AMERICA'S FIRST POLYMER SCIENTISTS: RUBBER PROCESSING, USE AND TRANSPORT IN MESOAMERICA

Michael J. Tarkanian and Dorothy Hosler

Ancient Mesoamericans were making rubber by at least 1600 B.C, mixing latex from Castilla elastica *trees with juice from* Ipomoea alba *(morning glory) vines. The combination of ethnographic, archaeological and mechanical data presented in this text illustrate that ancient Mesoamericans had fully developed this process, and consciously tailored the mechanical properties of rubber to suit requirements of specific applications by altering the ratio of latex to* I. alba *juice. Our data focus on rubber balls, sandal soles, and rubber bands for hafting and joining. Elasticity, the mechanical property that defines the ability of a rubber ball to bounce, is maximized with a 1:1 volume ratio of latex to* I. alba *juice. Rubber with high wear resistance, vital to the life and functionality of a sandal sole, can be created by mixing* C. elastica *latex with 25 percent* I. alba *juice by volume. Unprocessed* C. elastica *latex, without* I. alba *juice, is the material best suited for joining applications, such as adhesives or hafting bands, where strength and ability to absorb shock is of the greatest importance. Tribute data from sixteenth-century codices substantiate that rubber was processed for specific applications within the Aztec empire—rubber and latex goods were processed and constructed in the* C. elastica*-bearing regions, and then shipped to the capital for use or further distribution.*

Los antiguos pobladores de Mesoamérica procesaban el hule desde por lo menos 1600 a.C., mezclando el látex del árbol Castilla elastica *con el jugo obtenido de los bejucos de* Ipomoea alba*, una especie de dondiego de día. La combinación de los datos etnográficos, arqueológicos y físicos que se presentan en este texto muestra que los mesoamericanos descubrieron el amplio rango de propiedades mecánicas que se pueden obtener al combinar el látex con el jugo de* I. alba *en diferentes proporciones, y que aplicaron estos conocimientos para manipular las propiedades del hule según el uso específico que se le fuera a dar. Nuestro estudio se enfocará en tres ejemplos: las pelotas de hule, las bandas anchas de hule que servían para enmangaduras, y las sandalias con suelas de hule. Los datos de nuestra investigación revelan que el hule que se obtiene al mezclar un 50 por ciento de* Ipomoea alba *por volumen, sería la combinación ideal para la manufactura de las pelotas donde se requiere de una máxima elasticidad y rebote. En cambio, para las suelas de hule de las sandalias, la resistencia al desgaste y la fatiga son las propiedades mecánicas más importantes, y esto se lograba al agregar el 25 por ciento de jugo de* I. alba *por volumen. Por su parte, el látex seco, sin procesar, es el material más apropiado para crear las bandas anchas de enmangar, donde se requiere de una mayor fuerza de tensión, rigidez y capacidad de amortiguamiento. La hipótesis de que el hule se preparaba en varias formas en Mesoamérica es sugerida por algunas fuentes documentales del siglo dieciséis. En los documentos tributarios del imperio azteca se apunta que los artículos de hule y látex habrían sido procesados y manufacturados en las regiones donde los árboles de* C. elastica *son endémicos y desde ahí transportados a la capital mexica o a los centros tributarios del imperio.*

Rubber is a material that was first processed in ancient Mesoamerica. The history of rubber usually begins in 1839 with Charles Goodyear's discovery of vulcanization, a process that can increase the strength, elasticity and durability of rubber. During a period of 3,500 years before Goodyear's discovery, the Olmec, Maya, Aztec (Mexica), and other Mesoamerican peoples were employing rubber and latex in medicines and rituals, for rubber balls for the Mesoamerican ballgame, and for sandal soles. Several lines of evidence indicate that ancient Mesoamericans were making rubber by mixing latex from the *Castilla elastica* tree with juice from the morning glory vine *Ipomoea alba*, as early as the second millennium B.C. (Hosler et al. 1999; Tarkanian 2000,

Michael J Tarkanian ■ Center for Materials Research in Archaeology and Ethnology, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Room 8-003, Cambridge, MA 02139 (tarky@mit.edu)
Dorothy Hosler ■ Center for Materials Research in Archaeology and Ethnology, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Room 8-204, Cambridge, MA 02139 (hosler@mit.edu)

Latin American Antiquity 22(4), 2011, pp. 469–486
Copyright ©2011 by the Society for American Archaeology

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

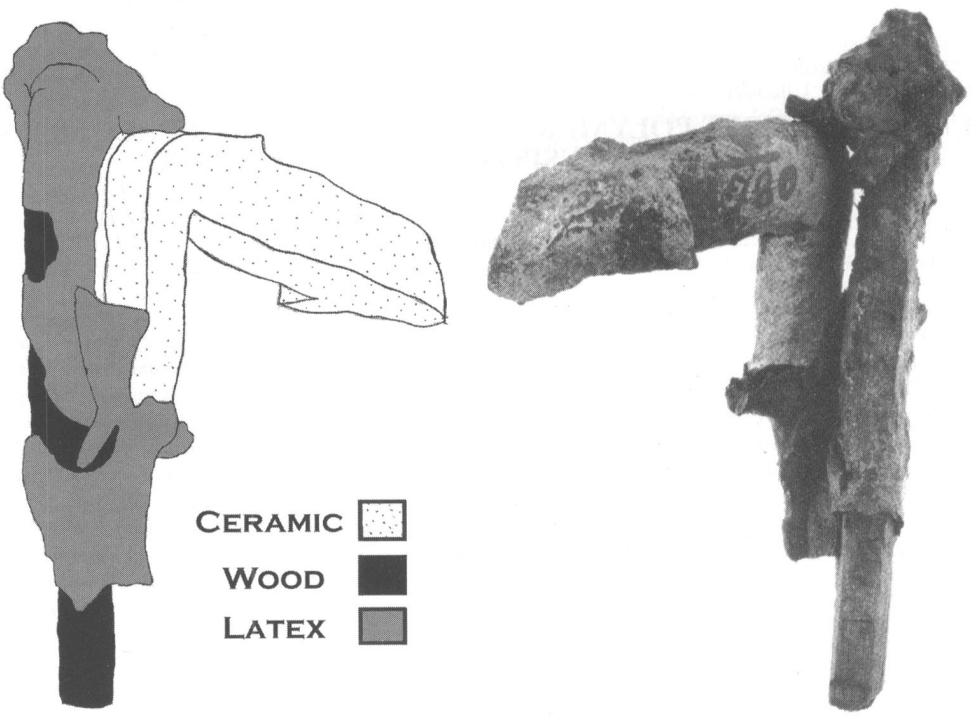


Figure 1. Line drawing and photograph of a portion of an effigy headdress: a ceramic element is hafted to a wooden shaft with latex bands. Cat. No. C4780 at Peabody Museum of Archaeology and Ethnology, Harvard University (image adapted from Ball and Ladd 1992:230).

2003; Tarkanian and Hosler 2000, 2001). Materials associated with large rubber balls excavated from the Olmec site of Manatí, Veracruz, Mexico have been radiocarbon dated to as early as 1600 B.C. (Rodríguez and Ortiz 1994; Ortiz and Rodríguez 1994), marking the earliest known use of rubber in the world. This complements data that place the earliest known ball court, at Paso de la Amada, Chiapas, Mexico, at 1400 B.C. (uncalibrated) (Hill et al. 1998). References to rubber balls are abundant in the *Popol Vuh* (Tedlock 1985), in which the ballgame plays a central role in the story of the heroes Hunahpu and Xbalanque and their fathers, One Hunahpu and Seven Hunahpu. The repeated references to rubber balls in the *Popol Vuh* make clear that this material was sufficiently embedded in the world of the Classic Maya to constitute a primary theme in that work, which explains the origins of the universe and the human species.

The data we present in this paper indicate that ancient Mesoamerican peoples were cognizant of the range of mechanical properties made possible by processing *C. elastica* latex with varying concentrations of *I. alba* vine juice. This knowledge was a prerequisite to their ability to process rubber selectively for specific applications such as rubber balls and sandal soles, and for joining applications such as adhesives or hafting bands. These three applications stand out from the many other Mesoamerican uses of rubber and latex documented in this paper.

Rather than using one static "recipe" for rubber, the experimental laboratory data we present suggests that ancient Mesoamericans employed an adjustable rubber-making procedure to process rubber for specific needs. This allowed them the ability to maximize the elasticity of rubber for use in balls, create wear-resistant material for sandal soles, and prioritize strength and shock-absorption for adhesion and hafting bands. By evaluating these data in conjunction with information from sixteenth-century tribute documents—specifically *Codex Mendoza* and *Información de 1554: sobre los tributos que los indios pagaban a Moctezuma*—we

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

contend that ancient Mesoamericans were likely processing latex and rubber for specific applications in the areas of Mesoamerica where *C. elastica* was indigenous. Finished goods would then be shipped as tribute throughout the Aztec empire.

