Experiments in Ceramic Technology: The Effects of Various Tempering Materials on Impact and Thermal-Shock Resistance

Gordon Bronitsky; Robert Hamer

American Antiquity, Vol. 51, No. 1 (Jan., 1986), 89-101.

Stable URL:
http://links.jstor.org/sici?sici=0002-7316%28198601%2951%3A1%3C89%3AEICTTE%3E2.0.CO%3B2-Z

American Antiquity is currently published by Society for American Archaeology.

1983 *Cultural Resource Investigations on Gallegos Mesa: Excavations in Blocks VIII and IX, and Testing Operations in Blocks X and XI, Navajo Indian Irrigation Project, San Juan County, New Mexico.* Navajo Nation Papers in Anthropology No. 24. Window Rock, Arizona.

Wait, Walter K.
1983 A Preliminary Model for the Preceramic at Star Lake. In *The Star Lake Archaeological Project,* edited by Walter K. Wait and Ben Nelson, pp. 131–152. Southern Illinois University Press, Carbondale.

Ward, Albert E. (editor)
1978 *Limited Activity and Occupation Sites.* Contributions to Anthropological Studies No. 1. Center for Anthropological Studies, Albuquerque.

Weston, Timothy, and Alan H. Simmons
1984 Archaeological Survey. In *Archaic Prehistory and Paleoenvironments in the San Juan Basin, New Mexico: The Chaco Shelters Project,* edited by Alan H. Simmons, pp. 116–130. Project Report Series No. 53. Museum of Anthropology, University of Kansas, Lawrence.

Wilson, John P.
1979 *Cultural Resources of the Alamito Coal Lease Area, Northwestern New Mexico.* Alamito Coal Company, Tucson.

Wills, Wirt H., Richard I. Ford, John D. Speth, and Austin Long
1982 Bat Cave Reinvestigated. Paper presented at the 47th annual meeting of the Society for American Archaeology, Minneapolis.

Wimberly, Mark
1972 Training Bulletin for the Tula Rosa Valley Project: 1972 Excavations at Fresnal Shelter. Ms. on file, Human Systems Research Corporation, Albuquerque.

Winter, Joseph C.
1980 Human Adaptations in a Marginal Environment. In *Human Adaptations in a Marginal Environment: The UII Mitigation Project,* edited by James L. Moore and Joseph C. Winter, pp. 483–522. Office of Contract Archaeology, University of New Mexico, Albuquerque.

Woodbury, Richard B., and Ezra B. W. Zubrow
1979 Agricultural Beginnings, 2000 B.C.—A.D. 500. In *Southwest,* edited by Alfonso Ortiz, pp. 43–60. Handbook of North American Indians, vol. 9, William G. Sturtevant, general editor. Smithsonian Institution, Washington, D.C.

EXPERIMENTS IN CERAMIC TECHNOLOGY: THE EFFECTS OF VARIOUS TEMPERING MATERIALS ON IMPACT AND THERMAL-SHOCK RESISTANCE

Gordon Bronitsky and Robert Hamer

Prehistoric potters used a wide variety of materials as temper, or filler. Although temper selection has often been assumed to be the result of purely cultural factors, recent research indicates temper had technological functions as well. Impact and thermal-shock resistance data of a range of kinds, grades, and amounts of temper are presented. Test results indicate that the use of finely-ground tempers in general and burned shell temper in particular produce briquettes that are significantly more durable than briquettes incorporating other materials.

Archaeologists interested in the study of prehistoric ceramics confront a wide and often bewildering array of nonplastic inclusions. Tempers as diverse as sand, shell, pulverized minerals, plant materials, feathers, and even blood (e.g., Duma and Lengyel 1970) have all been reported for archaeologically recovered ceramics. The reasons for selection of a particular material have generally been ascribed

Gordon Bronitsky, Department of Anthropology, University of New Mexico, Albuquerque, NM 87131
Robert Hamer, Department of Biostatistics, Virginia Commonwealth University—Medical College of Virginia, Richmond, VA 23284

American Antiquity, 51(1), 1986, pp. 89–101.

to the operation of non-technological cultural factors. In Southwestern archaeology, diversity of tempering materials has often been linked to factors of cultural differentiation (e.g., Hargrave 1974). Indeed differences in ceramic temper and paint type have been widely used as the basis for tracing historic groups back into the prehistoric period (e.g., the extensive review in Ford et al. 1972; Wendorf and Reed 1955). In Virginia, a wide variety of named pottery types have been defined, based primarily on differences in temper, rim profile, and surface manipulation; these differences are usually linked to prehistoric cultural differences among groups, rather than to technological requirements (e.g., Evans 1955:38). However, a growing body of archaeological research has begun to indicate that temper selection may have been directly linked to vessel function in a number of instances (e.g., Arnold 1981; Braun 1978, 1983; Hargrave and Braun 1981; Matson 1981; Rye 1981; Shepard 1963; Steponaitis 1979, 1981, 1982a) and improved workability through decreased plasticity (see Barna 1967 for a technical discussion). Selection of the proper temper can also eliminate microcracking, reduce shrinkage, and provide for acceleration of firing schedules (Robinson 1968b). Often potters themselves are aware of the functional uses of different tempering materials (e.g., Arnold's study of Maya potters at Ticul, 1971). At Hopi, Colton (1938) noted a Hopi preference for sand temper in culinary vessels, linked to greater durability of vessels with such tempers.

