Prehistoric Polymer Engineering: A Study of Rubber Technology in the Americas

by

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ABSTRACT

This thesis examines the history of rubber technology in Mesoamerica and the South American continent. This is achieved through an examination of ethnohistoric documents, ethnographic research, botanical evidence, and archaeological data pertaining to rubber use and processing in the Americas, combined with a battery of mechanical analyses of rubber and latex.

Ancient Mesoamericans used rubber made with a mixture of Castilla elastica latex and the juice of Ipomoea alba morning glory vines for a wide variety of applications such as rubber balls, hafting bands meant to hold stone blades to handles, and sandal soles. These three applications require different sets of mechanical properties in order to function properly. The data presented here -- from dynamic mechanical analysis, stress-strain investigations, creep testing, wear experiments and Dynastat analyses -- quantify the full range of mechanical properties that would have been available to ancient Mesoamericans through manipulation of their rubber-making procedures. A mixture of 50% I. alba juice by volume with C. elastica latex produces a rubber with high elasticity ideal for rubber balls. Unprocessed C. elastica latex functions best as a hafting band, as it exhibits high strength and superior damping ability. Rubber made with a 3:1 ratio of latex to I. alba juice produces a material resistant to wear and fatigue, best suited for employment in sandal soles.

The combination of three data sets -- mechanical analyses of raw and processed materials, archaeological and documentary evidence of Mesoamerican uses of latex and rubber, and ethnohistoric evidence from codices about the shipment of C. elastica in latex and rubber form -- offer the possibility that ancient Mesoamericans were cognizant of the varying effects achieved by processing C. elastica latex with different concentrations of morning glory vine juice, and that they used this knowledge to process rubber selectively for specific applications: balls, sandal soles and hafting bands. Mechanical analyses of H. brasiliensis latex suggest that ancient South American peoples did not process the latex available to them because it is sufficiently elastic and tough in its natural state.

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Part I: Cultural Data on Ancient Rubber Technology

Chapter 1: Introduction

The goal of this thesis is to examine rubber technology where it first developed: in the ancient Americas. Consideration of the current applications of latex and rubber may lead one to believe that rubber is a distinctly modern material. On the contrary, rubber was being utilized as a trade commodity, a utilitarian material, a medicine, and for ritual purposes by native Americans some 3,500 years before Goodyear invented the vulcanization process.

Rubber is a material that is pervasive in our everyday lives. After Goodyear’s 1839 discovery of the vulcanization process revealed to the modern world the advantageous and unique qualities of cross-linked rubber, rubber quickly became a material that impacted the way we live. Two of the most visible applications are tires and footwear. Rubber helps to transport us in our automobiles and on the soles of our shoes, making travel safe, comfortable and reliable. Rubber and similar materials also supply less visible needs in our everyday lives. Rubber gaskets seal the engines and turbines that power everything from factories to lawn mowers. Elastic bands, windshield wiper blades, shock absorbers, and rubber hoses, to name a few, utilize properties of rubber not present in any other class of materials. While many of the materials that surround us are rigid and inflexible both in terms of their properties and their applications, rubber is an exception. Depending on the way it is processed, rubber ranges from a substance that can extend to hundreds of times its original length without distortion, to what is known as “hard rubber” -- a stiff, brittle material.
Latex is the dried elastic material harvested from *H. brasiliensis* trees, the base material in Goodyear's vulcanization experiments. Commercial latex is collected almost exclusively from the *H. brasiliensis* tree, but there is an abundance of plants throughout the world that produce similar, albeit inferior, latexes. Latex-producing tree species, all indigenous to the Americas, number in the hundreds, along with numerous latex-bearing shrubs, weeds, and vines. Trees cultivated for commercial natural latex, mostly in South East Asia, number in the billions and fuel a multi-billion dollar global industry. In its pre-vulcanized state, latex is used as extensively as its cross-linked counterpart, rubber. Latex is commonly utilized in surgical gloves, condoms, and balloons, because of its ability to perform as a thin, effective barrier. Latex is also a material prevalent in the medical industry, employed in catheters, syringes and adhesive tape.

In the Americas, by 1,600 BC, people among the Olmec civilization on the Gulf Coast of Mexico were processing latex from the *Castilla elastica* tree in order to make large rubber balls for the ritual Mesoamerican ballgame (Hosler et. al. 1999; Tarkanian 2000). They mixed the raw latex with the juice from morning glory (*Ipomoea alba*) vines to enhance the elastic properties of the mixture and, thereby, produced rubber. The development of this processing regime, along with a deep understanding of the properties of unprocessed latex, allowed ancient Mesoamericans to create an array of items from latex and rubber rivaling the breadth of modern employment of these materials.

In the first half of this thesis, I explore the known applications of rubber and latex throughout the ancient Americas, with emphasis on Mesoamerica and the South American continent. My evidence consists of all ethno-historical and ethnographic documents, codices, and archaeological sources known to me that pertain to the collection of raw ingredients and the processing and use of rubber in the prehistoric
Americas. I also present botanical data detailing the sources of latex and the morning glory plant that were available to ancient Mesoamericans and South Americans.

Among the many uses of rubber and latex in ancient Mesoamerica attested in the archaeological record, three stand out as unique applications of rubber technology requiring considerably different mechanical properties of rubber. These three applications are in rubber balls, rubber bands for hafting stone tools to wooden handles, and rubber-soled sandals. An ideal rubber ball would have high elasticity. A hafting band would need to be strong and shock-absorbing in order to fulfill its function. Rubber soles for sandals should be resistant to wear and fatigue.

The second half of this thesis is a study of the mechanical properties of *H. brasiliensis* latex, *C. elastica* latex, and *C. elastica* rubber produced in the laboratory by processing *C. elastica* latex with a range of concentrations of morning glory juice. My previous research (Tarkanian 2000) showed that processing latex with different concentrations of *I. alba* produced rubbers with distinctly different mechanical behaviors.

The data presented in this thesis identify the full range of mechanical properties that would have been available to ancient Mesoamericans through manipulation of their rubber-making procedures. The differences in the mechanical behaviors of the *C. elastica* rubbers determined by this study offer the possibility that ancient Mesoamericans were cognizant of the varying effects achieved by processing *C. elastica* latex with different concentrations of morning glory vine juice, and that they used this knowledge to process rubber selectively for specific applications: balls, sandal soles and hafting bands.
Chapter 2: Literature on Rubber Processing

2.1: Rubber Processing in Mesoamerica

The arrival of the Spaniards in Mexico in the early 16th century marked the beginning of a series of monumental changes in the lives and cultures of both the native Mesoamericans and the European invaders. War and diseases introduced by the Spaniards dramatically reduced the Mesoamerican population and ultimately led to the end of the Aztec empire and to many indigenous ways of life. Despite the widespread destruction within Mesoamerica during the initial years of the 16th-century European occupation, some Spanish priests, scholars, and appointed court officials were charged with documenting the traditions, customs, economies, and daily lives of various Mesoamerican peoples.

These documentary publications vary widely in both the types of information they contain and their accuracy. As one might expect, some of the documents are substantially influenced by the religious and political biases of their authors. Others however, offer extremely insightful, detailed, and seemingly fair accounts of Mesoamerican life. One of the most trusted and respected Spanish sources on 16th century Mexico is the *Florentine Codex*, written by Fray Bernardino de Sahagún (Sahagún 1970). As a priest in the Franciscan Order, Sahagún was sent to Mexico in 1529 in an effort to convert the Aztec people to Christianity and to teach them the Spanish and Latin languages. During his duties, Sahagún learned *Nahuatl* and was able to rely on Aztec informants, in their own language, for the information in his codex. For this reason, *The Florentine Codex* is one...
of the most valuable primary sources on pre-Hispanic life in the New World (Cline, 1973).

*The Florentine Codex* is also one of the most in-depth sources on Mesoamerican life before and during the Spanish conquest. During his time with the Aztec, Sahagún recorded 12 volumes of observations and information volunteered by his informants. These include some of the earliest accounts of the use and processing of natural latex and rubber, as well as Aztec attitudes towards the elastic material. In terms of processing, Sahagún wrote that the Aztec source of natural latex was known as *Olquauitl* (Sahagún, 1970). *Olquauitl* is the Nahuatl word for the *Castilla elastica* tree (Figure 1), a common source of natural latex.

![Figure 1: Trunk and Leaves of *Castilla elastica*](image)

The latex that the *Castilla elastica* tree produces is a sticky white liquid that when dry is rigid and brittle. The natural latex does not have the necessary toughness or elasticity to have performed in the ways that Mesoamericans used rubber, such as for
balls, hollow figurines, or bands for hafting blades to handles. The following 16th-century and modern sources suggest that Mesoamericans mixed the *Castilla elastica* latex with the juice of the morning glory vine *Ipomoea alba* (Figure 2) to produce a tough, elastic rubber.

**Figure 2: Ipomoea alba morning glory vine**

Photograph courtesy of Michael E. Abrams

Fray Toribio de Benavente (commonly known as Motolinia), who was one of the first twelve Franciscan missionaries in the New World, recorded data on natural rubber in his *Historia de los Indios de la Nueva Espana*:

Rubber is the gum of a tree that grows in the hot lands, when [this tree is] punctured it gives white drops, and they run into each other, this is quickly coagulated and turns black, almost soft like a fish; and of this they make the balls that the Indians play with, and these balls bounce higher than the wind balls used in Spain, they are about the same size and darker; the balls of this land are very heavy, they run and jump so much that it is as if they have quicksilver within. (Benavente 1984:34-35, trans. By M. Tarkanian)

These observations are extremely important because they present evidence that rubber processing was occurring in ancient Mesoamerica. Unprocessed latex does not coagulate and turn black on its own, whereas latex processed with the juice from *Ipomoea alba*
transforms exactly in this manner. Unprocessed latex is also substantially less elastic than
the processed *C. elastica* + *I. alba* rubber and is unlikely to have performed like
"quicksilver," as described by Motolina.

In the 16th century, rubber was an unknown material in Europe. Rubber-
producing trees and shrubs are indigenous to the Americas, thus Europeans had never
encountered materials that were as elastic as rubber. Motolinia and other Spaniards were
not only seeing rubber for the first time, they were also encountering an entirely new set
of material properties (elasticity). At the time, the Europeans played their ball games with
stuffed leather balls, which would not have a bounce equal to that of the Mesoamerican
rubber balls.

While Motolinia described the mechanical behavior of the rubber he observed,
Pedro Mártir De Angleria provides documentation of rubber processing in ancient
Mesoamerica. From 1520 to 1526 Mártil was an official royal chronicler for the court of
Spain's Charles V. His letters communicating his observations of Mesoamerican life to
the Spanish courts were published in two works, *De Novo Orbe Decadas* (Mártir 1964)
and *Opus Epistolarum* (Anghiera 1966). In relation to rubber and its use in the
Mesoamerican ball game Mártir writes:

> These balls were made from the juice of a certain vine that climbs the trees like
> the hops climb the fences; this juice, when boiled becomes hardened and turned
> into a mass that is able to be shaped into the desired form...but I do not understand
> how when the balls hit the ground they are sent into the air with such incredible

Mártir's observations reiterate the Spaniards' amazement at the elastic properties of
rubber, but more importantly they establish the use of a certain type of vine in the ancient
Mesoamerican rubber processing regime. This information allowed Paul C. Standley, a
botanist from the Field Museum of Natural History in Chicago, to identify this vine as a
species of morning glory (Standley, 1942). Standley was familiar with the use of morning glory in modern Mesoamerican rubber processing and published this information, along with his interpretation of Mártir's quote:

After *Castilla* sap is collected, various substances often are added to it to make the rubber coagulate. The usual one is the juice of certain morning-glories (*Ipomoea*), or especially the juice of the moon-vine (*Calonyction*). In the [Mártir's] account of rubber preparation doubtless these vines were mentioned and someone misunderstanding --probably through faulty knowledge of the Nahuatl language-- got the idea that it was the vine that really furnished the rubber (Standley 1942, 123).

It should be noted that "moon-vine," *Calonyction aculeatum*, and *Ipomoea bona-nox* are synonyms for *Ipomoea alba*, the proper species name for this white-flowered vine (van Ooststroom 1940).

Use of the *Castilla elastica-Ipomoea alba* mixture for processing rubber is further substantiated by an article published in *Science* in 1943. This study, conducted in part by the United States Department of Agriculture, was probably carried out in an attempt to find an alternative source of rubber during World War II. It states that "for many years, a juice prepared by natives of Central America from the moonvine of Nacta vine (*Calonyction aculeatum* formerly *Ipomoea bona-nox*) has been used to coagulate the latex tapped from the *Castilla* tree (Wildman et al. 1943:471).

A wealth of information on ancient Mesoamerican rubber processing can be found in 16th-century trade and tribute records, in addition to the data gathered from 16th-century primary sources and modern ethnographic research. These tribute documents, such as the *Codex Mendoza* (Berdan and Anawalt 1997), the *Codex de Moctezuma* (Berdan and Durand-Forest 1980), and *Informacion de 1554: Sobre los Tributos que los Indios Pagaban a Moctezuma* (Rojas, 1997), present data about the location of rubber sources, the form in which the rubber was transported, and the amounts of rubber paid in
tribute. All of these classes of data add to our understanding of rubber processing and the extent to which rubber was used in Mesoamerica.

Informacion de 1554: Sobre los Tributos que los Indios Pagaban a Moctezuma (Rojas, 1997) attempts to reconstruct the pre-conquest Aztec tribute system through surveys conducted by the Spaniards in 1554. The Spaniards interviewed six elder Aztec noblemen about the tribute paid by 38 different provinces in the Aztec empire. These interviews are thought to have been aided by the existence of some older pictorial records of the tribute paid by each province.

Each of the six interviewees confirmed the annual payment of 2,000 cakes of rubber to the Aztec capital from the provinces of Tlapa and Tochitepeque (Figure 3). They also confirmed a payment of 2,000 rubber cakes every 80 days from the Cotlastla province (Figure 3). This suggests that Cotlastla was a much more fertile rubber-producing zone than Tlapa and Tochitepeque. Cotlastla was also responsible for the payment of 400 rubber statues of men (Estatuas de hombre de hule) (Rojas, 1997). This common use of rubber as a medium for figurines will be discussed in Chapter 5: Archaeological Evidence of the Use of Rubber.

The fact that the rubber was being transported in cakes is important in terms of both onsite processing and the final possible uses to which the material could be put upon arrival in the Aztec capital. Rubber cakes could be made by either of two methods: (1) processing the raw latex with I. alba juice and forming the resultant rubber into cakes, or (2) allowing unprocessed latex to dry in cake form. By mixing latex with I. alba on site, the rubber could be processed immediately after collection and sent to the Aztec capital. On the other hand, it would likely have taken weeks for unprocessed latex to dry into a cake of substantial size, thereby considerably delaying the payment schedule.
The decision about whether to process the latex onsite would determine the possible uses of the material when it reached the capital. If dried, unprocessed latex was shipped, the cakes could be used only for applications that were not mechanically intensive. This might have included materials for sacrificial offerings or for burning. Small latex or rubber balls were often used as wicks in ceremonial incense burners (described in the section on Rubber Use in Mesoamerica). If latex processed with *F. alba* was formed into cakes and sent as tribute, the Aztecs could have used the rubber for
mechanically intensive applications, but their choices in the shape and geometry of the rubber would have been limited. Once latex is processed into rubber it cannot be reshaped. The Aztec might have cut the shapes they needed from the *I. alba*-processed rubber cakes, but this would have severely limited possible uses of the rubber. It seems more likely that these cakes were made of unprocessed latex for use in burning and ritual ceremonies.

Like *Informe de 1554*, the *Codex Mendoza* presents data on tribute paid to the Aztec capital from various provinces. Tochtepec (also known as Tochitepeque) (Figure 3), a province on the Gulf Coast in what is now the state of Veracruz, paid an annual tribute of 16,000 rubber balls to the empire (Berdan and Anawalt 1997). The *Codex Mendoza* presents this information in pictorial form, typical of many Aztec documents. The rubber tribute paid by Tochtepec is represented by dark rubber balls above 2 incense bags (Figure 4). The incense bag was the Aztec symbol for the number 8,000.

**Figure 4: Depiction of Rubber Balls in the Codex Mendoza**

From Berdan and Rieff Anawalt, 1997.
The *Matricula de Tributos (Códice de Moctezuma)* (Berdan and Durand-Forest, 1980) presents tribute data for 33 Aztec provinces in a pictorial manner. This document and the accompanying translation by Berdan and Durand-Forest do not mention rubber explicitly. However, dark spirals are drawn in the tribute roll of the Tepeyacac province (Figure 3) in Lamina XXII. Current research (Stone 2002) suggests that these spirals were a common Aztec symbol for rubber balls.

In all of these examples from 16th century documents, we see rubber being transported as a solid in the forms reflecting the uses of rubber and latex in ancient Mesoamerica. For applications requiring enhanced mechanical properties, such as balls and figurines, the rubber was processed on-site and shipped in the desired form. For ceremonial burning, dried latex was shipped in cakes. Thus, it seems clear that most rubber and latex processing occurred in the rubber-bearing provinces of the Aztec empire, and the finished goods were exported out of these areas in latex or rubber form.

2.2: Rubber Processing in South America

Rubber processing with *Castilla elastica* and *Ipomoea alba* was widespread in Mesoamerica by the time of the Spanish arrival in the 16th century. However, indigenous rubber and latex usage was not confined to Mesoamerica. Natural latex is native to the Americas, and there are countless sources throughout Mexico, Central America, and South America. South American groups, in particular, processed latex from the various latex-producing plants around them for uses as varied as body paints, balls, and syringes. I was not able to find any pre-European source for latex usage in South America. All of the following information was gathered from the ethnographic present, the earliest source
being from 1772 AD. This does not preclude the fact that latex may have been used prior to the arrival of Europeans; however, I have no source to confirm the pre-European utilization of latex.

