



Lap-shear and compression testing of ethnographic compound adhesives and implications for archaeology

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Abstract

The properties of ancient compound adhesives are gaining increasing research attention through substance identification and mechanical testing. Research on the latter relies on experimental replication as ethnographic cases of hafted stone artifacts are rare. Here we characterize the lap-shear and compression stress behaviors of a hitherto undescribed compound adhesive used for hafting stone scrapers by hideworkers in Ethiopia. We found that the *Balanites aegyptiaca* resin mixed with charcoal powder provides high stability and cures within a few hours. However, this adhesive suffered catastrophic failure across substrate when subjected to strong tensile or compressive force. The relative elasticity and curing contrast with gum-based compound adhesives commonly used in experimental replications, with charcoal or ochre as filler. In acacia-ochre adhesives, adding beeswax resulted in increased elasticity but reduced bonding strength. Our observations, tests, and comparisons suggest that adhesive selection is governed by the properties of the main ingredient and the intended task, in addition to raw material availability. In stone hidescrapers hafted to wooden handles, relative adhesive stiffness affords tool stability within the haft. Our results have implications for the interpretation of archaeological hafted technologies, including decision-making processes involved in the selection of raw materials for adhesive production and qualities optimized for specific tasks.

Keywords Adhesive · Hafting · *Balanites aegyptiaca* · Ethnoarchaeology · Lap-shear · Compression test

Introduction

The traces of ancient technologies preserved in archaeological contexts help us understand past social organization, mobility, subsistence, and other behavioral aspects to ultimately infer the adaptive patterns and associated circumstances of our ancestors (Shea 2016). By virtue of their durability and ubiquity, stone tools are by far the most represented of such archaeological traces. The study of stone artifacts can inform archaeologists about sundry aspects

of technological decision-making processes, desired functions, raw material economy, and skills—to name but a few. An important source of information about these and other facets of stone tool technologies is experimental archaeology. Through experiments, archaeologists obtain a better understanding of the conscious decisions prehistoric knappers made, including raw material selection, careful edge shaping, optimized performance, and even probable aesthetically cohesive systems, etc. (Bril 2023; Stout 2005). The results of such experiments have, for example, shown that deliberate stone tool production techniques were the result both of learned cultural practices and the search for practical solutions to ecological necessities, with deliberate design choices often linked to improved functional performance (e.g., Schunk et al. 2024; Nora et al. 2025). One such improvement in tool edge design was to facilitate the mounting of stone artifacts onto organic handles, i.e., hafting.

The hafting of stone tools to organic handles allowed for greater practicality, durability, and efficiency compared to handheld stone artefacts and is, as such, considered a decisive invention (Barham 2013; Key et al. 2021). The

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production and use of multicomponent (i.e., compound) adhesives particularly represent a further innovation over relatively simple hafts using plant cordage, sinew, or single-ingredient adhesives. Compound adhesive production requires an understanding of the transformative properties of aspects involving temperature changes, as fire is often used during manufacturing, alongside recipe formulation and mixing techniques. Experimental and ethnoarchaeological studies of compound adhesive production support that these processes can be diverse, lengthy, and cognitively demanding, involving attention switching, greater planning depth, and careful monitoring (Wadley 2005, 2010; Wadley et al. 2009; Zipkin et al. 2014; Sahle 2019; Fajardo et al. 2023; Schmidt et al. 2022). As a result of these knowhow and skill requirements, the presence of compound adhesives in archaeological contexts is often considered to have implications for the cognitive prowess of prehistoric tool makers.

In addition to ingredient proportions and production techniques, the bonding strengths and mechanical properties of different compound adhesives are receiving increasing experimental research attention (e.g., Kozowyk et al. 2016, 2017; Veall 2019; Veall and Mitchell 2023; Mika et al. 2023; Koch and Schmidt 2023; Schmidt et al. 2023a). Some of these experimental studies assess the performance of compound adhesives reconstructed based on identification from archaeological contexts (Schmidt et al. 2022, 2024; Aleo et al. 2024). Similar studies on ethnographically used adhesives are, by contrast, lacking.

The African ethnographic evidence for adhesive production and hafting provides a rare opportunity through which distinct aspects of past material cultures can be explored for relational analogies (McCall 2012; Sahle et al. 2025). Some of the more common plant-based adhesives on the continent constitute the exudates of various species of euphorbias that are mixed with charcoal powder, ochre, or dry plant leaves (Sahle 2019; Fajardo et al. 2023). Exudates from euphorbias and other plant species, mixed with charcoal or ochre, have also been inferred from residues on archaeological stone tools at various Stone Age sites (e.g., Lombard 2007, 2011; d'Errico et al. 2012; Veall et al. 2023; Chasan et al. 2024; Aleo et al. 2024; Schmidt et al. 2024a). Acacia-based compound adhesives, with beeswax sometimes added as plasticizers, are by contrast more widely tested experimentally (e.g., Wadley et al. 2009; Kozowyk et al. 2016, 2020).

The documentation of acacia gum-based adhesives in ethnographic contexts is restricted to cursory mentions rather than detailed descriptions from direct observations (Brandt et al. 1996; Rots and Williamson 2004; Weedman 2005; see also Wadley et al. 2015). This lack of comprehensive ethnographic data limits our understanding of whether and how such gum-based adhesives were prepared, applied, and maintained in diverse settings. Furthermore, the poor

preservation of such gum-based mixtures, which are highly susceptible to degradation over time, diminishes their archaeological relevance even if they were to be positively identified in ethnographic settings. As a result, conclusive evidence for acacia, and gum-based adhesives more generally, from archaeological contexts is lacking, with suggestions of its use increasingly tested using experimental replication (e.g., Lombard and Wadley 2007; Zipkin et al. 2014; Kozowyk et al. 2020).

We describe here, for the first time, the ethnographic production of *Balanites aegyptiaca* resin-based adhesive, mixed with charcoal powder, for hafting stone scrapers to the sockets of wooden handles used by contemporary Konso hideworkers in southern Ethiopia. We assess the adhesive's bonding strength and mechanical properties as well as the implications for archaeological hafted technologies. We expand our study to include acacia gum-based compound adhesives—reportedly used in Ethiopia, and southern Africa—to further explore the potential impacts of the relative performance and technological advantages of *Balanites* resin to toolmakers.

