the object will return to its initial shape and size after removal. This is in contrast to plasticity, in which the object fails to do so and instead remains in its deformed state. The physical reasons for elastic behavior can be quite different for different materials. In metals, the atomic lattice changes size and shape when forces are applied (energy is added to the system). When forces are removed, the lattice goes back to the original lower energy state. For rubbers and other polymers, elasticity is caused by the stretching of polymer chains when forces are applied.*

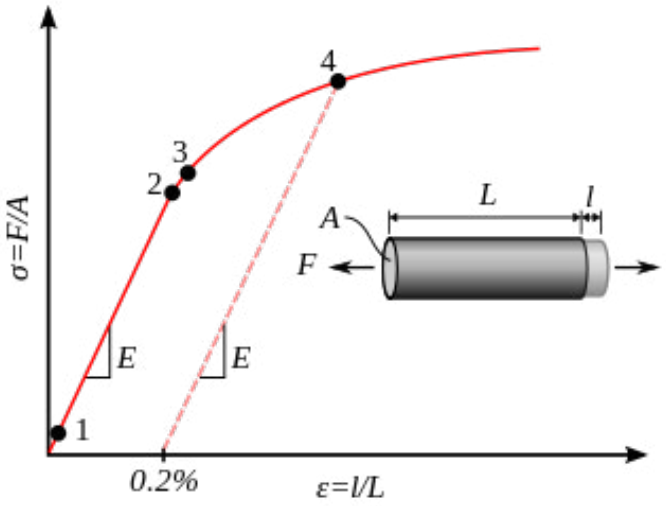
Hooke's law states that the force required to deform elastic objects should be directly proportional to the distance of deformation, regardless of how large that distance becomes. This is known as perfect elasticity, in which a given object will return to its original shape no matter how strongly it is deformed. This is an ideal concept only; most materials which possess elasticity in practice remain purely elastic only up to very small deformations, after which plastic (permanent) deformation occurs.

In engineering, the elasticity of a material is quantified by the elastic modulus such as the Young's modulus, bulk modulus or shear modulus which measure the amount of stress needed to achieve a unit of strain; a higher modulus indicates that the material is harder to deform. The material's elastic limit or yield strength is the maximum stress that can arise before the onset of plastic deformation.

Plasticity (Physics)

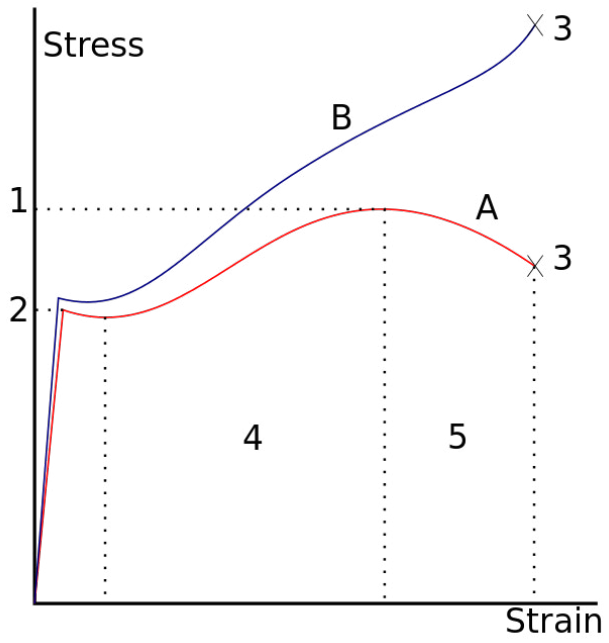
Deformation of a solid material undergoing non-reversible changes of shape in response to applied forces.

In physics and materials science, ***plasticity****, also known as* ***plastic deformation,*** *is the ability of a solid material to undergo permanent deformation, a non-reversible change of shape in response to applied forces. For example, a solid piece of metal being bent or pounded into a new shape displays plasticity as permanent changes occur within the material itself. In engineering, the transition from elastic behavior to plastic behavior is known as yielding.*



Stress–strain curve showing typical yield behavior for nonferrous alloys.

1. *True elastic limit*
2. *Proportionality limit*
3. *Elastic limit*
4. *Offset yield strength*



A stress–strain curve typical of structural steel.