By at least 1914, the Paressi and Paressi-Kabishi groups primarily of Bolivia (Figure 5) were playing a rubber ball game (Stern 1949). The balls for these games were constructed from latex of the *Hancornia speciosa*, which is commonly known as the Mangabeira tree. Unlike the Mesoamericans, the Paressí and Paressí-Kabishi used pure, unprocessed latex and did not mix any other ingredients into the latex. These people made hollow rubber balls by allowing a layer of latex to dry on a concave piece of wood. Once the layer had dried, they would roll the latex into a ball and pinch closed the edges. This ball would then be inflated through a small hole left in the pinched edges, and then sealed closed. The Paressí and Paressí-Kabishi would add latex on top of this inflated base, until the ball reached the desired dimensions. The typical Paressí ball was approximately 20 cm in diameter, while the Paressi-Kabishi preferred balls with a 9 to 11 cm diameter (Stern 1949:13).

Like the Paressí and Paressí-Kabishi, the Apinayé also utilized the latex from the *Hancornia speciosa* tree to make balls for a special initiation ceremony known as Peny-ta'g (Nimuendajú 1939). The Apinayé inhabited the areas along the Rio Araguaia and Rio Pindare, an area of dense rain forest in Brazil (Figure 5).
The Peny-ta'g ceremony is an initiation rite for young Apinayé men known as peb. This ceremony involves the production of a latex ball. The peb, carrying gourd bowls, follow the elders to the rubber trees (*Hancornia speciosa*). The leader incises the trees with a stone tool, and the peb collect the latex in their bowls. The elders then smear the latex on the bodies of the peb and allow it to dry. This is in part a chastity test, as peb are considered impure if the latex stripes break into beads on their bodies. Once the latex is dry, the strips are rolled off the bodies and onto a clay core, gradually taking the shape of a ball. When the ball reaches a certain size, they remove the clay core through cuts made in the side of the ball. The ball is continuously built up from the dried strips on the pebs, then adorned with feathers like a shuttlecock (Nimuendajú 1939).
Around 1772, the Mojo, inhabitants of eastern lowland Bolivia (Figure 5), were observed constructing solid and hollow rubber balls by Francisco J. Eder, a Jesuit missionary (Eder 1985). The solid balls were made by tapping rubber trees with a machete, then hand-forming the gathered latex into spheres. The construction of the hollow balls was considerably more complicated.

The Mojo would spread liquid latex in thin layers onto flat tables, allowing the latex to dry in sheets. When the latex reached a certain consistency, it would be cut into strips and wrapped around a hollow clay core. Once this ball reached a certain size, the Mojo would break the clay core and remove it, in pieces, from the center of the ball. They would then continue to cut and add the latex strips to the ball until it reached the appropriate size. This technique allowed the Mojo to create perfectly spherical balls, as they could cut strips of latex to the appropriate size while forming the balls, rather than building a ball out of pre-cut strips (Eder, 1985). It is unknown what species of latex the Mojo exploited.

The Chiquito, from the eastern Bolivian lowlands, and the Akawai, from the area where Brazil, Guyana, and Venezuela meet (Figure 5), employed similar methods for processing natural latex into solid rubber balls. These groups would spread the liquid latex onto their bodies until the latex began to solidify and could be rolled into solid ball form. The Akawai used the latex of *Siphonia elastica* and dried the material on the legs of women only. The Chiquito were less specific in their drying methods and used latex from the *Guatoroch* tree (Stern 1949).

In each of these examples of latex processing in South America, no other ingredients are mixed into the latex. The latex is used in its pure state and allowed to dry before it is manipulated into its final form. This is in marked contrast to Mesoamerican
rubber making, where the latex is often mixed with the juice of *I. alba* to create a tougher, more elastic rubber. There are two possible explanations for the lack of a coagulating agent in South American latex processing techniques. One is that South American latex is far superior to the latex produced by *Castilla elastica*, and it does not require additional ingredients to produce a tough, elastic material. This is indeed the case in regards to one South American species of rubber tree, *Hevea brasiliensis*. As is demonstrated in the mechanical data contained in Part II of this thesis, *H. brasiliensis* latex is mechanically far superior to the latex of *Castilla elastica* and does not require processing to yield a useful material. The other distinct possibility is that the latex items produced by South American peoples utilizing non-*Hevea* latexes were of poor quality but functional for a short-term basis. Instead of producing high quality rubber materials that would survive long-term use, they may have produced a high number of low quality latex items that could be easily replaced.
Chapter 3: Botanical Evidence

3.1: Rubber Processing Resources in Mesoamerica

In the Florentine Codex, Sahagún identifies the *olquauitl* tree as the main source of rubber and latex in pre-Columbian Mesoamerica (Sahagún 1970). *Olquauitl*, according to the editors Anderson and Dibble, is the Nahuatl word for the *Castilla elastica* tree. *C. elastica* is native to Mexico and Central America, and is most commonly found in the Mexican states of Chiapas, Yucatan, Tabasco, and Veracruz, below altitudes of 700 meters (Standley 1920). In Central America, the *C. elastica* tree can be found on the lowland coasts of both the Pacific and Atlantic Oceans. It is also present in the western Andes of Peru and Ecuador (Olsson-Seffer 1907) (Figure 6). The tree prefers to grow in a protected, shaded environment among other trees, in well-drained, porous soil (Olsson-Seffer 1908). In the ideal environment, *C. elastica* trees can reach heights of well over 20 m.

It should be noted that *Castilla elastica*’s native regions are also the areas where Mesoamerican civilizations first developed. The Veracruz area was the home of the Olmec people, who became an organized entity by the second millennium BC. Early Mesoamerican civilization also took hold in the area of lowland Chiapas, Mexico. These peoples utilized the latex resources in their geographical locations to make rubber balls and other rubber and latex items.
Although *C. elastica* was the main source of latex for ancient Mesoamericans, there were several other sources of latex available. One prevalent source, which was not exploited until the 18th century (Lloyd 1911), is the *Parthenium argentatum* shrub, commonly known as *guayule*. This shrub is native to the Mexican highlands and the Chihuahuan desert, including the states of San Luis Potosí, Zacatecas, Chihuahua, Durango, and Coahuila. In the United States of America, the natural habitat of the shrub extends into the southwestern states of Texas, New Mexico, and Arizona. *Guayule* is characterized by long branches of grey leaves, reaching up to 2 m in height.

Unlike *C. elastica*, *guayule* is a non-renewable source of latex. Though all parts of *guayule* contain latex – the branches, leaves and roots – it is a shrub and cannot be “tapped” in the manner of *C. elastica* or other latex-containing trees. *Guayule* latex is
obtained through grinding of the plant, thus killing it and rendering it useless for further latex production. The latex produced by guayule shrubs is inferior to the latex of Castilla elastica. The inferior quality of guayule latex, combined with the fact that it is a non-renewable resource, probably detracted from its utilization in ancient Mesoamerica. The plant is also native to an area far from the incipient Mesoamerican cultures, who had a superior and much closer latex source (C. elastica).

A third source of latex in Mexico is the Euphorbia elastica tree. This tree is native to western Mexico and reach heights of up to 8 m, with a trunk diameter of 0.5 m. It possesses a smooth, soft, yellow bark that yields large quantities of latex when tapped (Altamirano and Rose 1905). Any exploitation of this tree by ancient Mesoamericans is unknown.

The “Literature on Rubber Processing” chapter of this thesis identifies the morning glory species Ipomoea alba as the second component of ancient Mesoamerican rubber. Most morning glory species (including the genus Ipomoea and Rivea) are comprised of long green vines, broad heart-shaped leaves, and bell-shaped flowers. Ipomoea alba is a white-flowered variety that blooms only during the night and early morning, and closes its flowers upon daybreak. These species of morning glories are found throughout the Americas and the world at large.

Several species of morning glories were important in the medicinal and spiritual lives of the Aztec and Maya. In religious ceremonies, ancient Mesoamericans utilized the hallucinogenic properties of ololiuhqui (Rivea corymbosa) and Ipomoea violacea seeds to communicate with the gods (Hoffer and Osmond 1967). These plant seeds, as well as the vine and leaves, contain ergot alkaloids (d-lysergic acid amide (ergine) and d-isolysergic acid amide (isoergine)) similar to those contained in the well-known modern
hallucinogen LSD (d-lysergic acid diethylamide) (Figure 7) (Hofmann 1964). Preparations from the seeds of these morning glories were also used to “cure eye troubles” and other maladies (Hoffer and Osmond 1967).

Figure 7: Molecular Structure of LSD, Ergine and Isoergine

![Molecular Structure of LSD, Ergine and Isoergine](image)

It is not known whether the seeds of *I. alba* have hallucinogenic properties or if they were used in ritual or medicinal practices. Although we cannot know how or why ancient Mesoamericans first came to process latex with the juice of *Ipomoea alba*, it is
clear that morning glories were a familiar part of ancient Mesoamerican knowledge and life. Some preliminary experiments I performed show that one known-hallucinogenic variety of morning glory, the common purple-flowered *Ipomoea violacea*, is capable of coagulating *C. elastica* latex. Its efficacy in processing in comparison with *I. alba* is unknown.

3.2: South American Latex Sources

The “Literature on Rubber Processing” chapter shows that indigenous South American peoples used and processed latex for a variety of applications. These applications are documented only back to the mid-18th century, whereas the early date for Mesoamerican use of rubber is 1600 BC. This does not rule out the use of rubber and latex in South America prior to the arrival of the Europeans, and, indeed there were many sources of quality latex available to the South American groups.

*Hevea brasiliensis* is now the most prevalent source of natural latex in the world and is cultivated around the globe for industrial applications. Although it is used almost exclusively in the manufacture of all modern latex goods, this plant is native to South America. There are 10 species of *Hevea* found in the Amazon basin and its tributaries, as well as in eastern Peru, the valley of Paraguay, and the Guyanas. The tree flourishes in low, wet land but can be found at altitudes up to 1000 m (Stern 1966). Latex can be obtained from *Hevea* trees by tapping them in a manner similar to that used for *Castilla elastica*, as described in Chapter 4: Ethnographic Data on Rubber Processing in Mesoamerica.
Rubber-producing trees of the *Sapium* genus can also be found throughout South America. *Sapium murunda* and *Sapium micranda* are native to the middle Amazon and its tributaries, the Andes at altitudes of 1800 to 2400 m (Stern 1966), and in lowland and upland regions of Guiana, Colombia, Ecuador, and Bolivia (Williams 1944). In Brazil, these trees are known as *taparú* or *murupita* and can be found as far east as the state of Para (Williams 1944). *Sapium* latex is often misrepresented in Brazilian markets as being *Hevea* latex (Pittier 1908), though it is inferior in quality. *Sapium jenmani* (also known as *Sapium cladogyne*) is specific to Guiana and produces a high-quality latex used extensively within the region (Pittier 1908).

*Sapium* genus trees can reach heights of 30 m with a trunk diameter of up to 1 m. Latex is obtained from the tree by making incisions in the soft bark, following the method described for *C. elastica*. *Sapium* trees generally have much harder bark than the *Hevea* genus and *C. elastica*, and usually need to be tapped with the aid of a machete. Like *C. elastica*, *Sapium* trees should be tapped in the early morning (5 a.m. to 10 a.m.) to ensure maximum latex flow. *Sapium* can produce up to twice the volume of latex produced by *C. elastica* trees (Williams 1944).

Five species of latex-producing vines grouped together under the name *Hancornia speciosa* can be found throughout arid, rocky terrain in Brazil. This type of terrain can be found between Sao Paulo in the south to the northern Maranhao and Piauhy regions, sometimes extending into Guiana. The plant flourishes at altitudes up to 1000 m. In 1743 Barrere identified this plant as a source of latex for the indigenous peoples of French Guiana (Stern 1966).

The final group of latex-producing plants presented here is from the *Manihot* genus. *Manihot* currently enjoys wide cultivation throughout the world as a starch food
source known as cassava, but all species of the *Manihot* genus are native to the New World tropics (Rogers and Appan 1973). The plants of this genus range physically from latex-producing weeds such as *Manihot glaziovii*, to *Manihot grahami*, a small shade tree, though they are most often perennial woody shrubs. These wild *Manihot* shrubs are concentrated in eastern-central Brazil in the states of Goias, Minas Gerais and Bahia (Rogers and Appan 1973). The plants thrive in dry regions and rarely are found above 2000 m.
Chapter 4: Ethnographic Data On Rubber Processing in Mesoamerica

In my ethnographic research on rubber processing, I carried out a study of modern indigenous rubber production in Zacualpa, Chiapas, Mexico (Figure 12). I found that at least one of the local families is still familiar with the use of *Castilla elastica* latex and the juice of *Ipomoea alba* to make rubber. This work was conducted primarily with Luis and Fausto Guillen, the two elder men of the Guillen family, and their nephew, Alonso Castañeda, the owner of the land inhabited by the Guillens. These field studies were performed during June of 1997, March 2000, April 2001, and October 2002.

Luis and Fausto Guillen live with their families on “El Rancho Paraíso” in Zacualpa, approximately 10 kilometers south of Escuintla, Chiapas. The area is largely unpopulated, as there are few residences between Escuintla (estimated population of a few hundred) and the ranch. Alonso Castañeda is a newspaper reporter and deliveryman in Escuintla, and owner of the ranch.

In the early 20th century, the area around El Rancho Paraíso was home to La Zacualpa Botanical Station & Rubber Plantation (Olsson-Seffer 1907). This station was dedicated to research on the growth, development, and latex properties of the *Castilla elastica* tree. At present, most of the land in Zacualpa has been cleared for cattle raising. However, Castañeda’s land contains a small patch of tropical forest that is home to over a dozen *C. elastica* trees. I believe that some of these trees may be remnants from the Botanical Station plantings, as several of them exceed the maximum 20 m height characteristic of *C. elastica*.
To collect liquid latex from the *C. elastica* trees, the Guillens cut long incisions into the bark of the trees with a tool specifically made for gathering latex. A white slightly yellow-tinged latex flows from these cuts as soon as they are made. Although quite viscous, the latex flows freely and runs quickly through the channels cut into the tree and into collection buckets placed at the bottom of the trees.

The tool used to cut the rubber trees is comprised of a wooden handle with a thin U-shaped metal blade wrapped around one end (Figure 9). The U-shape blade allows the tool to “scoop” the bark from the tree, as opposed to a machete that cuts and compresses the bark. The blade scoops wide swatches of bark from the tree, and allows the bark to
fall away from the other side of the blade. The use of this cutting tool greatly increases the flow of latex from the trees when compared with the use of a machete. In conversation, Luis Guillen suggested that the early Mesoamerican peoples probably used a similar U-shaped tool, made of stone or bone, to gather latex from rubber trees. Mr. Guillen did not elaborate on his basis for this suggestion. The bark of *C. elastica* is soft enough to allow cutting with stone or bone tools.

**Figure 9: Cutting Tool for Latex Harvesting**

During my initial trip to Zacualpa, the Guillens used a machete to cut the trees. In the ensuing three trips, they used the U-shaped tool. Judging by the scars on the *C. elastica* trees, tappings previous to my arrival were performed with a similar U-shaped tool.

The first cut into the *C. elastica* trees is always a long vertical slice into the bark (Figure 10). The Guillens then hammer a small piece of metal flashing into the tree at the bottom of the vertical incision to guide the latex into the collection bucket (Figure 11). The Guillen brothers continued to cut diagonal channels into the tree, at approximately 45
degrees from the vertical, feeding latex into the central vertical channel (Figure 12).

These diagonal cuts can be stacked above one another, at intervals of several feet, all feeding into the central vertical incision (Figure 13). This maximizes the amount of latex that can be collected from one tree. Scars on the trees show that past rubber collections have utilized these V-shaped cuts along the first 10 m of the tree trunks.
After approximately 10 to 15 minutes, the latex ceases to run from the bark and solidifies within the cuts, providing a protective layer to the damaged area of the tree. The latex collected is strained into another bucket to remove any bark, insects, or other debris that may have gathered during the collection process (Figure 14).

Figure 14: Latex Filtering
Once the latex has been collected and strained, the *Ipomoea alba*, known locally as "bejuco de guamol," can be prepared for mixing. The Guillens cut a 5 m length of vine and stripped it of all leaves and flowers. Fausto Guillen wrapped the vine into a tight coil and setting it on top of a rock, struck it with a length of metal pipe (Figure 15). This softened the vine. He then squeezed the juice from the softened vine directly into the bucket of latex (Figure 16), mixing the *I. alba* juice with the *C. elastica* latex. In this demonstration, he added approximately 50 ml of *I. alba* juice to an estimated 750 ml of latex, then stirred the mixture. After 10 minutes of stirring, the latex coagulated into a solid, elastic mass of rubber (Figure 17). At this stage in the process, the solid white rubber can be formed into any desired shape. There is approximately a 5-minute interval during which the rubber can be shaped. After this, the rubber hardens and cannot be manipulated further. In this trial, we easily shaped the processed rubber into a ball of roughly 14 cm diameter (Figure 18). The elasticity of the rubber produced was immediately apparent, as the ball bounced vigorously 2 to 3 m into the air with little force input on our part.

Initially the rubber ball was a pure white color, but it immediately began to leach a dark brown liquid. With the emission of this liquid the ball turned yellow after several hours, and was black by the next day. Luis and Fausto Guillen assured us that this was a normal side effect of the processing. This blackening of the rubber coincides with depictions of rubber balls in Maya and Aztec art. In codices, murals, and on pottery, rubber is always depicted as a black material (Figure 19). This suggests that the rubber used was processed. Unprocessed, dried latex turns a light brown color.

While working with the Guillens, Fausto Guillen commented that latex collection should occur before 11 a.m., as the flow is at a maximum during the morning. He also
Figure 15: Softening the morning glory vine with a pipe

Figure 16: Squeezing *I. alba* juice directly into the latex

Figure 17: Coagulation of the latex

Figure 18: Fausto Guillen and Michael Tarkanian displaying the ball they made with *C. elastica* and *I. alba*. 
conveyed that the volume of latex is greatest in March and April, at the end of the dry season. My observations confirmed this, as we were able to collect a significantly greater volume of latex in March 2001 in comparison with our collections in June 1997.

