Going Elsewhere – Adapting Structures for Use in Space through Rigidizing Materials

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ABSTRACT

Inflation-deployed, space-rigidized structures hold the promise for lightweight, compactly-stowed objects, and to further reduce costs through a lower part number. The paper reviews designs of fibre-reinforced composites, rigidized by physical or chemical transition once deployed in space. We briefly discuss the importance of good thermal properties, examine the ability of thermosetting materials to achieve them, and discuss the potential for new directions in plasticized matrix systems.

1. INTRODUCTION

While large space structures could contribute positively and efficiently in many astronautical areas, after many years of development only few proposals have found implementation. In part, this reluctant progress derives from the need to transport the structural element from Earth to their operational location in space: as large structures cannot travel in a single piece, transport makes them more complex. Depending on the adopted design principle (variable-geometry assemblies unfurling at destination; "flexible-wall expandable structures" unfolding there to their full shape; erectable structures, assembled from ferried components), the design complexity may increase, reliability become more fragile, on-site operations grow more complex, limiting options, increasing risks and costs. But an additional fact needs consideration: the structure moves across quite different environments, with particularly strong differences existing between the transport and the operational conditions. Therefore, the structure's properties must adapt to the different processes and environments: it must be flexible for good packaging, then become rigid on site, to sustain the relevant loads. Inflation-deployed structures have long appeared to offer a good compromise. These objects are completed on ground, but do not contain complex unfurling mechanisms. They can well survive the launch in stowed configuration, but lead to very light unfolded items. Rigidization of the deployed structure eliminates the need for an apparatus to control the pressure and to replenish the unavoidable gas losses -- penalties that limit use of constantly-inflated objects to functions calling for internal pressure (habitats), or of short duration (e.g., 0.1 - 100 days).

2. RIGIDIZATION APPROACHES

2.1 Overview

Figure 1 outlines the different types of rigidization approaches under consideration. Materials and processes used accordingly differ: mechanically rigidized structures adopt completely processed materials (including metals), coming conceptually near to conventional unfurlable structures. Other kinds build on non-metallic materials either held in an intermediate state (prepreg), or modified into a similar condition. Because of space limitations, in this paper, we focus on designs based on fibre-reinforced composites undergoing some physico-chemical transition.

