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EXPERIMENTAL METHODOLOGIES IN ASSESSING CERAMIC SHRINKAGE IN RESIDUAL FINGERPRINTS FOR ARCHAEOLOGICAL APPLICATION

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EXPERIMENTAL METHODOLOGIES IN ASSESSING CERAMIC SHRINKAGE IN RESIDUAL FINGERPRINTS FOR ARCHAEOLOGICAL APPLICATION

A Thesis
Presented to the
Faculty of
California State University,
San Bernardino

In Partial Fulfillment
of the Requirements for the Degree
Master of Arts
in
Applied Archaeology

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by

Luke Aaron Burnor

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Approved by:

Dr. Matthew Des Lauriers, Committee Chair, Anthropology

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ABSTRACT

This research evaluates the extent of ceramic shrinkage using a natural clay source that was locally available and known to be used by native populations in the American Southwest. The experiment took into account variables of temper mixture and firing temperature to assess the extent and potential need for shrinkage calibration in archaeological biometric research (specifically fingerprints). An experimental design was employed to test shrinkage rates while accounting for natural temper materials found frequently in the archaeological record including sand, grog, and quartz. The experiment evaluated whether shrinkage rates may have skewed data collected in previous studies regarding sex and age determination from fingerprints left in ceramic artifacts, that can be corrected for with proper calibration protocols. The purpose of this experiment was to show whether ceramic shrinkage is variable and dependent on temper, temperature, and clay and if further research is necessary to determine specific shrinkage rates before fingerprint data obtained from fired clay can be used to determine probabilities of age and sex. The results of the experiment showed significant shrinkage rates ranging between 10.4–25.4% depending on temper and temperature. These values greatly exceed the standardized rate of shrinkage currently used for calibrating biometric research in archaeology. The experiment demonstrates that similar experimentation is required to calibrate data relative to the unique clay source, temper, and firing temper that the biometric data is collected from.

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CHAPTER ONE:

INTRODUCTION

The purpose of this thesis is to evaluate merit in assessing ceramic shrinkage for the purpose of calibrating biometric data on fingerprints left in pottery found in the archaeological record. The goal is to assess the need for further research and experimentation via the testing of additional clay sources and tempers relative to the appropriate region in which specific biometric data sets are derived. The experiment tests a single clay source obtained from the Salton Trough that was refined and produced using traditional methods and mixed in a series of batches. The purpose of the experiment is aimed at testing the shrinkage rate of the base clay as well as the clay mixed with a variety of tempers sourced from the region and fired at different temperatures to evaluate the effects. The results of the experiment were used to evaluate the necessity of biometric calibration and answer several research questions presented in the Materials and Methods section below.

The experiment demonstrates that shrinkage occurs to a greater degree than accounted for in current biometric research in archaeology, by as much as 23.4%. Currently the standard rate of shrinkage used in research is 7.5%, however the results of my experiment show a range much greater than this, even before firing occurs, and is greatly dependent on temper and firing temperature. When accounting for these new rates of shrinkage, ageing and sex determination results appear to change significantly and can be used to formulate new interpretations. Therefore, a thorough examination of current standards and methods is necessary to produce more meaningful data.

Previous experimentation has been limited, however what little data has been generated has been used to build the foundation for an entire mode of interpretation that is being used in archaeology more frequently. This type of research is nuanced and highly dependent on appropriate materials and preparation methods. For example, clay used in art studios and conveniently bought ready-made has been purposefully refined and created to withstand the effects of shrinkage and tolerate high rates of fire. Refined and natural clays generally shrink by 7 to 10%, although the full range is thought to be between 0 and 20% (Králík and Novotný 2003, 12). The latter end of this possibility warrants further investigation. However, little has been done, within the discipline of archaeology, to further assess rates of ceramic shrinkage for traditionally used sources of clay.

In one of the few examples, Kamp et al. (1999, 313) assessed Sinagua clays mixed with volcanic cinder by firing tablets of an unknown size for 3 hours at 800˚C (1472˚F). The experiment found only a .05mm difference after air drying and a further .002mm difference after firing, leading Kamp and colleagues to determine shrinkage was not significant enough to warrant further consideration within the experiment. The experiment tested a single type of clay with a single temper fired at a low temperature. However, a deeper examination of the multitude of variables involved in the production of ancient ceramics is necessary.

Since the publication of Kamp et al.'s work, minimal attempts have been made to further investigate rates of shrinkage for biometric calibration. Research conducted by Miroslav Králík (2000) for a Masters thesis evaluated the rate of clay shrinkage and concluded that the average rate can be calculated at 1.08108, or 7.5%. This calculation was used to modify the Kamp et al. linear regression equation to account for a single shrinkage rate. This, however, is reductive considering that Králík also states that shrinkage rates, as mentioned above, may vary by up to 20% (Fowler et al. 2019, 1482). Despite this, many investigations (e.g., Fowler et al. 2019; Králík and Novotný 2003; Lambert et al. 2018) in the archaeological investigation of sexing and ageing fingerprints have perpetuated this calculation. This calculation is now used as the standard for shrinkage calibration for biometric data collection in archaeology today. This thesis proposes an approach appropriate to each context in which fingerprint data is found. The experiment conducted is intended as an example of the method of how shrinkage rates should be assessed for the accurate calibration of biometric data.

The research aims to provide a thorough examination of the development of fingerprint technology as well as its transition into archaeological application. The processes of ageing and sex determination based on measurements of the papillary terrain on fingertips is explained to provide a foundation for

understanding biometric research in archaeology today. An exploration of the formation of fingerprints in the archaeological record and the raw material, tempers, and temperature used to create the ceramic on which they are impressed, and most often preserved, is described in detail. This thesis approaches these topics to contextualize why calibration of biometric data is important for accurate interpretation and support further experimentation to produce more meaningful data.

CHAPTER TWO:

CONCEPTUAL BACKGROUND

Fingerprints have been used for millennia as a form of identification (Grzybowski and Pietrzak 2015, 117). The practice of modern fingerprinting is primarily utilized in the forensic sciences but also finds applications in biometric security and the detection of some hereditary diseases (Babler 1991, 95; Gutiérrez-Redomero et al. 2013, 592; Rosa et al. 2002, 1512). From its inception, fingerprint analysis sought to identify generally unique and individualistic traits in the patterning of the papillary terrain (characteristics of the fingerprint surface) to match fingerprints with individuals. The papillary terrain primarily consists of ridges (the raised lines of the fingerprint), furrows (the lower depressions between ridges), and minutia (small unique features of the papillary terrain such as ridge endings and forks). The general patterning of the ridges and furrows, along with minutia, are unique to each person, even (to a degree) among identical twins (Jain et al. 2002, 2661–2662).

The systematic exploration and documentation of fingerprint characteristics was pioneered by the Czechoslovakian physiologist Jan Evangelista Purkynje in 1823 (Grzybowski and Pietrzak 2015, 118). Purkynje observed the ridges and furrows of the papillary terrain and attempted to classify the various whorl, arch, and loop patterns (identifying 9 in total) that varied from person to person, and even finger to finger (Galton 1892, 85–88). In the 1870s Sir William Herschel, the chief administrator of the Jungipoor district of India, collected fingerprints at the signing of contracts for later verification against fraud. It was Herschel's collection that was later used by Francis Galton in the 1890s to bring fingerprints under scientific scrutiny and further identify defining features, which he called "minutia" that significantly increased the possibility of positive matches (Galton 1892, 27–29; Stigler 1995, 859). Galton, among others, championed the need to incorporate the use of fingerprints in criminal investigation stating that, "a sure means of identification is to benefit society by detecting rogues" (Galton 1892, 149).

However, the forensic process we use today is attributed to several sources, each contributing to the growing concept of analyzing the unique features of fingerprints for investigative application at the end of the 19th century. In 1896, fingerprint identification was utilized by the English police officer Sir Edward Richard Henry to identify criminals from fingerprints left at crime scenes (Grzybowski and Pietrzak 2015, 120). In the same year, Croatian-born Juan Vucetich developed comprehensive fingerprint analysis for use in conjunction with a complex *Sistema Dactiloscópico Argentino* (Argentinian Dactyloscopy System), for the Argentinian police – a large referenceable index of repeat offender fingerprints. This system was immensely successful and would later become the model and inspiration for similar systems around the world (Garcia Ferrari 2016). It is Vucetich that is credited with the first arrest and conviction of a criminal based on fingerprints found at a crime scene (Teitelbaum 2018, 16). Fingerprinting in forensics was arguably the largest breakthrough in criminal investigation in history, debatably second only to 20th–century breakthroughs in DNA analysis.

For the last century, fingerprint analysis and technology have advanced significantly. Fingerprint comparison has largely been automated, returning matches in a fraction of the time it took to train analysts and compare them manually. The system of print classification has also become more sophisticated with the classification of three different types of residual fingerprints: latent, patent, and plastic (Yamashita and French 2011, 3–4). Latent prints refer to fingerprints that have been left by the oils and sweat secreted by the glands on the finger. Patent prints are visible copies of the print (either transferred from the finger to a surface or lifted by the finger from a surface and leaving a negative print) left in or on a type of medium such as paint, ink, or dirt. Lastly, plastic prints are three-dimensional prints left in a plastic medium such as clay, wax, or mud. Additionally, analysts have produced various comprehensive methods to determine the sex and general age of the individual who may have left prints behind.

Sexing Fingerprints

In recent decades fingerprint analysis (or dermatoglyphics) has explored the potential for sex and age identification through calculations of average ridge densities using a variety of imaging techniques and mathematical approaches, to be used primarily in the forensic sciences. The overall concept was to narrow the suspect pool by being able to determine, with a level of confidence, the sex and general age of the individual whose fingerprints were discovered at the crime scene.

Mark Acree (1999) produced a comprehensive study for the Federal Bureau of Investigation (FBI), to assess previously unsubstantiated claims that fingerprint ridge densities varied between men and women. Acree produced a methodology of selecting a 5mm x 5mm ($25mm^2$) portion of the papillary terrain above the “central core” that featured relatively parallel ridges to calculate ridge densities within the defined space. Upon application of Bayes Theorem, his study concluded that “a given fingerprint possessing a ridge density of 11 ridges/$25mm^2$ or less is likely to be of male origin. Likewise, a fingerprint having a ridge density of 12 ridges/$25mm^2$ or greater is most likely to be of female origin.” In this study, Acree sampled 400 individuals: 100 Caucasian males, 100 Caucasian females, 100 African American males, and 100 African American females. The results showed significant differences in epidermal ridge densities between males and females of both groups. Acree’s study was the first to conclusively show, through empirical study and a significant sample size, that it is possible to differentiate male and female fingerprints with a high level of confidence (95%). The study also presented a replicable method that would subsequently become the standard baseline for dermatoglyphic sexing.

Since the publication of Acree’s study, a multitude of experiments and research papers have been produced on the subject. Several of them have been focused on whether males and females within specific ethnic populations possess statistically significant differences between ridge densities within a defined area. Acree’s method of selecting a single 5mm x 5mm portion of the fingerprint was modified by Gutiérrez-Redomero and colleagues (2008) to include distal, radial, and ulnar portions of given prints, as well as a single central proximal area from all 10 fingers to provide stronger conclusions. This method was then reproduced throughout many of the later investigations into sex differences in the various populations. These population-specific studies include investigations into the differences between male and females, in addition to Acree’s 1995 study of Caucasian and African-American populations, in south Indian populations (Gungadin et al. 2007; Nithin et al. 2011), Spanish populations (Gutiérrez-Redomero et al. 2008), Chinese and Malaysian populations (Nayak et al. 2010), Egyptian populations (Eshak et al. 2013), Filipino populations (Taduran et al. 2016), and north Indian populations (Krishan et al. 2013), among others. All these studies concluded with ANOVA or t-test p-values indicating that statistically significant differences occur between male and female ridge densities within the population. The majority of these studies also calculated density thresholds using

Bayes Theorem to determine the probability that a given ridge count would belong to a male or female.

Mundorff and colleagues (2014) produced their own method for measuring ridge densities, measuring the linear span of 10 parallel ridges selected from an arbitrary distal portion of the fingerprint of 250 males and 250 females. Although the process differs from the Acree method by measuring the linear length of a set number of ridges instead of within a defined area, Mundorff and colleagues' experiment produced the same conclusion; males and females have a statistically significant differences in mean ridge densities. This method produced an 83–89% accuracy rate for the determination of sex. The authors also noted that the difficulty of achieving higher accuracy was found in a correlation between weight and stature affecting higher or lower ridge counts (i.e., shorter men possess smaller fingers and therefore greater ridge densities, heavier women possess thicker fingers and therefore lower ridge densities).

Several studies have explored whether the differences between male and female fingerprints from a specific population are distinguishable from other ethnic populations (e.g., Gutiérrez-Redomero et al. 2013a: Gutiérrez-Redomero et al. 2013b). The overall goal was to find whether it would be possible to further narrow the suspect pool by identifying the likely ethnic background of the individual who left prints. These studies, as well as those previously mentioned, have shown that while distinguishable differences between male and females exist, the thresholds between different populations fluctuate within overlapping parameters, making the distinction of populations difficult. Part of the difficulty of reaching a higher level of confidence for all aging and sexing studies may lie in genetics. The difference between male and female sexes, as well as genders, is not a definitive and binary line and, in reality, represents a spectrum (See Gero and Conkey 1991). The results of these studies and of the following research refer to results obtained from individuals who were born biologically male or female regardless of gender identity.

Aging Fingerprints

During embryonic development, approximately between the 10th and 13th weeks, the subsurface basal layer of the epidermis begins to form a corrugated undulating structure. This structure places pressure on the surface of the skin forming, by week 16, the basis of the pattern of the papillary terrain (Kücken and Newell 2005, 72). Primary ridges (those possessing sweat glands) and secondary ridges continue to spread and join with other growing ridges, which creates unique patterning shapes, until the entirety of the surface of the skin is populated with ridges. At approximately 24 weeks after conception, the papillary terrain is fully formed (Babler 1991, 100) and the pattern of the fingerprint will remain constant throughout the lifespan of the individual (Kücken and Newell 2005, 72–73). However, while the pattern may never change (with the exception of scarring and disease) as the individual grows, the overall thickness of the ridges increases (David 1981, 280).