Background

Compound adhesive production and use is common among different groups in southern Ethiopia, where stone tool-based hideworking survives to date (Fig. 1). The diversity of production processes, including underlying stylistic and/or environmental factors, have generally been understood as part of cultural differences, which are also reflected in raw material type, procurement method, toolstone pretreatment, handle type, and artisan gender (e.g., Brandt et al. 1996; Weedman 2005, 2006; Arthur 2008, 2010; Sahle and Negash 2016; Sahle et al. 2012, 2025). Hideworkers in the Gamo area reportedly used the gums of the now-revised acacia species of *Senegalia brevispica* or *Vachellia nilotica*, which they heated and mixed with ash/charcoal powder to haft hidescrapers onto wooden handles (Weedman 2005; Arthur 2008). The gum of unidentified acacia species, mixed with ash/charcoal, was also briefly reported to have been used for the same task by Gurage and Konso hideworkers (Brandt et al. 1996; Rots and Williamson 2004).

The clearest example of compound adhesive production and use for scraper hafting involves mixing *Balanites aegyptiaca* resin and charcoal powder (Arthur 2010; Sahle et al. 2025; Fig. 1). The effective use of *B. aegyptiaca* resin as adhesive for various applications, including hafting arrowheads and spear tips to wooden shafts and fixing cracks in household implements, has similarly been reported from semi-arid lowlands elsewhere in eastern Africa (e.g., Egadu et al. 2007). Among Hadiya hideworkers, the latex of *Euphorbia abyssinica* or *candelabrum* is mixed with

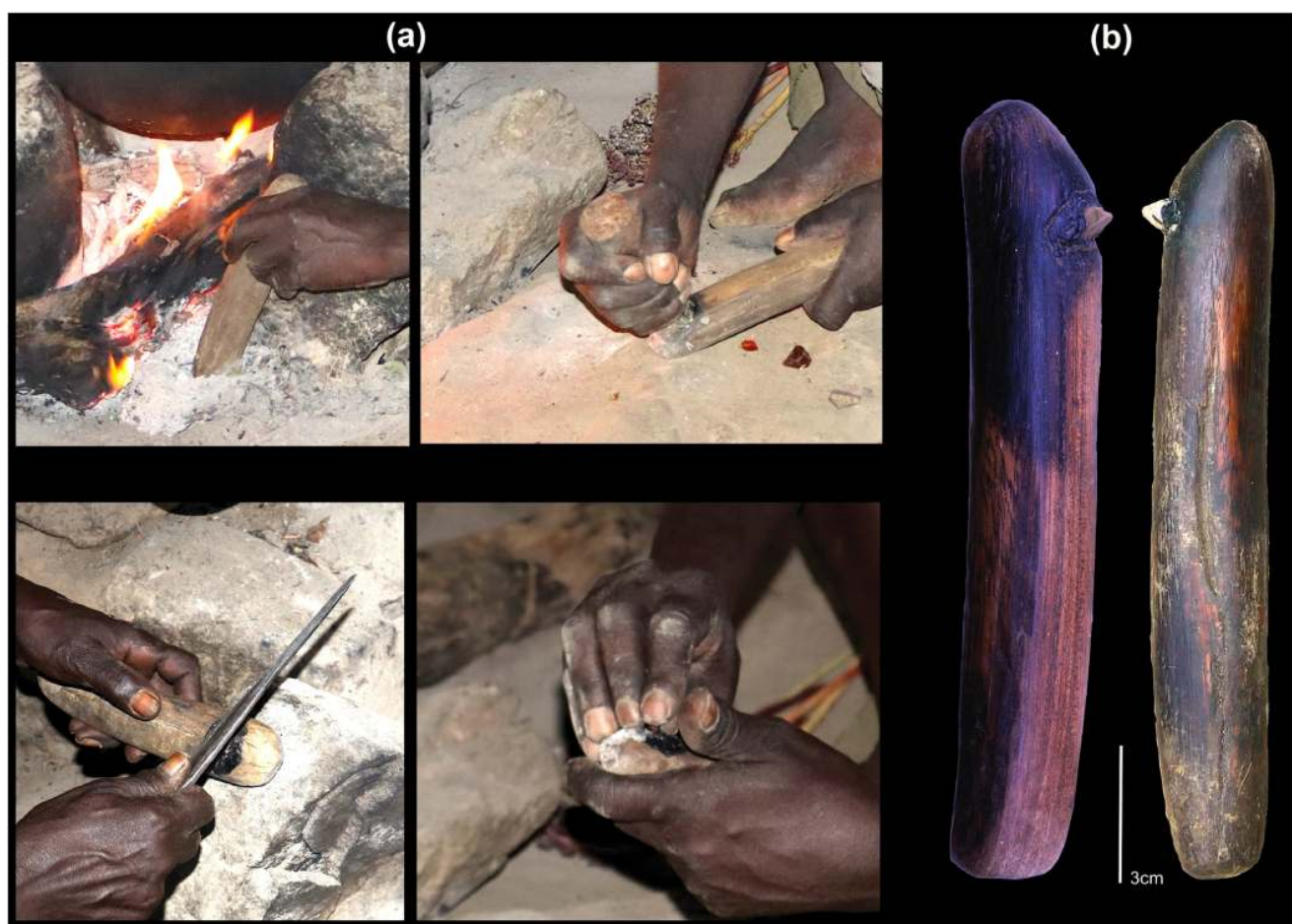


Fig. 1 Konso adhesive preparation and hafting. **(a)** Placing the handle near fire to heat up the socket and remnant mastic from a previous haft, adding *Balanites* resin and crushing it in the socket, adding charcoal

black soot to make an effective compound adhesive for hafting obsidian scrapers onto the sockets of wooden handles (Sahle 2019).