- *1: Ultimate strength*
- *2: Yield strength (yield point)*
- *3: Rupture*
- *4: Strain hardening region*
- *5: Necking region*
- *A: Apparent stress (F/A0)*
- *B: Actual stress (F/A)*

Plastic deformation is observed in most materials, particularly metals, soils, rocks, concrete, and foams. However, the physical mechanisms that cause plastic deformation can vary widely. At a crystalline scale, plasticity in metals is usually a consequence of dislocations. Such defects are relatively rare in most crystalline materials, but are numerous in some and part of their crystal structure; in such cases, plastic crystallinity can result. In brittle materials such as rock, concrete and bone, plasticity is caused predominantly by slip at microcracks. In cellular materials such as liquid foams or biological tissues, plasticity is mainly a consequence of bubble or cell rearrangements, notably T1 processes.

For many ductile metals, tensile loading applied to a sample will cause it to behave in an elastic manner. Each increment of load is accompanied by a proportional increment in extension. When the load is removed, the piece returns to its original size. However, once the load exceeds a threshold – the yield strength – the extension increases more rapidly than in the elastic region; now when the load is removed, some degree of extension will remain. Elastic deformation, however, is an approximation and its quality depends on the time frame considered and loading speed. If, as indicated in the graph opposite, the deformation includes elastic deformation, it is also often referred to as "elasto-plastic deformation" or "elastic-plastic deformation".

Perfect plasticity is a property of materials to undergo irreversible deformation without any increase in stresses or loads. Plastic materials that have been hardened by prior deformation, such as cold forming, may need increasingly higher stresses to deform further. Generally, plastic deformation is also dependent on the deformation speed, i.e. higher stresses usually have to be applied to increase the rate of deformation. Such materials are said to deform visco-plastically."

Viscoelasticity

Property of materials with both viscous and elastic characteristics under deformation.

In materials science and continuum mechanics, viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Viscous materials, like water, resist shear flow and strain linearly with time when a stress is applied. Elastic materials strain when stretched and immediately return to their original state once the stress is removed.

Viscoelastic materials have elements of both of these properties and, as such, exhibit time-dependent strain. Whereas elasticity is usually the result of bond stretching along crystallographic planes in an ordered solid, viscosity is the result of the diffusion of atoms or molecules inside an amorphous material.

In the nineteenth century, physicists such as Maxwell, Boltzmann, and Kelvin researched and experimented with creep and recovery of glasses, metals, and rubbers. Viscoelasticity was further examined in the late twentieth century when synthetic polymers were engineered and used in a variety of applications. Viscoelasticity calculations depend heavily on the viscosity variable, η. The inverse of η is also known as fluidity, φ. The value of either can be derived as a function of temperature or as a given value (i.e. for a dashpot).

Depending on the change of strain rate versus stress inside a material, the viscosity can be categorized as having a linear, non-linear, or plastic response. When a material exhibits a linear response it is categorized as a Newtonian material. In this case the stress is linearly proportional to the strain rate. If the material exhibits a non-linear response to the strain rate, it is categorized as Non-Newtonian fluid. There is also an interesting case where the viscosity decreases as the shear/strain rate remains constant. A material which exhibits this type of behavior is known as thixotropic. In addition, when the stress is independent of this strain rate, the material exhibits plastic deformation. Many viscoelastic materials exhibit rubber like behavior explained by the thermodynamic theory of polymer elasticity.

Cracking occurs when the strain is applied quickly and outside of the elastic limit. Ligaments and tendons are viscoelastic, so the extent of the potential damage to them depends both on the rate of the change of their length as well as on the force applied.

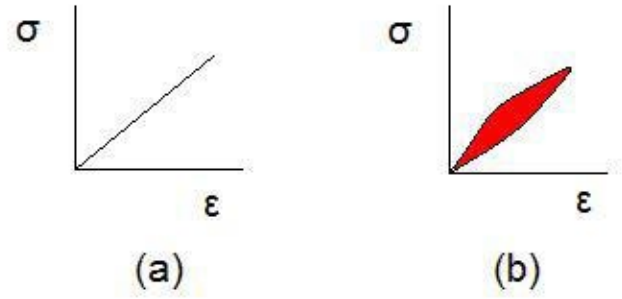
A viscoelastic material has the following properties:

- ***hysteresis is seen in the stress–strain curve***
- ***stress relaxation occurs: step constant strain causes***

decreasing stress

- ***creep occurs: step constant stress causes increasing strain***
- ***its stiffness depends on the strain rate or the stress rate.***

Elastic Versus Viscoelastic Behavior



Stress–strain curves for a purely elastic material (a) and a viscoelastic material (b). The red area is a hysteresis loop and shows the amount of energy lost (as heat) in a loading and unloading cycle. It is equal to

$\oint \sigma d\varepsilon$

where σ is stress and ε is strain.