The study of ridge breadth has been a subject of interest for almost a century. In 1924, A.F. Hecht (1924) conducted one of the first explorations into the growth of papillary ridges and found that average ridge breadth increased as an individual aged, theorized at the time as part of tactile sensory development. As the body grows, the individual becomes taller, the hands elongate, and the body gains mass until the individual reaches biological maturity. All of these factors lead to an increase in ridge breadth (Cummins et al. 1941, 138). As with ridge density, it was observed that men tend to have more robust ridge breadths, showing that the overall growth of the fingerprint is directly affected by the individual's sex chromosomes (David 1981, 281).

Outside of archaeology, current research into mean ridge breadth (MRB) and the changes to fingerprints that occur through adolescence is somewhat limited. One study, however, has attempted to model growth of the overall expansion of the pattern to provide law enforcement with age progression estimates for better positive match returns (Gottschlich et al., 2011). While this is not directly related to calculating MRB to estimate the age of a fingerprint, it may prove invaluable to future investigations of age estimates via alternative or combined methodologies.

CHAPTER THREE:

THEMATIC BACKGROUND

Fingerprints in Archaeology

Fingerprints are found in a variety of mediums throughout the temporal span of the archaeological record. These residual imprints are dependent on an individual's contact with a plastic medium such as clay, resin, or mud and leaving a three-dimensional imprint (Králík and Nejman 2007, 5). While the study of dermatoglyphics has seen a significant advancement in its capability through the identification of individuals in forensics, its application to archaeology has seen a marked increase in the last few decades with the introduction of various studies and technological advances. While fingerprints are often found on paper, parchment, mud, or other imprintable materials, clay is an ideal medium for capturing prints as the material is highly plastic. The moist nature of clay during the formation of vessels is highly conducive to the transfer of the papillary terrain and the firing process serves to harden and preserve prints. In the past, fingerprints were often seen as a novelty, a small link to an individual practicing a craft long ago. While this notion may still linger, archaeologists around the world are utilizing fingerprint data to bring new interpretations to analysis, largely concerning craft production and social dynamics, as the identities of potters are revealed.

Archaeologists are more likely to see value in dermatoglyphic data when there are several preserved fingerprints discovered between artifacts or during a small temporal span, as opposed to singular or few prints. While forensics is often concerned with the identification of an individual, archaeology is primarily concerned with the agency and practice of individuals as they relate to and participate in their community. However, the transition to studying dermatoglyphics of past populations brings with it an entirely new set of difficulties. For example, the potential for identifying individuals without a full set of prints to compare results to is challenging considering fingerprints differ from finger to finger and the assumption that differing fingerprints belong to separate individuals is problematic potentially leading to false interpretations (Lambert et al. 2018, 64; Rockwell 1970, 77). However, publications within the last 30 years are rife with examples of how fingerprints are being used in the archaeological world. It might be more effective to discuss the methodological challenges and ways in which they may be resolved by providing specific examples attempting to apply various approaches to paleodermatoglyphics.

In 1996, Chrisman and colleagues (1996) discovered baked clay nodules with impressions of finger and palm prints associated with extinct faunal remains and crude tools in Pendejo Cave, New Mexico. Several well-preserved strata containing datable charcoal returned pre– and post–Clovis dates ranging from 12,000 to 37,000 years BP. Clay petrography showed that the clay was composed of alluvial material, contrasting with soils found in the cave, and was not part of the natural in-situ soil, and was therefore likely brought there during the occupation. Using experimental comparisons, the clay was found to have been likely baked between 120 and 300˚ Celsius. Archaeologists illuminated and photographed the fingerprints using parallel beam fiberoptics to enable detailed analysis, resulting in the identification of patterning, minutia, and several sweat pores. All primates possess friction ridges on their papillary terrain and, considering prehistoric ecology and analysis of the sweat pore frequency, it was concluded that the fingerprints were likely human in origin.

In 2011, Mull and colleagues (2011) analyzed the preserved fingerprints of a bog mummy dubbed the “Girl of the Uchter Moor” or “Moora”. Analysis of the preserved right hand of the woman determined that she lived 2,650 years ago in Lower Saxony, Germany. Mull and colleagues used a combination of photography and image enhancement to record Moora’s fingerprints and catalog them into the Automated Fingerprint Recognition System (AFIS). Their analysis revealed visible and recognizable fingerprints on all five fingers, detailed enough to categorize pattern type (whorl on all 5 fingers) and identify at least 25 points of minutia. Due to contraction from decay and exposure, the authors estimated fingerprint shrinkage to calibrate their biometric results. Their goal was to use previously published research on the frequencies of fingerprint pattern types in continental populations to assess the likelihood of Moora’s genetic origin. A secondary goal of the research was to enter her fingerprints into the AFIS database for the possibility of making future matches. However, the feasibility of this secondary goal remains to be seen.

Lambert and colleagues (2018) investigated a multitude of finger and palm prints at a Roman outpost ceramic workshop with two production zones in Lezoux France, dated to approximately 30–175 AD. Their investigation aimed to identify fingerprints and determine whether the same individuals were involved in production at both sites, establish a minimum number of individuals, and explore age and sex estimates cross-referenced with funerary remains to examine the demography of the potters. The authors were interested in whether it was possible to identify individuals with specific tasks at the sites and evaluate whether age and sex determined these roles. Their sexing and aging methods followed the same techniques outlined later in this thesis, and used a fixed standard determined for clay shrinkage rates in age estimation. Their results found limited success, but the authors were able to determine that mostly young adults worked at the sites.

Lichthenburger and Moran (2018) investigated a Roman oil and figurine production site in Beit Nattif, Israel. This site was dated to approximately 300 AD and contained the waste fragments of several broken wares, with almost 20% of them possessing fingerprints. At the time of publication, fingerprint research was still being conducted, but it was determined early through manual comparisons that the majority of the prints belonged to the same individual. This single producer was identified on both oil lamps and figurines. Some of the material also showed signs of experimentation in the craft, but these elements were never produced afterward.

It is apparent from these examples that the analysis of finger and palm prints found in archaeological contexts possess the potential to contribute to the greater understanding of the human environment. They represent the multitude of potential avenues and methods used in the past that lend to the advanced analytical and methodological processes operating today. The examples presented above demonstrate the need to assess shrinkage for the accurate assessment of biometric data. An assessment of the conditions under which the finger or palm impressions were created and the circumstances that may have altered or distorted their accurate collection is required to make conclusions of biometric data. Without a form of calibration to assess shrinkage rates or distortion, the results of biometric data analysis can be flawed and misleading.

Preservation of Fingerprints

Archaeological fingerprints are found in a multitude of environments and on a vast array of mediums. Fingerprints have been preserved and studied on mummies and bog bodies, imprinted in the resin of oil lamps, found on cave walls in paint and ochre, on photosensitive film plates, and various other places and objects (Králik and Nejman 2007, 6–9). However, arguably the most frequent fingerprints in the archaeological record are preserved in ceramics. Clay is an ideal medium for capturing prints. The material is highly plastic and the moisture content of the clay, during the formation of vessels, is highly conducive to the transfer of prints. Clay vessels are also often formed by hand, several of the formation and decorative processes involve pinching and tactile manipulation in addition to requiring the potter to place the finished product in a kiln, pit, or space to dry, often leaving prints in the process. This makes the production of clay wares one the crafts with the highest potential for producing fingerprints in the archaeological record (Rockwell 1970, 82). Additionally, as clay loses its moisture during drying, the mineral composition of the clay contracts and becomes more compact increasing the durability of the clay. If the vessel is fired, the clay loses most, if not all, water, the matrix of the ceramic body may expand or contrast, and the crystalline composition of the minerals present in the clay may collapse or form new silicates (Stinson 2004, 161). The use of some techniques, such as burnishing, slipping, or painting the ceramics may obliterate fingerprints (Fowler et al. 2019, 1481) but in some cases may act to preserve the prints underneath paint or slip (Králik and Nejman 2007, 6). The resulting fired product is a highly durable material that retains excellent preservation, including the fingerprints they bear. Depending on the environment, these prints may last tens of thousands of years, as seen by the discovery of a fingerprint fragment on a Venus figurine dated to 25,000 BP (Králík et al. 2002, 107).

Sexing Fingerprints in the Archaeological Record

In recent decades, the publication of forensic sex determination studies and the refinement of these techniques have opened new avenues for analyzing the archaeological record. Archaeologists are beginning to move from proving that the method of fingerprint sex determination works to focusing more attention on how that information is applied and generating new interpretations and conclusions. Now, fingerprint data is presenting new challenges to traditional models concerning age and gender roles, the assessment of artisan demographics, and the examination of the production life of individuals. (Bennison-Chapman and Hager 2018; Fowler et al. 2019; Kantner et al. 2019; Lambert et al. 2018; Lichtenberger and Moran 2018; Sanders 2015; Stinson 2004). However, with the transition of applying methods developed for forensic analysis on living populations to its application on material remains of the past, the process encounters both new advantages and challenges.

Paleodermatoglyphic studies, regarding either sexing or aging, benefit from requiring much less of a finger imprint than is needed for positive matches to individuals. However, the accuracy of the conclusions made from these studies improves when researchers have access to a large sample size known to be created by a single population (Sanders 2015, 230). The population studies mentioned above (Acree, 1999; Eshak et al. 2013; Gungadin et al., 2007; Gutiérrez-Redomero et al. 2008; Krishan et al. 2013; Nayak et al., 2010; Nithin et al. 2011; Taduran et al., 2016) have shown that while men possess, on average, coarser ridges and lower ridge densities than women, the two groups overlap.

This is true within and outside of specific populations. Archaeologists cannot assess sex and age from single prints. Therefore, sexing and aging fingerprints found in archaeological assemblages require a significant sample size to produce statistically significant results where data can indicate multi-modal distributions (Fowler et al. 2019, 1477–1478). This is especially true when considering that thresholds between male and female prehistoric populations would need to be determined from the sample as there are no (as of yet) existing baselines for comparison from living descendants (Stinson 2004, 158). In addition, comparing cross-cultural data is not a viable option (Fowler et al. 2019, 1478). When considering the fact that all modern population studies have shown definitively that men and women possess statistically significant differences between ridge densities, it can be assumed with a high degree of confidence that the fingerprints of prehistoric populations would possess the same differences. Working under this assumption allows paleodermatoglyphic research to proceed using techniques refined and tested on modern populations if the method accounts for variables associated with material, production, and taphonomic processes.

Sex determination techniques in the archaeology of fingerprints are primarily concerned with following the Acree (1999) method of calculating ridge densities within a defined area or determining mean ridge breadths (MRB). The use of both techniques in combination with age studies (outlined below) helps reduce the rate of error in determinations (Králík and Novotný 2003, 22–23).

MRBs are calculated one of two ways, by either measuring from the center of one furrow to the center of the next or measuring a defined length (usually 1 cm) from the center of a furrow in a linear direction featuring parallel ridges to the center of another furrow and dividing by the number of ridges contained on the line (Fowler et al. 2019, 1474). Both processes have been found to yield similar and positive results and requires only the preservation of a small set of sequential papillary ridges. However, if the friction ridge impression is unknown as to what portion of the epidermis was imprinted (i.e., palm, fingertip, foot), there may be calculation bias as different places throughout the epidermis (for example the proximal portion of a fingerprint versus the distal radial or ulnar portion of the print) possess courser ridges (Gutiérrez-Redomero et al. 2014, 203–204). Therefore, in the case of fingerprints, identifying some portion of the print pattern is especially helpful.

Several confounding variables have been identified in the process of aging and sexing. Regarding data collection and comparison between studies, it is imperative that the data are collected from the same portion of the print and using the same method. Some studies (Gutiérrez-Redomero et al. 2014, 205–206; Králík and Novotný 2003, 26) have expressed concern over compatibility issues within the results comparing different data sets produced from different methods, which have produced erroneous or conflicting results. Gutiérrez-Redomero and colleagues (2014), have called for a standardization of methods to solve this issue. The process of deformation is also to be considered when assessing biometric data on clay. When the finger comes into contact with clay and the papillary imprint is transferred to the raw material, the pressure and direction of the grip distort the print to some degree (Králík and Nejman 2007, 5; Stinson 2004, 106). Therefore, it is important for the analyst to carefully examine the type of material and the print itself for indications of extreme distortion and ensure the obscured prints subsequent elimination from the analyzed sample.

Another issue of concern, and the primary topic of this thesis, is the fact that the majority of studies concerning fingerprints are conducted on prints left on fired clay. Depending on the type of clay, clay grain size, amount of water in the raw material, mineral composition, temperature at which it is fired, and tempers added - clay may shrink or expand. Sexing and aging studies identify clay shrinkage as a variable that needs to be considered for the accurate collection of biometric data interpreted for age and sex studies. Considering the relatively fine units of measurement observed during the process of aging and sexing, the effects of shrinkage can skew data. For sex studies, this skew, for the case of expansion, the data are primarily skewed in favor of males, whereas in the case of shrinkage, the data is skewed in favor of females (Fowler et al. 2019, 1482).

Aging Fingerprints from the Archaeological Record

As with sexing, aging fingerprints in the archaeological record is becoming a mainstay in the process of analyzing archaeological assemblages. The notion of ‘a time dominated by men’ is being dismantled (Slocum 1975, 49) and in its place is an archaeology that considers all aspects of the human condition, the prominent roles of women, non-binary genders, queer studies, and children. Children are ever present within every society but their existence has often been overlooked in the archaeological record despite the presence of burials, offerings, toys, cradles, and a whole host of other material remains, that existed simply as props for silent actors lacking agency (Baxter 2008, 160–161; Kamp 2015, 166). However, new studies developed alongside the process of sexing fingerprints have begun to integrate the roles of children and their influence on the archaeological record back into the dialog of past societies. Through fingerprint analysis of ceramic (and potentially other) artifacts, archaeologists can determine with a relatively high degree of accuracy which were produced by children and which were produced by adults. This allows us a pathway to examine the roles of individuals in craft production and specialization throughout various age groups.