In this text, we will refer to "latex" as the dried unprocessed material directly out of the tree, and we will refer to the processed material as "rubber."

Archaeological and Documentary Evidence for Rubber Use

Apart from rubber balls, which we treat in detail in a subsequent section, archaeological and documentary data provide evidence of a wide variety of rubber and latex items in ancient Mesoamerica. Some of these would have gained performance benefits through processing the *C. elastica* with *Ipomoea alba*. The performance of other items required the properties conferred by unprocessed *C. elastica* latex.

There is documented and archaeological evidence of latex being employed in ancient joining applications, such as hafting and adhesives. Among the Late Phase (ca. 1224–1461 A.D.) rubber and latex artifacts dredged from the *Cenote de Sacrificios* at Chichén Itzá (Coggins and Ladd 1992:353) is part of an effigy headdress composed of ceramic and wood. The wooden portion is coated in rubber, with the ceramic pressed against the rubber layer and fastened into place with a thick rubber band (Ball and Ladd 1992:230, Peabody Museum cat. No. C4780). This artifact uses latex as a hafting band. Coggins and Ladd (1992:356) also assert that Edward H. Thompson dredged and identified rubber-hafted blades from the *Cenote de Sacrificios*. Tensile strength is an essential material property for rubber to function effectively in any hafting application. In the case of the rubber-hafted blades described by Thompson, the band may also function as a damping mechanism. The extent to which the material absorbs shock could be a crucial attribute if the object is a striking tool.

Latex was used for adhesive applications in ancient Mesoamerica. Among the Maya, Tozzer (1957:1:144) explains that "[f]lint points from the Sacred Cenote at Chichen have at their base remains of a pitch, probably rubber, that served as an adhesive for attachment to shafts." In Ralph Roys' translation of *Ritual of the Bacabs*, he makes a similar suggestion in footnotes annotating the "the birth of the flint" (Roys 1965:61). In this section, the native text mentions "the resin of the white *kik-che*-tree" (Roys 1965:63), with very little context. Roys writes that he "can only surmise that the *kik-che* (rubber tree) is cited because its sap was employed in attaching the flint point to the arrow-shaft, although I do not know that it was so used" (Roys 1965:63). Like hafting bands, high tensile strength is essential in adhesives. If an adhesive has ability to wet and attach to a surface (which is quantified as "adhesive strength"), its efficacy as an adhesive is then largely dependent on its "cohesive strength." Cohesive strength is directly correlated with tensile strength.

The Florentine Codex contains repeated references to rubber-soled sandals, but the archaeological record has yet to produce corroborating physical evidence. In writing about the characteristics of the "Olmeca, Uixtoti, Mixteca" peoples, Fray Bernardino de Sahagún (1961:10:187-188) observes that "the sandals of the men were very precious; also, they walked in rubber sandals." The original Nahuatl text of this passage helps to confirm the existence of rubber-soled sandals, using the specific word *olcactli* for sandals. *Cactli* is a known Nahuatl word for "zapatos, sandalias, calzado en general" (Siméon 1977:58) . *Olcactli* is a literal compound of the *ol-* root of rubber and *cactli* for sandal (Louise Burkhart, personal communication 2004). Another passage describes the Aztec dress during a procession to a vigil on "feast day": "And there were their rubber sandals; their rubber sandals went with them" (Sahagún 1981:2:44). In this case, the Nahuatl compound for "their rubber sandals" is *ymolcac*, combining *ym-* (their) with the *ol-* from *olli* and *-cac* from *cactli*. The *–tli* suffix is dropped for possessive nouns (Louise Burkhart, personal communication 2004). In volume six, Sahagún describes the contents of prayers to Tlaloc, in which worshippers ask that the rulers and Gods "take up the rubber sandals" (Sahagún 1969:6:39).

In *Monarquía indiana*, Torquemada furthers the case for the existence of rubber sandals in his descriptions of natural products the Aztec derived from trees. In describing the products of the rubber tree "*uscuahuitl*" (Torquemada 1977:4:429) Torquemada writes: "Acostumbran antiguamente los reyes y señores hacer suelas y zapatos a su

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press



Figure 2. The distribution of Castilla elastica trees in Mexico and Central America. (Map adapted from image at: http://en.wikipedia.org/wiki/File:Mexico_states_map.png, accessed October 12, 2009).

usanza de este dicho ulli, y se las mandaban calzar a los truhanes o chocarreros, enanos y corcovados de palacio, para burlar de ellos, porque no podían andar con ellos sin caer..." (Torquemada 1977:4:430).

Diego Muñoz Camargo also writes of rubber-soled sandals in *Relaciones Geográficas del Siglo XVI: Tlaxcala*. He offers: "...entiendo que, si se hiciesen suelas de zapatos de este uli... que el que estas suelas se pusiese, le harían ir saltando contra su voluntad por dondequiera que fuese" (Muñoz Camargo 1984: 271). While Muñoz Camargo's assessment of the effects of wearing rubber-soled sandals is clearly exaggerated, his mention of this footwear, coupled with the accounts of Sahagún and Torquemada, provide ample evidence for the fabrication of rubber sandals in Mesoamerica prior to the arrival of the Spaniards.

Rubber Processing and Raw Materials

In *The Florentine Codex*, Fray Bernardino de Sahagún identifies the Aztec source of latex as the tree *olquauitl* (Sahagún 1963:11:112). *Olquauitl* is the Nahuatl word for *Castilla elastica*, a species of latex-producing tree found throughout Mexico and Central America. *C. elastica* is most commonly found in the Mexican states of Chiapas, Veracruz, Tabasco, and the Yucatán peninsula, (Figure 2) below altitudes of 700 m (Standley 1920). In Central America, the tree grows on the lowland coasts of both the Pacific and Atlantic Oceans. According to the botanist Paul C. Standley, *C. elastica* could also be found in the western Andes of Ecuador in the early twentieth century (Standley 1920).

Castilla elastica was the most practical source of latex available to ancient Mesoamerican societies. In terms of mechanical properties such as elasticity, toughness and strength, as well as ease of use, *C. elastica* is far superior to other Mesoamerican alternatives including Guayule (*Parthenium argentatum*) (Lloyd 1911) or plants from the *Euphorbia* genus (Altamirano y Rose 1905). Guayule, a shrub, requires grinding the plant matter to extract latex, while *C. elastica*, trees in the *Euphorbia* genus, and *Hevea brasiliensis* (the source of commercial latex) secrete latex when the bark is cut.

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

The latex from *C. elastica* is a sticky, viscous white liquid when gathered directly from the tree. The latex turns brown and becomes rigid, and brittle as it dries. In this form, the dried latex lacks the mechanical properties required for balls, sandals, or hafting bands—each of which may require specific combinations of elasticity, toughness, and strength. Elasticity is a quantification of "bounce," the ability of a material to store and release energy of deformation efficiently. Toughness describes a material's resistance to fracture. The strength of a material refers to its ability to bear load either in tension or in compression, without breaking or deforming.

Evidence of the use of *C. elastica* latex in ancient Mesoamerica predicates the development of the rubber processing regime we describe in Hosler et al. (1999), and in Tarkanian (2000 and 2003). The sixteenth-century documents, nineteenth-century ethnographic data, and other sources that have enabled us to decipher ancient Mesoamerican rubber processing regimes also suggest that ancient Mesoamericans were able to engineer *C. elastica*, the optimal source of latex available to them, for the applications we investigate here. As those publications demonstrate, Mesoamerican peoples did so by mixing the latex of *C. elastica* with juice from *Ipomoea alba* vines. *I. alba* is a white-flowered species of morning glory vine that flourishes throughout the Americas, commonly known as "moon-vine."

In *Historia de los indios de la Nueva España*, Fray Toribio de Benavente (Motolinía) established the case for an Aztec rubber-processing technology when he recalled some of the first European encounters with rubber:

> ...*ulli*, que es una goma de un árbol que se cría en tierra caliente, del cual punzando le salen unas gotas blancas, y ayúntanlo uno con otro, que es cosa que luego se cuaja y para negro, casi como pez blanda; y de éste hacen las pelotas con que juegan los indios, que saltan más que las pelotas de viento de Castilla, y son del mismo tamaño, y un poco más prietas; aunque son mucho más pesadas. Las de esta tierra, corren y saltan tanto que parece que traen azogue dentro de sí (Benavente 1984:35).