Unlike purely elastic substances, a viscoelastic substance has an elastic component and a viscous component. ***The viscosity of a viscoelastic substance gives the substance a strain rate dependence on time.*** Purely elastic materials do not dissipate energy (heat) when a load is ***applied, then removed. However, a viscoelastic substance dissipates energy when a load is applied, then removed. Hysteresis is observed in the stress–strain curve, with the area of the loop being equal to the energy lost during the loading cycle.*** Since viscosity is the resistance to thermally activated plastic deformation, a viscous material will lose energy through a loading cycle. Plastic deformation results in lost energy, which is uncharacteristic of a purely elastic material's reaction to a loading cycle.

Specifically, viscoelasticity is a molecular rearrangement. When a stress is applied to a viscoelastic material such as a polymer, parts of the long polymer chain change positions. This movement or rearrangement is called ***"creep".*** Polymers remain a solid material even when these parts of their chains are rearranging in order to accompany the stress, and as this occurs, it creates a back stress in the material. When the back stress is the same magnitude as the applied stress, the material no longer creeps. When the original stress is taken away, the accumulated back stresses will cause the polymer to return to its original form. ***The material creeps, which gives the prefix visco-, and the material fully recovers, which gives the suffix -elasticity.***

Viscoplasticity

Viscoplasticity is a theory in continuum mechanics that describes the rate-dependent inelastic behavior of solids. Rate-dependence in this context means that the deformation of the material depends on the rate at which loads are applied. The inelastic behavior that is the subject of viscoplasticity is plastic deformation which means that the material undergoes unrecoverable deformations when a load level is reached. Rate-dependent plasticity is important for transient plasticity calculations. The main difference between rate-independent plastic and viscoplastic material models is that the latter exhibit not only permanent deformations after the application of loads but continue to undergo a creep flow as a function of time under the influence of the applied load.

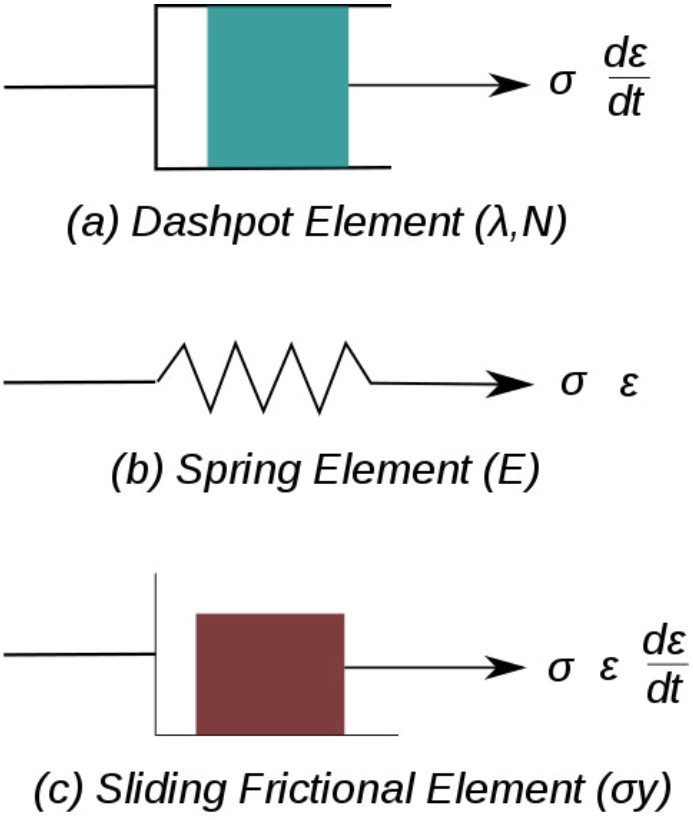


Figure 1: Elements used in one-dimensional models of viscoplastic materials.