As previously discussed, the patterns of the papillary terrain are finalized in utero. This includes the number of ridges present within that pattern. As the child grows, their fingers expand, including their friction ridges (Stinson 2004, 174). The driving concept behind age determination from fingerprints is the width of these ridges. As the body matures and the individual reaches puberty, sex differences begin to appear in the detail of the fingerprint. Between approximately 16 and 19 years of age, the child reaches adult proportions and the width of the ridges begins to plateau into adult ranges. It has been noted that females tend to reach ridge breadths comparable to adult sizes at an earlier age than males (Králík and Novotný 2003, 25), making some female prints ambiguous between the post-pubescent age and full womanhood (Fowler et al. 2019, 1476). Because individuals cease to grow after reaching adulthood, the aging of fingerprints is applicable to only sub-adults.

Aging of fingerprints is, so far, achieved solely through calculating mean ridge breadths. It must be considered that archaeologists measuring fingerprints are measuring a negative relief of the original print, so the ridges on ceramic or other materials are representations of the finger furrows and the depressions on the relief are the ridges (Kamp et al. 1999, 311). The calculation of the MRB can either, as mentioned above regarding sexing, be measured from the center of one furrow to the center of the next or a grouping of ridges measured and divided by the number of ridges in the grouping. In 1999, Kamp and colleagues (1999) produced a regression equation that allowed the estimation of age based on MRB measurements with a 95% confidence interval at 4.5 years:

$$\text{Age (months)} = 614 \times \text{ridge breadth (in mm)} - 112$$

In their own study, Králík and Novotný (2003) produced several regression equations based on experimental studies of modern populations, tested against the Kamp et al. equation, to refine the accuracy of age estimates. They found that a modification of the original Kamp et al. regression equation (called *KAmod*) accounting for a shrinkage rate of 7.5% (or 1.08108), previously determined during Králík’s (2000) Masters thesis work, provided the best accuracy with a slightly smaller error rate of 2.36 years:

$$\text{Age (months)} = 614 \times \text{ridge breadth (in mm)} - 112 \times 1.08108$$

In this study, Králík and Novotný’s (2003) conclusion was that a mean ridge breadth of .4 mm represented the threshold between children and adults. However, as previously discussed in aging studies conducted in forensics, confounding variables such as weight, height, sex, and even ethnicity can produce fluctuations in these values (David 1981, 281; Kamp et al. 1999, 311; Mundorff et al. 2014, 893). Both studies represent the foundation of aging analyses being conducted currently in archaeology today. The Králík and Novotný *KAmod* equation can be modified further, as the addition of multiplying 1.08108 (7.5 %) that accounts for shrinkage can be replaced with any value the researcher determines for the shrinkage rate of a specific type of clay. It is this value that the present thesis seeks to determine for various types of tempers and firing temperatures in a single source of clay. Using the results of the experiment conducted for this thesis, these equations are revisited and the resulting values are substituted for the standard shrinkage rate presented in the *KAmod* equation.

CHAPTER FOUR:

CERAMICS

Pottery is one of the few long-lasting and durable materials found in the archaeological record. Countless ceramic sherds are found during survey and excavation projects throughout the world and are common in the United States. These remnants often represent the final step in a *chaîne opératoire*; a production method or sequence of operations (Leroi-Gourhan 1993, 164). This process begins with locating a source of raw material, producing usable clay, forming, decorating, and firing the vessel, use of the vessel for its intended purpose, and finally, the abandonment or destruction of the vessel. For hundreds or thousands of years these durable remnants are often preserved due to their mineralogical, geochemical, and thermal properties. This is a testament of the ingenuity of past peoples to transform a natural plastic material, through the controlled use of fire, into a material capable of withstanding the effects of time and nature while preserving the minute details of the fingerprints of its creators.

In the American Southwest, there is some debate as to whether ceramics were, based on trade and exchange evidence, produced somewhat intensively (Harry et al. 2013, 395) or produced within familial spaces at a small-scale (Van Keuren et al. 2013, 676). However, a general lack of pottery production workshops or specialization centers discovered in the Southwest has led some archaeologists to lean towards the latter (Crown 2007, 679; Tite 1999, 217).

Regardless, the use life of ceramics, in terms of the *chaîne opératoire,* remains the same. More importantly for the current research is that the production process and the individual potter (or potters) physically leave traces of their identity on the surface of the vessel. The process of producing clay vessels is often conceptualized as the work of a single specialized individual, but research in the last two decades has highlighted the idea that ceramic production is often divided among many individuals. The contributions of children in the process as they refine motor skills and develop skills have also been explored (Crown 2007, 677).

With this concept in mind, it is important to understand the major steps in and components of the ceramic *chaîne opératoire.* This is to examine several variables that contribute to the current thesis research on fingerprints in ceramics, associated shrinkage rates with consideration of ceramic type and tempers, as well as the accurate calibration of collected biometric data from aging and sexing studies in archaeological contexts. The following sections will briefly assess variables of ceramic shrinkage including clay, clay sources, tempers, and firing methods. These are not meant to be comprehensive examinations, but explorations of considerations to be taken into account during the experimental process contained within this thesis.

Ceramic Sources and Clays

When clay deposits form, there is a hydrothermal and/or depositional process that forms concentrations of rare earth, alkaline, and transitional elements. These elements serve as indicators of the contributing sediments that are produced from specific erosional environments (Ratto et al. 2015, 13–14). Therefore, clay deposits are products of the accumulation of lithic debris produced from the natural forces of erosion and deposition where the combination of specific geochemical and mineralogical components make each deposit unique (Bishop et al. 1982, 276). There is some debate among sciences that deal with clays concerning the precise definition of clay and the size of the minerals required to fit that definition. There is a general consensus, though, about the basic composition of clay, as well as plasticity with water, and hardening when dried (Bergaya and Lagally 2013, 5). A grain size of <2 μm (micrometers or .02 millimeters) is generally the typical size of clay particles although particle size may remain plastic at sizes of up to <4 μm (Guggenheim and Martin 1995, 258; Santacreu 2014a, 19).

The specific minerals contained in clay are referred to as hydrous aluminum phyllosilicates where the elemental bonds produce particles that ‘layer’ or ‘sheet’ which in turn stack or interlock to create the matrix of the clay when wet, including the pores between the particles (called capillaries), and remain bonded after water is evaporated through hydrogen cohesion (Bergaya and Lagally 2013, 5). The pores between plates create space in which the water added to clay is absorbed and lend to the increased plasticity of the paste while remaining adherent. Clays will therefore absorb between 15 and 50 percent of their dry weight depending on how fine and tightly packed the clay particles become. Clay retains water for a long period of time and, if not exposed to dehydrating environments, will preserve in its pliable hydrated form. Preserved wet clays are typically extracted from beneath a humus layer up to 5 meters deep (Santacreu 2014a, 65), although it is possible to collect dry clay and rehydrate it.

Clays are extracted in specific locations where sources naturally occur with craftspeople sometimes traveling many kilometers and across cultural boundaries to collect from sources known to be of high quality (Beck and Neff 2007, 289). After the clay is collected, transported, and ready for paste preparation, the clay is often ‘cleaned’ or improved through sifting of large inclusions or non-plastic material to homogenize the material and sometimes mixing in other types of clay (Tite 1999, 184–185). Depending on the technique, different types of clays or mixtures can be produced from the same sources (Santacreu 2014a, 75). During this process, different types of tempers can also be added to the mixture to improve or stabilize the paste during the drying or firing process (Bishop et al. 1982, 283). Tempers are discussed more thoroughly in the following section.

Analysis techniques will be addressed at the end of the current chapter, but a few topics are worthy of note here. When analyzing the mineralogical and geochemical properties of fired clay for the potential source, the refinement process of removing inclusions, the addition of tempers, or the mixing of two different clays are important considerations that may alter the chemical signature (Bishop et al. 1982, 276; Ratto et al. 2015, 14). In terms of fingerprint analysis, it has also been noted that the quality of fingerprint preservation in working clay is highly dependent on the clay mineral size with larger grains and inclusions potentially obscuring measurable prints. In this case, the collection of fingerprint data is better served by measuring a grouping of ridges to calculate ridge breadths and densities (Králik and Novotný 2003, 11).

Tempers

Tempers are non-plastic materials that either occur naturally or are intentionally added to clay pastes which function to improve the quality of paste for vessel formation (Bishop et al. 1982, 283) or regulate ceramic shrinkage during the firing process (Tite 1999, 185). These inclusions often possess qualities of low thermal expansion or produce pores, which create a ceramic matrix naturally tolerant to temperature change, preventing cracking, popping, or complete destruction of the vessel form during firing (Bishop et al. 1982, 314). Temper may also act to reduce the amount of water required to make the raw clay particles adherent and pliable, resulting in the reduction of the dehydration phase of firing and aiding in strengthening the internal structure of the ceramic (Santacreu 2014a, 69, 90). The materials used to regulate the ceramic paste varies by region and the geochemical properties of the clay source. ‘Cleaning’, the use of temper, and mixing multi-source clays all may alter the chemical signature and properties of the clay paste resulting in a more workable and stable ceramic (Ratto et al. 2015, 13). These ‘recipes’ are often refined, shared, and replicated across multiple generations (Santacreu 2014b, 379–380) resulting in a tradition of practice often seen in the archaeological record.

Natural ceramic tempers utilized around the world may include zircon (Tochlin et al. 2012), trachybasalt (Gonzalez et al. 2014, 59–60), granite, mica, limestone, feldspar, hornblende, or a variety of other volcanic, metamorphic, or sedimentary materials (Bishop et al. 1982, 281, 314). Materials often added to clay pastes as temper include plant fibers, bone, shell, ashes (Santacreu 2014a, 70), grog (crushed ceramic) (Harry et al. 2013, 386; Santacreu 2014a, 70), mixed sand, and crushed quartz (Hildebrand et al. 2002, 125, 127). As a matter of focus for the experimental portion of this thesis, tempers common to the southwest United States (specifically the Salton Trough and ancient Lake Cahuilla area of California) are considered more closely. These tempers, most commonly found in samples of Salton Buff and Lower Colorado Buffware, include crushed quartz, sand, and grog (Beck and Ferguson 2016, 263; Hildebrand et al. 2002, 130, 139).

Firing Methods

After the clay was prepared and the vessel was shaped into its final form, the clay required a substantial amount of drying. This allowed water in the clay matrix to evaporate and reduced the effects of rapid moisture loss and shrinkage during the firing process. This was achieved by letting the items rest in open air or baking in a low-temperature firing environment. Once this process was done, the item was then fired at full temperature. The method of firing may also vary by time and location with some groups in the past burying vessels in campfires or pits and some firing them in more stable environments such as ovens or kilns (Gliozzo 2020, 2). Open firing produces temperature ranges between 500–900˚C, whereas a more regulated and encapsulated environment, such as a kiln, may reach temperatures approaching 1000˚C (Tite 1999, 189). Several variables affect the outcome of the finished vessel and may produce varying results, these include the mineral content of the clay, natural or added tempers, firing environment (i.e., reduction or oxidizing), fuel type, temperature, and several others (Kostadinova-Avramova 2018, 617).

Ceramic was fired at a variety of temperatures in the past. In addition to reducing or eliminating the water content of the clay, firing also produces physical changes in the clay mineral structures themselves through bonding, vitrification, or sintering (Gliozzo 2020, 25). At temperatures ranges above 500–700˚C the ceramic is largely dehydrated and shrinkage reduces significantly as the mineral structure of the clay bonds. This bonding process essentially waterproofs the vessel as porosity decreases, density increases, and results in a vessel able to hold water without sieving or reverting to a plastic state. At temperatures above 950˚C sintering begins (Santacreu 2014a, 91). Sintering is the breakdown of the clay particle structure resulting in the fusing of minerals in a liquid state that results in a more dense microstructure and increased matrix homogeny (Maca 2009, 13; Santacreu 2014a, 91). The range of vitrification, or the point at which ceramic becomes less porous and the minerals will melt into glass, depends on the type of minerals present within the clay matrix but generally takes place when ceramic is fired at some time over 1000˚C (Garzón 2022, 15890).

Some concern over the usefulness of determining maximum firing temperatures in archaeology has been expressed. Because firing environments are highly variable, ceramics fired in the same environment and even the same vessel can experience varying temperature rates depending on a multitude of factors including proximity to fuel, open or closed atmospheres, proximity to other vessels, etc. (Gosselain 1992, 252–253). Maximum temperature may differ between areas of the same vessel during firing by 150˚C (Tite 1999, 190). However, the determination of maximum firing temperatures on single sherds or fragments containing biometric data avoids this issue as the metrics obtained for aging and sexing are concerned with a single location on the vessel and not the entirety of the fired product. The experiment conducted for this thesis explored a variety of temperature ranges to assess the rate of shrinkage based on known changes in clay mineral composition.

Methods of Analysis

A few methods of analysis are available for the assessment of ceramic sherds in order to conduct biometric data calibration. These analyses include petrographic and archaeothermometry determination. Firstly, petrographic analysis includes identifying the geochemical and mineralogical composition of ceramics (Quinn 2013, 1). Geochemical and mineralogical identification can assist researchers in understanding the provenience and origin of the raw clays used in producing the vessel and any tempers that may have been added. Additionally, understanding the compositional makeup of the clay can assist research by identifying the likely shrinkage rate of fired clays based on predetermined rates of similar clays and clay mixtures without the need of experimentation. Geochemical and mineralogical analysis methods may include oxidation analysis to look at the provenience of clay particle deposition, laser-ablation inductively-coupled plasma spectrometry (LA-ICPS) (Beck and Neff 2007, 291; Tochlin et al 2012, 2586), instrumental neutron activation analysis (INAA) (Harry et al. 2013, 387; Ratto et al. 2015, 13–14; Santacreu 2014a, 35), X-ray powder diffraction (XRPD) (Santacreu 2014a, 18), X-ray fluorescence (XRF) (Quinn 2013, 1; Speakman et al. 2011, 3483), and a number of other methods that ultimately acquire the same result.