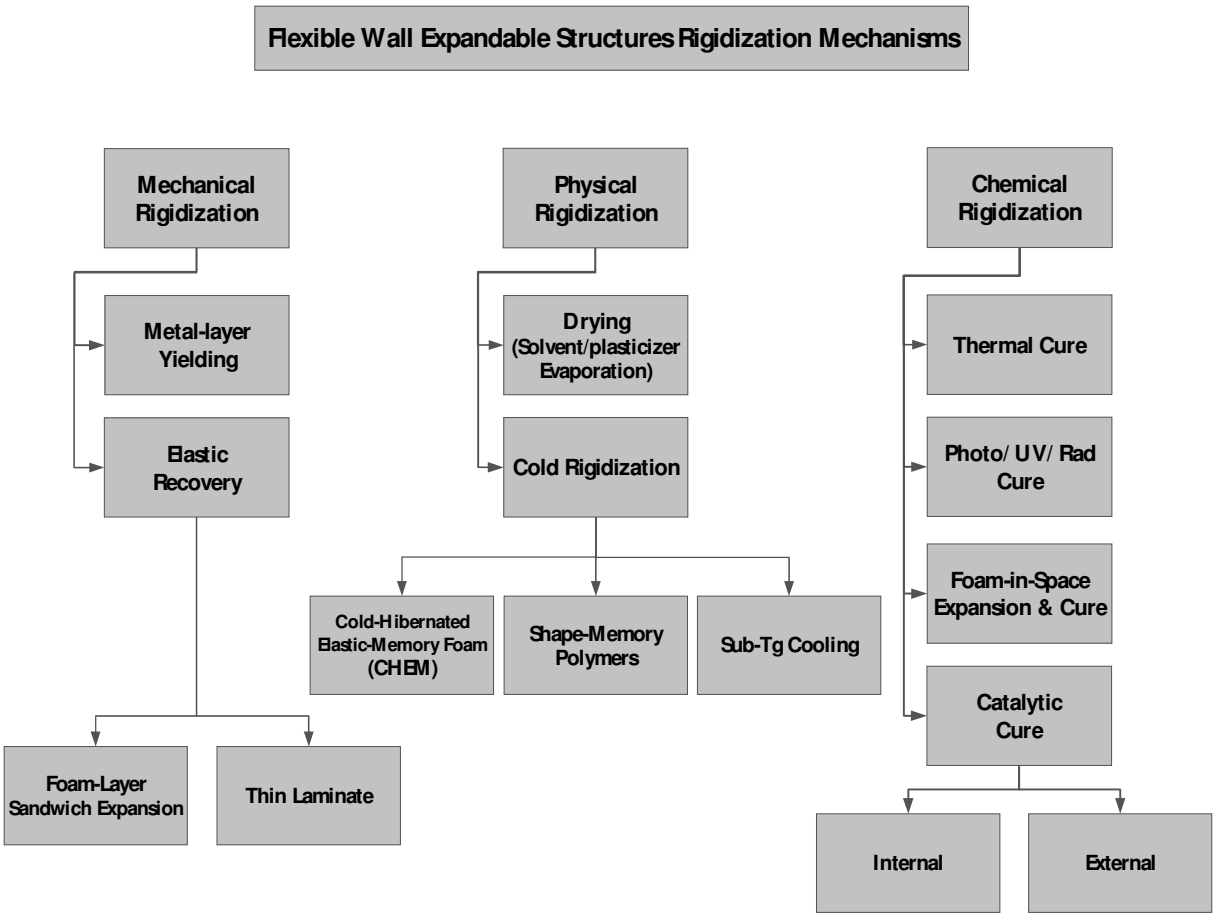

Figure 1: Rigidization mechanisms for thin-walled expandable structures.

2.2 Chemical Processes

The concept of "rigidizing inflatable satellites" through chemical means goes back to the very early 1960s, and the the work of Seymour Schwartz and Leon Keller at Hughes Aircraft Co (Schwartz & Zelman, 1962), Raymond Spain at the USAF Materials Laboratory (Spain, 1962), and FW Forbes at the USAF Aero Propulsion Laboratory (Forbes, 1964). Chemically-rigidized expandable structures (CRES) materials are a form of composites that can achieve a high design versatility for delivering the required laminate properties by choosing the reinforcement form or the structural layup (weave styles; orientation, number, or thickness of plies; etc). Different reinforcing fibers are available, including glass, graphite, and high-tenacity synthetics (Vectran, Kevlar, PBO). These materials can yield stiff laminates, with good-to-excellent resistance to the space environment (thermal cycling, radiation, etc.), and reach near-zero coefficient of thermal expansion (CTE).

Lightweight structural backbones and precision structures, as well as expandable honeycomb and similar "double-wall" concepts (s.e.g. Bernasconi, 2004a), can largely share the materials technologies, especially for the rigidizing matrix, and do not need a separate treatment here. As true chemical rigidization involves thermosetting polymers, the rigidization process can occur but once: thus, full ground testing of a flight item is not possible.

2.2.1 Thermal Cure of thermosetting polymers

Thermal curing is the very classical path for aerospace composites, offering excellent structural performance and flexibility in design. The composite's polymer resin is cross-linked when exposed to heat. The cure cycle is dependent on the matrix material selected and can range from one to several hours, making this an issue for this rigidization method. Methods of introducing heat include natural (solar illumination) and artificial sources (heating by embedded resistive elements).

Numerous epoxy laminating resin formulation have been investigated in this class. Ciba included in the evaluation for the inflatable space rigidized structures (ISRS) Study: aromatic-amine-cured, amide-cured, anhydride-cured epoxy-based resins, catalytically-cured cycloaliphatic epoxy, and acryl-terminated epoxy resin (Bernasconi, Seiz &. Reibaldi, 1984). The selected technology built on a modified cycloaliphatic epoxy resin, suitable for thermal as well for externally-catalyzed cure, with Kevlar as reinforcing material. The result was a prepreg that was flexible in its uncured state, had low volatiles content, and exhibited good UV and thermal stability (Cadogan & Scarborough, 2001). During the 1980s, this matrix system underwent a wide range of testing and characterization measurements. The basic approach utilized the Sun to heat a pigmented structure.

