Predicting the Environmental Response of Gelatin Containing Composite Structures

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☐ ABSTRACT

The mechanical response of objects having a complex composite structure can be accurately modeled if the material properties of the individual components are characterized using the approach briefly described in this paper. The three dimensional surface of the equilibrium stress-strain state and the methods required for its determination were the subject of several years of research by the authors. More detailed explanation of the experimental technique and mathematical treatment can be found in previous papers by the authors.[1–4]

☐ Introduction

This paper is a brief summary of our research on the mechanical properties of cultural materials. Gelatin containing composites were extensively investigated during the course of the research because gelatin and animal glues are found in a wide variety of cultural objects (e.g. furniture, paintings, photographs, books and paper). The mechanical properties of these objects are important because in many instances the type of deterioration encountered in museums and archives is not always chemical in nature. Rather, it is mechanical failure in the form of cracking, delamination, and irreversible warpage. Mechanical failure is not simply a question of poor handling. An environmental component of mechanical damage due to cycling of both temperature and relative humidity has long been recognized, but quantification of the environmental risk had not been attempted previously. The purpose of our research was to quantify this risk, and in order to do so, accurate material properties of the individual components in an object must be determined. Once the individual materials have been characterized properly, the behaviour of an object made with multiple types of materials can be modeled using engineering methods such as finite element analysis.[5]

☐ The Determination of Mechanical Properties

Stress-strain diagrams are commonly used to describe mechanical properties of a material. The data are collected under constant temperature and relative humidity conditions and a constant loading rate. Changes in these parameters significantly alter the results. For example, a higher rate of loading leads to higher values for elastic modulus and less ductile behaviour. In order to predict the response of a material to changes in relative humidity and temperature, the loading rate has to equate with one which can occur in the real world as a result of a change in temperature and/or relative humidity. From numerous environmental tests, we determined that an environmentally induced stress in a material, which is caused by changes in temperature and humidity while the material is not free to expand or contract, can be directly related to tensile stress tests where the material is stretched or compressed under constant environmental conditions. This relationship occurs when an equilibrium state of stress *vs* strain exists. This state reveals the correct mechanical properties necessary to predict accurately long term environmental behaviour. Fig. 1 illustrates the relationship for a change in relative humidity (RH). In Fig. 1, the slope of the tension test path correlates to the engineering modulus, while the slope of the free shrinkage path correlates to the humidity coefficient of expansion for the material under test. The museum path to the same stress level occurs in response to a decrease in RH when the material is not allowed to contract. For example, a gelatin emulsion coated on a glass substrate (e.g. a photographic plate) will try to shrink as relative humidity is decreased, but the glass substrate prevents the free movement. The gelatin layer then develops internal stress, or forces, equivalent to those that would have been required to stretch it back to its original length if the layer had first been allowed to shrink freely as the RH was lowered. Corresponding measurements and calculations can be made for changes in temperature. The results can be combined to predict behaviour for simultaneous changes in RH and temperature.

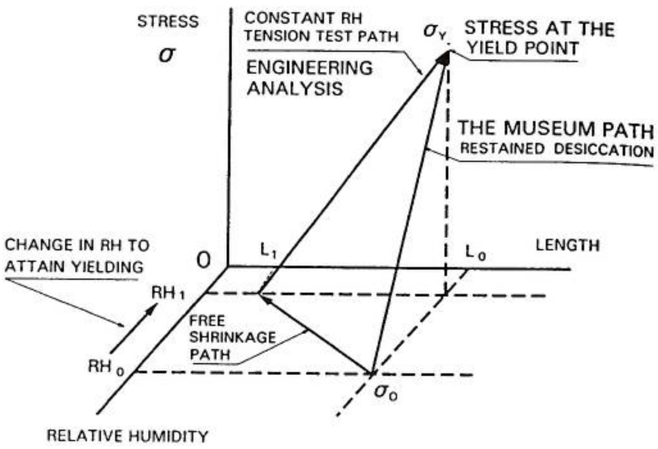

Fig. 1. Different paths to the same stress level.

The equilibrium stress-strain surface illustrated in Fig. 1 (the solid triangle) can be measured by conducting three basic tests. One is the simple measurement of the thermal or moisture induced linear expansion. From this measurement the thermal coefficient of linear expansion or humidity coefficient of expansion can be calculated. The second test is the measurement of the stress in a material resulting from the cooling or desiccation of a restrained specimen. RH is held constant during cooling tests and temperature is held constant during RH tests. The third type of test required is the measurement of the stress-strain properties under near equilibrium conditions. Fig. 2 shows the equilibrium surface plotted for gelatin after conducting these three types of experiments. Data along the lines containing intersection points I_{01}, I_{02}, I_{03} represent the free shrinkage path from which a function for the coefficient of expansion can be derived. A curve containing intersection points I_2, I_5, I_8, for example, plots data collected from the second type of test in which a restrained specimen is subjected to changes in RH. Finally, a curve containing intersection points I_3, I_4, I_5, for example, plots data collected from the third type of test which is essentially a conventional tensile test run at a very slow loading rate or by allowing stress relaxation to occur before determining the value for stress. The data from the three tests map a thermodynamic shell, and the instantaneous slope at any point on the surface of this shell yields modulus values required for accurate computer modeling using finite element analysis. The mechanical properties of each type of material in an object of

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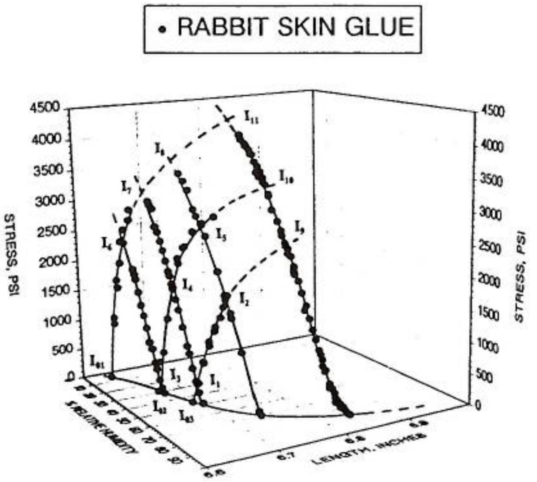

Fig. 2. The equilibrium stress/strain surface.