In addition to petrographic research, determining the firing temperatures of clay samples containing biometric data can also assist biometric research by providing additional information about how much a sample may have shrunk due to thermal factors when used in tandem with petrographic determinations. The study of ceramic firing temperatures is often referred to as ‘archaeothermometry’ or ‘palaeothermometry’ (Tarhan et al. 2021, 2) and the assessment of maximum firing temperatures has been extensively developed with a wide array of analytical methods available for determination. These methods include observation of mineral changes in the clay matrix including levels of sintering and vitrification, expansion analyses, magnetometry, X-ray diffraction (Kostadinova-Avramova 2018, 631); Rasmussen et al. 2012, 1705–1706), transmission electron microscopy (TEM), and Fourier Transform Infrared Spectroscopy (FT-IR) (Gliozzo 2020, 27), all with varying results and potential.

The purposes of these analyses is to determine information pertinent to understanding the provenience and production of ceramic sherds containing biometric data. If petrography and archaeothermometry can be utilized in tandem with further published data (such as the data produced in this thesis) on known regional clay sources, it may allow more accurate estimations of age and sex using residual fingerprints found in the archaeological record. This may be accomplished by perhaps creating a referenceable index of clay sources, their geochemical and mineralogical properties, and estimating known rates of shrinkage based on variables such as tempers and firing temperature.

CHAPTER FIVE:

RESEARCH QUESTIONS, MATERIALS, AND METHODS

Research Questions

In order to evaluate the current use of biometric calibration in archaeology, a series of research questions were developed to guide and facilitate interpretation:

1. Is the shrinkage rate of ceramic from the Salton Trough fired without temper at various temperatures sufficient to warrant a calibration when assessing biometric data?
2. Does mixing tempers (i.e., sand, grog, and quartz) reduce the effect of shrinkage sufficient to warrant a calibration when assessing biometric data?
3. If shrinkage or expansion occurs, is it within a reasonable amount to suspect a miscalculation in aging and sexing determination?
4. If shrinkage or expansion occurs, is it within reason to believe the differentiation between juveniles and adult women may be miscalculated?

Materials and Methods

This experiment was designed to test the shrinkage rate of a single natural clay source. Clay sourcing and types were evaluated in this experiment to produce ceramic that most closely reproduces a ceramic paste utilized by Southwest Native Americans. The clay used in this experiment is from an undisclosed source in the Salton Trough near the Salton Sea, California and was prepared by Tony Soares, a native ceramicist and flintknapper, utilizing a traditional clay source and materials. Preparation of the clay consisted of collection in a dry clumpy form and soaking in water before being thoroughly mixed. The clay and water mixture was left until clay particles settled and excess water was siphoned off. The clay was then filtered through a 1/16-inch screen to remove large inclusions and most organic materials. The mixture was then poured into large shallow basins and covered until excess water naturally evaporated and the clay was workable (Figure 1).

Figure 1 - Raw Salton Sea clay in processed form

Temper used in this experiment was collected and mixed by myself. The temper consists of material used often in the area from which the clay was sourced, found in the archaeological record, or was known to living descendants still practicing the craft today: quartz, grog, and sand. The quartz used for this thesis research was quartz crystal locally sourced from the Palm Springs area of

California. The quartz was crushed and strained through a 1/16-inch colander to ensure a consistent and appropriate size for use as temper (Figure 2).

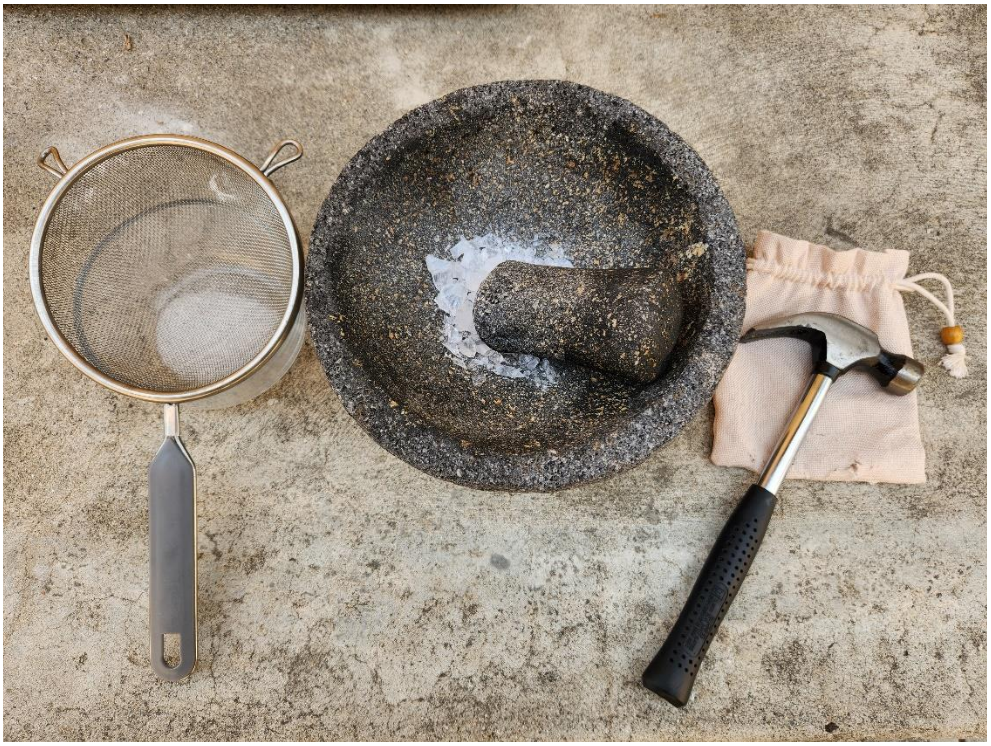

Figure 2 - Quartz being crushed for use as temper

The grog used as temper was derived from the same clay used to make the experimental tiles; fired at the highest temperature used in this experiment (1000˚C), crushed, and passed through a 1/16-inch colander before being added to the clay mixture (Figure 3).

Figure 3 - Crushed ceramic (Grog) being strained for use as temper

Lastly, the sand used as temper is fine dune sand sourced from near Joshua Tree, California (Figure 4). These were mixed with raw clay in various ratios to provide a consistency appropriate for the ceramic paste. Quartz was mixed with one tablespoon for every pound of clay; grog was mixed with one tablespoon for every pound of clay; and sand was added to the raw clay until an approximate 20% sand mixture was achieved. All tempers were added to the clay through thorough kneading or wedging by hand.

Figure 4 - Fine dune sand for use as temper

Four batches of different clay mixtures, one non-tempered batch, and three batches containing each temper, were required for the experiment. After the tempers were mixed with the clay, each temper mixture was divided into three sets (or sub-sets) of thirty tiles, each to be fired at different temperatures (i.e., thirty tiles for sand temper to be fired at 450˚C, thirty tiles for sand temper to be fired at 700˚C, and thirty tiles for sand temper to be fired at 1000˚C, etc.). Each sub-set was rolled with a rolling pin within a constructed wooden frame with two 1cm thick rails on each side to maintain a consistent thickness of the clay (Figure 5).

Figure 5 - Wood frames constructed for rolling clay

Each rolled sub-set was then cut into thirty 60mm by 58.5mm tiles using a preformed steel die cutter to ensure each tile was the same size (Figure 6). Four clay mixtures and their three individual sub-sets at thirty tiles a piece produced three hundred and sixty individual tiles for data collection.

Figure 6 - Clay tiles being cut with molded die cutter

Each tile was also imprinted at the center of the tile with a four-by-four plastic Lego construction block measuring 15.8mm. The process of marking the center attempted to produce an additional point of measurement to assess ceramic shrinkage at the center of the tiles. This mark was assessed for a shrinkage rate independently of the edge width and length, then averaged with the shrinkage rate determined by the edges. This was to provide a single shrinkage rate for the tile with consideration of shrinkage throughout the tile, not just contraction of the edges. An attempt to control for potential distortion was also considered by applying the minimum amount of pressure necessary to leave a clear imprint using both the Lego and coding instruments.

I additionally imprinted each tile with coding information to maintain a simple method of maintaining mixture and firing temperature provenience. The tiles were stamped with a metal stamping kit and coded to indicate temper and temperature while pliable. The coding was as follows: NT = Non-tempered, Q = Quartz Temper, P = Grog Temper (P was used to eliminate possible marking confusion between Q and G), and S = Sand Temper. In addition, the tiles within each temperature grouping were numbered (1–30) to facilitate data management in case of breakage or data loss. The tiles were also marked in the lower right-hand corner with roman numerals indicating the intended firing temperature and were coded as: I = 450˚C (842˚F), II = 700˚C (1292˚F), and III = 1000˚C (1832˚F). Therefore, the tile coding P-18 with a roman numeral II in the bottom right corner of the tile corresponded to the eighteenth tile in the grog temper sub-set to be fired at a temperature of 700˚C (Figure 7).

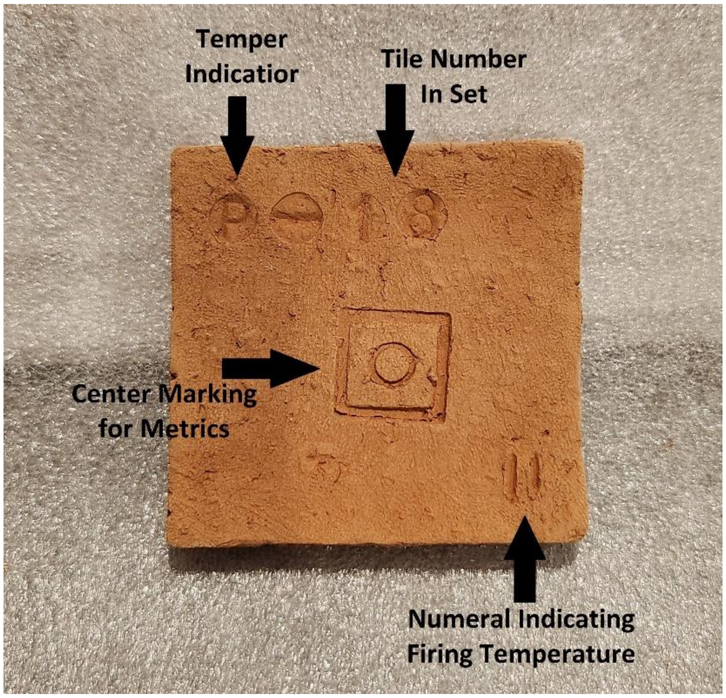

Figure 7 - Coded information found on each tile

The tiles, once formed and coded, were set out to dry in the open indoor air for no less than four days (Figure 8). Air circulation was achieved using an oscillating fan placed approximately six feet from the tiles. This was to ensure a gradual loss of moisture from the clay to reduce the possibility of cracking or exploding during firing. After air-drying, I measured the tiles and shrinkage was calculated before firing and packed into boxes using sheeted packing foam for transport to the California State University San Bernardino kilns.

Figure 8 - Cut and coded tiles laid out to air-dry

Each mixture underwent a series of three testable conditions with thirty tiles dedicated to each condition. First, thirty tiles were used from each of the sub-mixtures to test shrinkage rates of kiln firing temperatures 450˚C, 700˚C, and 1000˚C, for eight hours each. Kiln firing was conducted at the California State University of San Bernardino using three electric Skutt automatic kilns (two model KM-822-3” and one model KM-1027-3”) at the CSUSB Department of Art & Design (Figure 9).

Figure 9 - One of the Skutt Model KM-822-3" electric kilns used to fire tiles

The tiles were first preheated for twelve hours at 82˚C (180˚F), to completely dehydrate the tiles, slow fired to their appropriate maximum temperatures over the course of five hours, fired at maximum temperature for 8 hours, then subsequently left to cool gradually for another twenty-four hours (Figure 10).

Figure 10 - Batch of tiles fired at 1000˚C and ready to come out of the kiln

Once the tiles were fired, each was inspected for integrity and the production of a usable and measurable tile to ensure correction for data loss. The tiles and center marks were then each measured using a Carbon Fiber Composites digital caliper with an accuracy of ± 0.2mm. Each tile length and width were measured using an average of the top, middle, and right measurements to ensure the most accurate representation of the true metric (Figure 11).

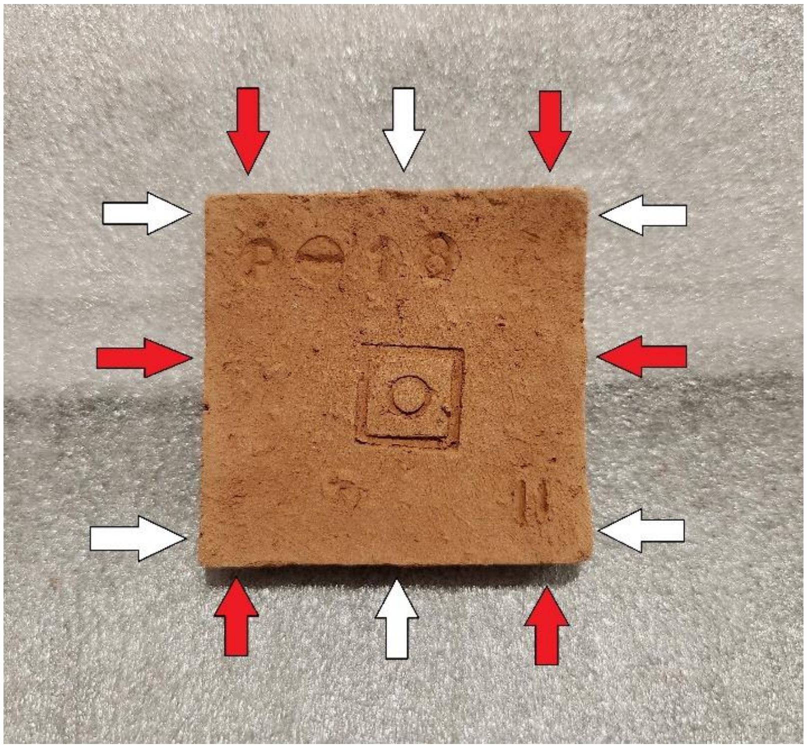

Figure 11 – Points of measurement to determine length and width

Metrics for length, width, and center were recorded for each tile and a raw data table was created for the resulting changes. The resulting data was also looked at two ways. 1) The center marking was measured after firing and compared against the known size of the Lego block (15.8 mm) to determine whether shrinkage was occurring at the center of the tile as opposed to contraction at the edges only. 2) Width and length of the tiles were multiplied together to determine the surface area of each tile, all 30 tiles from each temper and temperature sub-set were then averaged together, and then compared to the known constant of the die cutter (60 * 58.5 = 3510 mm^2) to determine an overall area shrinkage.