Luis and Fausto Guillen repeatedly used the word *sangrar* (to bleed) when referring to the latex collection process. The process is quite similar to bleeding, as the latex immediately begins to flow from the incisions in the bark or "skin" of the tree; it eventually hardens and clots within the cuts. The Guillens also referred to the latex as *leche* (milk), most likely due to its off-white color and the fact that the latex is more viscous than water.

While working, the men recounted the use of rubber in the area during their youth. Although they were familiar with the *C. elastica-I. alba* process, they had only used it as children to create balls for play. However, they recalled that Germans in the area after World War II often made rubber ponchos, capes, and solid and hollow balls.
using a mixture of *C. elastica* latex and *I. alba* juice. Alonso Castañeda said that the 
German occupants often purchased sulfur from the pharmacy to mix with the *C. elastica* 
latex when they ran out of *I. alba* vine.

4.2: Use of *Castilla elastica* latex and *Ipomoea alba* in Central America

An ethnographic study of the Miskito and Sumu peoples, published by Conzemius 
in 1932 describes the use of the *C. elastica*- *I. alba* process in Honduras and Nicaragua by 
at least 1860 AD (Conzemius, 1932). The Miskito and Sumu are native to the area known 
as the Mosquito Coast, which includes the Atlantic coast from Puerto Castilla, Nicaragua 
to Punta Gorda, Honduras (Figure 20). These people tapped their trees in a manner 
identical to the process I witnessed in Chiapas, although it is not known what type of 
tools the Sumu and Miskito used. They cut diagonal channels at three-foot intervals up 
the trunk of the *C. elastica* tree.

**Figure 20: Map of the Mosquito Coast**
Like the Guillens, the Miskito and Sumu would strain their latex after collection, then, according to Conzemius, coagulate the latex with *I. alba* or *Calonyction speciosum*. *C. speciosum* is a synonym for *Ipomoea Bona-nox* (from ipni.org database), which was a former name of *Ipomoea alba* (van Ooststroom, 1940). The Miskito and Sumu differed from the Guillens in the proportions they used of morning glory juice to latex; they mixed approximately 568 ml (1 British pint) of *I. alba* juice with 4546 ml (1 British gallon) of *C. elastica* latex. This is a 1:8 ratio of *I. alba* to latex, whereas the Guillens utilized an approximate 1:15 ratio. The Miskito and Sumu shaped the coagulated latex into flat round cakes for commercial export. These cakes became widely known as "sheet rubber" (Conzemius, 1932).

The use of *C. elastica* by the Miskito and Sumu peoples did not end with the latex from the tree. They also used the bark to make cloth. Removing the bark and hammering it until it was soft and flat, the Sumu and Miskito fashioned clothing from the altered bark. It seems that stripping the tree’s bark would be at odds with the rubber-making industry, as latex resides in the bark of *C. elastica*. Removing the bark from the tree would sacrifice the source of rubber, and would likely kill the tree since the continuity of the tree’s vascular system would be interrupted.

4.3: Rubber Processing in Sinaloa, Mexico

In 1986, Roberto Rochin produced a documentary film on the Mesoamerican ball game entitled "Ulama." (Rochin, 1986) Much of this film deals with the history, significance, and play of the ball game in Mesoamerica. One section of the film documenting modern ball play in the Mexican state of Sinaloa presents a ball maker...
processing rubber by combining latex with the large tuberous root of a plant he calls "machacuana." The latex used in this area is from a plant known locally as “Aguama” (\textit{Bromelia pinguin}) (Gomez, 2003). Aguama is a small plant, reminiscent of an aloe plant in shape. Although I cannot find any reference in the literature that identifies machacuana, Manuel Gomez, a scholar and promoter of the ball game in Sinaloa informed me that the scientific name of the plant is \textit{Operculina rhodocalyx}. The International Plant Name Index Query (http://ipni.org) identifies a synonym for \textit{O. rhodocalyx} as \textit{Ipomoea rhodocalyx}, making it a relative to \textit{I. alba}. In fact, \textit{I. rhodocalyx} is a white, flowering species of morning glory vine, and appears much like \textit{I. alba}. There is a distinct difference in the shape of the leaves between the two species. This provides evidence that two white-flowering species of morning glory are known by different local names and used for the same purpose -- processing natural latex. While the \textit{huleros} (rubber workers) in Chiapas use the juice from "bejuco de guamol" to make rubber goods, the ball makers in Sinaloa use the root of their "machacuana" in a slightly more complicated process. Perhaps as the knowledge of rubber processing spread from the Olmec and Maya area north towards Sinaloa, word arrived that white flowering vines were able to coagulate natural latex. On the other hand, it may have been thought that the plants were of the same species.

"Ulama" presents a condensed version of the ball making process in Sinaloa. The actual process takes an entire day, usually from 8 to 12 hours (Gomez, 2002). The process begins by removing the large machacuana root from the ground and slicing it into disks of approximately 1 cm in thickness. These disks are placed in water and cooked in small bowls over a fire. After cooking this mixture for a certain amount of time, the bowl is removed from the fire and a small amount of liquid latex is poured into the aqueous
liquid. The latex quickly coagulates into a small solid mass which the ball maker removes from the bowl. As in the *C. elastica-I. alba* process, the resulting rubber is white. He takes this white coagulated mass, flattens it by hand on a rock, and forms it into a small rubber ball. This process is repeated, and the flattened, coagulated rubber pieces are layered on top of each other to increase the size of the ball up to approximately 20 cm in diameter. As the layers are added, the ball maker continuously bounces the ball off a flat stone, apparently in an effort to compress the rubber, keep it spherical, and to remove any excess water from the coagulated rubber. The ball maker also repeatedly pierces the ball with a nail over its entire surface, allowing water and air trapped between the layers of rubber to escape. I imagine that this piercing also creates increased cohesion between the layers, as the punctures could function as “rivets” connecting the sheets of rubber. The ball maker continues the sequence of layering, bouncing, and piercing until the ball is exactly 4 kg in weight (Gomez, 2002).
Chapter 5: Archaeological Evidence of the Use of Rubber

5.1: Ball Courts In Mesoamerica

The most pervasive archaeological evidence for the use of rubber in ancient Mesoamerica is the presence of hundreds of architectural ball courts used for the Mesoamerican ball game. At least 1200 of these stone and earthen courts are regularly distributed throughout Mexico and Central America. Court architecture ceases to exist south of El Salvador (Stern 1966; Taladoire 1981). Similar courts can be found on islands of the Greater and Lesser Antilles.

Rubber ball games were played by many of the peoples inhabiting Mesoamerica, beginning by at least 1600 BC and continuing until the arrival of the Spaniards in the early 16th century. Some versions of the rubber ball game are played in areas of Mesoamerica. Radiocarbon determinations for material associated with large rubber balls excavated from the Olmec site of Manati, Veracruz, Mexico date to approximately 1600 BC (Rodriguez and Ortiz 1994). The earliest known ball court, in Paso de la Amada, Chiapas also dates to approximately 1600 BC (Hill, Blake and Clark 1998). The fact that these early rubber balls and the Paso de la Amada stone ball court were presumably contemporaneous, but found in different regions of Mexico, suggests that the ball game was already quite widespread by 1600 BC. Thus even this early date is likely considerably later than the emergence of the Mesoamerican ball game.

The ball court at Paso de la Amada is a flat, rectangular, earthen court flanked by stone walls parallel to its long axis. However, the majority of the more than 1200 stone ball courts found in Mesoamerica are shaped like the letter I. These I-shaped courts are constructed with a middle rectangular section that is capped on each end with smaller
rectangular areas oriented perpendicular to the middle section (Figure 21). Another common court geometry, known as “T-shaped,” is identical in construction to the I-shaped courts, but includes only one end-capping rectangle. Typically, this “I” geometry is completely enclosed by stone walls, which are often sloped and thought to have been seating areas for spectators.

Figure 21: The I-Shaped Ball Court at Chichén Itzá, Yucatan, Mexico

From Pasztory 1978
The ball courts in Mesoamerica vary widely in size. The largest, found at the Maya site of Chichén Itzá, Yucatan, Mexico, measures approximately 170 m long by 70 m wide. Smaller courts may run only several meters in length and width. The sheer size of the Chichén Itzá court suggests how elastic the rubber balls needed to be in order to function effectively in a game. Inelastic balls, given what we know about the mechanics and play of the game, would not have worked on such large courts. Court size may be partly a function of the size and elasticity of the balls used for play by the local people. Clearly, both human and material resources would dictate the final size of the courts, but large courts could only be used with large, elastic rubber balls.

The use of balls of different size is further supported by archaeological data. Many of the Mesoamerican ball courts have stone hoops attached to the walls, positioned vertically at the midpoint of the court (Figure 22). The hoops served as goals in the Mesoamerican ball game, much like a basketball hoop in the modern game of basketball.

Figure 22: Stone Hoop at Chichén Itzá, Yucatan, Mexico
The ball court at Chichén Itzá has the largest known hoop, with an opening of 50 cm in diameter. The smallest known hoop has an opening diameter of 10 cm (Leyenaar 1978). These hoop size data coincide with the dimensions of recovered rubber balls. Balls in the archaeological record range from approximately 8 cm to 30 cm in diameter. The balls must be able to pass through the hoops easily, and the smaller ball sizes correspond to the range of ring dimensions recorded archaeologically. In the modern game of basketball, players utilize a ball that is one-half the diameter of its associated hoop. Thus, the balls recorded in archaeological record were most likely compatible for use in archaeologically-known stone rings.

5.2: Ball Court Evidence in the Antilles and South America

The presence and use of ball courts in antiquity is almost entirely a Mesoamerican phenomenon. However, there are some courts present in the Greater and Lesser Antilles, as well as data suggesting possible court locations in South America.

Dozens of ball courts found in St. Croix, Puerto Rico and Haiti have rectangular geometries like the courts found throughout Mesoamerica (Morse 1990). These courts are often delimited by stone walls. The ball game is known to have been present in the Antilles by the time of the arrival of the Spaniards in the New World. The first known accounts of rubber and ball game play, recorded by Spaniards such as Las Casas (1994) and Oviedo (1959), often refer to their observations on the Antilles and the Taino people who inhabited the islands.

One excavated court at the Salt River site, St. Croix is rectangular and measures 30 m by 25 m. This court is enclosed by walls made from sandstone slabs, many of which
contain carvings and petroglyphs on their surfaces (Morse 1990). Pottery, shell, bone, and stone ornaments found in association with this court date stylistically to 1300 to 1500 AD. This coincides roughly with a 1270 AD radiocarbon date for materials associated with a ball court in Capa, Puerto Rico (Olsen 1973). Clearly, the ball game and the use of rubber was firmly entrenched in the Antilles well before the arrival of Europeans.

While the Salt River court can be linked stylistically to Mesoamerican ball courts, ball play equipment also ties the two geographical areas together. In Mesoamerica, the ball players wore protective wooden or leather yokes on their hips as padding during play. These U-shaped pads were often represented in stone replicas for ceremony and display. The stone pads are commonly found in the archaeological record. At Salt River, St. Croix, evidence of at least 20 stone rings were found in association with the ball court. Although the St. Croix stone belts are completely circular, unlike the U-shaped Mesoamerican yugos, their presence in association with a ball court suggests that they were used in a similar manner. It seems highly likely, when examining the dates and stylistic attributes of the courts of St. Croix and Puerto Rico, that the Mesoamerican ball game brought by travelers from Mexico or Central America to the Greater and Lesser Antilles regions.

There has been much speculation within recent years regarding an I-shaped court structure found at Pampa de las Llamas-Moxeke in the Casma Valley of Peru (Pozorski and Pozorski 1995) (Figure 23). While this “court” is highly similar to the classic I-shaped courts of Mesoamerica and occupies a prominent location at the site, Pozorski and Pozorski suggest that the structure is only coincidentally shaped like a ball court and was not used for ball play. Since no other ball courts have been unearthed in South America, and Pampa de las Llamas-Moxeke dates to the time of the origin of the ball game in
Mesoamerica (approximately 1600-1200 BC), it seems highly unlikely that this structure is a ball court. There is no archaeological evidence suggesting otherwise.

**Figure 23: Reconstructed View of the Ball Court at Pampa de las Llamas-Moxeke**

![Reconstructed View of the Ball Court at Pampa de las Llamas-Moxeke](from Pozorski and Pozorski 1995)

**5.3: Artifacts from the Cenote of Sacrifice, Chichén Itzá, Mexico**

I examined rubber artifacts currently housed in the Peabody Museum of Archaeology and Ethnology at Harvard University. Although these artifacts are heavily damaged and unable to yield any useful chemical or mechanical data, I was able to arrange them into four general categories of use: rubber as ritual incense, rubber for figurines, rubber in sheets, and rubber as a hafting material. In these cases, because of the extensive alteration of the material, it is often hard to determine whether or not unprocessed latex or processed rubber was used. For this reason, I will refer to all of the Peabody Museum artifacts as "rubber," although it should be noted that, in this section, my application of the word "rubber" does not imply that the material was processed with *I. alba.*
The rubber artifacts from the Peabody Museum are part of a collection of materials recovered from a limestone sinkhole known as *El Cenote de los Sacrificios* (The Well of Sacrifice), in Chichén Itzá, Yucatan, Mexico. Edward H. Thompson performed the dredging and collection of this well in 1904. *El Cenote* is rich in Maya sacrificial offerings, as it served as a major ceremonial center from approximately 1124 to 1461 AD (Coggins and Ladd 1992).

Rubber as a ritual incense material was the most popular use reflected in the artifacts of the Peabody Museum. The incense burning vessels, or *incensarios*, typically include a clay bowl filled with copal and rubber. Copal is a sweet smelling resin often used as incense. The rubber, usually in solid ball form, is embedded in the surface of the mass of copal and probably served as a wick to light the less flammable copal (Coggins and Ladd 1992). As previously mentioned, the rubber would also serve to produce a thick black smoke useful in ceremonies. A note in the *incensario* collection recovered from *El Cenote* identifies the copal as from the species *Protium Copal* and *Bursera bippinata engler*.

The 11 *incensarios* in the *Cenote* collection can be best described by grouping them into three different sub-groups: (1) those containing several rubber balls implanted into the copal; (2) *incensarios* with a single mass of rubber implanted into the copal; and (3) one *incensario* with a rubber figurine wick embedded in the copal.

One *incensario* containing several rubber ball wicks embedded into the copal is housed in a 16.6 cm diameter clay bowl (Figure 24). This three-footed bowl is painted in the classic "Maya blue" and filled with copal and 13 rubber balls of 3 - 4 cm in diameter.
Although this artifact as a whole represents a rather simple application of rubber, examination of the 13 balls holds a wealth of information regarding the construction of rubber balls in ancient Mesoamerica. The balls were constructed using four different methods. Most of the balls incorporated both copal and rubber in their fabrication.

Five balls were made by winding thin bands of rubber around a copal core. Two balls were made by wrapping rubber bands into a ball, as one would wrap a ball of yarn. Three balls are solid rubber, and two appear to be rubber-dipped copal. These rubber-dipped copal balls were made by dipping a copal core into liquid latex, as there are no seams or signs of the application of a sheet of rubber or latex. Only one ball was made with a combination of all of the aforementioned methods: rubber strips were wrapped around a copal core, and then the entire ball was dipped into latex to form a solid outer
layer. In both of these dipping applications it is likely that unprocessed latex would have been used, as a mixture of latex and *I. alba* could only be used for dipping in the few minutes prior to solidification. Unprocessed latex will stay in its liquid form for days.

Several *incensarios* incorporate one large mass of rubber as a wick, as opposed to many smaller rubber balls. One such artifact is a tripod bowl filled with copal (Figure 25). Pushed into the top of the copal is a single mass of rubber, weighing 39.2 g and measuring roughly 4.5 by 6.0 cm.

**Figure 25: Incensario with a Single Rubber Wick**

A second single-rubber mass *incensario*, which is missing its containing vessel, holds a mass of rubber that appears to have been pushed into a hole in the copal (Figure 26). Five jade beads and one wooden bead surround the rubber. A bead of what appears
to be Spondylus shell, a material imported from west Mexico, is located at the bottom of the artifact.

The most interesting *incensario* utilized a rubber-skinned human figurine as the wick (artifact #C4602) (Figure 27). This figurine, constructed from a copal core coated with rubber, was implanted into the side of the copal. The figurine in its current state measures 7.7 cm long and 1.8 cm wide, though the head and feet are missing. Unlike the other *incensarios* in the collection, this item appears to have been built for use without a
containing vessel. The copal is able to stand freely on its own and does not exhibit the smooth sides produced on copal in direct contact with the *incensario* containers.

**Figure 27: Incensario with Rubber Figurine Wick**

Solid and hollow rubber figurines mark the second category of rubber artifacts found in the Peabody Museum of Archaeology and Ethnology collections. These figurines include solid and hollow human effigies and body parts. As described in
Chapter 6 "Documented Evidence of Rubber Use," Sahagún reports that these figurines were often sacrificial offerings or burned in religious ceremonies.

Artifact C4764 includes the legs and head of a broken figurine (Figure 28). The head measures 6 cm by 5 cm. It was fabricated from two sheets of rubber that were joined at the edges to form a hollow pouch. Facial features such as lips and eyes were applied with separate strips of rubber. The legs of this figurine, also hollow, were constructed in a manner different from that of the head. The legs appear to have been pulled and twisted out of the mass of rubber corresponding to the torso of the figurine. The conical top of the figurine's head was probably pulled out of a mass of rubber in a similar manner. This suggests that the rubber used for this figurine was still plastic while it was being worked into final form. In latex processed with *I. alba*, such a stage of "plasticity" occurs in the few minutes between the time of initial coagulation and final solidification. Since the figurine needed a high level of elasticity to maintain its hollow shape, it is likely that rubber processed with *I. alba* was used in this type of application.