Motolinía's commentary provides evidence, substantiated by our laboratory studies and archaeological data, that latex was indeed processed by ancient Mesoamerican peoples to make rubber that was used for balls. Our ethnographic and laboratory work show that pure unprocessed latex does not "se cuaja" (coagulate) nor does it turn black, as does the material described in Motolinía's account. When untreated, a sample of *C. elastica* latex less than 1 cm thick takes several days to solidify fully. Solid, dried *C. elastica* latex is a rich brown color, not black as Motolinía describes. By contrast, *C. elastica* latex, when processed with *I. alba* juice, coagulates quickly and transforms from a milky white latex into black rubber. Motolinía witnessed the processing of rubber. Maya pottery and art related to the ballgame frequently depict balls distinctly black in color. Rubber balls are also portrayed as black in the *Codex Mendoza* (Berdan and Anawalt 1997: Folio 46R).

As a footnote to our discussion of rubber processing, Motolinía's comments also illustrate the European reaction to seeing rubber for the first time. In the sixteenth century, rubber-bearing trees such as *C. elastica* and *Hevea brasiliensis* were unique to the Americas, as were the material properties of the latex and rubbers borne of these trees. Elasticity, which is particularly apparent in a bouncing rubber ball, was not a property common to the material inventory of Europe. Materials with elastic properties were not prevalent outside of the Americas. It is not surprising, therefore, that Motolinía was only able to offer unusual, sensory descriptions of rubber — "soft like tar" and "like quicksilver" when comparing the properties of American rubber balls to the less "bouncy" stuffed hide or inflated bladder balls of sixteenth-century Europe. He may not have been equipped with the proper vocabulary to describe such a material. To this day, the Spanish word for rubber remains *hule*, adopted from the Nahuatl *ulli* or *olli* (Corominas 1954).

While Motolinía describes the behavior of processed rubber, Pedro Mártir de Anglería provides insight into the process itself. As an official royal chronicler for the court of Spain's Charles V (1500–1558 AD), Mártir compiled *De Orbe Novo Decades* (Mártir 1989) and *Opus Epistolarum* (Anghiera 1966). These volumes contain collections of his letters communicating observations of Mesoamerican life. Regarding rubber, Mártir writes:

> Estas [pelotas] se hacen del jugo de cierta hierba que trepa por los árboles como el lúpulo

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

> por los setos; cuécese dicho jugo, que al hervir se endurece, y convertido en masa, se le da la forma apetecida; otros dicen que fabricadas de las raíces de dichas hierbas son pesadas; pero no comprendo cómo al chocar en el suelo se lanzan al aire, con increíble salto [Mártir 1989:II:547; emphasis added].

Mártir's observations reiterate the astonishment of the Spaniards at the elastic properties of rubber. Mártir makes no reference to latex, but he is clear that rubber processing included boiling the juice of a certain vine. 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 early twentieth-century Mesoamerican rubber processing and published the following, 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 [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; emphasis in original].

It should be noted that "moon-vine," *Calonyction aculeatum,* and *Ipomoea bona-nox* are all 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 within the United States Department of Agriculture, was likely 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).

Ethnographic studies we carried out from 1997 to 2002 at Rancho Paraíso in Zacualpa, Chiapas, Mexico (Hosler et al. 1999, Tarkanian 2000, 2003; Tarkanian and Hosler 2001) revealed that modern *huleros* were also familiar with the *C. elastica-I. alba* process and had used it more than 40 years ago, as children, to fashion rubber balls for play. They use juice only from the vine of the *I. alba* plant, removing the leaves and flowers before use. At Rancho Paraíso, wild *Ipomoea alba* vines grow in close proximity to *Castilla elastica* trees. This facilitates the gathering of the raw materials and the processing of rubber on-site.

Rubber Performance and Mechanical Properties

The juice of *Ipomoea alba* vines transforms the properties of *C. elastica* latex through a two-part process: (1) by removing proteins that encase the latex and inhibit elastic behavior; and (2) by creating cross-links in the latex/rubber that increase elasticity (Hosler et al. 1999: 1990). Cross-linking is a chemical process that can alter elasticity, strength, and other mechanical properties of polymers.

We carried out a battery of mechanical analyses to quantify the range of mechanical properties of rubber and the applications of rubber made possible by processing *Castilla elastica* latex with varying amounts of *Ipomoea alba* juice. The analyses show that rubber made through this process can have a wide range of properties, varying in terms of elasticity, damping ability, wear resistance, strength and other properties depending on the concentration of *I. alba* used in the mixture.

Mechanical properties describe the way a material responds to specific forces or actions, and include hardness, toughness (a material's inherent capacity to resist brittle fracture), tensile strength, and others. "Elasticity" refers to the amount of "bounce" in a rubber ball. "Damping" is the ability of a material to absorb energy, such as a shock absorber in a car's suspension. "Wear resistance" quantifies rubber's capacity to resist "grinding down" when subjected to an abrasive surface, as shoe soles wear down over their lifetime of walking. "Strength" defines the maximum load that a material can withstand before breaking or plastically deforming. Plastic deformation is irreversible deformation: under an applied load the material stretches and cannot recover this strain, as when a paperclip is bent and does not return to its original shape.

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

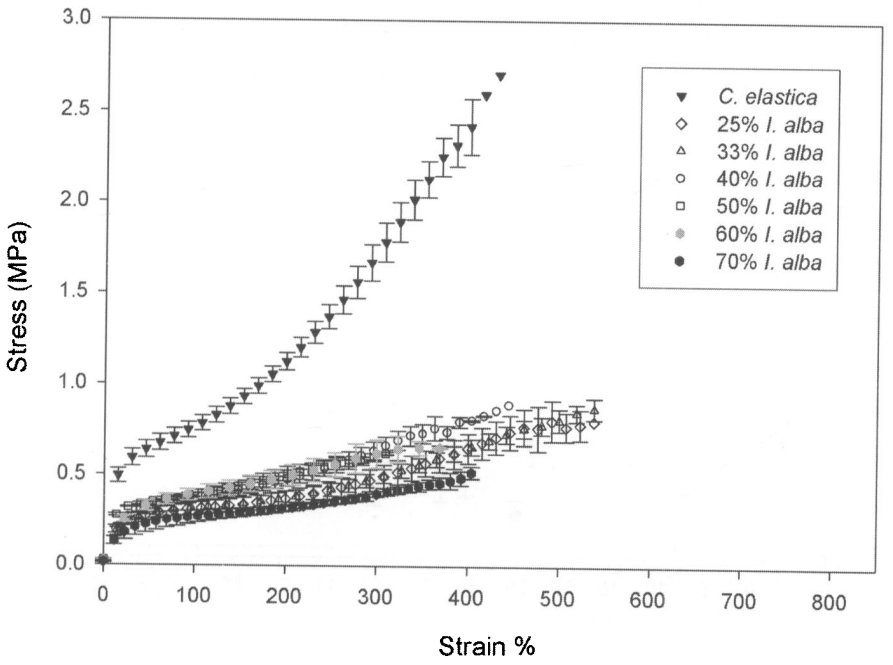


Figure 3. Tensile properties for *Castilla elastica* latex and rubber prepared with varying proportions of *Ipomoea alba* juice. These data make clear that the addition of *I. alba* to *C. elastica* transforms the mechanical properties of the resulting rubber. Error bars are ± one standard deviation.

The functional success of each of the three ancient Mesoamerican applications of rubber that are the focus of this paper—rubber balls, joining applications, and sandals—require markedly different mechanical properties. A material for adhesives or hafting bands would be chosen to maximize the strength and shock-absorbing abilities required for functional success. A specific ratio of the *C. elastica* to *I. alba* mixture produces rubber soles for sandals that are specifically designed to resist wear and fatigue. According to archaeological data and sixteenth-century Spanish documents, rubber balls fabricated through several unique methods (Coggins and Ladd 1992; Filloy Nadal 2001a; Hosler et al. 1999; Tarkanian 2000, 2003; Tarkanian and Hosler 2001) can be processed selectively for maximum elasticity or "bounce" (Tarkanian 2003).

Ancient Mesoamericans were able to process rubber selectively to maximize the elasticity or "bounce" of rubber balls for use in the Mesoamerican ballgame. Our laboratory results also suggest that the technology was adaptable to making adhesives or bands that possessed high strength for hafting and joining applications, while offering superior damping properties to reduce the shock of impact. Our mechanical tests indicate that by using a specific ratio of latex to morning glory, the effective life of rubber sandals can be greatly extended through improved fatigue and wear properties.