CHAPTER SIX:

RESULTS

All tiles fired during the experiment withstood the firing process and remained intact, resulting in optimal data collection. All tiles and their sub-sets displayed shrinkage during air drying, before kiln firing was conducted, to various degrees. As research previously indicated, the process of dehydration is where the tiles experience their largest percentage of shrinkage, even before firing occurs (Table 1). The most significant shrinkage from air drying occurred in the tiles without temper added to them, with these tiles being reduced in size by an average of 21.6%. The least amount of shrinkage from air drying occurred with the tiles containing a sand temper, with a contraction of only 9.9%.

Table 1 - Area (mm^2) Shrinkage

Temper Type	Air-Dry	Temperature 1 450˚C (842˚F)	Temperature 2 700˚C (1292˚F)	Temperature 3 1000˚C (1832˚F)
No Temper	21.6%	22.3%	22.0%	25.4%
Quartz	18.3%	19.8%	19.1%	22.4%
Grog	19.2%	19.9%	19.3%	23.2%
Sand	9.9%	10.1%	9.1%	10.4%

The first firing only reduced the size of the tiles by an additional <2% for all four clay mixtures. Consistent with the air-drying results, shrinkage after firing was observed the most in fired tiles that did not have temper added to them.

Firing reduced the size of the non-tempered tiles between 22.3% and 25.4% with each of the three different tested temperatures. Observation of surface area between temperature I (450˚C) and temperature II (700˚C) indicates that a process of slight expansion occurs, with all four clay mixtures experiencing a shrinkage percentage lower than the first firing temperature.

Comparisons of the tile dimensions after firing at the first two temperatures show very little change in all temper categories, apart from the expansion observed in all tiles between ranges I and II. This expansion only differs from the first firing temperature by 1% in sand tiles and <1% in the three others. However, the difference observed in shrinkage between firing temperature II and temperature III (1000˚C) displays the greatest rate of change. All four temper types were reduced to their highest value of shrinkage after being fired at temperature III, indicating that a physical change occurred that condensed the ceramic matrix between these two temperatures.

When analyzing the basic statistical package for the differences between all thirty tiles within each temper and temperature sub-set, the range of differences is fairly small (between 69.8 and 177.4 mm^2). Although the tiles have each shrank in response to each firing environment, some by more than a centimeter on each side, and affected by their individual tempers, the small range within each sub-set indicates that the variability of the different subsets is the product of each unique circumstance and not random chance. A basic bar graph

(Figure 12) shows that, after initial water loss during air-drying, the processes of shrinkage and expansion occur within fairly tight parameters.

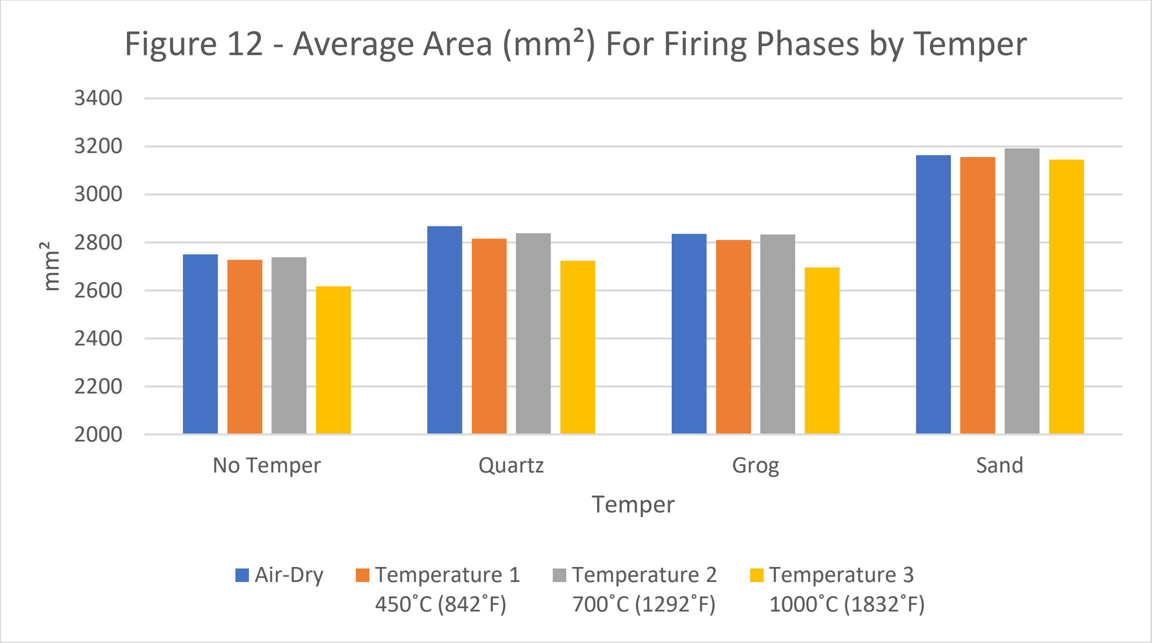

Figure 12 - Average area (mm²) for firing phases by temper

CHAPTER SEVEN:

DISCUSSION

When considering the results of the experiment, I argue that prehistoric pottery determined to originate from the Salton Trough and possessing biometric data requires calibration before an accurate estimation of age and sex can be determined. If Králík's (2000) Masters thesis work that determined a standard shrinkage rate of 7.5% and Králík and Novotný's (2003) modification of Kamp et al.'s (2015) regression equation to account for this shrinkage rate was required, then a shrinkage rate exceeding the 7.5% value would undoubtedly be required. Shrinkage exceeding 7.5% was observed in all four of the tempers even before kiln firing was conducted.

This experiment, along with the tests conducted by Králík (2000) and Kamp et al. (2015), indicate that shrinkage is based on several factors such as the specific mineralogical and geochemical composition of the clay, tempers added to it to control for shrinkage, and the temperature at which the clay is fired (or air-dried). This may require archaeologists to conduct similar shrinkage testing on each specific clay environment (source) with tempers appropriate to each ceramic tradition to accurately calibrate collected biometric data. The results of this experiment clearly show that shrinkage occurs to a considerable degree between formation of a vessel through the clay dehydration process.

The experiment shows that clay shrinks at various rates based on temper and temperature. The data suggest that the expansion observed is the product of the firing temperature between 450˚C and 700˚C, considering this change was consistent through all tempers and occurred regardless of the temper type. If both processes of shrinkage and expansion occur, calibration of biometric data would require a careful determination of the firing temperature on which the fingerprint is impressed. In addition, examination of the changes unique to each temper require a specific calibration. For example, quartz and grog produced similar results, whereas sand temper seemingly stabilized the paste and controlled shrinkage to a greater degree. When conducting sexing and aging of fingerprints found in Salton Trough clay, an analysis of geochemical and mineralogical composition, ceramic firing temperatures, and temper content would be required.

A stated above, age and sex are identified according to the minute measurements of fingerprint impressions that calculate ridge densities and mean ridge breadths. Králík and Novotný's (2003) KaMod equation which introduces a value to adjust for shrinkage is as follows:

$$\text{Age (months)} = 614 \times \text{ridge breadth (in mm)} - 112 \times 1.08108$$

Where “1.08108” represents the coefficient of a 7.5% shrinkage rate. If we insert a value for mean ridge breadths, such as 0.3 mm, the equation can be solved as follows:

$$\text{Age (months)} = 614 \times 0.3 - 112 \times 1.08108$$

$$\text{Age (Months)} = 184.2 - 121.08096$$

$$\text{Age (Months)} = 63.11904$$

The result places the age of the individual with a MRB of 0.3mm at approximately 5.25 years of age. However, if the equation were to be adjusted for a ceramic shrinkage rate produced by this experiment, the values change drastically. The following equation substitutes the 7.5% shrinkage rate for the shrinkage rate obtained from grog temper fired at 1000˚C (23.2%):

$$\text{Age (months)} = 614 \times 0.3 - 112 \times 1.232$$

$$\text{Age (months)} = 184.2 - 137.984$$

$$\text{Age (months)} = 46.216$$

The introduction of a new shrinkage rate changes the estimation of the age by 16.9 months, or 1.4 years. The child that produced the fingerprint is now estimated to be 3.9 years old.

Changing the values to account for specific shrinkage rates is the best method for accurately estimating the age and sex of an individual. Especially because rates of shrinkage and expansion may exacerbate the already ambiguous metrics between adult women and post-pubescent females. The values between the two may vary by only a few micrometers. Depending on the amount of shrinkage, the accurate classification of males, females, and juveniles may be obscured. The classification of age, like sex, also highly depends on the accurate calibration of biometric data.

CHAPTER EIGHT:

CONCLUSION

The relatively new method of aging and sexing fingerprints in the forensic sciences is based on the mean ridge breadths and ridge density calculations of fingerprints left in the environment. These methods are supported by studies showing that men, women, and children have statistically discernable fingerprints. This is true among all living human populations studied. Archaeologists are beginning to utilize the minute measurements of fingerprints found in the archaeological record and preserved on ceramic sherds to age and sex their crafters. This concept relies on the assumption that the identifiable differences between men and women remain constant for native populations in the past. However, as researchers have transitioned this concept to other applications, an entirely new set of variables must be considered.

With the experiment conducted for this thesis, I aimed to assess the need to calibrate biometric data collected in the field. I intended to demonstrate that a single clay source, mixed with various tempers and fired at temperatures relevant to archaeology in the American Southwest, experiences shrinkage worth accounting for when aging and sexing. The results of the experiment exceeded values used as a constant in archaeological interpretations and publications today and demonstrated that need. Considering the variability of the data from this experiment, I recommend that further testing be done on other clay sources in the American Southwest. It is important to determine the effects of shrinkage on specific geochemical and mineralogical clay compositions as well as tempers appropriate to the region in which the ceramic possessing biometric data is found.

Further research would also benefit from experimentation with the firing environments used in which the ceramic was traditionally produced. Kiln firing was used in this experiment to create an environment of controlled, even, and predictable temperatures for the production of equally fired tiles for better data collection. However, traditionally in the American Southwest the firing of ceramic was achieved through pit firing, which produces an unpredictable environment with varying temperature ranges and different atmospheres. Another factor not explored in this thesis is the effect of varying fuel types and what effect they may have on the firing process.

Ceramic on which fingerprint data can be found are found in a variety of contexts. From the desert floor (Figure X and X), on Spanish Mission tiles, specimens already curated, or even raw material preserved in a workshop or around a fire. It takes a keen observer to recognize the grooves and patterns of prints. However, as with most things, once you learn to recognize these signs of the past, they will appear more often than you imagined.

Figure 13 - Pottery sherds found in Arizona

Figure 14 - Pottery fragment found in California

APPENDIX A:

DATA

1. Basic Measurements Raw Data

Temper Type	Temperature 1 450˚C (842˚F)		Temperature 2 700˚C (1292˚F)		Temperature 3 1000˚C (1832˚F)	
	Length (mm)	Width (mm)	Length (mm)	Width (mm)	Length (mm)	Width (mm)
No Temper 1	53.4	51.5	53.6	51.5	52.3	50.1
No Temper 2	53.5	51.9	52.3	51.6	51.1	50.5
No Temper 3	53.3	51.8	53.4	50.1	52.2	50.7
No Temper 4	52.8	51.4	52.7	51.4	51.9	48.8
No Temper 5	52.9	51.8	51.7	51.2	51.9	49.8
No Temper 6	54.1	51.4	52.5	51	52.8	50.2
No Temper 7	52.5	52.1	53.5	51.6	52	51
No Temper 8	53.4	51.8	53.4	51.1	51.9	50
No Temper 9	54.5	51.1	52.9	51.5	52	50.5
No Temper 10	52.1	51.9	53	51.9	52.4	50.3
No Temper 11	53.1	51.8	52.8	52.3	51.6	50.7
No Temper 12	53.4	51.7	53.6	51.7	52.1	50.6
No Temper 13	52.3	51.1	53.3	51.8	52.5	50.2
No Temper 14	53.1	51.3	53.6	51.9	51.3	51.1
No Temper 15	53.4	52.5	53.4	52.1	52.5	51.4
No Temper 16	52.7	50.4	52.9	52.5	51.2	51.2
No Temper 17	52.7	50.4	53.9	52.4	51.9	49.6

No Temper 18	52.1	51.4	53.6	51.7	52	50
No Temper 19	54.2	49.3	53.3	50.6	52.6	50.6
No Temper 20	53.6	51	53.5	51.5	51.3	50.8
No Temper 21	52.8	51.5	53.2	51.7	50.7	50.6
No Temper 22	52.9	51.4	52.5	52	52.5	50.5
No Temper 23	53.9	51.4	53.7	51.7	52.2	51
No Temper 24	53	50.6	52.1	52	51.7	51
No Temper 25	53	50.8	52.6	51.9	52.4	50.1
No Temper 26	52.9	51.7	52.9	52.4	51	50
No Temper 27	54.1	51.8	52.6	51.8	51.8	50.3
No Temper 28	53	51.1	53	52.2	52.1	50.2
No Temper 29	52.9	51	53.6	50.9	52	50.4
No Temper 30	53	51	52.8	50.5	51.7	50.2
Quartz Temper 1	53.5	53.4	54.4	52.8	53.3	50.9
Quartz Temper 2	54.9	52.4	54.3	52.9	53.3	52.2
Quartz Temper 3	54	52.2	53.8	52.4	52.4	51.4
Quartz Temper 4	53.9	52.7	54.4	52.3	53.2	51.3
Quartz Temper 5	54.1	52.2	53.7	52.7	52.9	51.3
Quartz Temper 6	54.2	52	53.9	53	52.9	51.3
Quartz Temper 7	53.6	53.1	54	53.3	53	50.8
Quartz Temper 8	53.7	52.9	53.6	52.6	53.1	51.6
Quartz Temper 9	53.6	52	53.7	52.3	53	51.5
Quartz Temper 10	54.1	51.9	53.4	53.1	53.1	50.9
Quartz Temper 11	53.1	52.9	53.3	52.6	53.2	51.6
Quartz Temper 12	52.6	52.1	53.4	52.4	53	50.2
Quartz Temper 13	53.4	51.9	53.5	53	52.7	51.4
Quartz Temper 14	54.1	52.9	53.2	52.9	53.2	50.9
Quartz Temper 15	54.2	52	53.7	52.7	53.1	50.8
Quartz Temper 16	54.1	51.6	53.4	52.7	52.9	51.1
Quartz Temper 17	53.4	52.8	53.6	52.7	52.7	51
Quartz Temper 18	52.8	52.2	55	52.1	52.8	51.3
Quartz Temper 19	53.6	52.3	53.7	52.8	53	52
Quartz Temper 20	53.5	52.2	53.9	52.8	53	51
Quartz Temper 21	53.6	51.7	54.7	52.8	53.4	51.4
Quartz Temper 22	52.8	52.1	54.2	52.3	52.7	51.6
Quartz Temper 23	54	52.2	54.3	52.5	53.4	51.3
Quartz Temper 24	53.8	52.2	53.6	53	53.1	52
Quartz Temper 25	53.7	52	54.4	52.6	53.3	52.3
Quartz Temper 26	53.9	52.2	54.3	53	53.1	50.8
Quartz Temper 27	54.1	52.8	54	52.3	53.3	51.4