Solid figurines are also represented in the *Cenote* artifacts. Box B9:329:A contains a small human torso measuring approximately 2.8 cm by 2 cm (Figure 29). The torso itself is made of a solid plug of rubber. The left and right arms were fashioned separately and applied in the form of cylinders measuring approximately 1.8 cm in length. A necklace appears on the figurine, also applied as a thin rolled strip of rubber.
Figure 28: Head and Legs from Hollow Rubber Figurine

Figure 29: Solid Rubber Figurine
Rubber body parts, including hands, arms, and feet, are found throughout the Cenote collection. I presume that these body parts were at one time members of larger rubber figurines. Artifact C4784 is a partial left foot, made from copal and coated or dipped with rubber; the toes are individually sculpted (Figure 30). The foot measures 3.4 cm by 2.5 cm.

One simple arm effigy was constructed from a 1.4 cm diameter dowel (Figure 31). This dowel was dipped in rubber, and the "fingers" of the hand were pulled from the still-plastic material on the end of the dowel, much like the legs were "pulled" from the torso of the hollow figurine. A small piece of wood was then pressed into the palm of the hand, as if it were holding the wood. Small balls of rubber in the shape of a bracelet were applied around the wrist area. This style of rubber-coated stick construction occurs often in the Cenote artifacts. At least 15 artifacts fit into this category, although none is distinguishable as a body part. Many are simply sticks or dowels coated with rubber, while others have layers of both copal and rubber over the wood. These items were probably used for smoke production and burning.

Figure 30: Rubber Foot Effigy

Figure 31: Simple Arm Effigy
Two more detailed arm effigies in the Peabody Museum collections are noteworthy. Artifact C4783 is made from two thin pieces of wood that mimic the human radius and ulna (Figure 32). These wooden 'bones' terminate in a lump of copal sculpted into the shape of a hand, which was then coated or dipped in rubber. A second, more elaborate hand is also made from sculpted copal coated with rubber (Figure 33). This hand was made carefully enough so that it grips a wooden rod, but allows the rod to slide within its fingers. Since the rod is free of rubber, the hand must first have been constructed around the wood from copal, then removed and coated in rubber.
Sheets of rubber are another frequent artifact type in the collection from El Cenote de los Sacrificios. These sheets can be made purely from rubber, or from a combination of rubber and copal. One striking example incorporates a thin layer of copal (less than 1 mm thick) sandwiched between two 1-mm thick layers of rubber. This sheet measures 3.9 cm by 5 cm and weighs 3.2 g. My experience with latex and rubber leads me to believe that these sheets could have been crafted with either unprocessed latex or *I. alba*-processed rubber. On exposure to air, latex can be dried into sheets and cut or manipulated to form, though the material is brittle and prone to cracking. Processed rubber can be pressed into sheets immediately after coagulation with *I. alba* juice. The way in which the material is to be used dictates whether or not processing was required, as more mechanically intensive applications would require the increase in elasticity and decrease in brittleness that *I. alba* provides.

In one artifact from the collection, rubber appears in a previously archaeologically-unknown utilitarian application: as a hafting material. In this example, a stone blade was attached to a wooden handle by wrapping a rubber band around the two components (Figure 34). The tool also has a layer of rubber between the blade and the handle, possibly to act as a shock absorber. The handle of this artifact measures 9 cm by 1.5 cm in diameter. The right angle-shaped blade is 1.4 cm wide and extends 4 cm along the handle. This use of rubber is quite intriguing, as it requires a different set of mechanical properties than those of a hollow figurine or rubber ball. In this application the rubber would have to exhibit high strength, while being able to act simultaneously as a shock absorber.
I tested this application of rubber with a simple replication experiment. I wrapped strips of unprocessed latex and processed rubber around two dowels equivalent in dimensions to the previously described tool. I first heated the strips to approximately 100°C in order to aid adhesion and increase flexibility. I found that the latex strips would wrap around the dowels and function temporarily as a hafting material, but when bent exhibited brittle behavior and cracking. The *I. alba*-processed rubber functioned perfectly as a hafting material and did not crack or break. This suggests that Mesoamericans utilized processed rubber for hafting blades, and may have heated the rubber when used for this purpose. However, latex that has not yet fully solidified is able to bend without cracking. Hafting bands of latex could also have been used, if the latex bands were applied to the tool before the material had fully solidified and become brittle.
Rubber preserves very poorly in most archaeological contexts, and thus rubber artifacts are extremely rare in the archaeological record. The few artifacts that have survived have been found in aquatic, anaerobic environments, such as in El Cenote de los Sacrificios. In the swamps of Manatí, Veracruz, archaeologists discovered 14 large rubber balls in varied states of preservation, associated with pottery, axes, and large wooden figurines. These balls were excavated in 1994 by Maria del Carmen Rodriguez, an archaeologist from the Veracruz office of the Instituto Nacional de Antropología e Historia (INAH) (Rodriguez and Ortiz 1994). Rodriguez carbon-dated the material associated with the balls to 1600 BC. This provides the earliest known date for the existence of the Mesoamerican ball game and establishes these balls as the oldest in the world. I examined and took samples from these balls in May of 1998 at the INAH-Veracruz offices. The permits for this research were granted to Prof. Dorothy Hosler by INAH. The Manatí balls, along with the artifacts from the Peabody Museum of Archaeology and Ethnology at Harvard University and a set of balls found in an aqueous environment during the Templo Mayor excavations in Mexico City (conversations with El Museo Nacional de Antropología museum staff, 1998), are the only Mesoamerican rubber artifacts of which I am aware.

Upon examination of the Manati rubber balls, it was clear that the larger balls are much better preserved than the smaller balls. Of the 14, the 6 that ranged from 12 cm to 30 cm in diameter were the best preserved. A set of 8 smaller balls with diameters of less than 6 cm were heavily oxidized and deteriorated. I concentrated my efforts on the 6 large balls, which I labeled MITR:1 through MITR:6. The MITR nomenclature is short for MIT Rubber.
MITR:1 was the smallest ball, measuring approximately 13.1 cm by 12.5 cm by 10.7 cm, and was the most poorly preserved (Figure 35). This ball was completely oxidized and had become totally inelastic. The ball was black and crumbling.

Figure 35: Photograph of MITR:1

MITR:2 was in a much better state of preservation (Figure 36). The ball was still rather elastic and dark brown in color rather than the deep black associated with oxidized rubber artifacts. Like MITR:1, MITR:2 was somewhat aspherical, measuring approximately 15 by 16.5 by 13 cm. The ball was very moist, and when pressure was applied water would leak from the surface. Rodriguez informed me that she had been treating the balls routinely with water in an attempt to keep the material from drying out and cracking. This ball, like each of the other large balls, has an extremely smooth surface finish, but its surface is interrupted by some dimples that contain a rust-colored material. This may be due to iron-containing minerals absorbed while the ball was in the swamp or by minerals left on the ball from the application of water in the INAH-Veracruz office.
Like the other large balls, MITR:3 had an extremely smooth dark brown surface, and still retained some elasticity (Figure 37). Rodriguez informed me that this ball was found in the swamp beneath an axe, which had severely deformed the ball over time. Approximately one quarter of the ball had collapsed into itself, creating a large bulge around its equator. Although still elastic, MITR:3 seemed more brittle than MITR:2.
MITR:4 is one of the largest balls, measuring 21 cm in diameter (Figure 38). Like many of the other balls, it is very smooth, dark brown, and retained moisture from the conservation attempts. Although the ball was well preserved, its surface was beginning to crack. It has a large dent in its side, reminiscent of the damage on MITR:2 caused by an axe. Clearly this ball had been buried with a heavy object on top of it.

Figure 38: Photograph of MITR:4

MITR:5 is almost identical in size to MITR:4 (~21 cm in diameter), but did not preserve as well as some of the other larger balls (Figure 39). It shows clear signs of oxidation, is relatively inelastic, and has started to crack throughout the surface. One side of the ball is completely flat, as if collapsed under its own weight. A layer of a silver, crystalline material and the rust coloring present on some of the other balls marks the surface.
The final ball I examined, MITR:6, is the largest of the group (Figure 40).

Roughly spherical, the ball measures 31 cm in diameter, is still rather elastic, and slightly...
lighter brown in color than the other 5 balls, though still possessing the rust-colored
discoloration. In working with this artifact, I realized how heavy and awkward the ball is,
and how difficult it would have been to play the Mesoamerican ball game with such a
ball. The game clearly required a great deal of strength, skill, and resilience, as injuries
would be common when using a ball of this size.

It should be noted that each of these balls excavated from Manatí have a singular,
smooth, continuous outer layer of rubber. This suggests that they were not made using the
Sinaloa ball-making method described in Chapter 4 of this thesis. Balls made according
to the Sinaloa method would show many contiguous pieces of rubber compressed
together to form a smooth outer surface. The Manatí balls were most likely made using a
single, large mass of rubber.
6.1: Ritual Use of Rubber in Mesoamerica

In addition to the many uses of rubber in Mesoamerica revealed through the examination of archaeological evidence, a large body of data pertaining to ancient Mesoamerican rubber use can be found in ethnohistorical documents. Many of the functions described in the documents cannot be corroborated archaeologically. Rubber preserves poorly in archaeological contexts, and most of the rituals left no record of the employment of rubber.

In *The Florentine Codex* (Sahagún 1970), Sahagún describes a series of ceremonies in which the Aztec dressed as the gods they were worshiping. Many of the elaborate costumes they wore in an attempt to portray their gods involved the use of liquid latex as a body paint. People playing the roles of specific gods -- Tlaloc, the five devils Ciuapipiltin, Teteo innan, Tzapotlan tenan, Opochtli, and Xipe totec -- were all adorned with dried liquid latex.

Tlaloc was one of the more important gods to the Aztec and to many of their contemporary Mesoamericans. Tlaloc, as the overseer of rain and agriculture, was the recipient of a wealth of tribute and sacrificial offerings. In ceremonies honoring Tlaloc, Sahagún writes that "his [the actor’s] face was covered with soot; his face was painted with liquid rubber" (Sahagún 1970, v. 1:7) (Figure 41). In ritual activities, the group of five devils known as Ciuapipiltin also had faces painted with liquid rubber. Sahagún explains that "their array was [thus]: They had their faces whitened with chalk, and, over this, anointed with liquid rubber" (Sahagún 1970, v. 1:19).
In ceremonies related to Teteo innan (figure 42), the actor playing her would have "liquid rubber on her lips" and "[the representation of] a hole was placed on each cheek" (Sahagún 1970, v. 1: 16). Teteo innan was known as the mother of the gods.

Figure 42: Teteo innan

Similiar to Teteo innan, Xipe totec (the god of the seashore people) (Figure 43) had rubber on his lips, but in a slightly different manifestation. While Teteo innan seems to have been "painted" with "liquid rubber", "rubber divided [Xipe totec's] lips into two parts" (Sahagún 1970, v. 1:40). Sahagún’s meaning with regard to the configuration of the rubber is not entirely clear. I would offer that either a sheet of rubber was placed between Xipe totec’s lips, or that rubber was used as a paint to differentiate the two lips. It is interesting to note that in his description of Xipe totec, Sahagún does not use the
term "liquid rubber" (which I have presumed to mean latex) as he does in all other cases, but simply "rubber". This suggests that the "rubber" used in the portrayal of Xipe totec was in solid form, and not the typical liquid latex.

The human personifications of Tzapotlan tenan (Figure 44), the goddess healer of human wounds, utilized liquid latex as both a body paint and a decorative accent for the paper ornaments worn in ceremony. Sahagún describes that "the array [of Tzapotlan tenan] was as follows: two {drops} were painted on her face; she had a small paper crown; large drops of liquid rubber and small drops were spattered over her paper crown..." (Sahagún 1970, v.1:17) In this example we see a broadening of the use of latex in Aztec ritual. Tzapotlan tenan not only has her face painted with liquid latex, her paper crown is also painted with latex. This is the earliest evidence of latex employed as a paint on paper, a common use in ritual burning ceremonies.

Figure 43: Xipe totec

Figure 44: Tzapotlan tenan
Opotchli (Figure 45), the god of the water folk and believed to be the inventor of fish nets, the trident, and other fishing-related tools, is depicted as completely covered with latex. "His array was [thus]: he wore a paper crown. He was covered with black unguent - a liquid rubber covering" (Sahagún 1970, v. 1:37). The fact that Sahagún described the covering as "black unguent" is particularly interesting because dried C. elastica latex is typically brown. Perhaps in this instance, latex mixed with I. alba was applied to the face and allowed to solidify, producing a black layer of rubber.

**Figure 45: Opochtli**
6.2: Waterproofing with Latex in Mesoamerica

The use of latex in each of these depictions of the gods mirrors the more general handling of latex and rubber by the people of ancient Mesoamerica. In the example of Opotchli, it is hard to miss the connection between the ocean, fishing, and latex as a waterproofing agent. Most of the gods described above as having latex-painted body parts are related to water. Tlaloc, Xipe totec and Opotchli are all distinctly water-related and comprise 60% of the rubber-adorned god representations described by Sahagún. Although Sahagún never directly reports waterproofing with latex, the latex suit of Opotchli seems to suggest this use.

The employment of *C. elastica* latex as a waterproofing agent by Spaniards in Mexico in the late 18th century also suggests that this application of latex may have been derived from earlier, pre-Hispanic applications. Between 1785 and 1798, Spain’s "Director General of Tobacco", Don Silvestre Diaz de la Vega, conducted a series of experiments using latex as a sealant for bags carrying mercury between Spain and Mexico (Lowe and Ries 1944). Mercury was prized for its use in gold processing, and Vega used latex-and-cloth bags to produce containers that prevent the loss of mercury during shipping. These experiments were conducted in Mexico with *C. elastica* latex.

6.3: Latex as Paint in Mesoamerica

The introduction of latex as a paint on paper, such as in the example of Tzapotlan tenan, also parallels a common use of latex in ancient Mesoamerica. Papers covered or spotted with latex were frequently burned in ceremony or used for display purposes. In
one of many references to rubber-painted paper, Sahagún writes that the Aztec honored the gods by displaying "long, thin poles, poles coming to a point, on each of which they placed paper streamers with liquid rubber, spattered with rubber, splashed with rubber" (Sahagún v. 2:43). Paper covered or partially painted with latex was commonly burned to produce smoke in ritual activities. I burned several samples of paper covered with latex to determine the difference in the quality of smoke produced between burning plain paper and latex-painted paper. The painted paper burned with a much denser, blacker smoke. This increase in visibility would have been a great advantage in "Vision Serpent"-style ceremonies, where visions were divined in the smoke with the aid of hallucinogens and extensive blood-letting (Schele and Miller 1986). The dried latex also releases a sweet aroma upon burning.

In addition to using latex as a body paint in ceremonies honoring the gods, Sahagún relates that the Aztec used latex as a paint for other purposes. They placed stripes of latex on the bodies to prisoners of war as an identifying marker of their status. Presumably, this marking technique was water- and sweat-proof, and would also have been difficult to remove. In Tlalocan, the home of the water gods, the Aztec coated the faces of their deceased with a layer of latex and amaranth paste.

Whereas these body paint techniques involve the direct application of latex to the skin, latex was also used in figurine making as a representation of skin. Sahagún reports that by applying liquid rubber to figurines, Aztec craftsmen were able to "give them human form" (Sahagún 1970, v. 2:132). In Chapter 5, "Archaeological Evidence for the Use of Rubber," I documented several examples of figurines having rubber or latex as "skin" applied over wood or copal forms, including arm, hand, and feet effigies as well as complete torsos. These artifacts were all dredged from the El Cenote de Sacrificios in
Chichen Itza, Mexico, and are housed at Harvard University’s Peabody Museum of Archaeology and Ethnology (Communication with Museum Staff, 1997). Documentary evidence of these rubber figurines may also be contained in Información de 1554: Sobre los Tributos que los Indios Pagaban a Moctezuma (Rojas, ed., 1997), where it is revealed that the Cotlastla province paid a tribute of 400 “Estatuas de hombre de hule” (rubber statues of men) to the Aztec capital every 80 days. It is not known whether these statues were solid rubber or rubber applied over a form made of another material.

6.4: Medicinal Uses of Rubber and Latex

One of the major contributions of The Florentine Codex is its description of the medicinal practices of the Aztec. A portion of these practices incorporated the use of rubber and liquid latex, which Sahagún describes in great detail. The medicinal uses of natural latex within the Aztec world were widely varied, and while it appears likely some were effective, others were probably little more than a placebo.

Latex was often used as a salve and in drop form. Ear ulcers (Sahagún 1970, v 10:141) were treated by placing drops of liquid rubber within the ear. Drops were also used to cure dryness of the nostrils. In this remedy, latex drops were placed into the nose and followed with an infusion of deer fat (Sahagún 1970, v 10:145). The application of liquid latex was also used to coat lip sores (Sahagún 1970, v 10:146), and when accompanied by a tongue massage could cure protruding tongue (Sahagún 1970, v 10:147). With the lip sore example, we see another example of the mirroring between the Aztec uses of latex and their depictions of the gods. Tzapotlan innan and Xipe totec were both portrayed as having latex on their lips.
Latex salves seem to have been widespread in ancient Mesoamerica and are reported in sources other than *The Florentine Codex*. In *An Aztec Herbal, The Classic Codex of 1552* (Gates 2000), there is a report of a latex-based salve for the relief of "rectal swellings". Although the recipe is not specific, this salve calls for the mixture of latex with certain herbs and plants. Roys (1976) reports that the pre-Hispanic Maya used latex as a salve for several different maladies. They would bathe areas of the body containing splinters with liquid latex. Apparently, dried layers of latex on the skin extracted splinters when peeled from the body. The Maya also used the latex from *C. elastica* to cool and protect burns on the skin. A recipe including crushed *C. elastica* leaves (providing a small amount of latex) was applied to knees to reduce swelling.

Latex-based drinks were also used to cure common medical problems such as hoarseness. For more serious problems, such as the spitting of blood, the infirm Aztec could drink chocolate mixed with liquid rubber, small chilis, and water (Sahagún 1970, v.10:154). Similarly, the Maya used a concoction of *C. elastica* latex, red grass, red wine and lemons to ease “recurrent blood-vomit (probably yellow fever)” (Roys 1976, 40). The Maya also drank a boiled mixture of *C. elastica* latex and other plant material to lessen the effects of “poisonous snake dysentery” (Roys 1976: 52).