In southern Africa, limited early reports indicate that the San used different kinds of plant-based adhesives (Marshall 1976; Lee 1979; Silberbauer 1981). The Ju/'hoan San were documented to use different plant extracts and exudates (e.g., from *Ozoroa shinzii*, *Terminalia sericea*, *Ammocharis coranica*) mixed with carbonized grass and other additives (e.g., beeswax) to produce compound adhesives and bindings (Wadley et al. 2015). In addition, ochre powder was reportedly used in ethnographic compound adhesives (Webley 1994). This, combined with archaeological and experimental evidence, makes ochre one of the most widely documented fillers (Wadley et al. 2009; Lombard 2011; Zipkin et al. 2014; Schmidt et al. 2024b).

In this study, we exploit the unique context in which a *Balanites*-based adhesive is actively used by the Konso hideworkers (Fig. 1). Acacia gum-based adhesives are often tested in experimental studies. Given the claim that the

powder and mixing it well using knife, inserting a new scraper and adjusting the angle. **(b)** Chert and chalcedony scrapers secured in the sockets of wooden handles using a *Balanites*-charcoal adhesive

Konso and other groups in the region reportedly used acacia gum-based adhesives for the same function of hideworking, their inclusion as comparative samples is warranted to compare aspects of adhesive choice and performance. Such comparison can be informative of the relative advantages and limitations of each compound adhesive type to its users.

Methods

Samples

Ethnoarchaeological fieldwork among the Konso hideworkers was conducted, between 2022 and 2024, following observation and documentation methods described elsewhere (Sahle 2019). As part of our documentation of the *chaîne opératoire*, we collected resin and charcoal samples directly from the sources used by the Konso hideworkers. These raw materials were then used to produce compound adhesive samples for the controlled experiment using the most

common proportions and methods documented amongst the craft specialists. Acacia gum, ochre, and beeswax samples were procured from South Africa to compare the properties of a compound adhesive suggested to be effective in hafting tools (Wadley et al. 2009).

Two main plant ingredients, namely *Balanites aegyptiaca* (L.) Delile, and *Vachellia karroo* (Hayne) Banfi & Galasso, were investigated in the present study. *Balanites* resins were collected from the Teshmelle district of Konso. The *Vachellia* sample comes from the Limpopo Province of South Africa. Red ochre (powder grain size ~46 µm, as measured using the Olympus SZ40 Stereo Microscope,) was sourced near Piketberg while natural beeswax was purchased from a local beekeeper (<https://barbenbees.co.za/>), both in the Western Cape Province, South Africa.

Balanites aegyptiaca is a thorny, multibranched evergreen xerophytic tree that belongs to the family *Balanitaceae* or *Zygophyllaceae*, native to the Sudan-Sahelian region, the Middle East, and South Asia (Hines and Eckman 1993; Tesfaye 2015). Its oil-rich fruits and leaves are widely used as a food source and for medicinal purposes (Murthy et al. 2020; Okia et al. 2011). The resin of *Balanites aegyptiaca* is yellowish red to dark red in color and denser than acacia gum. By contrast, Acacia is a broad genus of trees and bushes within the *Fabaceae* family and has over 100 distinct African species under the two revised genera: *Vachellia* and *Senegalia* (Kyalangalilwa et al. 2013). Acacia as a genus name is restricted to Australian species. In our study, we use the term only as an informal common name. Among the more common species of African acacias are the iconic dome-shaped *Vachellia erioloba*, and the flat-topped *Vachellia abyssinica* (Kyalangalilwa et al. 2013). Acacia exudes a hydrocolloid and polysaccharide-based gum as a form of defense in response to damage. The gum is a soft, tacky, light to dark yellow/orange substance that subsequently darkens, thickens, and hardens entirely over time (Tahir et al. 2007). Although acacia gum bears a superficial physical resemblance to resin, their chemical compositions are distinctly different. Specifically, the presence of sugar in acacia gum makes it soluble in water while resins are predominantly composed of hydrophobic terpenoid compounds with no sugar, hence generally insoluble in water. *Vachellia karroo* is very similar to, hence difficult to distinguish from, *V. nilotica* ssp. *adstringens*, which is distributed across the Sahel, stretching from Senegal to southern Ethiopia (Wickens 1995, p. 37).

Adhesive preparation

Three adhesive mixtures were made from the two plant ingredients for the compound adhesives tested in this study. *Balanites* resin was mixed with charcoal, mimicking

the most common proportions, which contain anywhere between 85% and 90% *Balanites*, and method used by the Konso hideworkers. For acacia-and-charcoal adhesives, the ideal mix could not be established as our field study did not directly document its use among the Konso (cf. Rots and Williamson 2004). We, therefore, mixed the acacia gum with proportions of charcoal powder similar to those of the *Balanites* variants. Finally, our acacia-ochre-beeswax adhesive was produced using the recipe for the best-performing mix for the same species reported in Wadley et al.'s (2009) experiment.

As in the ethnographic and experimental settings, the production of the studied compound adhesives involved combining the plant ingredients and loading agents using a heat source. The *Balanites*- and acacia-based adhesives were prepared differently due to their differential solubility and loading agents. Resin and gum ingredients were ground, using aluminum-plated mortar and pestle, into fine powder before measuring. Heating temperature was measured using an infrared thermometer (Benetech GM550), which has an accuracy of ±1.5 °C and a resolution of 0.1 °C for measurements of −50 to 550 °C. Because different materials have different densities, measurement of the ingredients was done by weight (wt%), using a digital scale with sub-milligram accuracy.

Identification of the exact proportions for the *Balanites* and charcoal mixtures proved difficult as both our direct observation (Sahle et al. 2025) and Belkin et al.'s (2006) documentation showed the replenishing of existing mixtures left in the handle socket after each dehafting (Fig. 1). As a rapidly vanishing craft tradition (Sahle et al. 2025) where new handles are no longer made, none of the remaining practicing hideworkers could indicate exactly how much charcoal is added to a given weight of *Balanites* resin if one were to make the compound adhesive anew. Estimated *Balanites* proportions in Konso adhesives average at 87.5% resin to 12.5% of charcoal powder.

Balanites resin powder melts into a sticky paste at 250–300 °C; charcoal powder was added as filler once the resin was evenly melted. A similar procedure was followed for the acacia gum and charcoal mix, except that the acacia powder was soaked in water and left to dissolve before it was heated into a sticky paste with the desired viscosity (Wadley et al. 2009; Zipkin et al. 2014) and mixed with the charcoal powder. Compound adhesive mixtures were stirred until thoroughly mixed and ready to be applied onto the lapping plates and silicon molds.