Rubber in the Ballgame

Rubber made with 50 percent *I. alba* and 50 percent *C. elastica*, by volume, is the ideal combination for rubber balls, which require maximum elasticity and bounce. This specific blend produces rubber with greater elasticity than mixtures with a higher or lower concentration of *I. alba*. Figure 3 illustrates the stress versus strain curves—or tensile properties—obtained for samples of latex (0 percent *I. alba*) we prepared and tested, and for rubbers made by adding 25 percent, 33 percent, 40 percent, 50 percent; 60 percent, and 70 percent *I. alba* juice, by volume, to the latex.

These tensile test data quantify the behavior of a material that is undergoing uniaxial elongation, and the results can be correlated directly to the strength and elasticity of the material. Strain is defined as the ratio of the change in length of a sample as it is stretched to its original length. Strain refers to the response of a material under stress, in

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

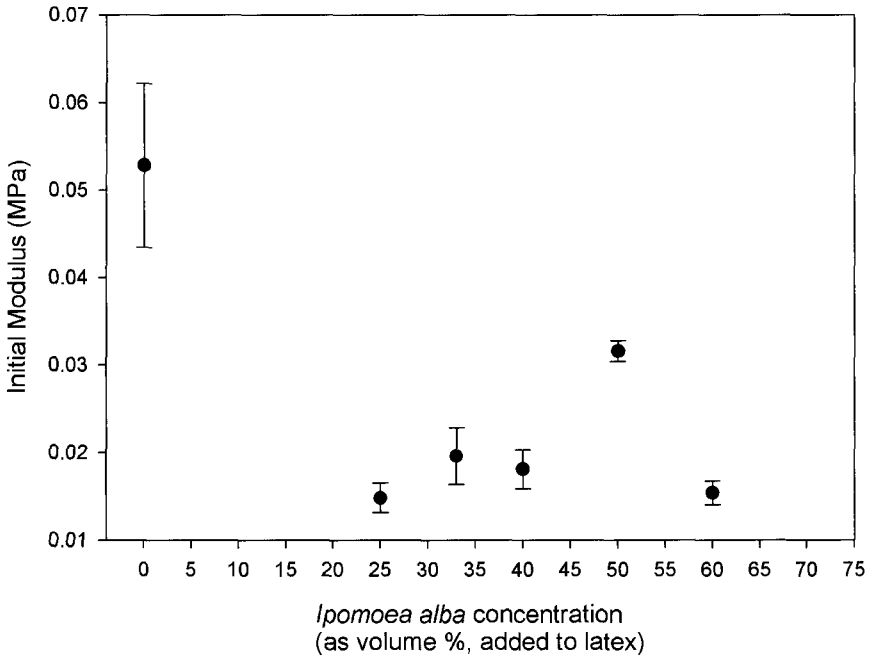


Figure 4. Initial Modulus, or Elastic Modulus, of *Castilla elastica* latex and rubber made with varying proportions of *Ipomoea alba* juice. Note that the addition of *I. alba* lowers the initial modulus; 50 percent *I. alba* maximizes elasticity. Error bars are ± one standard deviation.

this case, the tensile stress applied by an instrument that pulls on and elongates the latex or rubber samples. Stress is calculated by measuring the force the material exerts against the direction of strain, divided by the material's cross sectional area.

It is immediately evident in Figure 3 that there is a marked difference between the tensile properties of *C. elastica* latex and the response of all of the rubbers to tensile forces. *C. elastica* latex is a stiff, "non-rubbery" material, and thus exhibits much higher stress and stress rates (the change in stress versus strain) than any of the rubbers. In the case of the 33-70 percent *I. alba* samples, the addition of morning glory juice softens the samples, transforming the latex into a typical rubbery material. The behavior of the unprocessed *C. elastica*—it is stiff and prone to deformation under stress—makes it a poor material for use in sandals or rubber balls, where flexibility and elasticity are essential.

We can further differentiate the mechanical properties of the tested rubber and latex by examining a portion of the stress-strain data known as "initial modulus" or "elastic modulus." The elastic modulus directly relates to elasticity in rubbery materials. As in the bulk stress-strain data shown in Figure 3, Figure 4 shows that the addition of morning glory juice substantially lowers the value of the elastic modulus, transforming unprocessed (0 percent *I. alba*) *C. elastica* latex—which is hard and stiff—into a softer, rubbery material more suitable for use in balls, sandals, and other rubber items. These data also show that among the rubber samples the 50 percent *I. alba* by volume rubber has an appreciably higher value of elastic modulus than the others. This means that this rubber is correspondingly more elastic than its counterparts. Accordingly, a 1 to 1 ratio of *I. alba* juice to *C. elastica* latex by volume would be the ideal mixture for making rubber balls, because it maximizes elasticity or "bounce." Any other mixture produces a less elastic rubber that would be inferior for balls.

Joining Applications: Adhesives and Hafting Bands

Rubber made with 50 percent *I. alba* maximizes elasticity for balls, but the material for optimized joining ability requires a different set of properties: strength and damping ability. For this reason,

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

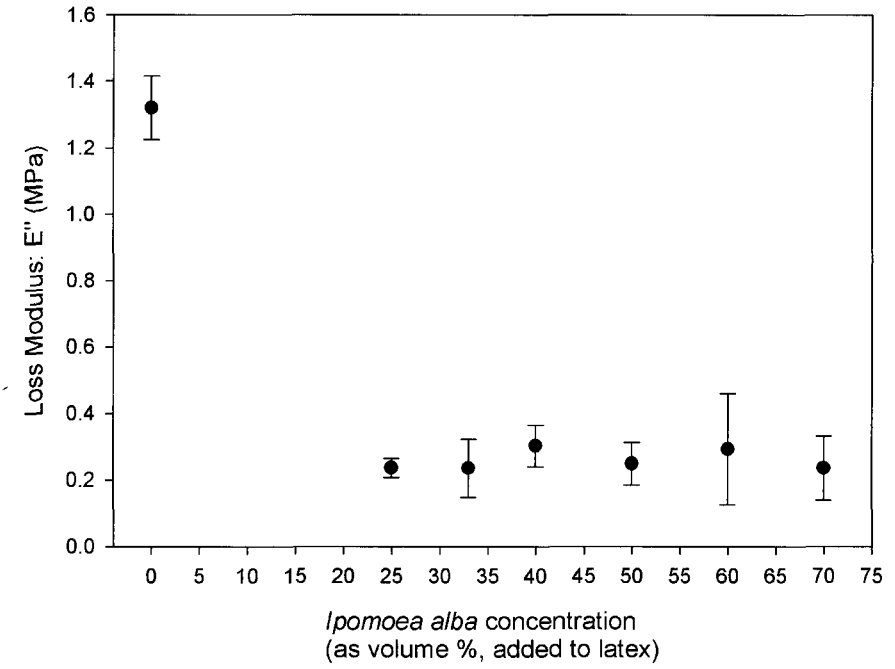


Figure 5. Damping ability (E'') for *Castilla elastica* latex and rubber made with varying proportions of *Ipomoea alba* juice. The damping ability of unprocessed latex is substantially greater than that of the *I. alba*- processed rubbers. Error bars are ± one standard deviation.

unprocessed *C. elastica* latex is the most likely candidate for use in adhesives and hafting bands. As seen in Figure 4, dried *C. elastica* is much stiffer than rubber. Whereas this degree of stiffness corresponds to an undesirably low level of "bounce" for a rubber ball, it correlates with high strength, which is the most important material property in the case of an adhesive or a hafting band. Latex also lends itself to use as an adhesive because of its liquid state, and ability to be spread onto mating surfaces and left to dry. Rubber processed with *Ipomoea alba* coagulates quickly into a solid, and immediately loses much of its tackiness, rendering it ineffective in adhesive applications.

Figure 5 illustrates that *C. elastica* latex has the greatest damping ability of all the latex and rubber samples tested. Damping ability (E'')—or the ability to absorb shock or energy—is plotted along the Y-axis in Figure 5. The values of E'' were determined through Dynamic Mechanical Analysis (DMA) tests. Whereas *C. elastica* latex has an average E'' value of 1.35 Mpa, the highest value among the *I. alba*-processed rubbers is 0.35 MPa. This demonstrates a dramatic increase in the damping ability of the latex versus the rubbers. Recalling the stress-strain elastic modulus data in Figure 4, unprocessed *C. elastica* also maintains the highest value of stiffness: it is the material capable of maintaining the highest loads in tension without breaking. *C. elastica* latex tested as having between about 1.5 and five times the tensile strength of the *I. alba*-processed rubbers.