Suppositories containing latex were used to alleviate colic and fertility problems. Suppositories for digestive problems were made with a combination of "flaked whitewash [and] a little saltpeter, with liquid rubber and chili" (Sahagún 1970, v.10:155). Women with fertility problems and men with urinary difficulties used latex suppositories made from the same components in an effort to cure themselves. These incorporated liquid latex, the root of a *Cucurbita* squash, and xomalli grass (Sahagún 1970, v. 10:155). I tested a mixture of *Cucurbita* squash and *C. elastica* latex to see if the
root could coagulate the latex into a solid, in the manner of *Ipomoea alba*. I was not able to coagulate the latex with the root, plant matter, or juices of the *Cucurbita* squash.

Outside of Mesoamerica, inhabitants of the upper Amazon basin in Colombia, Ecuador and Peru, including the Omagua, Maina, Caripuna and Cacharary peoples, used rubber for medicinal procedures. They used unprocessed natural latex to make syringes for cleaning nostrils and for enemas. These syringes were made by placing liquid latex onto pre-shaped clay molds and allowing the latex to dry into the desired form. The syringes could then be fitted with bone mouthpieces and used accordingly (Métraux 1944).

6.5: Mechanically Intensive Uses of Rubber

Sahagún gives evidence of several mechanically intensive uses of rubber that have not yet been substantiated by data from the archaeological record. These include rubber sandals, rubber hammers, and rubber-tipped drum sticks. He gives several accounts of rubber sandals, stating that these sandals were "very precious" (Sahagún 1970, v.10:188) and that, in the case of the Aztec, "their rubber sandals went with them" after they died (Sahagún 1970, v. 2:44). The use of rubber for sandals would have required processing of natural latex to improve its strength and wear properties. This necessity of processing will be demonstrated in the second half of this thesis.

The *Florentine Codex* also makes mention of rubber hammers and rubber-tipped drumsticks and their use in the playing of the two-toned drum, a common instrument in pre-Hispanic Mesoamerica. Maya documents dating to the 17th and 18th century refer to latex as "the gum used for beating a drum" (Roys 1976, 52). Although we do not have
physical data for the existence of these items, I have witnessed many modern marimba
and xylophone players throughout Mexico using homemade rubber-tipped mallets. These
mallets appeared to be made with unprocessed latex of an unknown species. It is likely
that the ancient drumsticks also utilized unprocessed latex. The latex tips would surely
break down quickly, due to the brittle nature of unprocessed \textit{C. elastica} latex and to the
fatigue experienced by the material in with striking a drum or other percussion
instrument.
Chapter 7: Part I Conclusions

Part I of my thesis is intended to present the history of rubber processing and usage in the Americas, with a focus on Mesoamerica. It is based on my examination of historical and ethnohistoric documents, ethnographic research I carried out in Chiapas, Mexico, and archaeological and botanical data. These sources enable me to provide the most complete study, to date, of the relationship between indigenous American peoples and natural latex.

In Mesoamerica, rubber processing began by about 1600 BC. Radiocarbon data from artifacts associated with rubber balls excavated from Manati, Veracruz, Mexico, (Rodriguez and Ortiz 1994) as well as from a ball court in Paso de la Amada, Chiapas, Mexico (Hill, Blake and Clark 1998) substantiate this period of time as the earliest evidence of rubber use in the world. The latex used for these Manati balls, and for any balls utilized for play in a ball court, would have to have been processed to make the material suitable for use. Unprocessed latex is too inelastic and brittle for implementation in ball making and ball playing.

In the Florentine Codex (Sahagún 1970), Sahagún identifies in Nahuatl the source of ancient Mesoamerican latex as the Olquauitl tree. Anderson and Dibble, translators of the Florentine Codex into English, identify Olquauitl as the Castilla elastica tree. Castilla elastica is present in Mexico and Central America, throughout the Gulf Coast and along the Pacific coast of Chiapas and the Pacific and Atlantic coasts of Central America. The coast of the Gulf of Mexico and the Pacific coast of Chiapas are the areas where incipient Mesoamerican culture developed. Rubber processing and use were a part of Mesoamerican life from the onset of their civilizations.
Sixteenth-century Spanish missionaries and political scribes in Mexico, including Fray Toribio de Benavente (Benavente 1984) and Pedro Martir de Angleria (Martir 1964), expressed great amazement upon seeing rubber and latex for the first time. Since latex is indigenous to the Americas, no European had witnessed the elastic properites of rubber or latex. These Spaniards also hinted at the ingredient ancient Mesoamericans added to the latex to produce a strong, elastic rubber: the juice of *Ipomoea alba*. *Ipomoea alba* is a species of white-flowered morning glory, found throughout much of the Americas. The addition of *I. alba* juice to *C. elastica* latex was necessary to produce rubber with the appropriate toughness and elasticity to perform in some of the ways that ancient Mesoamericans used rubber.

The ethnographic research I conducted in Chiapas, Mexico confirmed the modem usage and efficacy of the *Ipomoea alba-Castilla elastica* latex combination (Hosler, Burkett and Tarkanian 1999; Tarkanian 2000; Tarkanian and Hosler 2001). Rubber workers in Chiapas are able to make strong, elastic rubber from the mixture of these ingredients. The resultant rubber turns black, reflecting the dark colors of rubber balls depicted in Maya and Aztec art. The processing of *C. elastica* latex with the juice of *I. alba* has also been confirmed ethnographically by Conzemius amongst the Miskito and Sumu people in Honduras and Nicaragua (Conzemius, 1932).

In addition to the use of latex to make rubber balls, such as those excavated from Manatí, I identified several other ways ancient Mesoamericans employed rubber and latex. I achieved this through an examination of rubber artifacts dredged from the Cenote of Sacrifice in Chichén Itzá, Yucatan, Mexico (now in the collections of Harvard University’s Peabody Museum of Archaeology and Ethnology), as well as through cataloging references to rubber and latex implementation in historical and ethnographic
documents. Archaeological artifacts suggest the incorporation of rubber and latex in wicks for ceremonial incense burners, in figurines and body part effigies, in rubber and latex sheets, and in hafting materials used to attach blades mechanically to handles. Sahagún describes balls, sandals, drumsticks and hammers made of rubber, as well as “liquid rubber” being used as a paint and waterproofing agent. He also describes the common utilization of liquid latex in Aztec medicine.

Many of these implementations of “rubber” must actually have involved the use of unprocessed latex. I identify liquid rubber when used as a paint or waterproofing agent as latex, since processed rubber solidifies rapidly and could not be spread like a paint. Likewise, many of the materials from El Cenote de Sacrificios—latex balls as wicks, latex figurines and body parts and latex sheets—were made from unprocessed, dried latex and not rubber. In these Cenote artifacts, the latex coatings, whether they are over copal, wood, or other layers of latex, are smooth and continuous, suggesting a dipping process into a liquid medium. Again, such building up of form would be impossible with L. alba-processed rubber.

We must also consider the function of the items made with latex when determining whether or not L. alba processing was necessary. In the case of incensario ball wicks, for example, the balls were burned and did not require optimum mechanical properties. In many of the known uses of rubber in ancient Mesoamerica, however, there is an obvious need for processing latex with Ipomoea alba. For instance, rubber balls, rubber hafting material, hollow rubber figurines and rubber sandals, drum sticks, and hammers require a level of toughness and elasticity that is not present in unprocessed C. elastica latex. In these cases, the ancient Mesoamericans had to utilize the mechanical performance-enhancing properties that the I. alba vine confers to latex. The excavated
Manati balls provide an excellent example. It would be exceedingly difficult to create balls of the size and density of those from Manati with unprocessed latex. Unprocessed latex could not provide the elasticity required of balls used in the Mesoamerican ballgame.

The need for processing can also be seen when examining the stone ball courts that remain in the archaeological record throughout Mesoamerica. These courts can be found in an area ranging from the southeastern United States to El Salvador. The sheer size of the playing field within many of these courts, such as the court at Chichén Itzá, required balls with a high degree of elasticity. The entire court could not have been utilized without a ball that would bounce and be able to stand up to the rigors of play. The elasticity essential to these balls was gained through the addition of the juice of *I. alba* to natural latex.

The sizes of the rubber balls produced were likely tailored to specific courts. Larger courts would have required larger, more massive balls, while smaller courts could be played upon with less sizeable balls. Clearly, human and materials resources would dictate the final sizes of the courts, but the ball technology—processing and properties—also must have limited the maximum and minimum sizes of Mesoamerican ball courts. The ball and court must be matched so that the entire court can be utilized, while keeping the ball within the bounds of the structure. The Manati balls reflect a variation in diameter from 8 cm to approximately 30 cm. This coincides roughly with the range of the inner diameters of extant ball court scoring rings in Mesoamerica, which span from 10 cm to 50 cm (Leyenaar 1978).

While the rubber ball game began by about 1600 BC in Mesoamerica, Mesoamerican-style ball courts began to appear in the Antilles much later, by
approximately 1270 AD (Olsen 1973). Mesoamerican-style protective gear for use in the ball game is also found at archaeological sites in the Antilles. The presence of the protective gear and ball courts suggests contact between the peoples of Mesoamerica and the Antilles.

It is interesting to note that in both Mesoamerica and the Antilles the distribution of ball courts is much more extensive than the distribution of the *C. elastica* rubber sources. While courts can be found on various islands of the Greater and Lesser Antilles and throughout Mexico and Central America, *C. elastica* is available only in certain circumscribed regions within these areas. This means that rubber was a valuable commodity that needed to be shipped throughout the Mesoamerican empires, and possibly also to the Antilles, to meet the demand. Data from 16th century codices confirm that rubber was indeed traded throughout Mesoamerica, often in the form of tribute (Berdan and Anawalt 1997; Berdan and Durand-Forest 1980; Rojas 1997).

In the Aztec empire (approximately 1427-1521 AD), rubber was collected as tribute in variations of two forms: as processed rubber and as raw latex. Records from *Información de 1554: Sobre los Tributos que los Indios Pagaban a Moctezuma* (Rojas 1997) show that latex-bearing provinces within the empire sent rubber and raw latex to the Aztec capital in the form of “rubber cakes” and rubber figurines, while the *Codex Mendoza* (Berdan and Anawalt 1997) describes payments in the form of rubber balls. From these data I conclude that in ancient Mesoamerica most rubber processing occurred on-site within the latex-producing zones. The “rubber cakes” discussed in *Información de 1554* were likely dried, unprocessed latex cakes to be cut and used for non-mechanically intensive purposes, such as wicks for ceremonial incense burners. The materials for use in rubber balls and figurines, which required processing to develop the necessary
mechanical properties, or in the case of the figurines the necessary plasticity and formability, would have been processed on-site and shipped to the capital. Shipping the volumes of liquid latex that would have been necessary to supply the demand for rubber balls would likely have been too difficult from a logistical standpoint and given the limitations on packaging and containment. However, small amounts of liquid latex must have been shipped from the latex-bearing regions for use as paint and as a waterproofing agent.

In South America, at least from ethnographic observations within the last three centuries, latex was processed and used for balls in ball games among some indigenous groups. While the use of latex for ball games is well documented in South America, there are no known prehistoric ball courts with architectural features.

Groups throughout South America made latex balls from wound strips of dried unprocessed latex. In each case, only latex was used, without any additives. The species of latex used include *Hevea brasiliensis, Hancornia speciosa*, and species from the *Sapium* and *Manihot* genus. The latex from these species was not processed, but this may not have been due to a lack of technical knowledge or ingenuity. *Hevea brasiliensis* and *Sapium* latexes are known to be far superior in quality and strength to *Castilla elastica*, and may have functioned as well or better as balls in a ball game than *C. elastica* processed with *I. alba*. Mechanical data on the genus *Hancornia* and *Manihot* are not available.

There are several striking conclusions to be made regarding rubber and latex processing and use within the Americas. The first, and most obvious, is that latex was utilized throughout various time periods and regions as a material for making balls. This convergence on a common use occurred across many centuries and civilizations in
geographically disparate areas. When the latex gets on the skin, it dries quickly, and easily peels off into a ball form. Latex’s potential for elasticity and bounce is immediately apparent when working with the raw material. The balls are elastic and lively, and may be one possible reason for which different civilizations were initially motivated to form latex into balls.

In terms of ball play, each of the three regions examined in this thesis (Mesoamerica, South America and the Antilles) developed a competitive team style of play reminiscent of volleyball. While the ball game in the Antilles seems to have a Mesoamerican influence, the absence of courts in South America suggests that these peoples developed the concept of ball games independently. However, since most of our data on South America were collected after the arrival there of Europeans, one cannot be sure if ball games were introduced from outside or were a product of indigenous societies. This external introduction would explain the lack of courts in the archaeological context. On the other hand, many of the latex-utilizing societies in South America were not structured as large, complex civilizations like those in Mesoamerica, and they may not have had the resources to build such monumental structures.

The connection between latex and skin, in and of itself, is also a trait that connects Mesoamerica and South America. In Mesoamerica we see skin painted with latex in ceremonies and the application of latex or rubber skin to figurines to make them more lifelike. In South America, many of the latex-working procedures required the spreading of latex onto the skin for drying, then removal in strips to be formed into balls. In the ancient world, the connection between latex and skin is clear: they were likely the only two materials known with such a high degree of elasticity.
Laboratory Work

The laboratory portion of this thesis connects the latex-processing regime of ancient Mesoamerica with the rubber and latex items produced. Clearly, Mesoamericans used rubber and latex in a wide variety of applications, many of which would require the maximization of different properties: elasticity for rubber balls; strength and shock-absorption for the blade hafting; fatigue and wear resistance for sandals.

My previous research (Tarkanian 2000) showed that processing with different concentrations of *I. alba* to *C. elastica* produced rubber with distinctly different mechanical behaviors. The following portion of this thesis presents mechanical data on *C. elastica* latex processed with a full range of *I. alba* concentrations. These data determine the full extent of mechanical properties that would have been available to ancient Mesoamericans by tailoring their rubber-making procedure. The presented differences in mechanical properties found in this study are tied to their likely applications in ancient Mesoamerica, illustrating that through processing, Mesoamericans customized the properties of natural rubber to suit specific applications. The data for *C. elastica* are compared in all testing categories to *Hevea brasiliensis*, the most prevalent South American source of natural latex. These data show that *H. brasiliensis* is a suitable rubber for most applications, and did not require processing, as *C. elastica* does, to produce a tough, elastic material.
Part II. Mechanical Analyses of Rubber and Latex

Chapter 8: Part II Introduction

From 1600 BC until the arrival of the Spaniards in the early 16th century, latex and rubber were used for an array of applications in Mesoamerica. In South America, European ethnographers first reported the exploitation of natural latex and rubber by the early 18th century. It is likely that these materials were being used throughout the continent prior to European documentation. This text on “Mechanical Analyses of Rubber and Latex” quantifies the full range of mechanical properties that would have been available to ancient Mesoamericans through manipulation of the Castilla elastica-Ipomoea alba rubber-making procedure. These results are compared to data gathered on Hevea brasiliensis latex, the most prevalent source of South American latex.

Rubber samples made from C. elastica latex processed with I. alba juice have a wide range of mechanical properties, varying in terms of elasticity, damping, wear resistance and other properties depending on the concentration of I. alba used in the mixture. The data presented here offer the possibility that ancient Mesoamericans were cognizant of the effects of processing C. elastica latex with different concentrations of morning glory vine juice, and used this information to process materials for specific applications. The data I gathered are correlated to three applications of rubber in ancient Mesoamerica that would have required different mechanical properties in order to function efficiently: rubber balls, rubber bands for hafting blades to handles, and rubber-soled sandals.
An ideal rubber ball for use in the Mesoamerican ball game would have the highest possible elasticity. The use of rubber bands for hafting blades to handles necessitates high strength to hold the tool together and superior damping properties to reduce the effects of impact. Rubber-soled sandals require fatigue and wear resistance. The data presented here demonstrate that ancient Mesoamericans had likely developed the technology to optimize wear resistance, elasticity, strength and damping of *C. elastica* rubber to suit specific applications.

The data offered in this thesis also show that *H. brasiliensis* latex has mechanical properties extremely similar to those of *C. elastica* rubber. Since there is no documented evidence known to me of latex processing in pre-Columbian South America, my data suggest that ancient South American peoples did not need to process *H. brasiliensis* latex. It is a rubbery material suitable for use in balls and other items in its natural state.

8.1: Sample Preparations of Rubber and Latex

I prepared rubber and latex samples according to the following method for use in DMA (Dynamic Mechanic Analysis), tensile testing, Dynastat analyses, wear testing, and creep experiments.

In preparing dried *Castilla elastica* and *Hevea brasiliensis* latex for analyses, the liquid latex must be dried on a smooth, level surface. Samples dried on such a surface will have an even exterior and uniform thickness. This ensures that the mechanical data obtained from these samples will be reliable and repeatable, as surface irregularities, voids and dimensional asymmetry will affect the mechanical response of the materials. A smooth drying surface also allows for the easy removal of the sample after it is prepared.
Since latex is by nature an adhesive, removing dried latex from its container can sometimes be painstakingly difficult.

In my latex sample preparations, I poured *H. brasiliensis* and *C. elastica* into aluminum cups that measure 5 cm in diameter and 1.5 cm in height until the cups were filled with approximately 2 mm of latex. After several days of drying, these latex discs were usually around 1 mm in thickness. Care was taken to dry the materials in open air rather than a hood, as the airflow in a hood creates air bubbles in the surface of the dried latex that can cause errors in mechanical testing.

After drying and removal from the cups, I stamped “dog bone” tensile-style specimens from the sheets of latex using a cutting die. The *H. brasiliensis* samples consistently required less force for cutting out samples than the *C. elastica* latex. The testing area of these “dog bone” samples was 3 mm wide by 25 mm long. Thicknesses varied a small amount according to how much liquid latex was initially poured into the drying cups.