The elastic response of viscoplastic materials can be represented in one-dimension by Hookean spring elements. Rate-dependence can be represented by nonlinear dashpot elements in a manner similar to viscoelasticity. Plasticity can be accounted for by adding sliding frictional elements as shown in Figure 1. In the figure E is the modulus of elasticity, λ is the viscosity parameter and N is a power-law type parameter that represents non-linear dashpot [$\sigma(d\varepsilon/dt) = \sigma = \lambda(d\varepsilon/dt)(1/N)$]. The sliding element can have a yield stress (σy) that is strain rate dependent, or even constant, as shown in Figure 1c.

Viscoplasticity is usually modeled in three-dimensions using overstress models of the Perzyna or Duvaut-Lions types. In these models, the stress is allowed to increase beyond the rate-independent yield surface upon application of a load and then allowed to relax back to the yield surface over time. The yield surface is usually assumed not to be rate-dependent in such models. An alternative approach is to add a strain rate dependence to the yield stress and use the techniques of rate independent plasticity to calculate the response of a material For metals and alloys, viscoplasticity is the macroscopic behavior caused by a mechanism linked to the movement of dislocations in grains,

with superposed effects of inter-crystalline gliding. The mechanism usually becomes dominant at temperatures greater than approximately one third of the absolute melting temperature. However, certain alloys exhibit viscoplasticity at room temperature (300K). For polymers, wood, and bitumen, the theory of viscoplasticity is required to describe behavior beyond the limit of elasticity or viscoelasticity.

In general, viscoplasticity theories are useful in areas such as
• the calculation of permanent deformations,
• the prediction of the plastic collapse of structures,
• the investigation of stability,
• crash simulations,
• systems exposed to high temperatures such as turbines in engines, e.g. a power plant,
• dynamic problems and systems exposed to high strain rates.

Phenomenology

For a qualitative analysis, several characteristic tests are performed to describe the phenomenology of viscoplastic materials. Some examples of these tests are

1. hardening tests at constant stress or strain rate,
2. creep tests at constant force, and
3. stress relaxation at constant elongation.

Strain Hardening Test

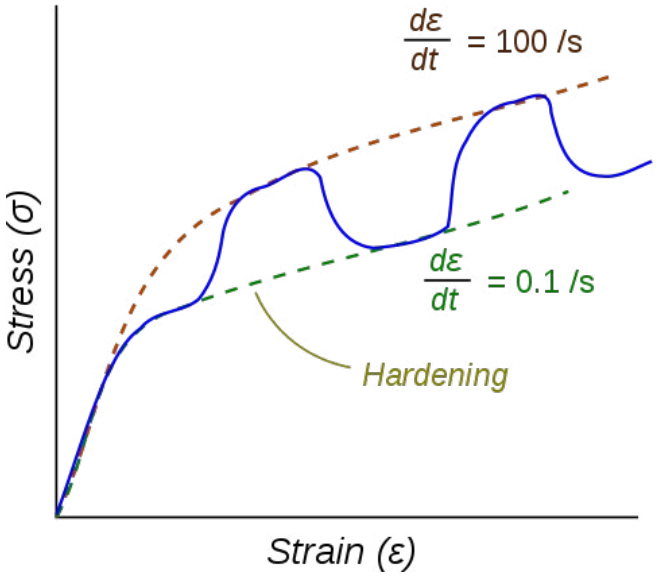


Figure 2: Stress–strain response of a viscoplastic material at different strain rates.

The dotted lines show the response if the strain-rate is held constant. The blue line shows the response when the strain rate is changed suddenly.

One consequence of yielding is that as plastic deformation proceeds, an increase in stress is required to produce additional strain. This phenomenon is known as Strain/Work hardening. For a viscoplastic material the hardening curves are not significantly different from those of rate-independent plastic material. Nevertheless, three essential differences can be observed.

1. At the same strain, the higher the rate of strain the higher the stress
2. A change in the rate of strain during the test results in an immediate change in the stress–strain curve.
3. The concept of a plastic yield limit is no longer strictly applicable.

The hypothesis of partitioning the strains by decoupling the elastic and plastic parts is still applicable where the strains are small, i.e.,

$\varepsilon = \varepsilon e + \varepsilon vp$

where εe is the elastic strain and εvp is the viscoplastic strain. To obtain the stress–strain behavior shown in blue in the figure, the material is initially loaded at a strain rate of 0.1/s. The strain rate is then instantaneously raised to 100/s and held constant at that value for some time. At the end of that time period the strain rate is dropped instantaneously back to 0.1/s and the cycle is continued for increasing values of strain. There is clearly a lag between the strain-rate change and the stress response. This lag is modeled quite accurately by overstress models (such as the Perzyna model) but not by models of rate-independent plasticity that have a rate-dependent yield stress.