For the acacia-ochre-beeswax mixture, 6 g of acacia was mixed with 3.75 g of ochre powder and 1.15 g of beeswax, following the proportion identified as most effective in Wadley et al. (2009). The acacia gum powder was left to soak in water (10 g gum powder to 2.5 g water) for ten

minutes. The dissolved gum in the water was then heated on a controlled heat surface at a temperature of 250–300 °C. The measured ochre powder was then added to the heated sticky gum paste and mixed thoroughly before adding 2.4 ml of melted beeswax to the mixture. The mixture was stirred thoroughly before being applied to the lapping plate surfaces and poured into compression molds.

Single-lap shear test

To assess the bonding strength of the different compound adhesives, lap-shear tests were conducted in the Centre for Materials Engineering, University of Cape Town, using an Instron 3365 dual-column Universal Testing System. The preload was set to 5 N and the pull rate to 1.3 mm/minute. Samples were prepared per the D1002 ASTM Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal) (ASTM International 2022). Aluminum plates with a 256 mm length, ~100 mm width, and 1.6 mm thickness were prepared, with the joint surfaces cleaned and abraded using a 100-grit sandpaper (Fig. 2). The adhesives were then applied, at a 0.64 mm thickness, to an overlap area of 12.7 mm—with customized Teflon sheets used as spacers—and left to cure under a constant 2 kg pressure for the first 12 h. The grip surfaces were prepared with alignment tabs measuring 25.4 by 25.4 mm and bonded to the same adhesives thickness using industrial glue. The bonded plates were then cut into test specimens following recommended

standard sizes (178 mm in bonded length, and 25.4 mm in width) after curing for 72 h (Fig. 2).

The shear area and adhesive bond thickness were measured before each lap was mounted for test (Fig. 2). Force (N) and displacement (mm) data from the tests were used to calculate stress (MPa) and strain curves, which are informative about the bonding strength and rupture behavior (*see* supplementary Table S1). As in Schmidt et al. (2023b), maximum shear stress τ_u was extracted as the highest stress value on the stress-strain plots, which represents the maximum stress tolerated before the curve declines. Shear strength τ_{yield} was calculated from these curves using the point of the curve's deviation from the elastic zone under increasing stress. The shear modulus G (MPa) was obtained by calculating the slope of shear stress τ over deformation strain (i.e., displacement/bond thickness) (Schmidt et al. 2021, 2023b).

The surface of failed bonds was examined under a Dino-Lite Polarizing Digital Microscope (Model AM-712115MTF) to assess the failure behaviour (e.g., cohesive vs. adhesive), and adhesive-substrate interaction (e.g., Kozowyk et al. 2016; Koch and Schmidt 2023).

Compression test

A separate test was conducted to determine how each compound adhesive responded to compressive loads. Depending on the elastic properties of the adhesive, brittle behaviour—where the adhesive tends to shatter—can be observed with

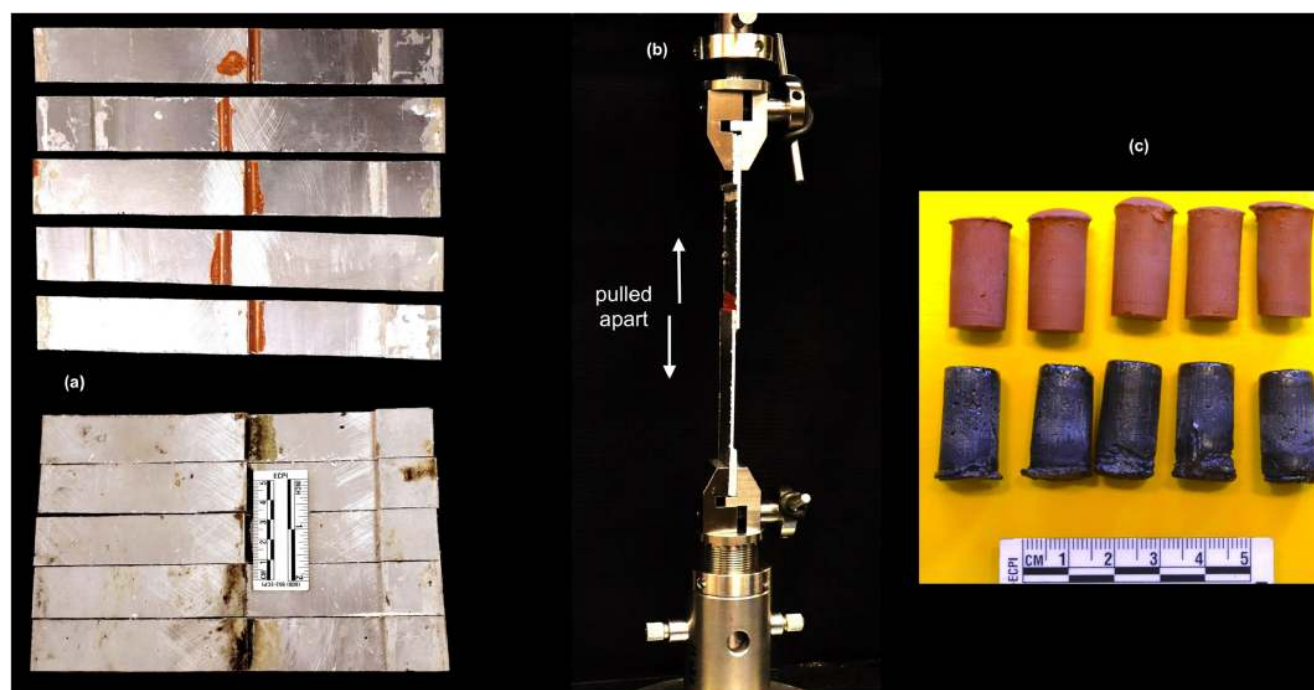
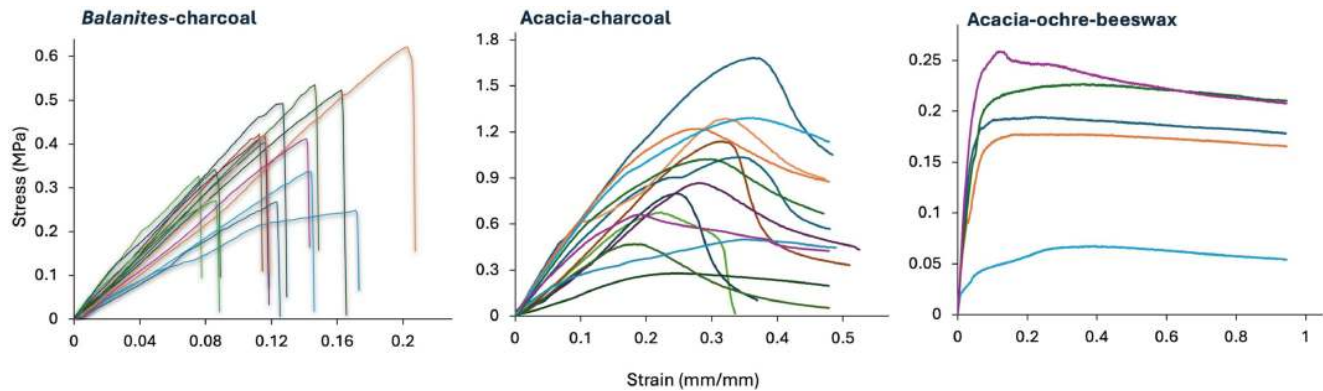