The need to introduce the initiation energy and to control the object's temperature represent the primary drawback of this solution, in particular if one has recourse to artificial sources. Curing with embedded resistive heating elements gives optimal control over the process, by providing strict control of the heat cycle and thermal distribution, but demands the addition of the heaters and multi-layer insulation (MLI) blankets to increase the structure's temperature (McElroy, Wise & alii, 2000; Carey and colleagues, 2000). In the 1990s, ILC Dover adopted a space-qualified epoxy matrix resin that at cures at 120°C in some 45 minutes, used with success with both graphite and Kevlar reinforcements (Cadogan & Scarborough, 2001). Glass transition temperatures of these materials are typically near their cure temperature (~120°C). Chemical modifications increased the room temperature storage life beyond two years, with cold temperature storage beyond six years.

Shelf-life limitations of some thermosetting materials can become prohibitive for a spacecraft's processing logistics, with at least two years (at RT) considered essential. The storage environment from manufacture to deployment must also be well understood because high thermal exposures for prolonged periods of time can begin cross-linking of the matrix and leave it unreactive. If properly protected, however, thermally cured composite materials provide excellent structural properties.

2.2.2 Photoinitiated or Radiation Cure

The use of UV for curing space-rigidized objects remains extremely popular, with a first proposed use considered for the Echo II balloon in the sixties. In the 1980s, Ciba included a UV-curing acrylic resin in the ISRS evaluation. With radiation cure a well-established industrial technology, both free-radical and cationic polymerization mechanisms can today be photochemically triggered by adequate initiators. Unlike free radical systems, cationic systems -- typically with epoxy materials for space use -- continue to cure after the light source is removed, but with a low rate, often requires a heating to be effective. Again, energy to initiate and sustain rigidization can come either from the Sun or from an internal source. An apparent recent trend, to help overcome the wall membranes' transmittance issue, concerns the use of visible-light wavelengths rather than conventional UV initiator (Harrah & colleagues, 2004).

When using a natural energy source, the spacecraft does not need to supply power to cure the system, if the material can otherwise reach a temperature level softening it for deployment. Drawbacks of this approach include self-shadowing, and some loss of control of the process, which may lead to differential cure and to shape deformation; also, the structure will undergo large temperature variation during its operational life. Alternatively, artificial radiation sources provides optimal process control. The required or allowed use of MLI blankets on the structure's exterior, improves thermal conditions and reduced thermal distortions -- but at the price of a mass increase.

For an efficient exploitation of the incident UV or visible light, the absorption spectrum of the photoinitiating package has to be adjusted to the spectral characteristics of the curable material and of light source. This allows the material to be handled without premature rigidization in a controlled manufacturing environment. Other compounds may be added to adjust the storage and cure behavior of a resin system, including sensitizers to increase light absorption, accelerators for better low temperature cure kinetics, and high molecular weight species to control viscosity. For instance, Adherent Technologies (ATI) investigated the use of benzophenone as sensitizer (transfering energy to the photoinitiator) to accelerate a cationic epoxy cure, and to allow the use of Mylar films, as these would otherwise block the wavelength necessary to fragment the photoinitiator.

A "rigidization on command" (ROC) is an avowed aim for this class, and Adherent Technologies has discussed and proposed such a solution (Allred, Hoyt & alii, 2000), based on cationic-cured epoxy resins. Depending on the resin system selected (high molecular weight materials, solids content, low vapor pressure materials, etc.), outgassing can respect the 1% TML and 0.1% CVCM limits normally imposed. However, comparisons remain difficult, as the reported data can differ widely wrt to test article used -- ranging from prepreg coupons to cured tubular constructions -- or to the test temperature (standard vs "representative"). A room temperature storage life of several years is reported to be possible for photoinitiated materials.

While generally similar to thermally cured composites, photocured do have several differences. The material does provides for some flexibility in design of the structure by altering thickness, weaves, etc.: however, UV-curable laminates are usually limited in structural performance because the reinforcement must be transparent to UV energy, such as with fiberglass or quartz. Therefore, these laminates generally do not use high performance fibers, such as graphite or PBO, although some design modifications can be made (isogrid open weaves, hybrid reinforcements, etc.) to enhance structural properties (Cadogan & Scarborough, 2001; Allred, Hoyt & alii, 2002). For instance, minimum cure (i.e. 80% conversion) of ATI AP600-2 resin was achieved for twisted carbon-fibre tows after 50 min sunlight exposure, while for hybrid carbon/S glass tows, this minimum cure was achieved already after some 15 min. In general terms, cure times can vary from minutes to hours depending on resin chemistry and the composite temperature during rigidization.