Results

Figure 1 shows a data table of the input and output for this study. It is noted that the values of both stress and strain for the viscoplastic case are larger than the viscoelastic case.

1/14/22	13.5 grams		Viscousity (eta)	1/14/22	85.7 grams		Viscousity (eta)
4,056 meals	4.28 k-steps		13.5	23 meals	3.532 k-steps		85.7
(<179 mg/dL)	Elastic PPG	Strain = PPG - Avg	Stress = eta*(de/dt)	(>180 mg/dL)	Plastic PPG	Strain = PPG - Avg	Stress = eta*(de/dt)
0-min	123	-3.2	0.0	0-min	142	-45.4	0.0
15-min	125	-0.8	2.1	15-min	153	-34.0	65.2
30-min	130	3.8	4.2	30-min	163	-23.6	59.2
45-min	133	7.3	3.1	45-min	177	-9.7	79.7
60-min	133	7.4	0.1	60-min	187	0.1	55.6
75-min	130	4.4	-2.6	75-min	192	5.2	29.6
90-min	128	1.7	-2.5	90-min	202	14.8	54.6
105-min	125	-1.4	-2.7	105-min	204	16.6	10.3
120-min	122	-3.6	-2.0	120-min	207	20.0	19.4
135-min	122	-4.5	-0.8	135-min	203	16.1	-22.3
150-min	122	-4.3	0.2	150-min	207	19.6	20.1
165-min	122	-3.5	0.7	165-min	203	16.0	-21.0
180-min	123	-3.4	0.1	180-min	191	4.3	-66.3
Average	126	0.0	0.0	Average	187	0.0	21.9

Figure 1: Input data and stress / strain data ($\eta = 13.5$ for viscoelastic & 85.7 for viscoplastic)

Figure 2 depicts the time-domain of elastic and plastic PPG waveforms. It is noted that the linear elastic (bouncing back) and plastic (residual strain) situations are clearly demonstrated.

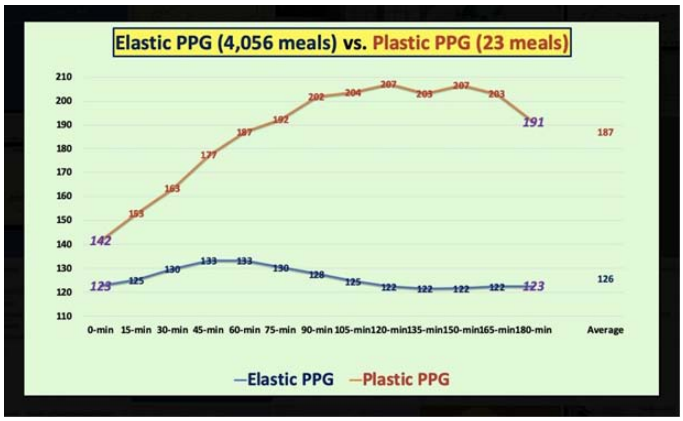


Figure 2: Time-domain of 2 PPG waveforms

Figure 3 reflects a space-domain for these two cases. It is noted that the viscoelasticity case has a completely closed elliptic curve with a hysteresis loop. However, the viscoplastic case has a large opening which indicates the plastic phenomenon with remaining or residual strain.