This paper reports on the results of testing for impact resistance and thermal-shock resistance on clay briquettes incorporating varying grades and amounts of sand, burned shell, and unburned shell temper in order to investigate the relation between temper selection and vessel performance. The relation between temper and weight loss in firing is also examined. This study was conducted as part of a larger research program investigating the function of ceramics in prehistoric Virginia, changes in ceramic technology, and the nature of these changes in relation to larger shifts in socioeconomic systems. Such work may ultimately enable archaeologists to estimate the fitness of particular ceramic techniques and materials for specific functions. Eventually we may be able to provide a means of assessing the expertise of particular potters in producing vessels for these functions. At a regional level, we may also begin to resolve some of the confusion about Virginia ceramics by focusing upon materials and their relations to different vessel functions in differing socioeconomic contexts.

In actual use, pottery failure is most often due to impact. Because of the nature of constituent materials, most ceramics fail in a brittle manner, i.e., with little or no plastic deformation (Kingery 1960:592). As a result, the mechanical strength of ceramic materials is usually expressed as impact resistance (Rado 1969:191). Resistance to impact does not refer to any single physical property but instead to the amount of energy, applied in an arbitrary fashion and direction, needed to fracture a given specimen (Dinsdale et al. 1967:369). Another cause of vessel failure is thermal shock, which commonly occurs as spalling and shattering due to repeated heating and cooling. In food preparation involving boiling, such as stews and gruels, vessels are repeatedly placed on a heat source and then removed (Searle and Grimshaw 1959:747).

METHOD

In order to examine the role of tempering materials in the resistance of ceramic vessels to impact and thermal shock, we made a series of commercial clay briquettes following procedures outlined by Matson (1963:492), Rye (1981:127–128), Windes (1977:569), and Weaver (1963:54). Sand, unburned shell, and burned shell were chosen as tempering materials because of their wide use by prehistoric Virginia potters, and by historic Indian groups in the area as well (e.g., Evans 1955; Fewkes 1944; Holmes 1903; Mason 1877; Pollard 1894; Speck 1925; Stern 1951). These tempering materials were then ground and sorted into fine and coarse categories. In order to maximize contrasts in the performance of materials, no medium-sized temper was used in the tests. Fine temper was defined as particle size less than or equal to 0.5 mm, based on temper grade definitions used in several archaeological studies of prehistoric American ceramics (Bennett 1974; Colton 1953; Evans 1955:34–35; Gifford 1928; Shepard 1956) and on geological studies (Folk 1968; Wentworth 1933). Coarse temper was defined, on the same basis, as particle size greater than or equal to 1.0 mm. Burned shell was made by dousing oyster shell in gasoline and burning until the fire extinguished

Table 1. Impact Testing: Mean Crack and Shatter Values for Selected Material/Grade/Amount Temper Sets (in ft-lb).

Material	Grade	Amount (%)	N	Crack	SD[a]	Shatter	SD[a]
Sand	fine	40	5	0.0363	0.0105	0.2488	0.1114
		80	5	0.0693	0.0190	0.1908	0.0691
	coarse	40	5	0.0373	0.0192	0.1149	0.0565
		80	5	0.0500	0.0464	0.0935	0.0706
Unburned shell	fine	40	5	0.0723	0.0382	0.2394	0.1122
		80	5	0.0792	0.0676	0.2801	0.1177
	coarse	40	5	0.0061	0.0045	0.1159	0.0605
		80	5	0.0061	0.0045	0.1015	0.0423
Burned shell	fine	40	5	0.0860	0.0496	0.3067	0.1083
		80	5	0.1501	0.0457	0.3681	0.0898
	coarse	40	5	0.1481	0.1086	0.3566	0.0879
		80	5	0.1149	0.0565	0.3453	0.0809
No temper	Fired at 600°C		5	0.0287	0.0085	0.0996	0.0318
	Fired at 800°C		5	0.0619	0.0511	0.1456	0.0933
	Fired at 1,000°C		5	0.0363	0.0105	0.0897	0.0490

[a] SD = standard deviation.

itself. The calcined shell was then ground for temper. Commercial clay was then mixed with each grade and type of temper in the amount of 40% and 80% by original weight of clay, so that the amount of temper ranged from 29% to 44% of total workable weight when it was mixed with water. Briquettes were made from the tempered clay, but the briquettes were not paddled or otherwise manipulated; hence the temper was aligned randomly with respect to the briquette surface.

Ten briquettes were made from each temper/grade/amount set, each 1″ × 1″ × ¼″ in size, with some exceptions, to approximate prehistoric vessel thickness and to facilitate handling in testing. Exceptions were due to difficulties encountered in forming certain temper/grade/amount sets to these specifications. The 80% shell temper briquettes, both burned and unburned, were 1½″ × 1½″ × ¼″ in size; coarse sand briquettes were 1¼″ × 1¼″ × ¼″ in size. As a control, briquettes were also made from commercial clay to which no materials were added. All briquettes were then dried in a drying oven at 105°C for one hour to insure uniform moisture loss and fired at 800°C in order to approximate native open-air firing temperatures. To examine the role of firing temperatures in impact and thermal-shock resistance, I fired 10 untempered clay briquettes at 600°C, 10 at 800°C, and 10 at 1,000°C to approximate the range available to non-kiln-using potters (e.g., studies by Guthe 1925; Rye 1981; Shepard 1956).