Two raw materials are needed for the production of rubber samples: *C. elastica* latex and juice from *Ipomoea alba* vines. I used several methods for the removal of juice from *I. alba* vines, including crushing with a 20-ton bottle jack, crushing with a rolling mill, using a food processor to liquefy the vines, and squeezing the juice from the vines by hand. I found that the rolling mill is by far the easiest and most efficient method of extraction, as you can monitor the plant material as it is being crushed and adjust the spacing of the cylinders of the mill accordingly. The bottle jack also worked well, but was more difficult to control and did not work well with smaller quantity of vines. The food processor introduced too much pulp into the morning glory juice, which becomes a major problem when mixing the vine juice with the latex. Any pulp mixed with the latex
will function as a void in the resulting rubber, drastically altering the mechanical properties of the material. Thus, the crushed morning glory juice should be strained before use.

Juice obtained from the *I. alba* vines becomes ineffective at coagulating latex after several days of refrigeration, so fresh juice should be prepared immediately prior to each coagulation session. The juice from uncrushed *I. alba* vines stored in refrigeration will maintain its coagulative power for at least a year. When inside the plant, the juice maintains its efficacy, but when stored outside the plant this ability quickly degenerates. Professor JoAnne Stubbe of MIT suggested that this degeneration of effectiveness might indicate that the coagulative ability of the *I. alba* juice is due to proteins that breakdown quickly outside of the plant (personal communication with J. Stubbe, January 2003).

I prepared rubber samples containing 25%, 33%, 40%, 50%, 60% and 70% morning glory (MG) juice by volume. These mixtures were usually in the range of 25 ml. For example, 60% MG samples were made using 15 ml of morning glory juice and 10 ml of *C. elastica* latex. 25% MG specimens were prepared using 5 ml of *I. alba* juice and 20 ml of latex.

After stirring the appropriate volumes of morning glory juice and latex together in a beaker, I heated the mixtures to approximately 50° C. Coagulation occurs within 15-45 minutes, depending on the percentage of morning glory used. The 33% through 50% samples consistently coagulated first at approximately 15 minutes, while the 25% and 70% samples always took 30 to 45 minutes to solidify.

A temperature above normal room temperature is necessary to catalyze the morning glory-latex reaction. In my fieldwork in Chiapas, Mexico, I observed *I. alba* coagulating *C. elastica* latex under ambient outdoor conditions, approximately 100° F
(38° C). In the temperature-controlled labs typical of most research institutions, this coagulation will not occur without heat input. If the samples are heated too high, breakdown of the polymer chains may occur. Temperatures around 38 °C to 50° C should not cause any degradation.

Once the samples solidify in the beakers, the excess liquid (the water phase of the latex) can be decanted off. For tensile style samples, I pressed the solid rubber between glass plates, to an approximate thickness of 1 mm. These rubber samples set in several minutes and could not be reshaped after this time period. The thin sheets of rubber were then left to dry for about 24 hours, turning the samples as often as possible to allow for even drying on both sides of the sheet. The dried sheets were then stamped with a cutting die of the desired size to provide samples ready for testing.

The latex and rubber discs for use in wear testing were prepared in an identical manner as the tensile-style specimens, but in sheets of 4 mm thickness. The sheets were then cut with a razor into discs with a diameter of 25 mm.
Chapter 9: Dynamic Mechanical Analysis

9.1: DMA Setup

I conducted dynamic mechanical analysis (DMA) on the rubber and latex using a TA Instruments Q800 DMA. DMA is an analytical technique capable of determining the mechanical behavior and molecular structure of a material over ranges of temperature and strain frequencies. In these experiments, I gathered data for $E'$, $E''$, and $\tan \delta$ at 1 Hz, over a temperature range of $-75^\circ C$ to $35^\circ C$. $E'$ is the “storage modulus” -- the energy stored by a material when it is deformed. $E''$ is the “loss modulus,” and is the energy dissipated as heat when a material is deformed. $\tan \delta$ is the ratio of $E''/E'$, literally the tangent of the phase lag of strain behind the stress. In addition to these quantitative values that DMA produces, it also can impart insight into the molecular structure of a material. DMA can determine the glass transition temperature ($T_g$) of a material, as well as information about the relative cross-link densities and molecular weights of polymeric materials.

These experiments were carried out in tension mode using the “thin film” grips of the TA Q800 and with a strain of 15 $\mu m$ at a rate of 1 Hz. Samples were tested in triplicate in order to verify the results and establish standard deviations for comparison between samples.

9.2: Glassy Moduli

At 1 Hz, the frequency of these DMA experiments, the temperature at which the loss modulus experiences a maximum is close to the value of $T_g$ empirically determined
by volume-temperature measurements (Murayama 1978). The $T_g$ of *C. elastica* latex is approximately $-53.2 \, ^\circ C$ ($\pm 0.8 \, ^\circ C$) according to the loss modulus ($E''$) peak. Below $T_g$ most polymers, including natural rubbers, are rigid and glassy. Translational motion and rotation of the polymer chains stop, effectively locking the chains in place. With all segmental motion stopped, any molecular or structural changes incurred through processing *C. elastica* latex with *I. alba* would not be expected to result in large changes in the glassy moduli. However, changes are seen in the glassy modulus data that correspond to the concentration of morning glory (MG%) in the rubber (Figure 46).

**Figure 46: Glassy Modulus vs MG %**

![Graph](image)

The standard deviations are quite large for the *C. elastica* latex sample at 0% MG, and the 33% MG and 50% MG samples, but a trend is visible among the averages of the
glassy moduli. From 0% MG up to 50% MG, the average moduli increase, then plateau at 60% MG and 70% MG. This seems to be a valid trend, as the coefficients of variation (C.V.) for 25% MG, 40% MG, 60% MG and 70% MG are less than 10%.

There are two possible explanations for the increase in glassy modulus with increasing morning glory concentration. One is that the addition of morning glory juice to the latex causes changes in the electronic interactions between the polymer chains. This could include an increase in the van der Waals forces between the polymers, explaining the increase in modulus with rising morning glory concentrations. Van der Waals forces between polymer chains, in combination with chain entanglements, may be of high enough magnitude to mimic the behavior of a chemically cross-linked material (Treloar 1958).

A second hypothesis involves the presence of shorter chains within the polymer matrix. While the large segments would be frozen in place below $T_g$, shorter polymers could remain mobile without affecting the larger chains, increasing the glassy modulus (Nielsen 1974). Previous research has shown that $I. alba$ removes proteins from $C. elastica$ latex (Hosler et al. 1999; Tarkanian 2000). In the pure $C. elastica$ latex sample (0% MG), the motion of these smaller chains may be inhibited by the presence of proteins. Higher percentages of $I. alba$ juice may remove these proteins more efficiently, freeing the shorter latex polymers to contribute to the modulus of the material below $T_g$.

$Hevea brasiliensis$ latex, shown in black in Figure 46, is close in glassy modulus to the moduli of all of the $C. elastica$ samples. It has an average modulus of 1043 MPa, +/- 97 MPa.

The data below the glass transition temperature are interesting from a molecular and processing standpoint, but do little for evaluating the performance of $C. elastica-I$. 

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rubber in applications typical of ancient Mesoamerica, the main focus of this thesis. DMA data such as the storage modulus (E'), loss modulus (E'') and tan δ values at 20 °C give a more useful picture of the performance of *C. elastica* rubber and latex within the temperature range of normal usage.

9.3: Storage Modulus

The E' data for the *C. elastica* and *H. brasiliensis* latex and *C. elastica* rubber samples at 20 °C can be seen in Figure 47. Evaluation of the storage modulus data is vital in the examination of the efficacy of *C. elastica* latex and rubber as a material for rubber balls in ancient Mesoamerica. Since E' is a measure of the energy stored in a material after deformation, it correlates directly with elasticity and the ability of a ball to rebound.

Figure 47 illustrates a distinct difference in moduli between the *C. elastica* rubber samples processed with morning glory juice and the dried unprocessed *C. elastica* latex. In the unprocessed latex sample, we see a high modulus of approximately 12 MPa. The rubber samples, processed with the juice of *I. alba*, have a much lower modulus in the range of 2 to 3 MPa. The *H. brasiliensis* latex also has a storage modulus in the 2 to 3 MPa range.

These data illustrate that the addition of morning glory juice transforms *C. elastica* latex from a stiff and brittle material into one that is softer and tougher. *C. elastica* latex, though higher in modulus, is too stiff, inelastic and brittle to function as a material for rubber balls. *C. elastica* latex in its natural state could not have been used for balls in ancient Mesoamerica; processing with *I. alba* was necessary for this particular application. The DMA data testify to the quality of rubber produced through the mixing
of *C. elastica* latex and *I. alba*, as the *C. elastica* rubbers behave comparably to the modern commercial source of latex and natural rubber, *H. brasiliensis*.

**Figure 47: Storage Modulus vs. MG% at 20° C**

![Graph showing storage modulus vs. MG% at 20° C]

Though DMA is unable to ascertain which morning glory:latex ratio would be best for rubber balls based on $E'$, it does quantify the transformation morning glory causes in the elastic properties of *C. elastica* rubber. Stress-strain data better differentiate the moduli of the rubber samples made with varying percentages of morning glory juice and are addressed in Chapter 10.
9.3.1: Chemical Data Related to \( E' \)

The morning glory-induced transformation from a stiff latex to a more rubbery material likely happens through a two-part mechanism. As mentioned in the section detailing “Glassy Moduli,” prior research shows that the addition of morning glory juice to \( C.\ elastica \) latex removes proteins from the latex (Hosler et. al 1999 and Tarkanian 2000). Figure 48 displays a \(^{1}H-^{13}C\) cross-polarization magic angle spinning (CP MAS) NMR spectra of \( C.\ elastic \) latex, \( C.\ elastica \) rubber, and a sample from one of the balls excavated from Manatí, Veracruz, Mexico. The data show protein peaks in the 150 – 200 ppm range of the latex spectrum that are not present in the \( I.\ alba\)-processed rubber or the ancient balls.

**Figure 48: \(^{13}C\ CP\ NMR\ of\ Latex,\ Rubber\ and\ Ancient\ Rubber**

![Figure 48: \(^{13}C\ CP\ NMR\ of\ Latex,\ Rubber\ and\ Ancient\ Rubber](image)

* and § are artifacts of the instrument
With the removal of these proteins, smaller molecules (MW on the order of hundreds) in the morning glory juice may act as plasticizers and ultimately soften the material -- making a tougher, more flexible rubber. This occurs, in part, because the plasticizer is able to separate the polymer chains and prevent any interaction between them (Treloar 1958), encouraging translational motion. Gas Chromatography/Mass Spectrometry (GC/MS) data on the juice of *I. alba* show evidence of many molecules with molecular weights on the order of hundreds.

### 9.3.2: E' Slopes

DMA is a powerful analytical tool, because it gives qualitative and graphical data that reflect the molecular behavior of the material being tested. The interpretation of the shapes of the E', E'' and tan δ curves --the slopes, peaks, and plateaus of the data-- may be more important than the raw numbers that DMA produces.

At temperatures well above $T_g$, the E' of a cross-linked rubber should not decrease as T increases (Murayama 1978). In order to test this phenomenon, I compared the slopes of the E' data from 0°C to 30°C of each sample tested. These results are summarized in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>E' Slope</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>H. brasiliensis</em></td>
<td>-0.04</td>
<td>18</td>
</tr>
<tr>
<td><em>C. elastica</em></td>
<td>-0.262</td>
<td>17</td>
</tr>
<tr>
<td>25% MG</td>
<td>-0.027</td>
<td>19</td>
</tr>
<tr>
<td>33% MG</td>
<td>-0.031</td>
<td>26</td>
</tr>
<tr>
<td>40% MG</td>
<td>-0.034</td>
<td>11</td>
</tr>
<tr>
<td>50% MG</td>
<td>-0.032</td>
<td>24</td>
</tr>
<tr>
<td>60% MG</td>
<td>-0.04</td>
<td>54</td>
</tr>
<tr>
<td>70% MG</td>
<td>-0.029</td>
<td>49</td>
</tr>
</tbody>
</table>

**Table 1: E' Slopes for Rubber and Latex Samples**
As demonstrated by Table 1, *C. elastica* has almost an order-of-magnitude steeper $E'$ slope than the rubber samples and the *H. brasiliensis* latex sample. These data show that the $E'$ "plateau" of *C. elastica* latex is decreasing at a much greater rate than the MG% samples and *H. brasiliensis*. This may indicate that the unprocessed *C. elastica* latex has a lower cross-link density than the latex samples processed with *I. alba*. This finding is somewhat at odds with the fact that the *C. elastica* latex is considerably stiffer than the other samples tested, but this piece of DMA data point towards higher levels of cross-linking in the rubber samples.

9.4: Loss Modulus

$E''$ data for *C. elastica* rubber and latex and *H. brasiliensis* latex at 20° C are presented in Figure 49. $E''$ is of interest in this study as a measure of the ability of a material to dissipate energy as heat upon distortion. Damping ability is one of the primary requirements for a rubber hafting band, but it is also important for rubber sandal soles.

Figure 49 shows a high modulus value for the *C. elastica* latex sample, followed by a sharp drop off in modulus values for the all of the rubber samples. This mirrors the behavior of the $E'$ data. As in the $E'$ data, the $E''$ values of the *C. elastica* rubber (0.23 to 0.3 MPa) are very close to that of the *H. brasiliensis* latex.

The plateau in loss modulus that occurs in the rubber samples implies that each of these materials would perform with the same efficacy in terms of damping. Therefore, no specific percentage of *I. alba*-processed rubber would have a distinct advantage for use in damping applications such as blade hafts. However, the high $E''$ of the unprocessed *C. elastica* latex, coupled with its higher $E'$, suggests that this may have been the most appropriate material for hafting tools in ancient Mesoamerica. Although this material is
the strongest and has the best damping qualities, it is brittle and prone to cracking. This could be a concern in a hafting application.

**Figure 49: Loss Modulus versus Morning Glory % at 20° C**

Above the glass transition temperature, $E''$ decreases as molecular weight or cross-link density increase. In Figure 49, the *C. elastica* rubbers and *H. brasiliensis* latex samples have significantly lower $E''$ values than the *C. elastica* latex. The $E''$ data at 20° C may indicate, in accordance with the $E'$ slope data, that the addition of *I. alba* juice to *C. elastica* latex results in an increase in cross-linking or molecular weight. Since *H. brasiliensis* and *C. elastica* are different species of latex-producing trees, it is feasible
that they produce latexes of different molecular weights. These data suggest that *H. brasiliensis* latex has a higher molecular weight than *C. elastica*.

**9.5: Glass Transition Temperature**

At 1 Hz, the loss modulus peak temperature is close to the value of $T_g$ as determined by volume-temperature measurements (Murayama 1978). Figure 50 presents the glass transition temperatures, $T_g$, as measured by the loss modulus peak, over the range of latex and rubber samples.

**Figure 50: Glass Transition Temperatures versus MG%**

![Graph showing glass transition temperatures versus Morning Glory %](image)
With increased cross-linking, $T_g$ values increase in temperature. Cross-linked polymers have less rotational and translational freedom than non-cross-linked polymers, because they have a more rigid network structure. Therefore, it is easier to counteract the segmental motion of cross-linked polymers thermally, resulting in higher $T_g$ values. The data portrayed in Figure 50 do not present a clear connection between cross-linking or molecular weight changes as a function of morning glory concentration.

The changes evident in the glass transition temperatures from sample to sample are distinct, but not significant. The *C. elastica* latex sample, 33% MG, 40% MG and 70% MG exhibit close $T_g$ values, taking error into account. The rest of the samples have a lower $T_g$, which ordinarily would suggest a lower level of cross-linking compared to the raw *C. elastica* latex. In this case, however, a matter of 2 to 3 degrees C does not result any real difference in behavior or chemical structure of the material.

**9.6: Tan δ Interpretation**

The data for tan δ as a function of morning glory concentration can be seen in Figure 51. Tan δ data can be used as a standard of comparison between the samples of rubber processed with different percentages of morning glory juice and the two species of latex. The peaks of tan δ values, as well as the tan δ values in the plateaus above $T_g$, illuminate data about the cross-link densities and molecular weight of the polymeric materials. As molecular weights or cross-link densities increase, the tan δ values above $T_g$ tend to decrease (Murayama 1978). In Figure 51, at 20 °C, we see a demonstrable decrease in tan δ values for the 25%, 33% and 50% MG rubber samples when compared to the *C. elastica* latex sample. This suggests that at these concentrations processing latex
with the juice of *I. alba* either increases the molecular weight or cross-link density of the polymer component in *C. elastica* latex.

**Figure 51: Tan Delta vs. MG% at 20 °C**

The peaks in the tan δ data also reflect changes in cross-linking and molecular weight. With increases in molecular weight or cross-linking, the peaks of the tan δ will shift to higher temperatures (Murayama 1978). Average Tan δ peak data are presented in Figure 52.
Here we see very little difference, with standard deviations, between the Tan δ peaks for the *C. elastica* latex and the *C. elastica* rubber samples processed with morning glory juice. However, the *H. brasiliensis* latex has a statistically-valid lower tan δ peak than any of the samples made with *C. elastica*. Though both species of latex contain primarily cis-1,4-polyisoprene as their polymer component, these data may suggest that *C. elastica* latex has a higher molecular weight than *H. brasiliensis* latex, as was suggested by the E'' data. *C. elastica* also has a greater ratio of trans-to-cis isomers than *H. brasiliensis*, which could create a greater amount of crystallinity in *C. elastica* and raise the tan δ peak values.
Chapter 10: Stress-Strain Data: Tensile Testing

I performed stress-strain analyses in tension on *C. elastica* rubber and latex and on *H. brasiliensis* latex. This work was carried out on 25 mm tensile specimens prepared according to Chapter 8.1, using a Texture Analyzer XT tensile testing device equipped with a 5 kg load cell and Texture Exponent 32 software. The Texture Analyzer XT is an “Instron”-style machine; it measures a material’s mechanical response to strain at a constant rate. This mechanical response is the stress. All samples were tested at a strain rate of 0.5 mm/s. The raw data collected via the Texture Analyzer are presented in Figure 53.