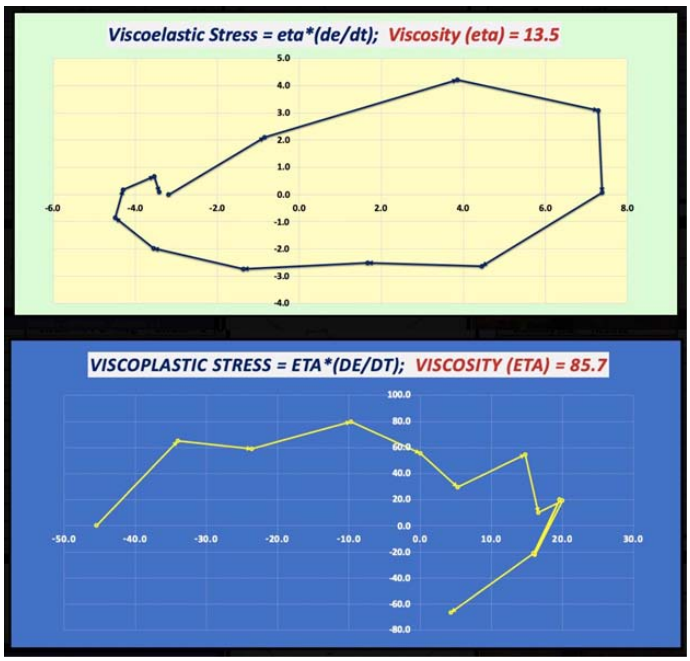


Figure 3: Space domain of stress-strain diagrams for viscoelastic (upper) and viscoplastic (lower)

Figure 4 illustrates two space-domain diagrams of the stress-strain versus strain-stress for both viscoelastic and viscoplastic cases. It is noted that they exhibit the same phenomena and send the same messages regardless of the different views for the curve appearance.

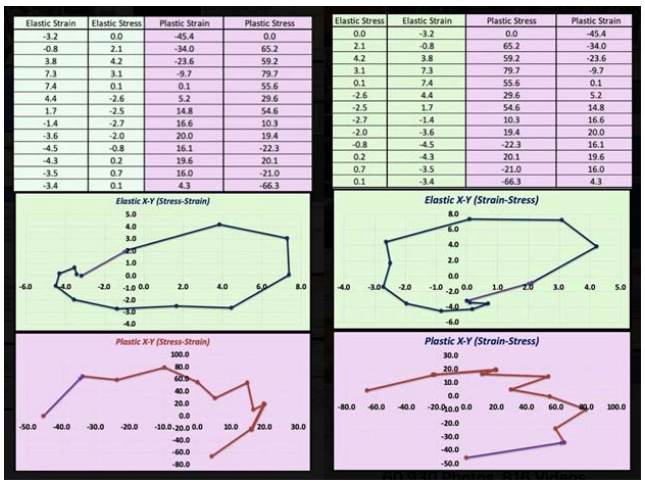


Figure 4: Two space-domain diagrams of stress-strain versus strain-stress for both viscoelastic and viscoplastic cases

Conclusion

In summary, the following three concluding remarks have described the findings of this research paper:

(1) From the time-domain diagram of the elastic glucose and plastic glucose waveforms, we can observe the differences between the two curves. The end-glucose at 180-minutes and initial glucose at 0-minute of the elastic case are identical at 123 mg/dL. However, the end-glucose at 180-minutes of 191 mg/dL has a "residual glucose" of 49 mg/dL in comparison with the initial glucose at 0-minute of 142 mg/dL of the plastic case.

(2) From the space-domain diagrams of the viscoelastic and viscoplastic cases, there is a vast difference. ***The viscoelasticity stress-strain curve is a "closed" hysteresis loop which means the glucose value bounces back to its original level. However, the viscoplastic stress-strain curve has a big "opening hole" which represents the 49 mg/dL of "residual glucose" gap.*** Incidentally, if we superimpose these two curves together, the viscoelastic loop will occupy a much smaller space (about 1/6 size) in the center portion of the viscoplastic open loop. This space area difference is caused by the two viscosity factors (13.5/85.7 = 1/6) and the two different datasets of strain rates (smaller elastic rate vs. larger plastic rate). This area difference indicates that the viscoplastic case has more energy loss than the viscoelastic case. It is interesting to find out that the initial portion (left portion) of the viscoplastic stress-strain curve has shown a similar pattern as the "strain hardening effect".

(3) The author has also plotted the space-domain diagram of stress vs. strain (X vs. Y) in a reverse way of ***strain vs. stress*** (X vs. Y). Although they look different when compared closely, but both diagrams still preserve the basic characters of both viscoelasticity and viscoplasticity.

Acknowledgement

Without Professor Norman Jones at MIT as his academic advisor, the author would not be able to conduct this particular research project and also published 500+ medical research papers. The author has never forgotten his advice to him that he should always enhance his strength on foundations, such as mathematics and physics, in order to make further improvement and ad-

vancement. Professor Jones has also provided him a personal example of doing outstanding teaching and research jobs with an excellent work attitude, extreme dedication, and ultimate commitment to advancing both science and engineering.

References

For editing purposes, the majority of the references in this paper, which are self-references, have been removed. Only references from other authors' published sources remain. The bibliography of the author's original self-references can be viewed at www.eclairemd.com.