In general, the most direct tests of durability are simulated service tests (see Kingery 1955:14). Impact testing and thermal-shock resistance were chosen as tests most closely duplicating actual ceramic use conditions. A variety of impact tests are used in mechanical testing, including Izod, Charpy, and drop weight tests as well as pendulum tests (Bortz and Burton 1969). These tests of transverse breaking strength are discussed by Shepard, but problems of specimen size necessitated a reduction in span of the knife edges used in the test, therefore making uncertain the comparability of her data to results gained by other experimenters (Shepard 1956:134; see Smith 1977 for a fuller discussion).

The pendulum test was chosen for its greater ease of use (no notching, special positioning, or specific specimen size is required) and on the basis of comparative tests reported in ceramic engineering studies that indicate greater reliability of results than with other tests (Davidge 1979:109; Jones and Berard 1972; see Smith 1977:188 for problems with Izod and Charpy tests, also Bortz and Burton 1969:102–103, and Dinsdale et al. 1962:261). Measurement of any physical parameter exhibits a range of results due to the random nature of the size and position of flaws, necessitating a presentation of a statistical distribution of values; accordingly, five briquettes from each temper/grade/amount set were impact tested (Budworth 1970:238; Davidge 1979:133).

Table 2. Thermal Shock: Mean Crack and Shatter Values for Selected Material/Grade/Amount Temper Sets (in ft-lb) After 40 Immersion Cycles.

Material	Grade	Amount (%)	N	Crack	SD[a]	Shatter	SD[a]
Sand	fine	40	5	0.0537	0.0133	0.1585	0.0583
		80	4	0.0453	0.0178	0.1599	0.0917
	coarse	40	—	—	—	—	—
		80	—	—	—	—	—
Unburned shell	fine	40	5	0.0363	0.0105	0.2167	0.0613
		80	5	0.0471	0.0235	0.2053	0.1005
	coarse	40	—	—	—	—	—
		80	2	0.0028	0.0000	0.0248	0.0000
Burned shell	fine	40	5	0.0325	0.0105	0.1259	0.0302
		80	5	0.0499	0.0185	0.1636	0.0339
	coarse	40	5	0.0384	0.0217	0.1064	0.0348
		80	5	0.0149	0.0097	0.2057	0.0374
No temper	Fired at 600°C		—	—	—	—	—
	Fired at 800°C		5	0.0259	0.0117	0.0879	0.0333
	Fired at 1,000°C		2	0.0561	0.0172	0.0830	0.0208

[a] SD = standard deviation.

Note: —indicates that the entire set cracked apart during the immersion cycles and therefore was not available for impact testing.

Resistance to impact was measured on a pendulum-type tester designed and built in the Biomedical Instrumentation Facility of the Medical College of Virginia. Pendulum length was 0.275 m; hammer mass was 0.367 kg. A similar device is mentioned by Shepard, but she notes that such impact tests had not been employed in the study of prehistoric ceramics to that date (1956:133). The pendulum angle at release necessary to initiate cracking was measured in degrees, as was pendulum angle resulting in briquette shatter. These measurements were then converted to energy in pound-feet using the following formula:

$$\text{ft-lb} = [1 - \cos(\theta/180)](0.729)$$

where θ = angle of pendulum in degrees. The results of the impact testing program are presented in Table 1.

Resistance to thermal shock is governed by the thermal expansion of materials. When a vessel is heated rapidly, the surface expands more rapidly than the interior. As a result it is subject to compressive stresses while the interior is under tension stress; on cooling, the reverse occurs. When these stresses exceed the strength of the material, thermal-shock failure occurs (Rado 1969:198). Such failure is one of the primary failure modes in ceramics; accordingly, there is a great deal of literature devoted to thermal shock and fracture (e.g., Davidge 1979; Davidge and Tappin 1967; Evans 1975; Jones and Berard 1972; Searle and Grimshaw 1959). To measure resistance to thermal shock, we immersed five briquettes from each temper/grade/amount set in boiling water for five minutes and then immediately placed them in ice water, a simplified version of the quench test used in testing industrial ceramics (Davidge and Tappin 1967; see Newcomb 1947:162). Each immersion in hot water and subsequent ice-water quenching was considered one cycle. The number of cycles required to cause failure was recorded for each briquette. Those briquettes that survived 40 cycles of quench testing were then impact tested to examine strength degradation due to thermal shocking. These data are presented in Table 2.

The data analysis was performed using multivariate analysis of variance (MANOVA). The specific multivariate test statistic was Wilk's Lambda, which was tested using F approximations found in Rao (1971:337). The data were arranged in a 3 (material: sand, burned shell, unburned shell) by 2 (grade: coarse or fine) by 2 (amount: 40% or 80%) factorial design. There were three dependent variables. These were defined as (1) loss: loss of weight on firing; (2) crack: amount of impact required

Table 3. Impact Testing: Multivariate Analysis of Mean Crack and Shatter Values (Loss, Crack and Shatter Considered Simultaneously).