2.2.3 External-Catalyst Cure

Thermal curing can be triggered or accelerated using catalyst carried by the inflation gas. Pure catalytic cure systems offer the potential for "cure-on-demand": in that case, however, a secondary gas delivery system needs to be implemented on the gossamer structure. Many different resin, catalyst and reinforcement combinations have been evaluated in early space inflatable work, including water-vapour cured polyurethanes, polyesters, and epoxies cured by various amine and other vapour catalysts. In the concept of external-catalyst curing, the wall of the structure is a laminate of materials that are impregnated with a resin and a gaseous catalyst is released within the inflated volume to activate and/or accelerate the reaction: such is the case of the BF_3 catalyst used with the Ciba resin H: reduced cure temperature and time, from 120°C for six hours to 80°C for three hours (Köse, 1987). The inner ply of the laminate must either be absent or highly permeable to the catalyst, and the thickness of the laminate must be limited to ensure penetration of the catalyst. The limitation on laminate thickness may restrict structural efficiency in some cases.

This approach does not require on-board power to support the reaction; separating reactants can lengthen storage life. On the other hand, reaction rates depend on the local temperature, and its

variation may cause different stress levels in the laminate, and affect an object's geometry. Further concerns include potential contamination effects by the release of excess catalyst; the difficulty to monitor the state of cure on orbit; and the material's thermal conditioning prior to deployment.

2.3 Physical Processes

2.3.1 Cold Rigidization (Sub-Tg Cooling)

The cold rigidization process – or sub-Tg cooling, or Second Order Transition Change (SOTC) -- relies on the exposure of originally flexible layers of polymeric matrix (typically, elastomers - Brewer & Jeppesen, 1964) to the deep-space thermal sink, cooling them below their glass-transition temperature (Tg), and rigidizing the structure essentially by freezing the matrix. This concept appears particularly indicated for shielding applications outside Earth's orbit, and received attention in the 1960s for supporting shadow shields of cryogenic stages for Mars flights.

More recently, ILC Dover and L'Garde presented structures rigidized using this technique, respectively a hexapod structure (Adetona & alii, 2002) and the Space Solar Power Truss (Guidanean & Lichodziejewski, 2002). However, the use of a thermoplastic matrix can lead to lower composite's properties (Darooka, Scarborough & Cadogan, 2001). Willis (1997) noted that the complex mechanical behavior of elastomer-impregnated fabrics represented a significant difficulty for this approach. These materials not only are weak in compression, but fiber and matrix phases continually compete with each other for dimensional stability. Above the glass transition the CTE is slightly positive; as the temperature drops, the fiber goes into compression and the CTE becomes negative. Below the glass transition temperature the matrix dominates and the CTE becomes positive again. Willis (1997) concluded that this behavior would lead to unpredictable dimensions and remain problematic for composites fabricated from fibers and elastomers.

In some recent developments, attention has turned to resins with higher Tg levels (including thermoset materials). In this case, however, the composites must be warmed on the ground to soften them for folding into their stowed configuration, then heated again in space before deployment. Afterwards, they are let to cool below their glass transition temperature and rigidize.

This technique is attractive mostly because of its apparent simplicity, reversibility, and relatively low energy requirements. Also, the rigidization process can take less time than needed for curing thermoset composites. Nonetheless, the need for temperature control measure (heating for deployment and/or cooling in operations) represents a clear drawback. Furthermore, these composites can be difficult to manufacture, requiring specialized equipment and processes -- with associated costs (Neubauer, 2001).

2.3.2 Drying: boil-off of solvent/ plasticizer

Rigidization of a structure can also be obtained using evaporation of a solvent or a plasticizer in the material. The major issue of this solution is the large amount of solvent or plasticizer involved (e.g. between 13-50% for the Ciba polyimide tested during the Contraves ISRS program (Bernasconi, Seiz &. Reibaldi, 1984). During the 1960s, a fairly large effort studied rigidizable structures of this type utilizing fiber-reinforced gelatin prepregs. This approach has been improved more recently (Derbès, 1999). The Lavochkin Association of the Babakin Center has undertaken development of a composite based on a cross-linked polyvinylalcohol, plasticized by water (~10%), and using an aramid cloth as reinforcement (Babayevsky & Ivanov, 2005).