It should be noted that Figure 53 displays the average *engineering* stress-strain curves for at least 5 iterations of each latex and rubber sample tested. *Engineering* stress-strain curves display stress as calculated using the initial cross-sectional area of the tensile specimen, rather than the cross-sectional area as a function of strain as in a *true* stress-strain diagram. These data clearly demonstrate a difference in behavior between unprocessed *C. elastica* latex and the *C. elastica*-I. *alba* rubber samples. Over the entire range of strain values, *C. elastica* latex exhibits significantly higher stresses than the *I. alba*-processed rubbers, again illustrating that the unprocessed latex is significantly stiffer than its rubber counterparts. These data also reiterate that the performance of *H. brasiliensis* is similar to that of the *C. elastica* rubber samples.
Materials generally exhibit linear stress-strain behavior at low strains, obeying Hooke's Law. Rubber maintains its linear behavior at much higher strains than most materials, but will still depart permanently from Hookean behavior after a certain degree of elongation. Rubber is able to recover fully and instantly from strains below this point of deviation from linearity. Strains greater than this point will cause irrecoverable
deformation in the material. In these experiments, the departure from Hookean behavior occurred at 5 or 6% strain for every sample.

In Figure 53, every stress-strain curve has a positive second derivative at high strains; the slopes of the curves increase as strain increases. This is evidence of two related phenomena: strain hardening or strain-induced crystallization. This is clearly the case in the behavior of the *H. brasiliensis* and *C. elastica* latexes, though lesser so in the *I. alba*-processed rubbers. At strains above the threshold of permanent deformation, polymer chains tend to line up in parallel with the strain. This increase in anisotropy increases the force needed to deform the material in the direction of strain, and thus increases the resulting stress. This effect is known as strain hardening. Strain-induced crystallization often occurs in latex and rubber when the molecular alignment encouraged by strain causes the newly anisotropic domains to crystallize (Ward and Hadley 1993).

It is evident in Figure 53 that the *C. elastica* rubbers are less prone to strain hardening and crystallization than *C. elastica* latex. This suggests that *I. alba* adds plasticizing molecules to the latex which deter molecular re-alignment and prevent crystallization. Such a resistance to crystallization may explain the lower values of stiffness for the *C. elastica* rubber samples as seen across all categories of data. The absence of crystallinity will result in lower moduli in rubber and latex.

The factor relating the stress to the strain in the domain of Hookean behavior is the initial slope of the stress-strain curve, known as the elastic modulus or Young’s modulus. The Young’s modulus values for the latex and rubber samples are plotted in Figure 54.
Figure 54: Initial Modulus versus MG%

Figure 54 illustrates that processing *C. elastica* latex with *I. alba* juice lowers the Young’s modulus of the material. This confirms the data collected with DMA, showing a unilateral reduction in modulus upon the addition of morning glory juice. According to the Texture Analyzer data, the *C. elastica* latex has a Young’s modulus of approximately 0.05 MPa, while the *I. alba*-processed rubber samples have moduli ranging between 0.015 MPa and 0.03 MPa. These values seem extremely low for Young’s moduli, but this is due to the fact that the rate of strain is extremely low at 0.5 mm/s. At slow strain rates, the polymer chains have more time to uncoil conformationally and slip translationally, giving the appearance of a softer material. Although these values are low...
on the absolute scale, they are valuable for comparing the properties of rubber and latex to each other.

The Texture Analyzer is able to differentiate the moduli of the *I. alba*-processed rubbers. Figure 54 shows that 50% MG is the stiffest of the rubber samples with a modulus of approximately 0.03 MPa. Although the rest of the samples have varying average Young’s moduli values, their standard deviations overlap. This renders the variation in moduli statistically insignificant.

Unprocessed *C. elastica* latex is too brittle and stiff to function when made into a rubber ball. These data for Young’s modulus, which is a measure of elasticity, demonstrate that 50% MG is appreciably more elastic than the rest of the rubber samples, which as a whole are tough enough for employment in balls. This suggests that a 1 to 1 ratio of *I. alba* juice to *C. elastica* latex would be the ideal mixture for the production of rubber balls, as it maximizes elasticity. Any other tested ratio of mixing produces a less elastic rubber that would be inferior for use in a ball.

Tensile testing data can be used to determine the average extension-to-break ratios of materials. Small voids and imperfections in specimens can cause large errors in this type of analysis due to premature breakage. Accordingly, 5 samples of each latex and processed rubber were tested in order to average out any anomalies. Extension-to-break ratios provide insight into the network structure of the polymers being studied. Polymer chains in non-crosslinked materials will slide past each other when subjected to a force, and will achieve very high strains before breaking. Physical or chemical cross-links prevent polymer chains from sliding past each other when subjected to a force, and they tend to break under much lower strains. Along with increased cross-linking, tendencies to strain harden or strain crystallize could result in a resistance to deformation and a trend to
rupture at lower strains. The extension-to-break data for these stress-strain experiments are presented in Figure 55.

**Figure 55: Extension-to-Break Data**

This figure shows that the *C. elastica* rubber samples have extension-to-break ratios similar to the *C. elastica* latex. Only 25% and 33% MG are significantly different from the rest of the *C. elastica* latex or rubber samples, with average breaking points at approximately 500% strain. This is a 100% increase in strain from the next closest sample, suggesting that 25% or 33% MG rubbers are less cross-linked or less likely to crystallize or strain harden. *H. brasiliensis* is able to deform considerably more than any *C. elastica*-based material, as it reaches an average strain of almost 800% before...
breaking. *H. brasiliensis* latex has a higher ratio of *cis*-polyisoprene to *trans*-polyisoprene than *C. elastica* latex, which makes it less likely to crystallize. This could account for the difference between the extension-to-break data for the *H. brasiliensis* latex and the *C. elastica* latex and rubbers.
Chapter 11: Creep

Creep is the study of strain caused by a constant stress as a function of time. Creep is vital in understanding the performance of a material under sustained loads and provides a wealth of information about the structure of materials, particularly in the case of polymers. Creep experiments offer insight into the ability of latex and rubber to function as a sandal sole. They provide more data on the differences between the two species of latex and the samples produced by processing with I. alba.

11.1: Experimental Setup

I built a customized test stand to conduct these experiments. The apparatus can be seen in Figure 56.

![Figure 56: Creep Testing Apparatus](image)

I fabricated this test stand using a piece of plywood that had graph paper with $\frac{1}{4}$-inch increments applied to one surface. I drilled holes through the board, and secured 5-inch
bolts through the holes with nuts and washers. The bolts served as the suspension points for the creep specimens.

The specimens were held using a combination of small binder clips, pennies and cyanoacrylate glue as shown in Figure 57.

![Figure 57: Creep Testing Clamps](image)

To clamp the rubber and latex, I used cyanoacrylate glue to cement each end of the sample between two pennies, with the “tails” sides touching the specimen. This prevented the samples from slipping out of the grips. I found that the “tails” side held the samples better than the “heads,” as the Lincoln Monument provided a rough surface that mechanically keyed the glue, helping to attach it to the samples. I then used the glue to bond each set of pennies into the binder clips, pushing the pennies as deep into the clips as possible. After each experiment, I peeled the samples from the pennies and reused the entire clamping system.

With the sample glued into the clamps, I attached a sand bag to one binder clip with fishing line. The weights of these bags were adjusted to equal 0.5 MPa for each specimen, depending on its cross-sectional area. I then slid the un-weighted binder clip onto the bolt attached to the board. Care was taken during this time not to load the
specimen. With the binder clip on the bolt and the clamps and sample stabilized, I quickly released the sandbag, beginning the period of constant stress.

The strain as a function of time was recorded with a digital camera, set to take photographs every second. The graph paper on the testing board allowed for measurements of the strain, while the time-incremented digital photos gave a measurement of time. The camera was placed far enough away from the board in order to prevent perspective from altering the strain measurements. I also tested only 1 or 2 samples at a time in order to avoid camera perspective issues in the horizontal plane. After the test, I examined the photos, recording the times at which the samples strained to each ¼ inch line on the backing graph paper. This eliminated the need to guess approximate strains when the sample was between lines on the paper. With these data I was able to plot “creep compliance” -- strain as a function of time divided by stress -- versus log time, in seconds (see Figure 58).

11.2 Experimental Results

Creep compliance (variable $J$) is the strain as a function of time over the stress:

$$J = \frac{\varepsilon(t)}{\sigma}.$$ Creep data were collected for 3 to 4 iterations for each latex and rubber sample. All of the experiments were conducted in a temperature-controlled room kept at approximately 21° C. Creep is generally quite sensitive to temperature, but in polyisoprene creep does not appreciably change within +/− 5 ° C (Nielsen 1974). These experiments were conducted within a range of 1 to 2° C. The average data for creep are illustrated in Figure 58.
These data present clear differences in the creep behavior of *C. elastica* latex, the *C. elastica* rubber samples, and *H. brasiliensis* latex. The *C. elastica* latex is the most notably different from the other samples. When subjected to the default stress of 0.5 MPa, the *C. elastica* does not behave like a typical rubber; it does not undergo an instant, reversible deformation. Up until 2 minutes at 0.5 MPa stress, the latex shows no appreciable strain. From 120 seconds until the rupture point, the *C. elastica* latex sample
behaves similarly to the rubber samples, in terms of both the values and rates of $J$. This material did have the longest average time to rupture, at 33.5 hours (+/- 3.9 hours)

The *C. elastica* rubber samples (25% MG to 70% MG) behave more like an ideal rubber. An ideal rubber, much like a spring, will strain at a constant value until the load is removed. All of the rubber samples behaved in this manner, and with relatively close rates of creep, taking into account the standard deviations and the resolution of the testing apparatus. However, 25% MG does stand out in that it has the lowest values and rate of $J$ among the rubber samples, as well as one of the longer average time-to-rupture values for the *I. alba*-processed specimens. Unlike the *C. elastica* latex, all of the rubbers, along with the *H. brasiliensis* latex, have very low average times to rupture, as seen in Table 2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Avg. Rupture Time (min)</th>
<th>Error (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>C. elastica</em></td>
<td>2583</td>
<td>411</td>
</tr>
<tr>
<td>25% MG</td>
<td>59.3</td>
<td>6.6</td>
</tr>
<tr>
<td>33% MG</td>
<td>14.4</td>
<td>3</td>
</tr>
<tr>
<td>40% MG</td>
<td>68.1</td>
<td>8.4</td>
</tr>
<tr>
<td>50% MG</td>
<td>7.8</td>
<td>3.2</td>
</tr>
<tr>
<td>70% MG</td>
<td>2.2</td>
<td>.8</td>
</tr>
<tr>
<td><em>Hevea</em></td>
<td>169.7</td>
<td>21.1</td>
</tr>
</tbody>
</table>

*Table 2: Average Rupture Times*

These changes in average rupture time, in conjunction with the distinction of creep rates and values between *C. elastica* latex and the *I. alba*-processed rubber, are clear indicators of changes in the polymer structure induced by the addition of *I. alba*.

The creep data on the *H. brasiliensis* latex also portray a material with substantial differences from its fellow polyisoprene-based *C. elastica* latex. There are many factors that can alter creep values, creep rate, and average rupture time. These may include cross-
linking, molecular weight, percentage of crystallinity, and entanglements due to branching and dangling chain ends (Ward and Hadley 1993; Nielsen 1974). In general, cross-linking and crystallization (Nielsen 1974), and likely the physical cross-links caused by increased molecular weight and branching, affect creep as demonstrated in to Figure 59.

**Figure 59: Creep in SBR Rubber: the Effects of Cross-links and Crystallinity**

![Graph showing creep in SBR rubber](image)

from Nielsen 1974

Figure 59 displays the creep in SBR rubbers with varying degrees of cross-links. "A" is not cross-linked; samples B, C, D, and E, in that order, increase in their level of cross-linking. As is clearly illustrated in this figure, both the value of percent elongation (which translates to the value of $J$), and the rate of elongation (which is equivalent to the rate of $J(t)$), substantially decrease as cross-linking increases. The cross-links allow the material to resist deformation, and thus creep less with time. This graph can also be used to explain the effects of crystallinity on creep. Just as the cross-linking demonstration, "A"
would have the lowest percentage of crystallinity with “E” having the highest degree of crystallinity.

Since *H. brasiliensis* and *C. elastica* are different species, it is highly likely that these trees produce polyisoprene molecules of differing molecular weights, propensities to crystallize, and abilities to cross-link under ambient conditions. As previously mentioned, *C. elastica* does have a higher percentage of the trans-isomer of polyisoprene, which is more likely to crystallize and produce a stiffer material. This is reflected in the creep data, as *C. elastica* behaves as a rigid material.

It is clear from the creep data that *H. brasiliensis* latex has a considerably lower amount of cross-linking or crystalline domains than *C. elastica* latex. Processing *C. elastica* with *I. alba* produces a rubber whose behavior falls between that of the two latex species. Thus, *I. alba* likely prevents crystallization that occurs in unprocessed *C. elastica* latex, or prevents cross-links that may occur naturally in this material while it is drying.

These data identify *C. elastica* latex and 25% MG rubber as being superior, in terms of creep, for use in sandals. These two materials resist deformation at short time spans, and strain the least out of all samples when subjected to long instances of stress. This resistance to deformation is vital in sandals, as soles undergo long exposures to constant strains. *C. elastica* latex may not be advantageous for use in soles because of its tendency to crack when bent repeatedly, an occurrence that would be common during walking or running. The *C. elastica* rubbers do not crack when bent, suggesting that 25% MG may be the ideal material for sandals. Wear experiments confirm this suggestion.
Chapter 12: Wear Experiments

Wear resistance is one of the most important qualities a material must possess to function as a sole for footwear. This is especially the case for ancient Mesoamerican sandals, where a sheet of rubber or latex as a sole comprised the entirety of a sandal, along with the sandal straps. The sole would be responsible for bearing all of the forces exerted on the sandal, without support from leather uppers or insoles as in modern footwear. Fatigue is also a factor in footwear soles. Repeated bending while striding will eventually crack a brittle material.

I conducted sliding abrasive wear experiments on *C. elastica* latex and rubber samples using a custom-built apparatus. The entire wear testing assemblage included a dowel, a sled, weights, and sandpaper. The sled used for sliding the rubber and latex over the sandpaper is displayed in Figure 60.
The pink sled seen in Figure 60 was first designed as a three-dimensional computer model using the program Solidworks, then "printed" using a 3D-printer courtesy of Z Corporation in Burlington, Massachusetts. The printed part is made primarily of plaster, reinforced with cyanoacrylate resin for strength.

The wooden dowel in Figure 60 functions as a "sample holder." The disc-shaped samples (approximately 4 mm thick, 25 mm in diameter) were glued onto the dowel with cyanoacrylate before testing. Weights attached to the top of the dowel put a 0.3 MPa downward stress on the rubber and latex discs. The dowel is free to move vertically within the center hole of the sled. As the rubber disc wears, the dowel is free to move down and continue wearing the specimen.

While conducting the wear experiments, I slid this entire assemblage – the sled holding the weighted dowel and rubber disc – along a track of 11 inches of 240-grit SiC sandpaper. I slid the track both forwards and backwards over the sandpaper in order to keep the wear even on the leading and trailing edges of the rubber discs. Each "slide," or "stroke," forward or backwards was counted as 1 stroke. Every 150 strokes the sandpaper was changed, to prevent clogging of the paper and to maintain a standard abrasive environment throughout all experiments. I measured the height of the rubber discs with calipers every 50 strokes. Four iterations of each sample were tested and averaged to give the most accurate picture possible of the relative wear performance of the tested materials. I plotted these data as "Average Rubber Loss versus Strokes," as seen in Figure 61.
The most striking attribute in Figure 61 is the difference between the wear behavior of 25% MG compared to the other samples. The 25% MG wears at a lower rate than most of the other rubber, except for the unprocessed latex and 33% MG. The *Castilla elastica* latex wears quickly at first, but the wear rate levels off around 100 strokes and progresses slowly after this point. 33% MG wears very little until approximately 200 strokes, where it begins to wear more rapidly until ultimately it breaks down. In addition to a low wear rate, 25% MG has a substantially longer average wear lifetime compared to the latex and *I. alba*-processed rubbers, as seen in Figure 62. This longer wear lifetime, coupled with
the low rate of wear, makes 25% MG the ideal C. elastica rubber for employment in rubber-soled sandals.

Figure 62: Average Wear Lifetimes versus MG %

Abrasive wear in rubber is thought to occur via two different mechanisms: tearing and smearing. Wear via tearing is a function of tensile strength and fatigue properties of the rubber (Schallamach 1968). Smearing is governed by oxidation and molecular decomposition into a low molecular weight material (Gent and Pulford 1983).

Wear via tearing occurs due to the growth of cracks under repetitive loading, similar to tensile fatigue. In each sample tested in these experiments, the materials would wear for a certain length of time, and ultimately fail through a tear that had propagated through the material. The strokes-to-failure points are averaged in Figure 62.
In the tearing process, small 1-5 \( \mu \text{m} \) particles break away from the material being worn. Over time, these micron-scale particles coagulate into larger 100 \( \mu \text{m} \) “ridges” of abraded material. After repeated wear of these surfaces the larger ridges break away from the bulk material. The cumulative effect of the frictional wearing force coupled with repeated loading slowly creates cracks in the material, which ultimately lead to catastrophic failure (Gent 1989).

Smearing is the result of macromolecules rupturing under friction and decomposing into low molecular weight materials (Gent and Pulford 1983). The oily, low molecular weight residue can slowly wear away and break from the bulk material, or remain on the surface and act as a protectant and lubricant, effectively limiting overall wear (Schallamach 1968).

In natural rubber, wear is often dominated by fracture or tearing (Gent and Pulford 1983). However, in the experiments reported here, I saw evidence of both categories of wear. The \textit{C. elastica} latex, 25\% MG and 33\% MG samples all exhibited smearing behavior, while the wear occurring in the rest of the samples was solely controlled by tearing. In the case of the smearing samples, the residue left by the wearing process did seem to function as a lubricant, as these samples had the lowest rates of wear among the materials tested. However, the samples that smeared ultimately failed through tearing. The samples that wore the fastest, such as 60\% MG and 70\% MG, did not show any evidence of smearing. The cast-off material from these samples was dry and powdery, and would be unlikely to provide any relief from abrasive wear.