Hafting bands are an application in which fracture would cause catastrophic failure. In this text we have described *C. elastica* latex as a rigid material prone to deformation and cracking, and these properties are cause for concern in any stress-intensive application. However, the main failure mode for *C. elastica* latex occurs 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 function effectively as a hafting material. We have employed dried *C. elastica* latex successfully as a hafting band in several simple replication experiments. In these cases, the partially dried latex was wrapped around the tool to secure the blade to the handle without break-

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

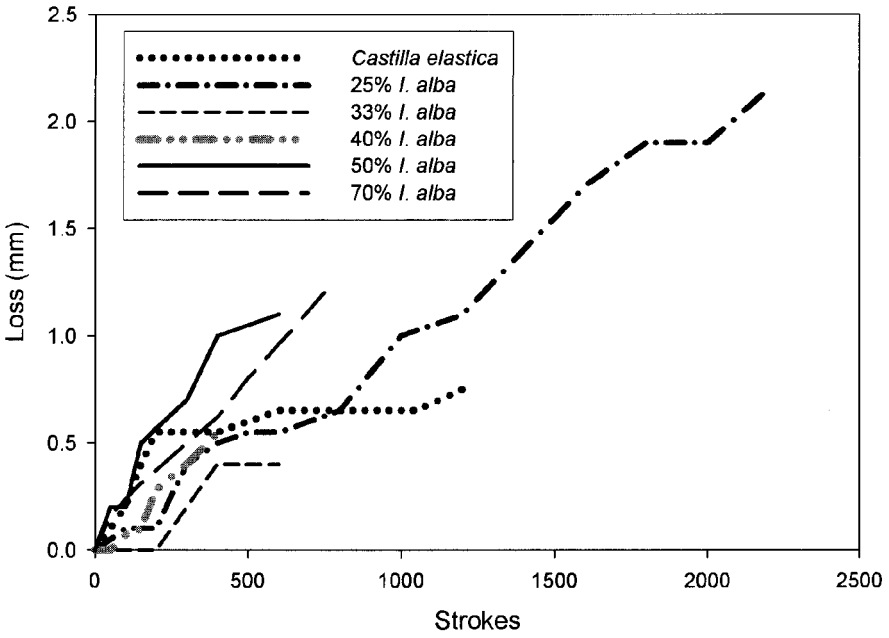


Figure 6. Wear versus distance (strokes) of *Castilla elastica* latex and rubber made with varying proportions of *Ipomoea alba* juice.

ing or cracking. Once fastened, the tool could be "used" without hesitation and would hold together indefinitely.

Sandal Soles

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. Figure 6 illustrates wear data collected for the various rubber and latex samples tested in the laboratory. These data were collected by measuring the amount of rubber or latex lost due to pushing samples back and forth (strokes), at a set load, over an abrasive surface. The x-axis represents the period of time during which the material was subjected to wear, and the y-axis is a measure of material lost to wear. The end point of each graphed line corresponds to the average stroke at which catastrophic failure occurred in the sample.

As is evident from Figure 6, rubbers made with 25 percent *I. alba* and unprocessed *C. elastica* latex are among the samples with the lowest wear rates. They also have the highest times-to-failure during wear. *C. elastica* latex undergoes brittle failure in the bending mode, effectively eliminating it from use in sandal soles, as human strides are dependent on bending actions between the foot and toes. This type of motion would quickly destroy a sandal made from unprocessed *Castilla* latex. For this reason, sandals made from rubber made with any proportion of *I. alba* would be superior to those made with *C. elastica* latex. The 25 percent *I. alba* mixture would have been the best material available to ancient Mesoamericans for use in sandal soles, due to its longer wear lifetime, coupled with the low rate of wear. For rubber, wear resistance can often be directly correlated with fatigue performance (Schallamach 1968), further substantiating our finding that rubber made with 25 percent *I. alba* would have been the material best suited for sandal soles. Here, in Figure 7, we present our wear data solely in terms of lifetime. Translating these data into "real world" numbers suggests that rubber sandals produced with 25 percent *I. alba* would last for more than double the walking distance of the next best material, 70 percent *I. alba*, when used by the same person.

The differences in the mechanical behaviors of the *C. elastica* rubbers determined by this study offer the strong possibility that ancient Mesoamericans were aware of the varying effects achieved

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

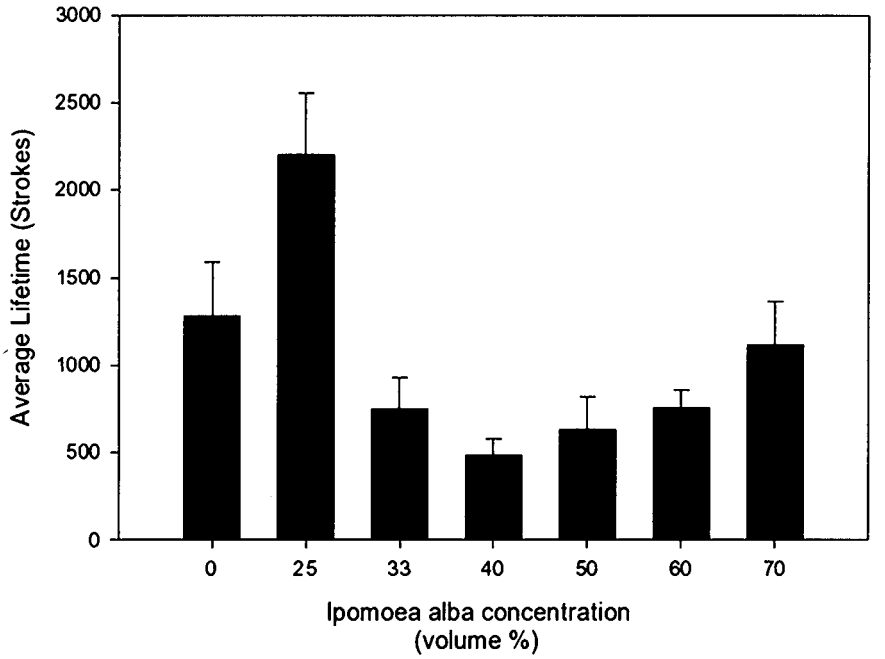


Figure 7. Average lifetime due to wear for *Castilla elastica* latex and rubber made with varying proportions of *Ipomoea alba* juice. Error bars are one standard deviation.

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. Rubber balls are best made with 50 percent *I. alba* juice, by volume. This mixture maximizes elasticity or "bounce." Hafting bands and adhesives would utilize unprocessed *C. elastica* latex. *C. elastica* latex provides maximum strength and damping ability. The use lifetime of sandals greatly benefits from the utilization of rubber made with 25 percent *I. alba* juice, by volume.

Construction Methods for Mesoamerican Rubber Objects

Analyzing the mechanical properties of materials incorporated into an object can help to predict performance and efficiency, but construction methods and design also play a crucial role in the performance of the finished goods. We are able to combine a variety of archaeologically known construction methods with mechanical data on *C. elastica-I. alba* rubber to form a substantially complete picture of the performance of ancient Mesoamerican rubber balls. Unfortunately, we do not have a complete data set for the construction methods of hafting bands or rubber sandal soles, so we cannot examine these items as thoroughly.

The preceding mechanical data show that rubber made with 50 percent morning glory juice by volume would produce a ball with the maximum elasticity possible via the *C. elastica—I. alba* process. Nonetheless, archaeological evidence exists for a wide variety of construction methods used to fabricate ancient rubber balls. The construction methods of a ball markedly affect its mechanical properties, such as its elasticity. The sixteenth-century Spanish sources discussed earlier indicate that ancient balls were made by shaping a solid mass of rubber. Historical accounts, ethnographic studies, and archaeological data provide evidence for at least three other construction methods: balls built up with extremely thin rubber layers (Kelly 1943; Rochín 1986); balls rolled in a "spiral" fashion from one or several thick sheets of rubber (Filloy Nadal 2001a); and balls constructed from wound rubber strands (Coggins and Ladd 1992; Tarkanian 2000, 2003).