Advantages of this solution include its simplicity and the reliance on the natural environment, as well as its reversibility (although rather daunty on large structures). Among its drawbacks were listed to shelf-life issues, outgassing, sensitivity to temperature variations, matrix shrinkage risks.

Another possibility uses a plasticizer or solvent that is polymerized -- thus avoiding both the outgassing issue and the risk of shrinkage. Obviously then, such an approach gets confronted with the problem of providing the necessary initiation energy for the reaction, following one of the options discussed in the previous Section. However, as a further advantage, the resulting matrix can often achieve better characteristics that a straightforward thermosetting product.

The most advanced within this family seems a development by Lavochkin, relying on an amine-cured epoxy and on a monomers as temporary plasticizer, reinforced with glass fibre cloth (Babayevsky & Ivanov, 2005). The monomer is cured via a hardener and a UV-sensitive initiator complex. We have examined a different option, which could use a polyimide resin with an isocyanate monomer as flexibilizer, although the known thermal path for curing the cyanate still calls for too high temperatures.

Table 1: CRES resins: Assessment of design aspects

	Thermal cure	**Rad cure**	**Catalyst cure**	**SOTC**	**Drying**
Composite design flexibility	Excellent	Good	Excellent	Excellent	Good
Reinforcement options	Unlimited	Limited (UV transparent)	Unlimited	Unlimited	Unlimited
Shelf life	1 to 2 a	> 2 a "indefinite"	1 to 2 a	"indefinite"	1 a?
Cure temperature	100°-120°C	25°C	80°C	20°-100°C	various
Tg	168°C	?	150°C	various	150°-200°C
Operational temperature	<100°C	?	<80°C	n.a. (screen)	<100°C
Cure time	1-10 h	1-5 h	3 h	<1 h	1-10 h
Major thermal control system additions	Yes, for artificial sources	Yes	No	Yes	No

3. THERMAL CONSIDERATIONS

Among so many options, which one appears more worthwhile? Clearly, the mechanical concepts appeal the more conservative administrators, as they may come so near conventional technologies to form a continuum with them. The chemical processes remain the most innovative ones, allowing and requiring the greatest changes in practice. They do, however, suffer because of the specific need for initiation energy in thermosetting reactions. While in the Earth orbit environment the Sun represent a sufficient natural source of thermal, light, or ultraviolet radiation, in the search of a better control for the rigidizing object's environment, many developers have resorted to the use of artificial sources -- adding heaters, lamps, screens, and additional layers to the structural element proper. These items obviously increase the objects mass, tend to make its realization more complex, and require the use of various amounts of onboard power. Particularly these rather demanding designs let similar modifications of the physical concepts as a more manageable middle ground (Table 1 above).

3.1 Relevance

The thermal aspects of space-cured resin systems do assume a fairly significant role. We can consider that, in first approximation, the reinforcement controls the mechanical properties of a lightweight CRES element for space application (stiffness, foremost). The matrix must provide good adhesion to the reinforcement to duly stabilize it, and high resistance against radiations -- as well as stability against heat loads. As a general objective, one ought to aim at a limit working temperature as high as possible. While bulk temperature on large space structures at 1 AU from the Sun can hardly exceed 400 K, applications for shorter solar distances do exist

The glass transition temperature (T_g) offers itself as a primary parameter for evaluating a resin system's suitability with respect to its thermal behaviour. In fact, one notes that many of the rigidization methods presented in the preceding Chapter aim at influencing the structure's T_g, either by raising it in absolute terms (with thermosetting resins, or with drying-out matrices), or by adjusting it in relation to the structure's temperature (with cold-rigidized products).

Historically, one addressed this requirement empirically through the choice of the basic material. For instance, when planning the use of a boil-off system, one trusted the relatively high thermal stability of gelatin; or, for a thermoset formulation, one gave preferred epoxy over acrylic resins for the same reason. With the increasing ability to "taylor" a polymeric product for a purpose, the field has opened to an ever-increasing number of candidates, with raising demands on the process conditions -- which may help to explain the surge in investigations of design including artificial sources. And yet, part of the original appeal of inflatable structures derived from their simplicity.