Source	*F*	*df*	*p*
Grade	37.44	3, 58	.0001
Amount	1.10	3, 58	NS[a]
Material	19.84	6, 116	.0001
Grade × amount	8.56	3, 58	.0002
Grade × material	5.06	6, 116	.0002
Amount × material	4.54	6, 116	.0004
Amount × material × grade	3.60	6, 116	.0030
Control (800°C) vs. mean of twelve temper sets	7.29	3, 58	.0004
Temperature	19.04	6, 116	.0001
Material within grade	8.9	6, 116	.0010

[a] NS = not significant.

to cause first visible cracking of briquette; and (3) shatter: amount of impact required for structural collapse. In addition, three control groups did not receive any tempering material. These groups differed in the temperature at which they were fired (600°C, 800°C, 1,000°C). All briquettes in the experimental groups were fired at 800°C.

In a MANOVA, univariate analyses of variance (ANOVA) are also obtained for each dependent variable. These univariate analyses are the analyses that are actually interpreted; however, the MANOVA is used to "give permission" to look at the corresponding univariate analyses. If the MANOVA for an effect is not statistically significant, the results of the univariate analyses that were included are viewed as unreliable. Thus, the MANOVA answers the question, "Did something happen?," while the univariate ANOVAs answer the question, "Given that something happened, to which dependent variable did it happen?"

Table 3 contains MANOVA results for the three dependent variables of loss, crack, and shatter. All effects (main and interaction) are significant except for amount of temper. Because interpretation of main effects in the presence of significant interactions is problematic, simple effects and contrasts of interest were tested. These were linear contrasts among cell means that addressed the research questions we wanted to answer. The contrasts tested the statistical hypotheses derived from the research questions.

The specific contrasts of interest tested were: (1) control (untempered briquettes fired at 800°C) versus the mean of the experimental groups, which tested the hypothesis that tempering material had some effect on performance; (2) firing temperature within the three control groups, to see whether temperature had any effect on performance; and (3) effect of temper material within specific grades.

The sample size of five per cell was sufficient because of the low variability in the data and the large number of cells. On the average, there were between 50 and 116 error df for each statistical test, which is exceptionally large. The fact that all but one of the multivariate tests were significant indicates high power. Pre-firing weights among briquettes varied by 2%, a statistically insignificant variation, indicating that variations in weight did not significantly affect performance results.

WEIGHT LOSS AFTER FIRING

Univariate analysis of mean weight loss upon firing showed extremely strong values for almost all sources. The only sources that had no significant effect on weight loss were amount of temper and the type of temper within any given grade (coarse or fine). These data are presented in Tables 4 and 5. As might be expected, firing temperature significantly affected weight loss. Firing briquettes to 800°C and 1,000°C caused much more water loss than firing to 600°C. This weight loss is a reflection of the loss of hygroscopic and adsorbed water, loss of colloidal water, and loss of water of hydration, which occur at temperatures above 120°C (Searle and Grimshaw 1959:263).

Table 4. Univariate Analysis of Weight Loss.

Source	*F*	*df*	*p*
Grade	103.69	1, 60	.0001
Amount	1.73	1, 60	NS[a]
Material	31.23	2, 60	.0001
Grade × amount	25.41	1, 60	.0001
Grade × material	6.90	2, 60	.002
Amount × material	13.74	2, 60	.0001
Amount × material × grade	9.22	2, 60	.0003
Control (800°C) vs. mean of twelve temper sets	16.61	1, 60	.0001
Temperature	84.8	2, 60	.0001
Grade within material	39.15	3, 60	.0001
Material within grade	2.7	2, 60	NS
Amount within burned shell	0.18	1, 60	NS

[a] NS = not significant.

IMPACT RESISTANCE

The same univariate analysis was then performed on mean crack values, i.e., the amount of force in ft-lb needed to initiate visible cracking in the briquettes. Cracking is equivalent to initial failure in the ceramic engineering literature (e.g., Dinsdale et al. 1967:370). These data are presented in Table 6. For ease of understanding, we have omitted test values of sources of variation that are not significant. The analysis indicates that the only variable significantly affecting resistance to crack initiation is material. Here the mean value for burned shell (0.125 ft-lb of pressure required to break them for all amounts and grades) is three times higher than the means for either sand (0.048) or unburned shell (0.041). Within certain materials, grade of temper also makes a difference in resistance to crack initiation. For unburned shell, fine shell is over 12 times more resistant to cracking (0.07575 versus 0.0061 ft-lb of pressure required to break them, respectively) than coarse unburned shell temper. Grade and amount had no effect on resistance to cracking for any other materials. Firing to 600°C, 800°C, and 1,000°C did not result in significantly different mean crack values.

Table 5. Percentage of Weight Lost After Firing.

Material	Grade	Amount (%)	N	Mean Loss (%)	SD[a]
Sand	fine	40	5	6.85	0.0094
		80	5	11.41	0.0070
	coarse	40	5	5.92	0.0096
		80	5	5.39	0.0075
Unburned shell	fine	40	5	10.61	0.0114
		80	5	9.78	0.0064
	coarse	40	5	9.37	0.0186
		80	5	8.38	0.0088
Burned shell	fine	40	5	10.00	0.0052
		80	5	10.79	0.0090
	coarse	40	5	8.52	0.0051
		80	5	7.38	0.0082
No temper	Fired at 600°C		5	1.09	0.0003
	Fired at 800°C		5	7.39	0.0091
	Fired at 1,000°C		5	7.87	0.0100

[a] SD = standard deviation.