Solid rubber balls were made shaped from a singular lump of rubber made by mixing latex with morning glory juice. Mártir (1989:II:547) writes

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

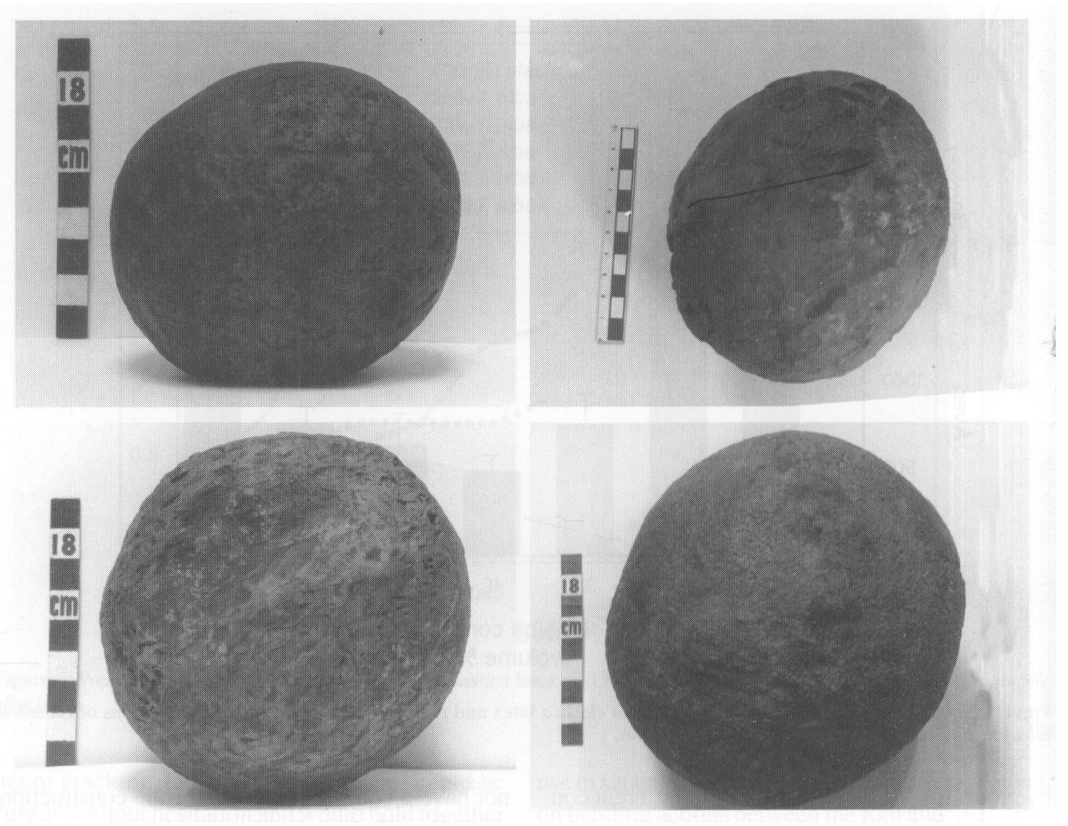


Figure 8. *Manatí* **balls, ranging from approximately 12 cm to 30 cm in diameter, from the collections at the Instituto Nacional de Antropología e Historia (INAH) Veracruz (Photographs by Michael J. Tarkanian).**

that when making balls, the rubber "se endurece, y convertido en masa, se le da la forma apetecida". Similarly, Fernandez de Oviedo (1959:I:145) recounts that mixing with the juice of roots and herbs creates "una pasta; e redondéanla e hacen la pelota tamaña como una de las de viento en España". These descriptions mirror precisely the ball-making process we observed at *Rancho Paraíso* in Chiapas (Tarkanian and Hosler 2001). There, rubber balls were made by mixing latex collected from C. *elastica* trees with juice squeezed directly from crushed *I. alba* vines. Approximately 10 minutes after mixing the two liquids, the latex coagulated into a solid mass of rubber. This rubber is extremely pliable and able to be shaped as desired. Within minutes, however, the rubber sets into place and its shape cannot be altered. This process significantly reduces the labor required to make a ball compared with the other construction methods. The balls made with this method are formed as a seamless mass, without any specific areas prone to breakage or fatigue.

Photographs of several solid rubber balls, likely made using this technique, can be found in Figure 8. These balls were excavated from Manatí, Veracruz in the early 1990s (Ortiz et al. 1997). Material found in conjunction with the rubber balls was radiocarbon dated to the First through Third Phases of Manatí, ranging from 1600 B.C. to 1200 B.C. (Ortiz and Rodríguez 1994). As Figure 8 makes clear, the diameters of the balls from Manatí vary greatly.

Modern ethnographic data reveal a second style of ball construction. This method requires layering extremely thin sheets of rubber until the ball reaches the desired size. Roberto Rochín's film *Ulama* (Rochín 1986) documents this process in Sinaloa. There, latex from the plant known as *aguama* (*Bromelia pinguin*) is mixed with slices of the root of *machacuana (Ipomoea rhodocalyx)*. Like *I.*

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

alba, *machacuana* is also a white-flowering plant from the *Ipomoea* genus. This mixture is then heated in bowls in an aqueous solution. After mixing, small amounts of rubber harden in the bowls. They are flattened and layered so as to form a ball. Balls can attain 4 kg in weight using this method (Rochín 1986).

In *Notes on Middle American Archaeology and Ethnology* (Kelly 1943), Isabel Kelly describes a process witnessed in Nayarit that is almost identical to that depicted in *Ulama*. Kelly writes:

> The ball was thus built up, layer by layer, as small quantities of rubber were added to the pellet-like nucleus [also rubber]. After each increment of rubber was squeezed free of the liquid, the ball was shaped on a flat board held slanting against the knees to let the liquid run off...When perfectly round, the finished ball was smoothed and polished with a stick." [Kelly 1943:164, emphasis in original]

The method described by Kelly also requires the use of *I. rhodocalyx*. Kelly (1943:164) writes that "to coagulate the latex, the root of the machaquana was diced and added to water." This method, like that depicted in the film *Ulama,* is much more labor-intensive than making a ball from a solid mass of rubber. In *Ulama*, the ballmaker constructs a 4 kg ball in a time-intensive process that occurs over the course of an entire day. In Chiapas, the ballmakers can produce a ball of equivalent size, from a single mass of rubber, in half an hour.

The layered construction may also produce a ball that is more prone to breakdown than the Chiapas-style balls, since it relies on cohesive bonds between the rubber-to-rubber layers. Immediately after coagulation, rubber is in its pliable state and able to form an inseparable bond with rubber in a similar state (or with itself). Once the rubber hardens and can no longer be shaped, it also loses the ability to bond, and is no longer tacky. Loss of bond within the layers of a ball develops over time or can result from faulty construction. These circumstances would create a discontinuity in the elastic behavior of a ball, thus decreasing its ability to bounce. They would also produce a ball that could fail catastrophically in play.

The third construction method consists of rolling thick sheets of rubber into a spiral shape, forming the sheets into balls, a method revealed by Filloy's Helical Computer Tomography (Helical CT) scans of balls recovered from excavations at Tenochtitlan (Filloy Nadal 2001a). Late Classic and Postclassic Maya codices and art substantiate the case for ball construction with rolled sheets of rubber. During these time periods, rubber balls were often depicted as "tight black spirals" (Stone 2002:24). These balls were likely only used as offerings and not meant for use in the ballgame (Filloy Nadal 2001b). They contain deep grooves cut into their surfaces meant to hold feathers, as was typical for ceremonial balls (Filloy Nadal 2001a).

Rubber ball construction using the "spiral" method identified by Filloy Nadal exhibits some similarities to the method described by Kelly (1943) and Rochín (1986) in modern Sinoloa and Nayarit. At the same time, the spiral method uses much thicker "layers" of rubber, perhaps even a single thick sheet. Using this construction method, the "spiral" balls would be subject to the same mechanical shortcomings as the "layered" balls. In the "spiral" balls, the likely absence of strong coherent bonding between the layers of rubber would lead, under stress, to mechanical failure and deadening of elastic behavior. However, since spiral-constructed balls were apparently produced for ceremonial use, mechanical rigor would not have been a priority.

Other rubber ball construction methods are evident in a single *incensario* housed at Harvard University's Peabody Museum of Archaeology and Ethnology as part of a collection of materials recovered from El Cenote de los Sacrificios at Chichén Itzá, Yucatán, Mexico. El Cenote, which is rich in sacrificial offerings, served as a major ceremonial center for the postclassic Maya. The *incensario*, reproduced in Figure 9, is composed of a clay tripod bowl filled with copal and 13 small rubber balls likely used as "wicks" to aid in the burning of the copal (Coggins and Ladd 1992:348). This artifact represents a rather simple application of rubber. Our macroscopic examination of the 13 balls revealed four other construction methods.