Abrasive wear through tearing decreases as tensile strength increases (Schallamach 1968). This is reflected in the data for the \textit{C. elastica} latex. The latex had a very low rate of wear, and possesses a tensile strength several times greater than that of
the *I. alba*-processed rubbers. Likewise, materials that have poor fatigue resistance will be more prone to wear and catastrophic failure through tearing. This means that 25% MG has the best wear properties as well as the best fatigue resistance. This material would be the most suited for use in sandal soles.
Chapter 13: Dynastat

13.1 Dynastat Setup

The Dynastat is an analytical device that measures the tensile or compressive properties of materials versus frequency of strain oscillation. I performed Dynastat experiments in tensile mode, using the 25 mm tensile specimens described in Chapter 8.1. Four to five samples were tested for each species of latex and each MG% rubber. This work was conducted in Prof. Alan Grodzinsky’s lab at MIT with the help of Dr. Eliot Frank. With Dr. Frank’s assistance I developed the following Dynastat protocol to test and compare the properties of the latex and rubber:

1. ramp to a 5% strain (1.25 mm for 25 mm sample length)
2. oscillate the strain +/- 1% at 0.02, 0.05, 0.01, 0.1, 0.5, 1, 2, and 5 Hz.
3. ramp to 10% strain (2.5 mm for 25 mm sample) and hold for 1 hour for relaxation
4. repeat step 2 after the relaxation

13.2: Dynastat Stiffness Data

I collected stiffness data using this protocol. This procedure allowed me to generate a picture of the behavior of the latex and rubber through a wide range of strain frequencies before and after a 1-hour relaxation time. Figure 63 illustrates the stiffness of the latex and rubber samples over a range of frequencies.
Figure 63: Dynastat Stiffness Data

![Graph showing Dynastat Stiffness Data with Morning Glory % on the x-axis and MPa on the y-axis.](image-url)
In Figure 63, the different colors signify the frequencies of oscillation of the strain, while the different rubber samples are graphed according to the percentage of *I. alba* they contain. The data for *H. brasiliensis* is the left most series of points on the X-axis.

Clearly, the latex is much stiffer at all frequencies than all of the MG% rubber samples and the *H. brasiliensis* latex. This corroborates the data produced by DMA and traditional stress-strain tensile testing. Differences in the values of stiffness for the *I. alba*-processed rubber samples can be seen when the resolution of the Dynastat data is increased. These data are graphed in Figure 64.

Since the error values for the Dynastat data are so low, definite trends can be seen in the stiffness values over the range of *I. alba* processing. At every frequency, 50% MG is the stiffest, followed by 70% MG. 33% MG is the softest *I. alba*-processed rubber, with 40% MG and 60% MG registering stiffness values between those of 33% and 70% MG. The fact that 50% MG is the stiffest, and thus most elastic, among the morning glory-processed samples in the Dynastat data confirms the findings of the stress-strain data. 50% MG would be the material best suited in ancient Mesoamerica for use in rubber balls.
The stiffness values within each type of rubber or latex are inversely proportional to the frequency of strain oscillation. As the frequency increases, the stiffness values decrease. For the most part, the drop in stiffness as frequency increases is not steep, until
5 Hz. Between 2 and 5 Hz, the stiffness for every sample drops sharply. Table 3 illustrates the percentage of decrease in stiffness between 0.2 Hz and 5 Hz, both pre- and post-relaxation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pre-relax</th>
<th>Post-relax</th>
</tr>
</thead>
<tbody>
<tr>
<td>H. brasiliensis</td>
<td>43%</td>
<td>43%</td>
</tr>
<tr>
<td>C. elastica</td>
<td>39%</td>
<td>39%</td>
</tr>
<tr>
<td>33% MG</td>
<td>32%</td>
<td>31%</td>
</tr>
<tr>
<td>40% MG</td>
<td>29%</td>
<td>29%</td>
</tr>
<tr>
<td>50% MG</td>
<td>44%</td>
<td>48%</td>
</tr>
<tr>
<td>60% MG</td>
<td>42%</td>
<td>43%</td>
</tr>
<tr>
<td>70% MG</td>
<td>29%</td>
<td>28%</td>
</tr>
</tbody>
</table>

Table 3: Decrease in Stiffness Between 0.2 Hz to 5 Hz

This table illustrates that each of the samples exhibits a similar drop-off in stiffness, regardless of the processing used to produce the materials. 33% MG, 50% MG, and 70% MG lose only 32%, 29% and 29% of their stiffness, respectively, when comparing the decrease experienced between 0.2 Hz and 5 Hz. The rest of the samples do not perform as well; their stiffness values decrease in the high 30 to 40 percentiles. The 1-hour relaxation time does not affect the percentage decrease in stiffness values of the rubber and latex between 0.2 and 5 Hz, as the percentages of decrease do not change. The 1-hour relaxation time also has little effect on the stiffness of each sample at the same frequency, as seen in Table 4.

<table>
<thead>
<tr>
<th>Sample</th>
<th>0.2 Hz</th>
<th>5 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>H. brasiliensis</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>C. elastica</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>33% MG</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>40% MG</td>
<td>2%</td>
<td>3%</td>
</tr>
<tr>
<td>50% MG</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td>60% MG</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>70% MG</td>
<td>2%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 4: Decrease in Stiffness after 1-Hour Relaxation
Table 4 shows almost negligible decreases in stiffness, at 0.2 Hz and 5 Hz, after the 1-hour relaxation at 10% strain. These percentages are small and within the standard deviation of the stiffness data before relaxation. Therefore, the 1-hour relaxation did not significantly affect the mechanical properties of the rubber and latex. At a 10% strain, this is to be expected for natural rubbers, since rubber should not relax or plastically deform at such a low strain.
Chapter 14: Conclusions

The goal of Part II of this thesis is to identify the full range of mechanical properties that would have been available to ancient Mesoamericans through manipulation of their rubber-making procedures. The differences in the mechanical behaviors of the *C. elastica* rubbers determined by this study offer the possibility that ancient Mesoamericans were aware of the varying effects achieved by processing *C. elastica* latex with different concentrations of morning glory vine juice, and that they used this knowledge to process rubber selectively for specific applications. Part II is also intended to quantify the properties of *H. brasiliensis* latex, gaining insight into the quality of natural latex available to ancient South American peoples and how that material compares to *C. elastica* latex and rubber. These objectives were met through a battery of mechanical analyses, including Dynamic Mechanical Analyses (DMA), stress-strain tensile tests, Dynastat (stiffness) experiments, creep tests, and wear analyses. I will summarize these data in terms of their significance to the three ancient Mesoamerican applications of rubber that are the focal point of this thesis: rubber balls, sandal soles, and hafting bands.

Rubber Balls

The data presented in Part II illustrate that processing *C. elastica* latex with *I. alba* is necessary for making a material suitable for use in rubber balls. Specifically, a mixture of 50% *I. alba* juice and 50% *C. elastica* latex produces what would have been the best rubber available for ball making in ancient Mesoamerica.

The data from DMA, stress-strain analyses and the Dynastat show that the *C. elastica* latex is approximately four times stiffer than the *C. elastica* rubber samples.
High stiffness alone does not eliminate *C. elastica* latex as a material suitable for balls. *C. elastica*'s other deficiencies eliminate it from utilization as a ball-making material. Creep data illustrate that *C. elastica* latex is highly rigid and brittle and does not behave in a manner that could be considered “rubbery.” These data show that the latex takes 120 seconds to respond to 0.3 MPa stress, a trait hardly desirable in a rubber ball. The rubber samples made with a combination of *C. elastica* and *I. alba*, as well as the *H. brasiliensis* latex, respond with an instantaneous linear deformation when subjected to stress. The processing of *C. elastica* latex with the juice of *I. alba* results in a rubber that is tougher and more elastic than the unprocessed latex.

The Dynastat and stress-strain data provide independent lines of evidence confirming that a mixture of 50% *I. alba* juice and 50% *C. elastica* latex produces a rubber that would have been ideal for ancient Mesoamerican balls. Both of these analytical techniques measure stiffness, which can correlate with elasticity in rubbery materials. The Dynastat data show that at 0.2 Hz, 50% MG has a stiffness of 3.3 MPa, whereas rubber samples made with other mixtures have moduli of 2.0 to 2.9 MPa. This marks an increase in elasticity of between 14% and 65% for the 50/50 mixture of *C. elastica* and *I. alba* compared to the other mixtures. The stress-strain data show a similar trend, as the initial modulus of the 50% MG rubber is 60% to 150% greater than the moduli of the other *I. alba*-processed rubbers.

**Hafting Bands**

The archaeological evidence presented in Part I reveals that ancient Mesoamericans utilized *C. elastica*-based materials to haft handles to blades in tools used for cutting or splitting. In this application, the rubber requires a different set of
mechanical properties for adequate performance than those that are optimal for a bouncing ball. Here, elasticity is not prized, but rather strength and damping ability. In the case of materials selection in ancient Mesoamerica, the data point to unprocessed *C. elastica* latex as the most likely candidate for the production of hafting bands.

The DMA data, Dynastat, and stress-strain analyses all corroborate the superior stiffness of *C. elastica* latex compared to its rubber counterparts. Whereas this degree of stiffness corresponds to an undesirably low level of elasticity for a rubber ball, the high strength it imparts is ideal in the case of hafting. The DMA data also illustrate that *C. elastica* latex has the greatest damping ability of all the latex and rubber samples. DMA measures $E''$, a quantification of the amount of energy dissipated as heat when a material is deformed. DMA shows that the highest average $E''$ value among the *I. alba*-processed rubbers is 0.35 MPa, while *C. elastica* latex has an average $E''$ value of 1.35 MPa. This demonstrates a dramatic increase in damping ability.

I have described the *C. elastica* latex as rigid and brittle, and this is cause for concern in any stress-intensive application. However, the main failure mode for *C. elastica* latex is in bending, as repeated cycles of bending quickly cause crack propagation in the material. For a hafting band, freshly dried, still-pliable latex could be applied to hold a blade and handle firmly together without initiation of cracks. Since the latex does not undergo bending in this application, it could likely function as a hafting band.

**Sandal Soles**

Ethnohistoric and archaeological evidence presented in Part I provide evidence of rubber having been employed as sandal soles in ancient Mesoamerica. Sandal soles require a completely different set of rubber properties from balls and tool hafting bands.
In this application, wear and fatigue resistance are of the utmost importance. These properties govern the kinetic performance of sandal soles as the wearer moves, but resistivity to creep is vital in static sandal applications such as standing for extended periods of time.

The data in Part II show that both 25% MG and *C. elastica* latex have the lowest wear rates, the highest times-to-failure due to wear, and the best resistance to creep. However, the propensity of *C. elastica* latex to undergo brittle failure in the bending mode effectively eliminates this material from use in sandal soles. As the human stride is largely dependent on a bending action between the foot and toes, the 25% MG mixture would have been the best material available to ancient Mesoamericans for use in sandal soles. Rubber produced with 25% *I. alba* and 75% *C. elastica* latex by volume has a substantially longer wear life than any other rubber or latex sample tested. The 25% MG rubber failed at an average of 2200 strokes. The next closest material in terms of wear lifetime was the *C. elastica* latex, at 1200 strokes. This marks a reduction of approximately 100% in sandal lifetime due to wear. Since wear in rubber is correlated with fatigue (Schallamach 1968), and as 25% MG is among the better performers in terms of creep, the data show unequivocally that 25% MG would have been the best suited material for sandal soles in ancient Mesoamerica.

*Hevea brasiliensis* and South America

This thesis attempts to address the use and processing of latex and rubber among indigenous South American peoples. The data disclosed in Part I show that South American peoples used latex in ball making, medical devices, and as a body paint. I found no description of processing in any source that addresses the use of latex in South
America. The mechanical data presented in Part II of this thesis may explain the absence of a latex-processing technology among indigenous South American peoples.

In Mesoamerica, the primary source of latex -- *C. elastica* -- is an inelastic, brittle material in its natural state. Rubber workers among ancient Mesoamerican peoples circumvented this deficiency in the raw material available to developing the *I. alba*-*C. elastica* rubber-making process and refining this technology to suit their needs. The latex available to them necessitated the invention of a processing regime to impart and enhance elasticity in natural latex.

In South America, no such processing technology was needed. The dried latex tapped directly from the *H. brasiliensis* tree is comparable in all mechanical properties I have measured to *C. elastica* rubber, as illustrated by the DMA, stress-strain, Dynastat and creep data presented here. There was no impetus in South America to improve the properties of the available latex. Dried, unprocessed *H. brasiliensis* already has the properties that enable it to function when made into small rubber balls, the main application of latex in ancient South America.

The mechanical data presented in this thesis demonstrate that ancient Mesoamericans developed a technology that could have allowed them to produce rubber and latex with properties optimized for specific applications. These experimental data are supported by Mesoamerican archaeological and documentary evidence, which present at least three Mesoamerican uses of rubber requiring markedly different mechanical properties: balls, hafting bands and sandal soles. Ethnohistoric documents from 16th century codices reveal that *Castilla elastica* was being shipped in both its raw and
processed state within the Aztec tribute system. Items that required processing with *I. alba*, such as rubber balls, were shipped directly from the latex-producing regions in their finished form. These items were processed with *I. alba* and shaped to specified designs on-site. Latex, which was used extensively in ritual activities and in many other applications that did not require mechanical enhancement, was simply dried and shipped as cakes.

The combination of these three data sets -- mechanical analyses of raw and processed materials, archaeological and documentary evidence of Mesoamerican uses of latex and rubber, and ethnohistoric evidence from codices about the shipment of *C. elastica* in latex and rubber form -- offers the possibility that ancient Mesoamericans had developed the *C. elastica- I. alba* processing regime sufficiently to produce rubber and latex with mechanical properties tailored to specific applications.
REFERENCES CITED

Altamirano, F. and Rose (no first name given)
1905 *El Palo Amarillo*. Imprenta y Fototipia de la Secretaria de Fomento, Mexico

Anghiera, Pietro Martire d’
1966 *Opus Epistolarum*. Akademische Druck- u, Verlagsanstalt, Austria.

Benavente, Toribio de
1984 *Historia de los Indios de La Nueva Espana*. Editorial Porrua, Mexico.

Berdan, Frances F. and Patricia Rieff Anawalt

Berdan, Frances F. and J. De Durand-Forest (Editors)
1980 *Matricula de Tributos (Codice de Moctezuma)*. Akademische Druck-u Verlagsanstalt, Austria.

Blanton, Richard, Stephen A. Kowalewski, Gary M. Feinman and Laura M. Finsten

Casas, Bartolomé de las

Cline, H.F. (ed.)

Coggins, Clemency Chase, and John Ladd.

Conzemius, Eduard

Eder, Francisco Javier
1985 *Breve Descripcion de las Reducciones de Mojos ca. 1772*. Historia Boliviana, Cochabamba.

Gates, W.
Gent, A.N.

Gent, A.N. and C.T.R. Pulford

Gomez, Manuel


Hill, Warren D., Michael Blake and John E. Clark

Hofer, Abram and and H. Osmond

Hofmann, Albert
1964 *Psychedelic Review*, 3, 234.

Hosler, Dorothy, Sandra L. Burkett and Michael J Tarkanian

Leyenaar, Ted J.J.
1978 *Ulama: The Perpetuation in Mexico of the Pre-Spanish Ball Game Ullamaliztli*. E.J. Brill, Leiden, Netherlands.

Lloyd, Francis Ernest
1911 *Guayule*. Carnegie Institution of Washington, Washington, DC.

Lowe, S.K. and M. Ries

Mártir, Pedro de Angleria

Métraux, A.

Morse, Birgit Faber
1990 The Precolumbian Ball and Dance Court at Salt River, St. Croix, *Folk*, 32, 45.
Murayama, Takayuki

Nielsen, Lawrence E.

Nimuendajú, Curt
1939 The Apinaye. The Catholic University of America Press, Washington, D.C.

Olsen, Fred
1973 The Arawak Ball Court at Antigua and The Prototype Zemi. From Fifth International Congress for the Study of Pre-Columbian Cultures of the Lesser Antilles. Antigua Archaelogical Society.

Olsson-Seffer, Pehr
1907 Rubber Planting in Mexico and Central America. Kelly & Walsh Limited Printers, Singapore.


Oviedo, Gonzalo Fernandez de

Pasztory, Esther, ed.

Pittier, Henry

Pozorski, Thomas and Sheila Pozorski
1995 An I-Shaped Ball-court Form at Pampa de Las Llamas-Moxeke, Peru. Latin American Antiquity, 6, 274.

Rand McNally & Co.

Rodriguez, Maria del Carmen and Ponciano Ortiz

Rogers, David J. and S.G. Appan
de Rojas, Jose Luis (editor)
1997 Información de 1554: sobre los tributos que los indos pagaban a Moctezuma. Centro de Investigaciones y Estudios, Mexico City.

Roys, Ralph L.
1976 The Ethno-Botany of the Maya, Institute for the Study of Human Issues, Philadelphia, PA.

Sahagún, B., A.J.O Anderson (trans.) and C.E. Dibble (trans)
1970 The Florentine Codex. The School Of American Research and The University of Utah, Santa Fe.

Schallamach, A.

Schele, Linda and M.E. Miller

Standley, Paul C.

1942 Masterkey 15(4), 123.

Stern, Theodore

Stone, A.J.

Taladoire, Eric.

Tarkanian, Michael J.

Tarkanian, Michael J. and Dorothy Hosler
Treloar, L.R.G.  

van Ooststroom, S.J.  
1940 *Blumea*, 3, 547.

Ward, I.M. and D.W. Hadley  

Wildman, S.G., A. V. McMullan, R. Griggs  
1943 Isolation of an Active Substance from *Calonyction aculeatum* Capable of Coagulating *Castilla* Latex. *Science*, 97, 47.

Williams, Llewelyn  