Fig. 2 Lap-shear test. (a) test specimens: acacia-ochre-beeswax (top) and *Balanites*-charcoal (bottom). (b) instrument set up. (c) compression test molds before being prepared by polishing

Table 1 Mean values from the lap-shear and compression tests performed for each adhesive type

Adhesive type	Lap-shear Test			Compression Test		
	Shear Modulus (MPa)±SD	Max. Force (N)±SD	Shear Stress (MPa)±SD	Elasticity Modulus (MPa)±SD	Max. Force (N)±SD	Compressive Stress (MPa)±SD
<i>Balanites</i> -charcoal	3.20±0.73	200.4±34.7	0.42±0.12	562.55±242	730.2±170	5.76±1.02
Acacia-charcoal	4.06±1.42	542.48±122	0.91±0.38	--	--	--
Acacia-ochre- beeswax	3.32±0.87	83.5±23.4	0.19±0.07	90.53±32.9	183.9±24.5	1.45±0.33

**Fig. 3** Stress-strain curves for the lap-shear tests on the three compound adhesive types

adhesives more sensitive to compressive loads (Procopio et al. 2003). Understanding the compressive properties of the adhesive along with tooling and intended use thus allows us to make inferences about the suitability of a given compound adhesive for a specific purpose.

Due to limited sample size, the compression test was conducted only on the *Balanites*-charcoal and the acacia-ochre-beeswax adhesives to assess their resistance to compressive stress before failure. The same adhesive proportions and preparations were retained for both the *Balanites*-charcoal and acacia-ochre-beeswax adhesives. Adhesives were poured into a silicone mould to produce cylindrical test specimens for compression (Fig. 2c) using the D695ASTM standard (ASTM International 2015). After a 72-hour curing period without any pressure, the top and bottom surfaces of the cylindrical specimens were polished flat on both contact surfaces, then measured per standard. The polishing of both surfaces is crucial to guarantee consistent contact between the loading plates of the universal tester and the specimen (Wanatowski and Chu 2008).

Ten compression test specimens (five *Balanites*-charcoal, and five acacia-ochre-beeswax) were molded, cured, flattened, and measured. The height and diameter of each specimen were standardized to 24.4 and 12.7 mm, respec-

tively. Cross-sectional area was calculated as $\frac{\pi d^2}{4}$, where d is the diameter of the circular cross section of the cylindrical specimens. The data collected from the universal tester were given in displacement and force and used to calculate compressive stress and strain on each specimen.

Results

Balanites-charcoal and acacia-ochre-beeswax adhesives exhibited lower shear modulus values with an average of ~0.554 MPa compared to the acacia-charcoal adhesive (Table 1). The shear strength of the acacia-charcoal adhesives is further reflected in the maximum force data, with the highest force withstood by the bonded laps before failure reaching 100.3 N. By contrast, the lowest maximum force recorded was obtained for the acacia-ochre-beeswax adhesive while the *Balanites*-charcoal adhesive showed an intermediate value (Table 1). This pattern is also reflected in the absolute shear stress values where the acacia-charcoal mixture exhibited an average of 1.57 MPa, followed by the *Balanites*-charcoal adhesive with half that value. At an average of ~0.26 MPa, the acacia-ochre-beeswax adhesive recorded the least absolute shear stress value (Fig. 3; Table 1).

Although the acacia-charcoal mixture yielded superior stress-bearing capacity, it also showed higher variability, as inferred from the standard deviations. The *Balanites*-charcoal adhesive, on the other hand, showed better consistency, suggesting predictability and stability. Comparisons of the recorded shear moduli between the *Balanites*- and acacia-based adhesives did not rise to the level of statistical insignificance (Kruskal-Wallis test $H=3.66$, $p=0.159$; confirmed via Dunn's post-hoc test with Bonferroni correction). On the other hand, differences in shear strength as well as maximum shear stress were significant between *Balanites*- and

acacia-charcoal (Mann-Whitney test, $p=0.0001$ in both cases).

The shear stress-strain curves for the three different compound adhesives tested are distinctively different (Fig. 3). The *Balanites*-charcoal adhesive exhibited a linear behavior initially, followed by vertical drops after the maximum shear stress was reached, hence a characteristically catastrophic failure. On the other hand, our acacia-based adhesives showed plastic failure, with the acacia-ochre-beeswax mix showing a much gentler drop (Fig. 3). An initial linear behaviour was observed for the acacia-charcoal adhesive and, in instances where a higher stress was recorded, humps were observed after the maximum stress value. The variability in these curves thus highlights not only the differences in shear strength but also in their stress-strain trajectories and failure behaviors.