Table 6. Impact Testing: Univariate Analysis of Mean Crack Values.

Source	*F*	*df*	*p*
Grade	—	—	—
Amount	—	—	—
Material	20.61	2, 60	.0001
Grade × amount	—	—	—
Grade × material	4.41	2, 60	.0200
Amount × material	—	—	—
Amount × material × grade	—	—	—
Control (800°C) vs. mean of twelve temper sets	—	—	—
Temperature	—	—	—
Grade within material	4.07	3, 60	.0200
Material within grade	20.90	2, 60	.0001

Values of non-significant sources omitted.

Results of analysis of mean shatter values are presented in Table 7. Shatter refers to the point at which the specimen lost its structural integrity, equivalent to final failure (Dinsdale et al. 1967:370). Again, test values of sources of variability that did not yield statistically significant results have been omitted for clarity. Here, too, material significantly affected resistance to shatter, with the mean value for burned shell (0.344 ft-lb of pressure required to break them) approximately twice as great as the values for sand (0.162) or unburned shell (0.184). Again, firing temperature did not affect mean crack values. As with crack initiation, grade of temper made a significant difference in the performance of unburned shell in impact testing, with fine unburned shell over twice as resistant as coarse unburned shell (0.2597 versus 0.1087 ft-lb of pressure required to break them, respectively). However, in contrast to crack initiation, grade affected shatter values within the category of sand temper as well, with fine sand temper twice as resistant to shatter as coarse sand temper (0.2234 versus 0.1042 ft-lb, respectively). Differences in grade did not affect shatter values for burned shell temper. Nonetheless, burned shell temper was significantly stronger than other temper materials in both coarse and fine grade categories.

To summarize, amount of temper did not significantly affect weight loss in firing, crack, or shatter values. For crack initiation, burned shell was more resistant than either sand or unburned shell, and fine temper was more impact resistant than coarse temper. For shatter, burned shell was

Table 7. Impact Testing: Univariate Analysis of Mean Shatter Values.

Source	*F*	*df*	*p*
Grade	15.46	1, 60	.0002
Amount	—	—	—
Material	28.64	2, 60	.0001
Grade × amount	—	—	—
Grade × material	5.44	2, 60	.0067
Amount × material	—	—	—
Amount × material × grade	—	—	—
Control (800°C) vs. mean of twelve temper sets	5.59	1, 60	.0213
Temperature	—	—	—
Grade within material	8.78	3, 60	.0001
Material within grade	23.46	2, 60	.0001

Values of non-significant sources omitted.

Table 8. Thermal Shock Testing: Univariate Analysis of Mean Crack Values.

Source	*F*	*df*	*p*
Grade			
Amount	—	—	—
Material	—	—	—
Amount × material	—	—	—
Burned shell vs. unburned shell	—	—	—
Control (800°C) vs. mean of eight sets	5.71	1, 27	.0241
Grade (burned shell only)	—	—	—
Grade × amount (burned shell only)	8.21	1, 27	.0112

Values of non-significant sources omitted.

more resistant than sand or unburned shell, and fine sand temper was similarly more resistant than coarse sand temper. In terms of potential performance, vessels with burned shell temper would be much more resistant to stresses causing initial cracking, and vessels with such temper would retain their structural integrity much longer in the face of continued impact stresses. This relationship holds for both coarse and fine unburned shell temper and for amounts of 40% and 80% by weight.

THERMAL SHOCK

Analysis of the thermal-shock data presented some problems in that certain material/grade/amount sets cracked apart during the repeated cycles of boiling-water and ice-water immersion. Although this fact was in itself significant, it precluded statistical tests and limited the kinds of comparisons that could be made. In addition, for statistical reasons, cells with two or fewer observations were not used in the analysis. The following sets were thus omitted from statistical analysis: coarse sand (40% and 80% by weight), coarse unburned shell (40% and 80%), and the untempered control briquettes fired at 600°C and 1,000°C.

These data (see Table 8) indicated immediately that fine temper is more resistant to thermal shock than coarse temper in all cases, because four of the six coarse temper groups did not provide data for analysis. In addition, briquettes fired at 800°C were more resistant to thermal shock than those fired at 600°C or 1,000°C, for the same reasons. Only in the burned shell temper category did all briquettes survive the immersion cycles. This contrasts with results reported by Steponaitis (1979). However, Steponaitis's work has involved "catastrophic" thermal shock, involving temperature differences of 200–400°C. The briquettes in this study were quenched over temperature differences of less than 100°C; such temperature differences may well be below the critical temperature difference (t_c) at which catastrophic failure occurs (V. Steponaitis, personal communication 1982; after Hasselman 1969, 1970). In theory, quenching over sub-critical temperature differences such as those used in this study should not result in loss of strength; in practice, repeated cycling over sub-critical temperature differences, a practice similar to actual cooking use, *does* result in strength degradation, a phenomenon sometimes known as "thermal fatigue" (V. Steponaitis, personal communication 1982).