3.2 the glass transition temperature

In terms of a polymeric matrix structure, Tg depends on the degree of (cross-linking) polymerization (Di Benedetto & Nielsen, 1969). The cross-linking reaction kinetics is controlled by the reaction rate constants as long as the species retain sufficient mobility. However, as the polymerization proceeds, and the cross-link number increases, the viscosity of the polymer and its Tg also increase. Once the glass transition temperature approaches the curing temperature, the mobility of unreacted groups is highly reduced and the reaction is controlled by the diffusion rate of these groups within the bulk (Boogh & Mezzenga, 2001). Laminate manufacturers recognize this direct correlation between the curing temperature level and Tg in the resulting polymer through relations like:

$$T_g = T_{cure} \pm 10°C$$

In other words, because of the diffusion phenomena, the glass transition temperature may surpass the cure temperature, but only by a very limited extent. Using the mixture rule provided by Nielsen (1974), we can rather successfully estimate e.g. the Tg of resin H prepregs (still including some plasticizers) and of cured resin (while assuming that the Tg of the basic reacting monomer will not exceed the cure temperature).

In this context, a very interesting case is offered by drying systems, especially those using water as plasticizer. To allow the necessary manipulations, a prepreg's Tg must lie below RT. Gelatine's prepregs can comply with this requirement even with relatively low water content, e.g. with as little as 35% by weight (Figure 2). Since dry gelatine has a fairly high glass transition temperature -- around 207°C (Kozlov & Burdygina, 1983), such a matrix can give even better thermal properties than a rather complex mixture as resin H. But even inorganic matrices can be sufficiently flexibilized by water -- e.g. sodium silicate (with a water content as little as ~45%), recovering a rather high Tg (~700°C) as it dries. Its chemical stability would seem to make it even more interesting for terrestrial applications. With respect to the outgassing, drying the matrix from 47% to 22% water content, would raise the Tg from some 22° to a quite satisfactory 195°C (Figure 2).

3.3 Outlook

Following the summary in the preceding Section, one could say that -- just as, in a manner of speaking, all rigidization methods base on the control of the glass transition temperature -- all rigidization methods are thermal curing, because their cure temperature seems to strictly limit their thermal quality. As Coqueret (2005) elegantly summarized, however, matrix formulations do exist to achieve glass transition temperatures higher than the curing temperature level, in consequence of:

- effects of the exothermic power of the polymerization reaction,
- flexibilization of the material by plasticizers, eliminated during the cure process, or

- the recourse to a heterogeneous material formulation.

The exothermic power generally seems insufficient for free-space polymerization purposes, as it accesses only a limited energy store that -- to exclude interferences from the deployment process -- perforce must spread over a sensible time interval (1 – 10 ks), which renders the available power level excessively low. On the other hand, the radiated power increases rapidly with the temperature, making it doubtful that the exothermic store will suffice even if cure is greatly accelerated (Bernasconi, 1995). Mixtures of polymers can yield successful matrix formulations, but still suffer under the initiation-energy issue.

The old plasticizer option seems could bring about innovative products that join simplicity of process, high heat resistance, and even low or less problematic (water vapour) outgassing.

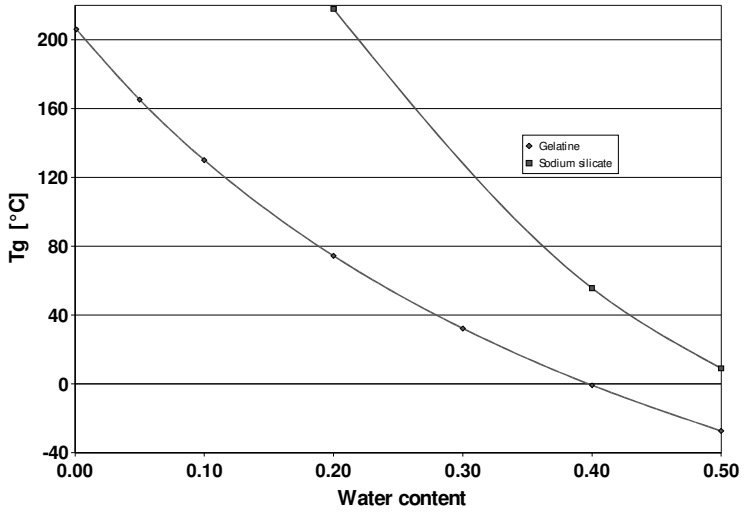

Figure 2: Evolution of glass transition temperature for water-gelatin and water sodium-silicate matrices, as predicted by the mixture rule.

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