Photomicrographs of the adhesives after the shear tests further exhibit the catastrophic and exclusively adhesive- or substrate-based failure of the *Balanites*-based adhesive tested in this study, emphasizing the stiff and brittle nature of the resin and the stronger intramolecular bond within

the adhesive than with the adherend. The acacia-charcoal adhesive exhibited an intermediate ductile failure where the cohesive failure after a certain threshold is characterized by internal cracks. The acacia-ochre-beeswax adhesive, on the other hand, exhibited a failure with the clearest ductile fracture most visible in the smear trace on the cohesively failed surfaces, which indicates the highly elastic properties due to the beeswax addition and better adhesive-adherend bonding (Fig. 4). Similar patterns have been documented for acacia-ochre-beeswax adhesives in other experiments (Kozowyk et al. 2016).

Compressive strength data for the *Balanites*-charcoal and acacia-ochre-beeswax adhesives reveal a range of performance patterns that suggest their differential suitability for specific functions. The *Balanites*-charcoal adhesive showed a much higher elastic modulus, hence considerably stiffer and more resistant to deformation under stress than the acacia-ochre-beeswax adhesive. This stiffness is matched by its capacity to withstand greater force, as indicated by an average maximum force four times as high as that of the acacia-ochre-beeswax adhesive. Furthermore, the

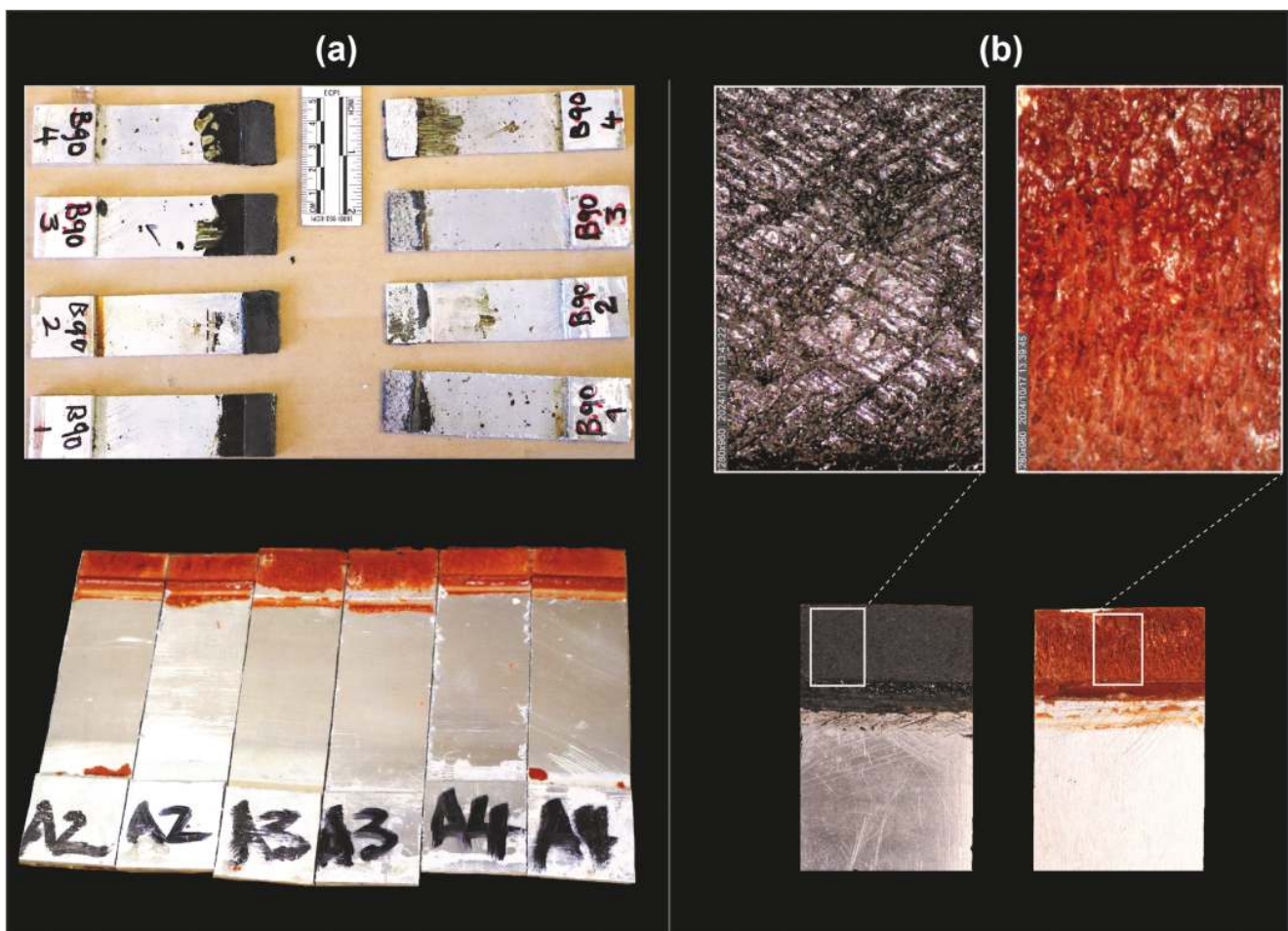


Fig. 4 Failure behavior. (a) Example of *Balanites*-charcoal and acacia-ochre-beeswax test laps showing adhesive and cohesive failure patterns, respectively. (b) Photomicrographs of surfaces showing a clean break for the *Balanites*-charcoal, and a smear for acacia-ochre-beeswax adhesives