Within the fine temper grade, there were no significant differences among mean crack values, with the exception that the non-tempered control differed significantly from the means of eight temper groups. Addition of temper, regardless of kind, made the briquettes more resistant to thermal shock as indicated by impact testing after completion of four immersion cycles. Neither the kind of temper nor the amount affected mean crack values.

In regard to mean shatter values (see Table 9), unburned shell was significantly more resistant to thermal shock than burned shell (0.2110 versus 0.14475 ft-lb, respectively). However, consideration of mean values of different amount categories shows much greater resistance to impact testing after thermal shocking for briquettes tempered with 80% coarse burned shell temper in comparison to those tempered with 40% of the same temper (0.2057 versus 0.1064 ft-lb, respectively). This is the

Table 9. Thermal Shock Testing: Univariate Analysis of Mean Shatter Values.

Source	*F*	*df*	*p*
Amount	—	—	—
Material	—	—	—
Amount × material	—	—	—
Burned shell vs. unburned shell	5.54	1, 27	.0261
Control (800°C) vs. mean of eight sets	7.55	1, 27	.0105
Grade (burned shell only)	—	—	—
Grade × amount (burned shell only)	20.09	1, 16	.0004

Values of non-significant sources omitted.

only instance in the entire testing program in which amount of temper affected briquette performance. Steponaitis has shown the same pattern in his test data—the more shell, the greater the thermal-shock resistance (Steponaitis 1982b:20–22, Figure 12).

Strength degradation refers to the amount of strength lost during the course of thermal shocking and is reflected in lower mean crack and shatter values (see Braun's concept of performance, 1983: 110). These values are presented in Table 10. Burned shell temper suffered considerable strength degradation in terms of both grades, much more so than either sand or unburned shell temper. Fine burned shell temper mean crack values were about the same as the other temper types, due to its greater strength degradation. Similarly, shatter values for fine burned shell temper were about the same as fine sand temper, and lower than fine unburned shell temper. Coarse burned shell temper also underwent considerable strength loss, but high values before thermal shocking resulted in briquette survival during the immersion cycles, in contrast to the other temper types.

DISCUSSION

These relative advantages have their origins in the chemistry and physics of the tempers themselves and changes that occur during firing. First, it is a general principle in ceramics that specimen strength increases with decreasing grain size, although the reasons for this are unclear at present (Kirchner 1979:8). Several factors affect the initiation of cracks, including the nature of the cohesive bond and atomic structure, the structure of the defects, and the history of the specimen itself (Lawn and Wilshaw 1975:16). Of these, it is the structure of the material and its defects that are of greatest concern in this analysis. Materials that contain many volume crack sources such as voids and irregular particles show greater resistance to crack propagation than to crack initiation because stresses are more evenly distributed. However, these same imperfections act as crack nuclei, creating concentrations of stress that result in greater crack initiation (Davidge and Tappin 1967:172; Kingery 1963:292).

In all likelihood, the shell temper may be more irregular than the riverine sand, creating a greater number of volume crack sources, or creating a better bond with the clay (Shepard 1956:131). Burning the shell before use as temper probably further increases this irregularity by rendering the shell very friable, which also reduces the effort needed for crushing (Steponaitis 1982b:4). Further, the calcite in the shell undergoes major changes during firing. Between 650–750°F, calcite begins to decompose into calcium oxide and carbon dioxide. This decomposition continues until about 850°F when the decomposition is complete. The hydration that occurs after firing is the hydration (from water vapor from the air) of calcium oxide to calcium hydroxide. Calcium hydroxide occupies a larger space in the paste than the original calcite, and spalling results. Burning shell before use minimizes the possibility that this change will occur during firing, with resultant loss through spalling and shattering. Firing at temperatures above 800°C results in calcite decomposition and hydration of $CaCO_3$ after firing to form $Ca(OH)_2$ with resultant vessel wall damage through spalling (Rye 1976; Steponaitis 1982b:4–6).

Burning shell before use may minimize this risk, and render its rate of thermal expansion similar

Table 10. Strength Degradation (in ft-lb).

Source	Grade	Crack/ Shatter	Impact	Thermal Shock
Sand	fine	crack	0.0528	0.0495
		shatter	0.2198	0.1592
	coarse	crack	0.0328	0.0
		shatter	0.1042	—
Unburned shell	fine	crack	0.0758	0.0417
		shatter	0.2598	0.2110
	coarse	crack	0.0045	—
		shatter	0.1087	—
Burned shell	fine	crack	0.1181	0.0412
		shatter	0.3374	0.1448
	coarse	crack	0.1315	0.0267
		shatter	0.3510	0.1561

to that of the clay, reducing risk from inhomogenous expansion in firing. Studies of calcined clay (Robinson 1968a:480) show a reduction in firecracks due to a reduced thermal gradient during dehydroxylation through dilution of the clay substance. Finally, it has been suggested that a cementation process may result from the hydration of partially burned shell during firing that may strengthen vessels (Matson 1981:452). Although unproven, it certainly might account for the much higher values for burned shell. In commercially produced whitewares fired at much higher temperatures than used in this study, small amounts of bone ash act as a flux due to the reaction of the $CaCO_3$ in the bone ash with feldspar alkalies in the clay (Newcomb 1947:64).