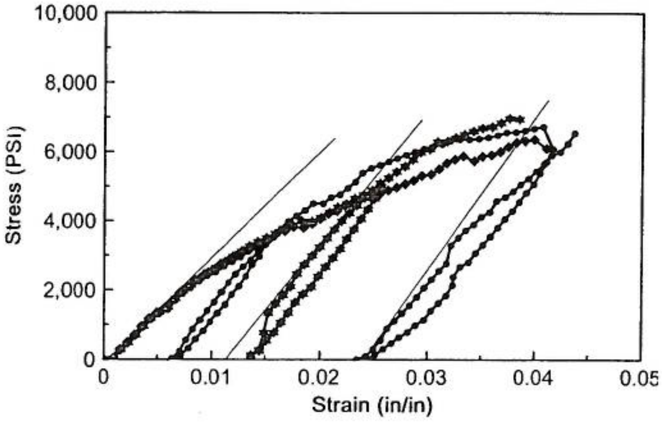

Fig. 3. Long term gelatin behaviour (2.5 year compliance test).

complex construction must be determined in this same way in order to model the environmental response of the composite structure.

Measuring the equilibrium modulus of a material from a tensile test requires significantly more time than is typically used by automated tensile test equipment. If one is to determine the true equilibrium modulus, the time dependent properties must be nearly eliminated. One of the ways to satisfy this requirement is to load the specimen incrementally and allow it to stress-relax until nearly all stress reduction ceases. After no or very minimal stress relaxation continues then further load is applied and the load/stress-relation cycle repeated. Some materials stress relax a considerable amount in a relatively short time and others very little, even over extended periods. Fig. 3 shows the equilibrium stress-strain curves for three gelatin specimens loaded at a strain rate of 0.001 inch/inch per week. This rate discounts time dependent behaviour in the usual sense. Compliance curves were determined during the course of the experiment by unloading the specimens at various strain levels. Displacement in the strain value along the x-axis after the force was removed represents permanent deformation of the specimens. Continuation of the experiment after each successive unloading also shows an increasing elastic region as well as an increasing strain hardening of the gelatin film as evidenced by the increasing value of the elastic modulus (illustrated by the slope of the solid lines).

☐ Glass Transition Temperature Behaviour in Hygroscopic Materials

Another important factor to consider in the computer modeling of hygroscopic polymers is the influence that moisture content has on the glass transition temperature (T_g). T_g can change dramatically. Gelatin is an extreme example of this type of behaviour.[6,7] Virtually all objects containing gelatin that are found in a museum or archive should be properly exhibited and stored at environmental conditions below T_g for the gelatin. Below T_g, the gelatin is in the dry state rather than the gel state, even though dry gelatin can still contain considerable amounts of absorbed water. The curvature associated with the thermodynamic surface plotted in Fig. 2 takes into account the elastic-plastic behaviour of the material, as well as differences in modulus at any point on the diagram's surface caused by changes in moisture content of the gelatin. The true yield point for elastic-to-plastic behaviour is approximately 0.4% elongation, although strain hardening effects observed in Fig. 3 increased the yield point to approximately 0.6%. The 0.4% threshold value for true yielding (the onset of irreversible deformation) is surprisingly consistent for a wide variety of polymeric materials and its determination has been largely overestimated by engineering tests which are run under much more rapid loading conditions.

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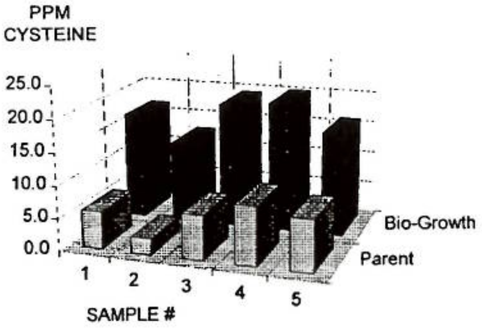

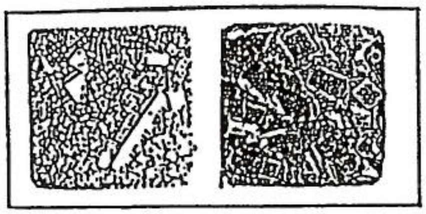

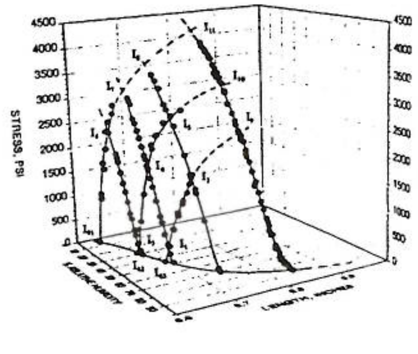

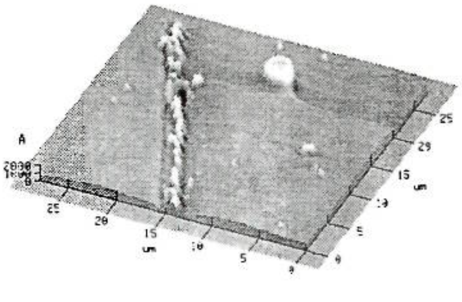

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