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 of solid rubber, and two appear to be rubber-dipped copal. These rubber-dipped copal balls were apparently made by dipping a copal core into liquid latex. No seams are

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

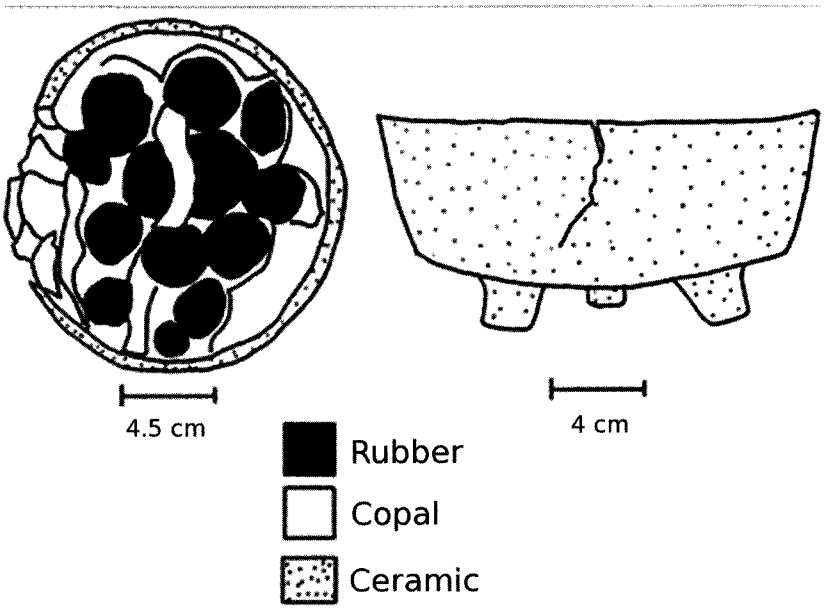


Figure 9. *Incensario* with 13 rubber balls embedded in *copal*. Recovered from the Cenote de Sacrificios, now in the collections of the Peabody Museum of Archaeology and Ethnology, Harvard University.

evident. One ball was made using all of these 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 was used, as a mixture of latex and *I. alba* could be used for dipping only within the few minutes prior to solidification. Unprocessed latex will remain in its liquid form for days; a hardened "skin" forms on the surface when exposed to air.

Organization, Production and Transport of Rubber Tribute Items

The finding that rubber was prepared in numerous forms in ancient Mesoamerica is substantiated by accounts in sixteenth-century documents. The *Codex Mendoza* (Berdan and Anawalt 1997) and *Información 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. These documents provide insight into the infrastructure of the ancient Mesoamerican rubber "industry" and its production techniques.

Información de 1554 compiles information gathered through Spaniard-led interviews of six elder Aztec noblemen conducted in 1554. In this text, the Spaniards reconstructed a record of the tribute paid by 38 provinces to the Aztec capital. These interviews were aided by the presence of extant pictorial tribute records. Each of the Aztec noblemen recalled that 2,000 "*panes de hule*" (rubber cakes) were delivered on a yearly basis from the provinces of Tlapa, in west Mexico, and Tochitepeque, on the Gulf Coast (Figure 10). Cotlastla, directly north of Tochitepeque, paid 2,000 *panes de hule* every 80 days and 400 *estatuas de hombre de hule* (rubber figurines) yearly. The large differences in the volume of rubber tribute paid by Cotlastla, Tlapa, and Tochitepeque suggests that Cotlastla was able to produce substantially greater volumes of latex and rubber, either through a distinct advantage in labor force, production techniques, greater density of *Castilla elastica* trees, or other factors.

Codex Mendoza (Berdan and Anawalt 1992), which details the tributes paid by various provinces to the Aztec capital, provides evidence for the transport of finished rubber goods from latex-bearing areas. In the case of the Tochtepec (called Tochite-

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press



Figure 10. Map of Aztec provinces related to rubber production, tribute and transportation.

peque in *Información de 1554)* province, on the Gulf coast of modern Mexico, 16,000 rubber balls were paid as annual tribute (Berdan and Anawalt 1992:116). The 16,000 balls are depicted as two rubber balls, each on top of an incense bag. The bags are symbols for the value 8,000 (Berdan and Anawalt 1992: Folio 46R).

Andrea J. Stone addresses the logistics of shipping of rubber balls in her article on the iconography of rubber balls in Mesoamerican art (Stone 2002). Stone argues that individual balls may have been shipped while bound with ropes, as commonly depicted throughout Mesoamerican art. This would prevent balls from sticking to each other during shipping to Tenochtitlan. Sticking would be less of an issue for rubber processed with *I. alba,* as processed rubber loses its inherent tackiness. Stone also argues that the balls were lashed with rope to prevent sagging in the ambient heat of the environment. Rubber from natural sources (i.e., not synthetic) will not readily deform or "sag" at temperatures around 100° F, but *Castilla elastica* rubber and latex are amorphous and will "flow" extremely slowly at ambient temperatures and above. This is often referred to as "cold flow." On a time scale of days, rubber balls made with *C. elastica* will develop flat spots due to cold flow if left on a flat surface. Flat spots on a ball would preclude it from effective use in the ballgame, as the direction of bounce would become unpredictable. If suspended with ropes, as Stone (2002) illustrates with examples from codices, a ball would remain roughly spherical, without flat spots, for longer periods of time and become distorted only around the bound areas. The areas distorted by the ropes would not have as great an effect on bounce as flat spots have, as the "rope marks" would be recessed from the still-spherical surface of the ball. Balls were likely bound with rope for storage purposes, to prevent flat spots due to "cold flow" of the amorphous rubber balls.

Tribute data are exceptionally useful in gaining insight into the labor, resources, and production technology necessary to satisfy the demand for rubber in ancient Mesoamerica. *Información de 1554* suggests that over 11,000 "rubber cakes" were shipped yearly from Tlapa, Tochitepeque and Cotlastla. Rubber cakes can be made by one of two methods: (1) by processing liquid latex with morning glory juice and shaping the coagulated rubber into the desired form; or (2) allowing unprocessed *C. elastica* latex to dry in a cake-shaped mold. The first method presents distinct advantages with respect to time: cakes processed with *I. alba* juice could be ready for shipment in a matter of hours. Unprocessed latex dries extremely slowly. A cake of substantial size would take weeks to solidify fully, greatly extending the delivery schedule of

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

these materials. The 16,000 balls due annually also could have been made using any of the methods described previously. If we assume a skilled ballmaker can make a ball by layering in four hours, this translates into 64,000 work-hours for the production of the yearly quota of balls. Making balls out of a solid mass from *I. alba*-coagulated *C. elastica* at 30 minutes per ball would require only 8,000 work hours, a substantial reduction in time.

The processing choices made in the latex-bearing regions of lowland Mesoamerica would also determine the use of the latex or rubber when the products reached the Aztec capital or other centers. If the cakes were made of dried, unprocessed latex, they would be useful only in applications that were not mechanically intensive, such as for sacrificial offerings or wicks for incense burners, as described by Coggins and Ladd (1992). Conversely, if the cakes were made of rubber processed with *I. alba* juice, the material could be used in more mechanically demanding applications. However, the use of rubber that arrived as cakes would be constrained by the already solidified form. Any application made from caked rubber would have to be cut (or sculpted) from the original cake. This would exclude rubber balls, which could not be reformed after the *I. alba*–*C. elastica* mixture has solidified. Rubber for balls would have to be processed into shape on-site. Shipping cakes of processed rubber would, therefore, have been an inefficient use of latex, morning glory, and shipping infrastructure. It is far more likely that the "rubber cakes" detailed by *Información de 1554* were actually unprocessed cakes of latex used for copal burning and other ritual activities.

These data from sixteenth-century sources make clear that tribute was paid to the Aztec in both processed rubber form and as dried unprocessed latex. The surveys conducted in *Información de 1554* document that the latex-bearing provinces within the empire sent rubber and latex to the capital in the form of "cakes" and figurines. The *Codex Mendoza* refers to payment in the form of balls. Given the data concerning processing presented here, it seems clear that a large portion of rubber processing occurred on-site where the latex was collected. 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 then shipped out. The other option—to ship the volume of liquid latex and morning glory necessary to supply the demand for rubber balls—would have been difficult logistically. It is likely, nonetheless, that small amounts of liquid latex were shipped from the latex-bearing regions for use as paint and as a waterproofing agent.

Conclusions

The combination of the mechanical properties data presented here and the ethnohistoric evidence from codices regarding the shipment of *C. elastica* in both latex and rubber form suggests 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. Simply by adjusting the ratios of latex to morning glory juice, they could optimize specific mechanical properties. In balls, where elasticity is essential, adding 50 percent *I. alba* juice by volume to latex is ideal. According to the archaeological evidence, these balls were made from solid masses of rubber, or by building up layers of rubber into a sphere, or by winding rubber sheets or strips. For joining applications, unprocessed *C. elastica* latex provides optimal performance with maximum strength and shock absorbing ability. For sandals, rubber made with 25 percent *I. alba* juice gives the wearer double the walking distance of sandals made from the next best material.