In contrast, quartz, the main component of sand, has a much higher rate of thermal expansion than does fired clay (Rye 1976). This can cause inhomogenous expansion with resultant vessel loss during firing. One response is to make the same temper finer, which also increases its strength, as demonstrated herein. That potters were aware of this fact is evident in a gradual trend to fine sand temper documented in the Midwest (Braun 1982:188–190, 1983) and the Southeast (Steponaitis 1982b:28–29). In addition, quartz requires high temperatures to produce a well fired pot due to the phenomenon of quartz inversion. Between 550–573°C, quartz particles increase in size; when kiln temperatures drop below this range, the original size is restored, leaving voids around the quartz grains (Jacobs 1983:8). This necessitates the use of large quantities of fuel and an equal temperature distribution, which may be difficult to achieve in open firings (Kalsbeek 1969:75). Shell, in contrast, needs high temperatures for relatively short periods of time (Kalsbeek 1969:75), which may have been another factor that favored its selection by aboriginal potters.

SUMMARY

Archaeologists have generally considered variation in ceramics to be primarily a result of factors of style and cultural differentiation. The results presented in this report indicate that the tempering materials available to prehistoric potters differed considerably in their mechanical performance. In order to assess the choices of alternative materials and processes in the construction of ceramics, archaeologists must develop methods that measure performance under simulated and actual use conditions. The destructive nature of many of the tests employed in measurement of ceramic performance will require an ongoing interaction among experiments in ceramic technology, replicative studies, and the actual sherds recovered in excavation. Research will require thorough analyses of the range of factors involved in ceramic production and use, from clay workability and plasticity, to tempering materials, to manufacturing processes and firing techniques, to use conditions. As such studies are incorporated into investigations of the socioeconomic context of production (e.g., Adams 1979; Rice 1981), we can begin to approach an understanding of the evolution of ceramic technology, but this understanding will require efforts from researchers in many disciplines. To quote Anna

Shepard (1963:22) "just as a snowball held in the hand melts, so questions left to the narrow specialist fail of solution and are soon forgotten."

Acknowledgments. The research presented in this paper is part of a much larger effort conducted as part of an archaeological mitigation for the County of Henrico, Virginia, and was funded by the County under the supervision of Stephen Perlman and Dan Mouer of Virginia Commonwealth University. The research design was considerably improved by discussion and suggestions from Stephen Perlman and Dan Mouer. The impact tester that forms the core of this research was designed and constructed by Alex Clarke and Tom Gentry of the Biomedical Instrumentation Facility of Virginia Commonwealth University. Vincas Steponaitis, David Braun, Stephen Perlman, Michael Schiffer, Patty Jo Watson, Dan Mouer, and two anonymous reviewers for *American Antiquity* made helpful comments and suggestions. We are especially indebted to Gwen Brandon for help with the testing procedures and clarity of presentation. Of course, any errors or misinterpretations of the results are strictly our own responsibility.

REFERENCES

Adams, W.
1979 On the Argument from Ceramics to History: A Challenge Based on Evidence from Medieval Nubia. *Current Anthropology* 20(4):727–744.

Arnold, D.
1971 Ethnomineralogy of Ticul, Yucatan, Potters: Etics and Emics. *American Antiquity* 36(1):20–40.
1981 A Model for the Identification of Non-Local Ceramic Distribution: A View from the Present. In *Production and Distribution: A Ceramic Viewpoint,* edited by H. Howard and E. Morris, pp. 32–44. B.A.R. International Series No. 120.

Barna, G.
1967 Plasticity of Clay Minerals. *Bulletin of the American Ceramic Society* 46:1091–1093.

Bennett, M.
1974 *Basic Ceramic Analysis.* San Juan Valley Archaeological Project Technical Series No. 1. Eastern New Mexico University Contributions in Anthropology 6(1).

Bortz, S., and K. Burton
1969 Analysis and Reviews of Mechanical Testing Procedures for Brittle Materials. In *Structural Ceramics and Design,* edited by S. Acquaviva and S. Bortz, pp. 95–147. Gordon and Breach, New York.

Braun, D.
1978 Woodland Ceramic Technology and Chronological Implications, Western Illinois. Paper presented at Midwest Archaeological Conference, Bloomington, Indiana.
1982 Radiographic Analysis of Temper in Ceramic Vessels: Goals and Initial Methods. *Journal of Field Archaeology* 9:183–192.
1983 Pots and Tools. In *The Hammer Theory of Archaeological Research,* edited by A. Keene and J. Moore, pp. 107–134. Academic Press, New York.

Budworth, D.
1970 *An Introduction to Ceramic Science.* Pergamon, New York.

Colton, H.
1938 The Making of Hopi Pottery. *Museum of Northern Arizona Notes* 11(1):6–11.
1953 Potsherds. *Museum of Northern Arizona Bulletin* No. 25. Flagstaff, Arizona.

Davidge, R.
1979 *Mechanical Behavior of Ceramics.* Cambridge University Press, London.

Davidge, R., and G. Tappin
1967 Thermal Shock and Fracture in Ceramics. *Transactions of the British Ceramic Society* 66:405–422.