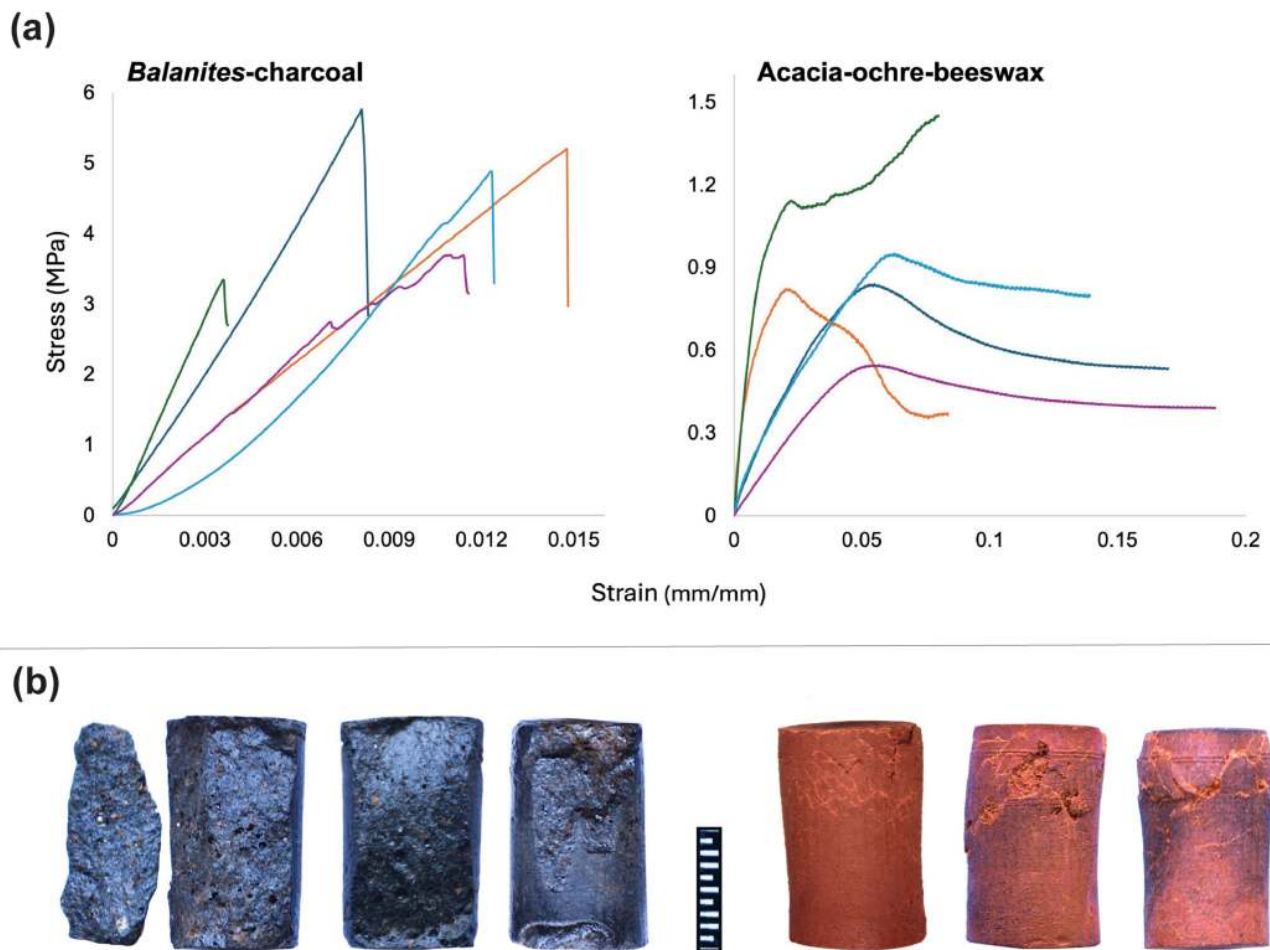


Fig. 5 (a) Stress-strain curves from the compression tests on *Balanites*-charcoal and acacia-ochre-beeswax adhesives. (b) Patterns of failure during the compression tests depict shattering and longitudinal break-

age of the more brittle *Balanites*-based adhesive, and plastic deformation with side bulging and minimal cohesive cracking of the acacia-ochre-beeswax samples

Balanites-charcoal adhesive exhibited greater compressive stress (i.e., internal resistance) than that of the acacia-ochre-beeswax mixture (Table 1; Fig. 5). As in the lap-shear test, the stress-strain curves for the *Balanites*-charcoal adhesive here exhibited an initial linear elastic behaviour until maximum stress was reached. Following this, brittle failure occurred with the absence of plastic flow unlike the acacia-based adhesive. The distinct failure patterns are also visible in the morphologies of the tested specimen where the acacia-ochre-beeswax samples were deformed via bulging from the compressive stress, exhibiting minimal external cracking but never shattering. By contrast, all tested *Balanites*-charcoal samples shattered longitudinally, showing failure behaviors similar to compression-induced fractures in ceramic materials, in some cases even registering conical fractures that form in brittle materials such as rocks upon the application of point loads or impacts (Fig. 5b).

Discussion and conclusions

The production and use of technologies is affected by contextual factors, including raw material type and availability, functional needs, and sociocultural attributes (Lemonnier 1993; Weedman 2002; Zipkin et al. 2014; Sahle et al. 2025). Comprehensive comparisons of technologies must, therefore, consider these dynamics. For example, investigations of the context in which each compound adhesive type is produced and used promise better insights from mechanical adhesive tests beyond comparative performance. Where different raw material options are available for the user, the factors determining the differential technological choices and decision-making processes must be similarly closely examined.

The performance of adhesives particularly when subjected to shear and compressive stress is informative about their bonding strength, elasticity, and stiffness. The *Balanites*- and acacia-based adhesives tested in this study have

distinctive bond strengths as well as elastic properties that affect their suitability for different functions. While the tool user's intention is generally to attain the desired adhesive quality from a mastic, it is important to recognize that this cannot be always measured in terms of adhesive bond strength. In cases where the role of the adhesives is to mechanically, rather than adhesively, secure a stone insert in the haft, stiffness becomes an optimized quality while elasticity and adhesive strength beyond a given threshold may not be as prioritized. In this regard, the results of our ethnographic experiments are consistent with the interpretation of Kozowyk and colleagues (2016) that the intended purpose (e.g., as filler, stabilizer) and context of adhesive use must be considered in archaeological inferences.