Quartz Temper 28	54.5	52.6	53.8	52.6	53.8	51.8
Quartz Temper 29	54.5	52.8	53.9	52.5	53	51.7
Quartz Temper 30	54.1	52.6	54.1	52.2	53	51
Grog Temper 1	53.7	52.6	54.3	52.5	52.2	51.2
Grog Temper 2	53.7	51.9	54.6	52.3	52	50.9
Grog Temper 3	54	51.7	54.1	52.8	52.3	50.8
Grog Temper 4	53.8	51.9	53.8	52.5	52.4	50.4
Grog Temper 5	53.9	52.4	54.3	53	52.1	51.3
Grog Temper 6	54.1	52.4	54.4	52.2	52.8	51.4
Grog Temper 7	53.8	52.5	54.4	52	53	50.5
Grog Temper 8	53.5	52.6	54	52	52.9	51.4
Grog Temper 9	53.6	52.3	53.9	52.7	53	51.4
Grog Temper 10	53.9	52.1	53.7	52.6	52.4	51
Grog Temper 11	53.7	52.4	53.9	52.7	52.8	51.6
Grog Temper 12	53.6	52.3	53.9	52.7	52.7	50.8
Grog Temper 13	53.7	52	53.8	51.9	52.8	51
Grog Temper 14	53.3	52.4	53.7	52.2	52.9	51.3
Grog Temper 15	53.5	52.5	53.7	52.3	53.3	51.5
Grog Temper 16	54.3	52.3	54.1	52.3	52.8	50.9
Grog Temper 17	53.5	52.3	53.8	52.4	53	51.6
Grog Temper 18	53.9	52.8	53.6	52.5	52.9	51
Grog Temper 19	53.9	52.1	54.2	52.4	53	50.9
Grog Temper 20	54	52.3	54	52.3	51.4	50.9
Grog Temper 21	54	52.4	53.8	52.8	53.2	51.3
Grog Temper 22	53.9	51.8	54.2	52.5	53.5	51
Grog Temper 23	54.4	52	54.7	52.6	53.5	51.4
Grog Temper 24	54	51.7	54	52.4	53.1	51.2
Grog Temper 25	53.8	51.7	54.1	52.2	53.2	50.4
Grog Temper 26	53.7	51.8	54.4	52.3	53	51
Grog Temper 27	53.8	51.6	53.9	52	53	51
Grog Temper 28	54.3	52.2	54.5	51.9	53.1	50.7
Grog Temper 29	54	52.5	54.1	52.5	53.1	50.6
Grog Temper 30	53.8	52.5	54.7	51.9	53.6	50.6
Sand Temper 1	57.4	55.7	57.2	55.2	56.9	55.2
Sand Temper 2	57	55.2	57.1	55.6	57.8	54
Sand Temper 3	56.7	55.2	57.4	56	56.9	54.9
Sand Temper 4	57.4	55.1	57.1	55.5	56.7	55.1
Sand Temper 5	57.3	55.1	58	55.9	56.2	55.2
Sand Temper 6	56.9	55.3	57.1	55.6	56.7	55
Sand Temper 7	56.6	55.7	57.5	55.5	57	54.7

Sand Temper 8	57.2	55.5	56.9	56	56.5	56
Sand Temper 9	56.9	55.4	57	55.4	56.6	55.5
Sand Temper 10	57.3	55.5	56.9	55.3	56.8	55.3
Sand Temper 11	57.4	55.9	57.4	55.4	57	55.3
Sand Temper 12	57	55.8	57.7	55.7	56.8	55
Sand Temper 13	57.2	54.6	57.3	55.7	56.7	55.2
Sand Temper 14	56.8	55.2	57.3	55.6	57	55
Sand Temper 15	57	55.4	57.4	55.7	57	55.8
Sand Temper 16	56.8	55.3	57.5	55.6	56.9	55.4
Sand Temper 17	56.7	55.6	57.3	55.8	56.9	55
Sand Temper 18	56.9	55.4	57.8	55.4	57.5	55.1
Sand Temper 19	57.1	55.2	57.7	56.2	57.2	54.8
Sand Temper 20	56.9	55.3	58.4	55.5	57.1	55
Sand Temper 21	56.6	56.1	57.6	56	56.9	55
Sand Temper 22	56.3	55.7	57.7	55.9	57.6	55.1
Sand Temper 23	57.2	55.8	57.3	55.7	57.2	54.9
Sand Temper 24	56.7	55.4	57.9	55.3	57.6	55.4
Sand Temper 25	56.1	54.5	57.5	55.8	57.6	55.1
Sand Temper 26	56.5	54.9	57.3	55.2	57.9	55.4
Sand Temper 27	57	55.3	57.5	55.2	56.6	55.3
Sand Temper 28	57.3	55.9	57.3	55.4	56.7	55.1
Sand Temper 29	57.2	55.3	57.3	56.1	57.6	55.5
Sand Temper 30	57.6	55.6	56	55.8	57.3	55.2

2. No Temper – Calculations for Difference between Wet Size and Fired Area

Temper Type	**Temperature I 450˚C (842˚F)**					
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**
No Temper 1	60.0	58.5	3510.0	53.4	51.5	2750.1
No Temper 2	60.0	58.5	3510.0	53.5	51.9	2776.7
No Temper 3	60.0	58.5	3510.0	53.3	51.8	2760.9
No Temper 4	60.0	58.5	3510.0	52.8	51.4	2713.9
No Temper 5	60.0	58.5	3510.0	52.9	51.8	2740.2
No Temper 6	60.0	58.5	3510.0	54.1	51.4	2780.7
No Temper 7	60.0	58.5	3510.0	52.5	52.1	2735.3
No Temper 8	60.0	58.5	3510.0	53.4	51.8	2766.1
No Temper 9	60.0	58.5	3510.0	54.5	51.1	2785.0

No Temper 10	60.0	58.5	3510.0	52.1	51.9	2704.0	
No Temper 11	60.0	58.5	3510.0	53.1	51.8	2750.6	
No Temper 12	60.0	58.5	3510.0	53.4	51.7	2760.8	
No Temper 13	60.0	58.5	3510.0	52.3	51.1	2672.5	
No Temper 14	60.0	58.5	3510.0	53.1	51.3	2724.0	
No Temper 15	60.0	58.5	3510.0	53.4	52.5	2803.5	
No Temper 16	60.0	58.5	3510.0	52.7	50.4	2656.1	
No Temper 17	60.0	58.5	3510.0	52.7	50.4	2656.1	
No Temper 18	60.0	58.5	3510.0	52.1	51.4	2677.9	
No Temper 19	60.0	58.5	3510.0	54.2	49.3	2672.1	
No Temper 20	60.0	58.5	3510.0	53.6	51.0	2733.6	
No Temper 21	60.0	58.5	3510.0	52.8	51.5	2719.2	
No Temper 22	60.0	58.5	3510.0	52.9	51.4	2719.1	
No Temper 23	60.0	58.5	3510.0	53.9	51.4	2770.5	
No Temper 24	60.0	58.5	3510.0	53.0	50.6	2681.8	
No Temper 25	60.0	58.5	3510.0	53.0	50.8	2692.4	
No Temper 26	60.0	58.5	3510.0	52.9	51.7	2734.9	
No Temper 27	60.0	58.5	3510.0	54.1	51.8	2802.4	
No Temper 28	60.0	58.5	3510.0	53.0	51.1	2708.3	
No Temper 29	60.0	58.5	3510.0	52.9	51.0	2697.9	
No Temper 30	60.0	58.5	3510.0	53.0	51.0	2703.0	**Shrink %**
Average	60.0	58.5	3510.0	53.2	51.3	2728.3	22.3%

Temper Type	**Temperature II 700˚C (1292˚F)**					
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**
No Temper 1	60.0	58.5	3510.0	53.6	51.5	2760.4
No Temper 2	60.0	58.5	3510.0	52.3	51.6	2698.7
No Temper 3	60.0	58.5	3510.0	53.4	50.1	2675.3
No Temper 4	60.0	58.5	3510.0	52.7	51.4	2708.8
No Temper 5	60.0	58.5	3510.0	51.7	51.2	2647.0
No Temper 6	60.0	58.5	3510.0	52.5	51.0	2677.5
No Temper 7	60.0	58.5	3510.0	53.5	51.6	2760.6
No Temper 8	60.0	58.5	3510.0	53.4	51.1	2728.7
No Temper 9	60.0	58.5	3510.0	52.9	51.5	2724.4
No Temper 10	60.0	58.5	3510.0	53.0	51.9	2750.7
No Temper 11	60.0	58.5	3510.0	52.8	52.3	2761.4
No Temper 12	60.0	58.5	3510.0	53.6	51.7	2771.1
No Temper 13	60.0	58.5	3510.0	53.3	51.8	2760.9
No Temper 14	60.0	58.5	3510.0	53.6	51.9	2781.8

No Temper 15	60.0	58.5	3510.0	53.4	52.1	2782.1	
No Temper 16	60.0	58.5	3510.0	52.9	52.5	2777.3	
No Temper 17	60.0	58.5	3510.0	53.9	52.4	2824.4	
No Temper 18	60.0	58.5	3510.0	53.6	51.7	2771.1	
No Temper 19	60.0	58.5	3510.0	53.3	50.6	2697.0	
No Temper 20	60.0	58.5	3510.0	53.5	51.5	2755.3	
No Temper 21	60.0	58.5	3510.0	53.2	51.7	2750.4	
No Temper 22	60.0	58.5	3510.0	52.5	52.0	2730.0	
No Temper 23	60.0	58.5	3510.0	53.7	51.7	2776.3	
No Temper 24	60.0	58.5	3510.0	52.1	52.0	2709.2	
No Temper 25	60.0	58.5	3510.0	52.6	51.9	2729.9	
No Temper 26	60.0	58.5	3510.0	52.9	52.4	2772.0	
No Temper 27	60.0	58.5	3510.0	52.6	51.8	2724.7	
No Temper 28	60.0	58.5	3510.0	53.0	52.2	2766.6	
No Temper 29	60.0	58.5	3510.0	53.6	50.9	2728.2	
No Temper 30	60.0	58.5	3510.0	52.8	50.5	2666.4	**Shrink %**
Average	60.0	58.5	3510.0	53.1	51.6	2738.9	22.0%

Temper Type	**Temperature III 1000˚C (1832˚F)**					
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**
No Temper 1	60.0	58.5	3510.0	52.3	50.1	2620.2
No Temper 2	60.0	58.5	3510.0	51.1	50.5	2580.6
No Temper 3	60.0	58.5	3510.0	52.2	50.7	2646.5
No Temper 4	60.0	58.5	3510.0	51.9	48.8	2532.7
No Temper 5	60.0	58.5	3510.0	51.9	49.8	2584.6
No Temper 6	60.0	58.5	3510.0	52.8	50.2	2650.6
No Temper 7	60.0	58.5	3510.0	52.0	51.0	2652.0
No Temper 8	60.0	58.5	3510.0	51.9	50.0	2595.0
No Temper 9	60.0	58.5	3510.0	52.0	50.5	2626.0
No Temper 10	60.0	58.5	3510.0	52.4	50.3	2635.7
No Temper 11	60.0	58.5	3510.0	51.6	50.7	2616.1
No Temper 12	60.0	58.5	3510.0	52.1	50.6	2636.3
No Temper 13	60.0	58.5	3510.0	52.5	50.2	2635.5
No Temper 14	60.0	58.5	3510.0	51.3	51.1	2621.4
No Temper 15	60.0	58.5	3510.0	52.5	51.4	2698.5
No Temper 16	60.0	58.5	3510.0	51.2	51.2	2621.4
No Temper 17	60.0	58.5	3510.0	51.9	49.6	2574.2
No Temper 18	60.0	58.5	3510.0	52.0	50.0	2600.0
No Temper 19	60.0	58.5	3510.0	52.6	50.6	2661.6

No Temper 20	60.0	58.5	3510.0	51.3	50.8	2606.0	
No Temper 21	60.0	58.5	3510.0	50.7	50.6	2565.4	
No Temper 22	60.0	58.5	3510.0	52.5	50.5	2651.3	
No Temper 23	60.0	58.5	3510.0	52.2	51.0	2662.2	
No Temper 24	60.0	58.5	3510.0	51.7	51.0	2636.7	
No Temper 25	60.0	58.5	3510.0	52.4	50.1	2625.2	
No Temper 26	60.0	58.5	3510.0	51.0	50.0	2550.0	
No Temper 27	60.0	58.5	3510.0	51.8	50.3	2605.5	
No Temper 28	60.0	58.5	3510.0	52.1	50.2	2615.4	
No Temper 29	60.0	58.5	3510.0	52.0	50.4	2620.8	
No Temper 30	60.0	58.5	3510.0	51.7	50.2	2595.3	**Shrink %**
Average	60.0	58.5	3510.0	51.9	50.4	2617.4	25.4%