The rubber or latex required for these applications had to be processed at the *Castilla elastica* collection locations, such as Cotlastla, Tlapa, and Tochtepec, and distributed throughout Mesoamerica. Latex for non-mechanically intensive applications such as offerings or wicks could be dried on-site in cakes or *panes* in preparation for shipping. Likewise, balls and sandals, which required enhanced mechanical properties for optimal performance, would have been made in the rubber producing regions and then shipped. Small amounts of liquid latex may have been moved for paints or waterproofing and for assembling tools with partially dried latex hafting bands. The broad distribution and temporal depth of ball courts throughout Mesoamerica provides clear evidence of a long-term, high-volume demand for rubber. The cir-

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

cumstances created by this demand for rubber juxtaposed with the localized availability of *Castilla elastica* in the Gulf Coast and Pacific lowlands, must have given rise to a complex rubber production and distribution system based in the rubber-bearing regions.

It has long been known that ancient Mesoamericans were master architects, mathematicians, civil and mechanical engineers, and metallurgists. The data presented here, together with our prior discovery that rubber processing was pioneered in Mesoamerica some 3,500 years before Charles Goodyear invented his process of vulcanization in the United States, show us that the inhabitants of ancient Mesoamerica were also chemical engineers. Over time, the technology was perfected to produce rubber with specific mechanical properties through chemical manipulation. This makes the Olmec, and the peoples that followed them, the Americas' earliest polymer scientists.

Acknowledgments. We would like to thank Heather Lechtman and Frances Berdan for their help with the preparation of this article. We would also like to thank Joaquín Garcia-Bárcena, Ma. del Carmen Rodríguez, and Ponciano Ortiz at the Instituto Nacional de Antropología e Historia (INAH); Jan Gasco, the Guillen family, and Alonso Castañeda in Chiapas; past and present members of the MIT community: Christine Ortiz, David Roylance, Samuel Allen, Eliot Frank, Russell Gorga, Kristin Domike, Raúl Martinez, and Alfonso Reina Cecco; and William Shambley.

References Cited

Altamirano y Rose, Fernando
1905 *El palo amarillo*. Imprenta y Fototipia de la Secretaría de Fomento, Mexico City.

Anghiera, Pietro Martire d'
1966 [1530] *Opus Epistolarum*. Akademische Druck- u, Verlagsanstalt, Austria.

Ball, Joseph W., and John M. Ladd
1992 Ceramics. In *Artifacts from the Cenote of Sacrifice, Chichén Itzá, Yucatan*, edited by Clemency Chase Coggins, pp. 191-233. Harvard University Press, Cambridge, Massachusetts.

Benavente, Toribio de
1984 *Historia de los Indios de la Nueva España*. Editorial Porrúa, Mexico City.

Berdan, Frances F., and Patricia Rieff Anawalt
1997 *The Essential Codex Mendoza*. University of California Press, Berkeley, California.

Coggins, Clemency Chase, and John M. Ladd.
1992 Copal and Rubber Offerings. In *Artifacts from the Cenote of Sacrifice, Chichén Itzá, Yucatán*, edited by Clemency Chase Coggins, pp. 345-357. Harvard University Press, Cambridge, Massachusetts.

Corominas, Joan
1954 *Diccionario crítico etimológico de la lengua castellano*. Editorial Franckes, Bern.

Fernández de Oviedo y Valdés, Gonzalo
1959 *Historia general y natural de las Indias*. Ediciones Atlas, Madrid.

Filloy Nadal, Laura
2001a Rubber and Rubber Balls in Mesoamerica. In *The Sport of Life and Death: The Mesoamerican Ballgame*, edited by E. Michael Whittington, pp. 21-31. Thames & Hudson, London.
2001b Rubber. In *The Oxford Encyclopedia of Mesoamerican Cultures*, Volume 3, edited by David Carrasco, pp. 92-93. Oxford University Press, Oxford.

Hill, Warren D., Michael Blake, and John E. Clark
1998 Ball Court Design Dates Back 3,400 Years. *Nature* 392:878-879.

Hosler, Dorothy, Sandra L. Burkett, and Michael J Tarkanian
1999 Prehistoric Polymers: Rubber Processing in Ancient Mesoamerica. *Science* 284:1988-1991.

Kelly, Isabel
1943 *Notes on a West Coast Survival of the Ancient Mexican Ball Game*. Notes on Middle American Archaeology and Ethnology Vol. I, No. 26. Carnegie Institution of Washington, Division of Historical Research, Cambridge, Massachusetts.

Lloyd, Francis Ernest
1911 *Guayule (Parthenium argentatum gray), A Rubber Plant of the Chihuahuan Desert*. Carnegie Institution of Washington, Washington, D.C.

Mártir de Anglería, Pedro
1989 *Décadas del Nuevo Mundo*. Sociedad Dominicana de Bibliofilos, Inc., Santo Domingo, Dominican Republic.

Muñoz Camargo, Diego
1984 *Relaciones geográficas del siglo XVI: Tlaxcala*. Edited by René Acuña. Universidad Nacional Autónoma de México, México City.

Ortiz, Ponciano, and María del Carmen Rodríguez
1994 Los espacios sagrados olmecas: El Manatí, un caso especial. In *Los olmecas en Mesoamerica*, edited by John E. Clark, pp. 69-92. El Equilibrista y Turner Libros, Mexico City.

Ortiz, Ponciano, María del Carmen Rodríguez, and Alfredo Delgado C.
1997 *Las investigaciones arqueológicas en el cerro sagrado Manatí*. Universidad Veracruzan, Xalapa, Veracruz.

Rochín, Roberto (director)
1986 *Ulama, el juego de la vida y la muerte*. Clasa Films Mundial, Mexico City.

Rodríguez, María del Carmen, and Ponciano Ortiz
1994 *El Manatí, un espacio sagrado de los olmeca*. Universidad Veracruzana, Jalapa, Veracruz.

Rojas, Jose Luis de (editor)
1997 *Información de 1554: sobre los tributos que los indios pagaban a Moctezuma*. Centro de Investigaciones y Estudios Superiores en Antropología Social, Mexico City.

Roys, Ralph
1965 *Ritual of the Bacabs*. University of Oklahoma Press, Norman.

Sahagún, Bernardino de
1961 *The Florentine Codex, Book 10*. Translated by Arthur J. O. Anderson and Charles E. Dibble. The School of American Research and The University of Utah, Santa Fe.
1963 *The Florentine Codex, Book 11*. The School of American Research and The University of Utah, Santa Fe.
1969 *The Florentine Codex, Book 6*. The School of American Research and The University of Utah, Santa Fe.
1981 *The Florentine Codex, Book 2*. The School of American Research and The University of Utah, Santa Fe.

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press

Schallamach, Adolph
1968 Abrasion, Fatigue, and Smearing of Rubber. *Journal of Applied Polymer Science* 12:281.
Siméon, Rémi
1977 *Diccionario de la lengua náhuatl o mexicana*. Editorial Siglo XXI, Mexico City.
Standley, Paul C.
1920 *Trees and Shrubs of Mexico*. Government Printing Office, Washington, D.C.
1942 On the Use of Rubber by the Ancient Mexicans. *Masterkey* 15:123-124.
Stone, Andrea J.
2002 Spirals, Ropes and Feathers. *Ancient Mesoamerica* 13:21-39.
Tarkanian, Michael J.
2000 3,500 Years Before Goodyear: Rubber Processing in Ancient Mesoamerica. Unpublished Bachelor's Thesis, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.
2003 Prehistoric Polymer Engineering: A Study of Rubber Technology in the Americas. Unpublished Master's thesis, Barker Engineering Library, Massachusetts Institute of Technology, Cambridge, Massachusetts
Tarkanian, Michael J., and Dorothy Hosler
2000 La elaboración de hule en Mesoamérica. *Arqueología Mexicana*, 8(44):54-58.
2001 An Ancient Tradition Continued: Modern Rubber Processing in Mexico. In *The Sport of Life and Death: The Mesoamerican Ballgame*, edited by E. Michael Whittington, pp. 117-121. Thames and Hudson, London.
Tedlock, Dennis
1985 *Popol Vuh: The Definitive Edition of the Mayan Book of the Dawn of Life and the Glories of Gods and Kings*. Simon and Schuster, New York.
Torquemada, Juan de
1977 *Monarquía Indiana*. Universidad Nacional Autónoma de México, Mexico City.
Tozzer, Alfred M.
1957 *Chichen Itza and its Cenote of Sacrifice*. Peabody Museum, Cambridge, Massachusetts.
van Ooststroom, Simon Jan
1940 The Convolvulaceae of Malaysia. *Blumea* 3:547.
Wildman, Sam G., Albert V. McMullan, and Rosamond Griggs
1943 Isolation of an Active Substance from *Calonyction aculeatum* Capable of Coagulating *Castilla* Latex. *Science* 97:471-472.

Submitted: February 11, 2010; Accepted: April 8, 2010; Revised: August 8, 2011.

https://doi.org/10.7183/1045-6635.22.4.469 Published online by Cambridge University Press