The *Balanites*-based adhesive required significantly shorter curing time, but this also means that consistent heating and adjustment within a short time window is required in its use for hafting. By contrast, the acacia-based adhesives require greater curing time, which allows for moldability across a longer time window. The addition of beeswax further enhances the elasticity of an adhesive, thus requiring even longer curing time during which the adhesive remains largely moldable (Wadley et al. 2009; Kozowyk et al. 2016). These patterns affect (re)tooling in settings where a stone artefact is hafted to an organic handle. We thus infer that adhesives using such plant exudates as the *Balanites* resins would be most suitable for activities that are performed near home bases where there is easy and persistent access to fire, and for tasks that prioritize securing a piece in place such as in wooden haft sockets.

It has been suggested that adhesives with lower stiffness may be more suitable for hafting hunting weapon tips and/or barbs where their deformation and dislodgement within a prey animal upon impact might be a desired advantage. This would be particularly plausible in cases where the adhesive is meant to hold the piece in place until initial impact during which poison is delivered, rather than potentially fatal blows through greater penetrative depth (Bradfield 2015; Sahle and Lombard 2024; cf. Aleo et al. 2024). Contrary to this, and as is the case in our studied examples, adhesives with similar properties to the *Balanites*-charcoal mix would be more suitable for functions as fillers and mechanical stabilizers, such as by securing a scraper inside a handle socket.

Notwithstanding variation in raw material type and experimental settings, differences in the proportion of plant-derived main adhesive substances, loading agents, and plasticizers have been shown to variably influence the adhesive and mechanical behaviors (Wadley et al. 2009; Kozowyk et al. 2016). The results from our compressive tests highlight similar differences along the mechanical properties and potential applications of adhesive materials where charcoal

plays a similar stiffening role as other loading agents such as ochre. The addition of beeswax makes adhesives even more elastic and helps prevent brittleness and cracking. However, such additive compromises the adhesive stiffness and ability to resist deformation under stress, which could be a disadvantage depending on the task and haft type. As demonstrated experimentally, some plant exudates can maintain relatively high bonding strength when used without any loading agent (Kozowyk et al. 2016). In cases such as ours, this is not a quality prioritized by the toolmakers.

The availability of raw materials greatly influenced adhesive choice and production (Langejans et al. 2022; Schmidt et al. 2024a; Chasan et al. 2024). *Balanites aegyptiaca* is native to arid and semi-arid regions, such as is much of the Konso country (Belkin et al. 2006; Tesfaye 2015; Sahle et al. 2025). On the other hand, in the Gamo highlands, where *Balanites* trees do not grow, acacia resin combined with charcoal is used for the same function of securing hidescrapers in the sockets of wooden handles (Arthur 2008). Yet another plant exudate (i.e., *Euphorbia* latex) is used by the Hadiya as the main ingredient of the compound adhesive (Sahle 2019). Given the Konso, Gamo, and Hadiya all use their adhesives for the same function, the differential adhesive use reflects technological solutions developed in response to environmental constraints, hence emphasizing local resource availability while maintaining the desired functionality. In archaeological cases, different adhesive types may have similarly been adopted as long as the minimum requirements for adhesive strength, elasticity/stiffness and failure behaviors are met.

A comparison of the mechanical properties of various exudate-based adhesives and the thermally processed birch tar reveals two fundamentally different approaches to achieving the desired functional performance (e.g. Schmidt et al. 2021, 2023a; Kozowyk et al. 2017). The *Balanites* resin-based compound adhesives—as well as the experimental acacia-based mixes—gain their strength through a composite strategy, quickly reaching a shear modulus of ~3 to 4 MPa and a maximum shear stress of up to 0.91 MPa (Table 1). By comparison, Schmidt et al. (2021, 2023a) have shown that birch tar produced using the double-pot method initially lacks adhesive qualities and must undergo additional cooking and controlled thermal reduction to develop its mechanical properties. This process dramatically raises the tar's shear modulus to about 3.13 GPa, and allows its shear strength to increase greatly. Therefore, while the exudate-based compound adhesives rely on material combination for their bonding strength, the performance of birch tar is derived from an expert thermal manipulation of its chemical structure. Producing a high-performance birch tar adhesive is, therefore, more technologically demanding, requiring not only its initial preparation but also a time critical and

high-risk reduction phase that must be carefully managed to avoid irreversible degradation from overheating.

The stress-strain behaviour of these adhesives further illustrates their differing mechanical responses and likely failure modes under load. The relatively ductile or quasi plastic deformation of exudate-based adhesives can be advantageous for hafted tools as it prevents sudden and irreparable breakage. Birch tar, on the other hand, undergoes a notable change in rupture behaviour as cooking time increases, with extended reduction leading to a more brittle tar material that fractures abruptly at its peak shear stress (Schmidt et al. 2023b). The implication here is that a skilled birch tar maker could deliberately tailor the adhesive's failure mode, choosing between a gradual, ductile yield or a strong, brittle break, depending on the functional needs of a tool, whether a rigid projectile point or a hand tool requiring shock absorption.

The selection and optimization of adhesive recipes reveal the breadth of knowledge of Stone Age toolmakers about the distribution and properties of resources that can be utilized for their technological production. By balancing resource availability, mechanical behaviors, and other functional requirements, early humans would have thus exploited a wide variety of plant resources than have been documented in ethnographic and archaeological contexts (Chasan et al. 2024; Schmidt et al. 2024a). The accumulating data thus underscore not only the knowledge of different plant adhesive materials and production techniques but also the behavioral flexibility of early humans in adopting different adhesive technologies within the context of raw material constraints and functional necessities. Such ability to adapt recipes to specific contexts and circumstances reflects a broader understanding of material properties, resource management, and functional optimization, and even the simplicity of technological solutions that have contributed to the adaptability of early human material cultures, sometimes without the need to invoke cognitive implications based only on the length of the production sequence and the number of recipes. Where the desired outcome could be attained through fewer steps and using multiple alternatives that meet the minimum functional requirements and are suited for the type of haft, there would not be a practical reason to choose otherwise.

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Author contributions Y.S. conceived the research. M.M., Y.S. and S.A. collected samples and data. M.M., Y.S. and S.G. developed method and analyzed the data. M.M. and Y.S. wrote the main manuscript text and prepared figures. All authors reviewed the manuscript.

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Data availability Data that support the finding of this study have been provided within the manuscript or electronic supplementary materials.

Declarations

Competing interests The authors declare no competing interests.

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