3. Quartz Temper – Calculations for Difference between Wet Size and Fired Area

Temper Type	**Temperature I 450˚C (842˚F)**					
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**
Quartz Temper 1	60.0	58.5	3510.0	53.5	53.4	2856.9
Quartz Temper 2	60.0	58.5	3510.0	54.9	52.4	2876.8
Quartz Temper 3	60.0	58.5	3510.0	54.0	52.2	2818.8
Quartz Temper 4	60.0	58.5	3510.0	53.9	52.7	2840.5
Quartz Temper 5	60.0	58.5	3510.0	54.1	52.2	2824.0
Quartz Temper 6	60.0	58.5	3510.0	54.2	52.0	2818.4
Quartz Temper 7	60.0	58.5	3510.0	53.6	53.1	2846.2
Quartz Temper 8	60.0	58.5	3510.0	53.7	52.9	2840.7
Quartz Temper 9	60.0	58.5	3510.0	53.6	52.0	2787.2
Quartz Temper 10	60.0	58.5	3510.0	54.1	51.9	2807.8
Quartz Temper 11	60.0	58.5	3510.0	53.1	52.9	2809.0
Quartz Temper 12	60.0	58.5	3510.0	52.6	52.1	2740.5
Quartz Temper 13	60.0	58.5	3510.0	53.4	51.9	2771.5
Quartz Temper 14	60.0	58.5	3510.0	54.1	52.9	2861.9
Quartz Temper 15	60.0	58.5	3510.0	54.2	52.0	2818.4
Quartz Temper 16	60.0	58.5	3510.0	54.1	51.6	2791.6
Quartz Temper 17	60.0	58.5	3510.0	53.4	52.8	2819.5
Quartz Temper 18	60.0	58.5	3510.0	52.8	52.2	2756.2
Quartz Temper 19	60.0	58.5	3510.0	53.6	52.3	2803.3
Quartz Temper 20	60.0	58.5	3510.0	53.5	52.2	2792.7

Quartz Temper 21	60.0	58.5	3510.0	53.6	51.7	2771.1	
Quartz Temper 22	60.0	58.5	3510.0	52.8	52.1	2750.9	
Quartz Temper 23	60.0	58.5	3510.0	54.0	52.2	2818.8	
Quartz Temper 24	60.0	58.5	3510.0	53.8	52.2	2808.4	
Quartz Temper 25	60.0	58.5	3510.0	53.7	52.0	2792.4	
Quartz Temper 26	60.0	58.5	3510.0	53.9	52.2	2813.6	
Quartz Temper 27	60.0	58.5	3510.0	54.1	52.8	2856.5	
Quartz Temper 28	60.0	58.5	3510.0	54.5	52.6	2866.7	
Quartz Temper 29	60.0	58.5	3510.0	54.5	52.8	2877.6	
Quartz Temper 30	60.0	58.5	3510.0	54.1	52.6	2845.7	**Shrink %**
Average	60.0	58.5	3510.0	53.8	52.4	2816.1	19.8%

Temper Type	**Temperature II 700˚C (1292˚F)**					
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**
Quartz Temper 1	60.0	58.5	3510.0	54.4	52.8	2872.3
Quartz Temper 2	60.0	58.5	3510.0	54.3	52.9	2872.5
Quartz Temper 3	60.0	58.5	3510.0	53.8	52.4	2819.1
Quartz Temper 4	60.0	58.5	3510.0	54.4	52.3	2845.1
Quartz Temper 5	60.0	58.5	3510.0	53.7	52.7	2830.0
Quartz Temper 6	60.0	58.5	3510.0	53.9	53.0	2856.7
Quartz Temper 7	60.0	58.5	3510.0	54.0	53.3	2878.2
Quartz Temper 8	60.0	58.5	3510.0	53.6	52.6	2819.4
Quartz Temper 9	60.0	58.5	3510.0	53.7	52.3	2808.5
Quartz Temper 10	60.0	58.5	3510.0	53.4	53.1	2835.5
Quartz Temper 11	60.0	58.5	3510.0	53.3	52.6	2803.6
Quartz Temper 12	60.0	58.5	3510.0	53.4	52.4	2798.2
Quartz Temper 13	60.0	58.5	3510.0	53.5	53.0	2835.5
Quartz Temper 14	60.0	58.5	3510.0	53.2	52.9	2814.3
Quartz Temper 15	60.0	58.5	3510.0	53.7	52.7	2830.0
Quartz Temper 16	60.0	58.5	3510.0	53.4	52.7	2814.2
Quartz Temper 17	60.0	58.5	3510.0	53.6	52.7	2824.7
Quartz Temper 18	60.0	58.5	3510.0	55.0	52.1	2865.5
Quartz Temper 19	60.0	58.5	3510.0	53.7	52.8	2835.4
Quartz Temper 20	60.0	58.5	3510.0	53.9	52.8	2845.9
Quartz Temper 21	60.0	58.5	3510.0	54.7	52.8	2888.2
Quartz Temper 22	60.0	58.5	3510.0	54.2	52.3	2834.7
Quartz Temper 23	60.0	58.5	3510.0	54.3	52.5	2850.8
Quartz Temper 24	60.0	58.5	3510.0	53.6	53.0	2840.8
Quartz Temper 25	60.0	58.5	3510.0	54.4	52.6	2861.4

Quartz Temper 26	60.0	58.5	3510.0	54.3	53.0	2877.9	
Quartz Temper 27	60.0	58.5	3510.0	54.0	52.3	2824.2	
Quartz Temper 28	60.0	58.5	3510.0	53.8	52.6	2829.9	
Quartz Temper 29	60.0	58.5	3510.0	53.9	52.5	2829.8	
Quartz Temper 30	60.0	58.5	3510.0	54.1	52.2	2824.0	**Shrink %**
Average	60.0	58.5	3510.0	53.9	52.7	2838.9	19.1%

Temper Type	**Temperature III 1000˚C (1832˚F)**					
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**
Quartz Temper 1	60.0	58.5	3510.0	53.3	50.9	2713.0
Quartz Temper 2	60.0	58.5	3510.0	53.3	52.2	2782.3
Quartz Temper 3	60.0	58.5	3510.0	52.4	51.4	2693.4
Quartz Temper 4	60.0	58.5	3510.0	53.2	51.3	2729.2
Quartz Temper 5	60.0	58.5	3510.0	52.9	51.3	2713.8
Quartz Temper 6	60.0	58.5	3510.0	52.9	51.3	2713.8
Quartz Temper 7	60.0	58.5	3510.0	53.0	50.8	2692.4
Quartz Temper 8	60.0	58.5	3510.0	53.1	51.6	2740.0
Quartz Temper 9	60.0	58.5	3510.0	53.0	51.5	2729.5
Quartz Temper 10	60.0	58.5	3510.0	53.1	50.9	2702.8
Quartz Temper 11	60.0	58.5	3510.0	53.2	51.6	2745.1
Quartz Temper 12	60.0	58.5	3510.0	53.0	50.2	2660.6
Quartz Temper 13	60.0	58.5	3510.0	52.7	51.4	2708.8
Quartz Temper 14	60.0	58.5	3510.0	53.2	50.9	2707.9
Quartz Temper 15	60.0	58.5	3510.0	53.1	50.8	2697.5
Quartz Temper 16	60.0	58.5	3510.0	52.9	51.1	2703.2
Quartz Temper 17	60.0	58.5	3510.0	52.7	51.0	2687.7
Quartz Temper 18	60.0	58.5	3510.0	52.8	51.3	2708.6
Quartz Temper 19	60.0	58.5	3510.0	53.0	52.0	2756.0
Quartz Temper 20	60.0	58.5	3510.0	53.0	51.0	2703.0
Quartz Temper 21	60.0	58.5	3510.0	53.4	51.4	2744.8
Quartz Temper 22	60.0	58.5	3510.0	52.7	51.6	2719.3
Quartz Temper 23	60.0	58.5	3510.0	53.4	51.3	2739.4
Quartz Temper 24	60.0	58.5	3510.0	53.1	52.0	2761.2
Quartz Temper 25	60.0	58.5	3510.0	53.3	52.3	2787.6
Quartz Temper 26	60.0	58.5	3510.0	53.1	50.8	2697.5
Quartz Temper 27	60.0	58.5	3510.0	53.3	51.4	2739.6
Quartz Temper 28	60.0	58.5	3510.0	53.8	51.8	2786.8
Quartz Temper 29	60.0	58.5	3510.0	53.0	51.7	2740.1

Quartz Temper 30	60.0	58.5	3510.0	53.0	51.0	2703.0	**Shrink %**
Average	60.0	60.0	3510.0	53.1	51.3	2723.6	22.4%

4. Grog Temper – Calculations for Difference between Wet Size and Fired Area

Temper Type	**Temperature I 450˚C (842˚F)**					
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm^2)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm^2)**
Grog Temper 1	60.0	58.5	3510.0	53.7	52.6	2824.6
Grog Temper 2	60.0	58.5	3510.0	53.7	51.9	2787.0
Grog Temper 3	60.0	58.5	3510.0	54.0	51.7	2791.8
Grog Temper 4	60.0	58.5	3510.0	53.8	51.9	2792.2
Grog Temper 5	60.0	58.5	3510.0	53.9	52.4	2824.4
Grog Temper 6	60.0	58.5	3510.0	54.1	52.4	2834.8
Grog Temper 7	60.0	58.5	3510.0	53.8	52.5	2824.5
Grog Temper 8	60.0	58.5	3510.0	53.5	52.6	2814.1
Grog Temper 9	60.0	58.5	3510.0	53.6	52.3	2803.3
Grog Temper 10	60.0	58.5	3510.0	53.9	52.1	2808.2
Grog Temper 11	60.0	58.5	3510.0	53.7	52.4	2813.9
Grog Temper 12	60.0	58.5	3510.0	53.6	52.3	2803.3
Grog Temper 13	60.0	58.5	3510.0	53.7	52.0	2792.4
Grog Temper 14	60.0	58.5	3510.0	53.3	52.4	2792.9
Grog Temper 15	60.0	58.5	3510.0	53.5	52.5	2808.8
Grog Temper 16	60.0	58.5	3510.0	54.3	52.3	2839.9
Grog Temper 17	60.0	58.5	3510.0	53.5	52.3	2798.1
Grog Temper 18	60.0	58.5	3510.0	53.9	52.8	2845.9
Grog Temper 19	60.0	58.5	3510.0	53.9	52.1	2808.2
Grog Temper 20	60.0	58.5	3510.0	54.0	52.3	2824.2
Grog Temper 21	60.0	58.5	3510.0	54.0	52.4	2829.6
Grog Temper 22	60.0	58.5	3510.0	53.9	51.8	2792.0
Grog Temper 23	60.0	58.5	3510.0	54.4	52.0	2828.8
Grog Temper 24	60.0	58.5	3510.0	54.0	51.7	2791.8
Grog Temper 25	60.0	58.5	3510.0	53.8	51.7	2781.5
Grog Temper 26	60.0	58.5	3510.0	53.7	51.8	2781.7
Grog Temper 27	60.0	58.5	3510.0	53.8	51.6	2776.1
Grog Temper 28	60.0	58.5	3510.0	54.3	52.2	2834.5

Grog Temper 29	60.0	58.5	3510.0	54.0	52.5	2835.0	
Grog Temper 30	60.0	58.5	3510.0	53.8	52.5	2824.5	**Shrink %**
Average	60	58.5	3510.0	53.8	52.2	2810.3	19.9%

Temper Type	**Temperature II 700˚C (1292˚F)**						
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**	
Grog Temper 1	60.0	58.5	3510.0	54.3	52.5	2850.8	
Grog Temper 2	60.0	58.5	3510.0	54.6	52.3	2855.6	
Grog Temper 3	60.0	58.5	3510.0	54.1	52.8	2856.5	
Grog Temper 4	60.0	58.5	3510.0	53.8	52.5	2824.5	
Grog Temper 5	60.0	58.5	3510.0	54.3	53.0	2877.9	
Grog Temper 6	60.0	58.5	3510.0	54.4	52.2	2839.7	
Grog Temper 7	60.0	58.5	3510.0	54.4	52.0	2828.8	
Grog Temper 8	60.0	58.5	3510.0	54.0	52.0	2808.0	
Grog Temper 9	60.0	58.5	3510.0	53.9	52.7	2840.5	
Grog Temper 10	60.0	58.5	3510.0	53.7	52.6	2824.6	
Grog Temper 11	60.0	58.5	3510.0	53.9	52.7	2840.5	
Grog Temper 12	60.0	58.5	3510.0	53.9	52.7	2840.5	
Grog Temper 13	60.0	58.5	3510.0	53.8	51.9	2792.2	
Grog Temper 14	60.0	58.5	3510.0	53.7	52.2	2803.1	
Grog Temper 15	60.0	58.5	3510.0	53.7	52.3	2808.5	
Grog Temper 16	60.0	58.5	3510.0	54.1	52.3	2829.4	
Grog Temper 17	60.0	58.5	3510.0	53.8	52.4	2819.1	
Grog Temper 18	60.0	58.5	3510.0	53.6	52.5	2814.0	
Grog Temper 19	60.0	58.5	3510.0	54.2	52.4	2840.1	
Grog Temper 20	60.0	58.5	3510.0	54.0	52.3	2824.2	
Grog Temper 21	60.0	58.5	3510.0	53.8	52.8	2840.6	
Grog Temper 22	60.0	58.5	3510.0	54.2	52.5	2845.5	
Grog Temper 23	60.0	58.5	3510.0	54.7	52.6	2877.2	
Grog Temper 24	60.0	58.5	3510.0	54.0	52.4	2829.6	
Grog Temper 25	60.0	58.5	3510.0	54.1	52.2	2824.0	
Grog Temper 26	60.0	58.5	3510.0	54.4	52.3	2845.1	
Grog Temper 27	60.0	58.5	3510.0	53.9	52.0	2802.8	
Grog Temper 28	60.0	58.5	3510.0	54.5	51.9	2828.6	
Grog Temper 29	60.0	58.5	3510.0	54.1	52.5	2840.3	
Grog Temper 30	60.0	58.5	3510.0	54.7	51.9	2838.9	**Shrink %**
Average	60	58.5	3510.0	54.1	52.4	2833.0	19.3%

Temper Type	Temperature III 1000˚C (1832˚F)						
	Wet Length (mm)	Wet Width (mm)	Wet Area (mm^2)	Fired Length (mm)	Fired Width (mm)	Area (mm^2)	
Grog Temper 1	60.0	58.5	3510.0	52.2	51.2	2672.6	
Grog Temper 2	60.0	58.5	3510.0	52.0	50.9	2646.8	
Grog Temper 3	60.0	58.5	3510.0	52.3	50.8	2656.8	
Grog Temper 4	60.0	58.5	3510.0	52.4	50.4	2641.0	
Grog Temper 5	60.0	58.5	3510.0	52.1	51.3	2672.7	
Grog Temper 6	60.0	58.5	3510.0	52.8	51.4	2713.9	
Grog Temper 7	60.0	58.5	3510.0	53.0	50.5	2676.5	
Grog Temper 8	60.0	58.5	3510.0	52.9	51.4	2719.1	
Grog Temper 9	60.0	58.5	3510.0	53.0	51.4	2724.2	
Grog Temper 10	60.0	58.5	3510.0	52.4	51.0	2672.4	
Grog Temper 11	60.0	58.5	3510.0	52.8	51.6	2724.5	
Grog Temper 12	60.0	58.5	3510.0	52.7	50.8	2677.2	
Grog Temper 13	60.0	58.5	3510.0	52.8	51.0	2692.8	
Grog Temper 14	60.0	58.5	3510.0	52.9	51.3	2713.8	
Grog Temper 15	60.0	58.5	3510.0	53.3	51.5	2745.0	
Grog Temper 16	60.0	58.5	3510.0	52.8	50.9	2687.5	
Grog Temper 17	60.0	58.5	3510.0	53.0	51.6	2734.8	
Grog Temper 18	60.0	58.5	3510.0	52.9	51.0	2697.9	
Grog Temper 19	60.0	58.5	3510.0	53.0	50.9	2697.7	
Grog Temper 20	60.0	58.5	3510.0	51.4	50.9	2616.3	
Grog Temper 21	60.0	58.5	3510.0	53.2	51.3	2729.2	
Grog Temper 22	60.0	58.5	3510.0	53.5	51.0	2728.5	
Grog Temper 23	60.0	58.5	3510.0	53.5	51.4	2749.9	
Grog Temper 24	60.0	58.5	3510.0	53.1	51.2	2718.7	
Grog Temper 25	60.0	58.5	3510.0	53.2	50.4	2681.3	
Grog Temper 26	60.0	58.5	3510.0	53.0	51.0	2703.0	
Grog Temper 27	60.0	58.5	3510.0	53.0	51.0	2703.0	
Grog Temper 28	60.0	58.5	3510.0	53.1	50.7	2692.2	
Grog Temper 29	60.0	58.5	3510.0	53.1	50.6	2686.9	
Grog Temper 30	60.0	58.5	3510.0	53.6	50.6	2712.2	**Shrink %**
Average	60	58.5	3510.0	52.8	51	2696.3	23.2%

5. Sand Temper – Calculations for Difference between Wet Size and Fired Area

Temper Type	Temperature I 450˚C (842˚F)						
	Wet Length (mm)	Wet Width (mm)	Wet Area (mm²)	Fired Length (mm)	Fired Width (mm)	Area (mm²)	
Sand Temper 1	60.0	58.5	3510.0	57.4	55.7	3197.2	
Sand Temper 2	60.0	58.5	3510.0	57.0	55.2	3146.4	
Sand Temper 3	60.0	58.5	3510.0	56.7	55.2	3129.8	
Sand Temper 4	60.0	58.5	3510.0	57.4	55.1	3162.7	
Sand Temper 5	60.0	58.5	3510.0	57.3	55.1	3157.2	
Sand Temper 6	60.0	58.5	3510.0	56.9	55.3	3146.6	
Sand Temper 7	60.0	58.5	3510.0	56.6	55.7	3152.6	
Sand Temper 8	60.0	58.5	3510.0	57.2	55.5	3174.6	
Sand Temper 9	60.0	58.5	3510.0	56.9	55.4	3152.3	
Sand Temper 10	60.0	58.5	3510.0	57.3	55.5	3180.2	
Sand Temper 11	60.0	58.5	3510.0	57.4	55.9	3208.7	
Sand Temper 12	60.0	58.5	3510.0	57.0	55.8	3180.6	
Sand Temper 13	60.0	58.5	3510.0	57.2	54.6	3123.1	
Sand Temper 14	60.0	58.5	3510.0	56.8	55.2	3135.4	
Sand Temper 15	60.0	58.5	3510.0	57.0	55.4	3157.8	
Sand Temper 16	60.0	58.5	3510.0	56.8	55.3	3141.0	
Sand Temper 17	60.0	58.5	3510.0	56.7	55.6	3152.5	
Sand Temper 18	60.0	58.5	3510.0	56.9	55.4	3152.3	
Sand Temper 19	60.0	58.5	3510.0	57.1	55.2	3151.9	
Sand Temper 20	60.0	58.5	3510.0	56.9	55.3	3146.6	
Sand Temper 21	60.0	58.5	3510.0	56.6	56.1	3175.3	
Sand Temper 22	60.0	58.5	3510.0	56.3	55.7	3135.9	
Sand Temper 23	60.0	58.5	3510.0	57.2	55.8	3191.8	
Sand Temper 24	60.0	58.5	3510.0	56.7	55.4	3141.2	
Sand Temper 25	60.0	58.5	3510.0	56.1	54.5	3057.5	
Sand Temper 26	60.0	58.5	3510.0	56.5	54.9	3101.9	
Sand Temper 27	60.0	58.5	3510.0	57.0	55.3	3152.1	
Sand Temper 28	60.0	58.5	3510.0	57.3	55.9	3203.1	
Sand Temper 29	60.0	58.5	3510.0	57.2	55.3	3163.2	
Sand Temper 30	60.0	58.5	3510.0	57.6	55.6	3202.6	**Shrink %**
Average	60.0	58.5	3510.0	57.0	55.4	3155.8	10.1%

Temper Type	**Temperature II 700˚C (1292˚F)**						
	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**	
Sand Temper 1	60.0	58.5	3510.0	57.2	55.2	3157.4	
Sand Temper 2	60.0	58.5	3510.0	57.1	55.6	3174.8	
Sand Temper 3	60.0	58.5	3510.0	57.4	56.0	3214.4	
Sand Temper 4	60.0	58.5	3510.0	57.1	55.5	3169.1	
Sand Temper 5	60.0	58.5	3510.0	58.0	55.9	3242.2	
Sand Temper 6	60.0	58.5	3510.0	57.1	55.6	3174.8	
Sand Temper 7	60.0	58.5	3510.0	57.5	55.5	3191.3	
Sand Temper 8	60.0	58.5	3510.0	56.9	56.0	3186.4	
Sand Temper 9	60.0	58.5	3510.0	57.0	55.4	3157.8	
Sand Temper 10	60.0	58.5	3510.0	56.9	55.3	3146.6	
Sand Temper 11	60.0	58.5	3510.0	57.4	55.4	3180.0	
Sand Temper 12	60.0	58.5	3510.0	57.7	55.7	3213.9	
Sand Temper 13	60.0	58.5	3510.0	57.3	55.7	3191.6	
Sand Temper 14	60.0	58.5	3510.0	57.3	55.6	3185.9	
Sand Temper 15	60.0	58.5	3510.0	57.4	55.7	3197.2	
Sand Temper 16	60.0	58.5	3510.0	57.5	55.6	3197.0	
Sand Temper 17	60.0	58.5	3510.0	57.3	55.8	3197.3	
Sand Temper 18	60.0	58.5	3510.0	57.8	55.4	3202.1	
Sand Temper 19	60.0	58.5	3510.0	57.7	56.2	3242.7	
Sand Temper 20	60.0	58.5	3510.0	58.4	55.5	3241.2	
Sand Temper 21	60.0	58.5	3510.0	57.6	56.0	3225.6	
Sand Temper 22	60.0	58.5	3510.0	57.7	55.9	3225.4	
Sand Temper 23	60.0	58.5	3510.0	57.3	55.7	3191.6	
Sand Temper 24	60.0	58.5	3510.0	57.9	55.3	3201.9	
Sand Temper 25	60.0	58.5	3510.0	57.5	55.8	3208.5	
Sand Temper 26	60.0	58.5	3510.0	57.3	55.2	3163.0	
Sand Temper 27	60.0	58.5	3510.0	57.5	55.2	3174.0	
Sand Temper 28	60.0	58.5	3510.0	57.3	55.4	3174.4	
Sand Temper 29	60.0	58.5	3510.0	57.3	56.1	3214.5	
Sand Temper 30	60.0	58.5	3510.0	56.0	55.8	3124.8	**Shrink %**
Average	60.0	58.5	3510.0	57.4	55.6	3192.2	9.1%

Temper Type	**Temperature III 1000˚C (1832˚F)**

	Wet Length (mm)	**Wet Width (mm)**	**Wet Area (mm²)**	**Fired Length (mm)**	**Fired Width (mm)**	**Area (mm²)**	
Sand Temper 1	60.0	58.5	3510.0	56.9	55.0	3129.5	
Sand Temper 2	60.0	58.5	3510.0	57.8	54.0	3121.2	
Sand Temper 3	60.0	58.5	3510.0	56.9	54.9	3123.8	
Sand Temper 4	60.0	58.5	3510.0	56.7	55.1	3124.2	
Sand Temper 5	60.0	58.5	3510.0	56.2	55.2	3102.2	
Sand Temper 6	60.0	58.5	3510.0	56.7	55.0	3118.5	
Sand Temper 7	60.0	58.5	3510.0	57.0	54.7	3117.9	
Sand Temper 8	60.0	58.5	3510.0	56.5	56.0	3164.0	
Sand Temper 9	60.0	58.5	3510.0	56.6	55.5	3141.3	
Sand Temper 10	60.0	58.5	3510.0	56.8	55.3	3141.0	
Sand Temper 11	60.0	58.5	3510.0	57.0	55.3	3152.1	
Sand Temper 12	60.0	58.5	3510.0	56.8	55.0	3124.0	
Sand Temper 13	60.0	58.5	3510.0	56.7	55.2	3129.8	
Sand Temper 14	60.0	58.5	3510.0	57.0	55.0	3135.0	
Sand Temper 15	60.0	58.5	3510.0	57.0	55.8	3180.6	
Sand Temper 16	60.0	58.5	3510.0	56.9	55.4	3152.3	
Sand Temper 17	60.0	58.5	3510.0	56.9	55.0	3129.5	
Sand Temper 18	60.0	58.5	3510.0	57.5	55.1	3168.3	
Sand Temper 19	60.0	58.5	3510.0	57.2	54.8	3134.6	
Sand Temper 20	60.0	58.5	3510.0	57.1	55.0	3140.5	
Sand Temper 21	60.0	58.5	3510.0	56.9	55.0	3129.5	
Sand Temper 22	60.0	58.5	3510.0	57.6	55.1	3173.8	
Sand Temper 23	60.0	58.5	3510.0	57.2	54.9	3140.3	
Sand Temper 24	60.0	58.5	3510.0	57.6	55.4	3191.0	
Sand Temper 25	60.0	58.5	3510.0	57.6	55.1	3173.8	
Sand Temper 26	60.0	58.5	3510.0	57.9	55.4	3207.7	
Sand Temper 27	60.0	58.5	3510.0	56.6	55.3	3130.0	
Sand Temper 28	60.0	58.5	3510.0	56.7	55.1	3124.2	
Sand Temper 29	60.0	58.5	3510.0	57.6	55.5	3196.8	
Sand Temper 30	60.0	58.5	3510.0	57.3	55.2	3163.0	**Shrink %**
Average	60.0	58.5	3510.0	57.0	55.1	3145.3	10.4%

6. Basic Sample Statistical Values for Wet Versus Fired Tile Calculated Area Differences

Sample Statistics of Wet Versus Fired Size

Temperature 1 450˚C (842˚F)				
Statistic	**Temper**			
	No Temper	**Quartz**	**Grog**	**Sand**
Area Mean (mm^2)	2728.3	2816.1	2810.3	3155.8
Area Mode (mm^2)	2656.1	2818.8, 2818.4	2791.8, 2824.5, 2803.3, 2808.2	3146.6, 3152.3
Area Median (mm^2)	2728.8	2818.4	2808.5	3152.4
Area Range (mm^2)	147.4	137.1	69.8	151.2
Area Standard Deviation (mm^2)	42.20212	36.655577	19.712946	31.171522
Area Variance (mm^2)	1781.0189	1343.6313	388.60023	971.66378
Temperature 2 700˚C (1292˚F)				
	No Temper	**Quartz**	**Grog**	**Sand**
Area Mean (mm^2)	2738.9	2838.9	2833	3192.3
Area Mode (mm^2)	2771.1	2830.0, 2835.5	2840.5	3174.8, 3191.6
Area Median (mm^2)	2750.6	2835.1	2834.25	3191.6
Area Range (mm^2)	177.4	90	85.7	117.9
Area Standard Deviation (mm^2)	40.581018	23.732019	20.064508	28.491932
Area Variance (mm^2)	1646.819	563.20875	402.58447	811.79016
Temperature 3 1000˚C (1832˚F)				
	No Temper	**Quartz**	**Grog**	**Sand**
Area Mean (mm^2)	2617.4	2723.6	2696.3	3145.4
Area Mode (mm^2)	2621.4	2713.8, 2697.5, 2703.0	2703	3129.5
Area Median (mm^2)	2621.1	2713.8	2697.8	3137.7
Area Range (mm^2)	165.8	127	133.6	105.5
Area Standard Deviation (mm^2)	35.57365	30.648648	31.480518	26.282546
Area Variance (mm^2)	1265.4846	939.33964	991.02303	690.77223

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