Dinsdale, A., J. Camm, and W. Wilkinson
1967 The Mechanical Strength of Ceramic Tableware. *Transactions of the British Ceramic Society* 66:367–404.

Duma, G., and I. Lengyel
1970 Mesocsat Pots Containing Red Blood Pigment. *Acta Archaeologicae Scientiarium Hungaricae* 22: 69–93.

Evans, A.
1975 Thermal Fracture in Ceramic Materials. *Proceedings of the British Ceramic Society* 25:217–237.

Evans, C.
1955 A Ceramic Study of Virginia Archaeology. *Bureau of American Ethnology Bulletin* 160. Smithsonian Institution, Washington, D.C.

Fewkes, V.
1944 Catawba Pottery-Making with Notes on Pamunkey Pottery-Making, Cherokee Pottery-Making, and Coiling. *Proceedings of the American Philosophical Society* 88:69–124.

Folk, R.
1968 *Petrology of Sedimentary Rocks.* Hemphill's, Austin, Texas.
Ford, R. I., A. Schroeder, and S. L. Peckham
1972 Three Perspectives of Puebloan Prehistory. In *New Perspectives on the Pueblos,* edited by A. Ortiz, pp. 19–39. University of New Mexico.
Gifford, E.
1928 Pottery-Making in the Southwest. *Publications in American Archaeology and Ethnology* 23(8). University of California Press, Berkeley.
Guthe, C.
1925 Pueblo Pottery Making, a Study of the Village of San Ildefonso. *Papers of the Phillips Academy Southwestern Expedition* No. 2. New Haven, Connecticut.
Hargrave, L. L.
1974 Type Determinants in Southwestern Ceramics and Some of Their Implications. *Plateau* 46(3):76–95.
Hargrave, M., and D. Braun
1981 Chronometry of Mechanical Performance Characteristics of Woodland Ceramics: Methods, Results and Applications. Paper presented at Annual Meeting of Society for American Archaeology, San Diego, California.
Hasselman, D.
1969 Unified Theory of Thermal Shock Fracture Initiation and Crack Propagation in Brittle Ceramics. *Journal of the American Ceramic Society* 52:600–604.
1970 Thermal Stress Resistance Parameters for Brittle Refractory Ceramics: A Compendium. *Bulletin of the American Ceramic Society* 49(12):1033–1037.
Holmes, W.
1903 Aboriginal Pottery of the Eastern United States. *Bureau of American Ethnology Twentieth Annual Report,* pp. 1–234. Smithsonian Institution, Washington, D.C.
Jacobs, L.
1983 Notes About the Relation Between Filler and Clay, and Filler and Shrinkage, Respectively. *Newsletter of the Department of Pottery Technology of the University of Leiden* 1:6–12.
Jones, J., and M. Berard
1972 *Ceramics: Industrial Processing and Testing.* Iowa State University, Ames.
Kalsbeek, J.
1969 A Systematic Approach to the Study of the Iron Age Pottery. In *Excavations at Tell Deir 'Alla,* edited by H. Franken, pp. 73–80. E. J. Brill, Leiden.
Kingery, W.
1955 Factors Affecting Thermal Stress Resistance of Ceramic Materials. *Journal of the American Ceramic Society* 38:3–15.
1960 *Introduction to Ceramics.* John Wiley and Sons, New York.
1963 Effects of Microstructure on the Properties of Ceramics. In *The Physics and Chemistry of Ceramics,* edited by C. Kingsberg, pp. 286–305. Gordon and Breach, New York.
Kirchner, H.
1979 *Strengthening of Ceramics.* Marcel Dekker, New York.
Lawn, B., and T. Wilshaw
1975 *Fracture of Brittle Solids.* Cambridge.
Mason, O.
1877 Anthropology News. *American Naturalist* 11(10):624–627.
Matson, F.
1963 Some Aspects of Ceramic Technology. In *Science in Archaeology,* edited by D. Brothwell and E. Higgs, pp. 489–498. Basic Books, New York.
1981 Archaeological Ceramics and the Physical Sciences: Problem Definition and Results. *Journal of Field Archaeology* 8:448–456.
Newcomb, R.
1947 *Ceramic Whitewares.* Pitman, New York.
Pollard, G.
1894 The Pamunkey Indians of Virginia. *Bureau of American Ethnology Bulletin* 17. Smithsonian Institution, Washington, D.C.
Rado, Paul
1969 *An Introduction to the Technology of Pottery.* Pergamon Press, Oxford.
Rao, C. R.
1971 *Linear Statistical Inference and Its Applications.* Wiley, New York.
Rice, P.
1981 Evolution of Specialized Pottery Production: A Trial Model. *Current Anthropology* 22(3):219–227.
Robinson, G.
1968a Design of Clay Bodies for Controlled Microstructure. *Bulletin of the American Ceramic Society* 47: 477–480.

1968b Design of Clay Bodies for Controlled Microstructure Part II—Clay Aggregate Bodies. *Bulletin of the American Ceramic Society* 47:548–553.

Rye, O.
1976 Keeping Your Temper Under Control: Materials and the Manufacture of Papuan Pottery. *Archaeology and Physical Anthropology in Oceania* 11(2):106–137.
1981 *Pottery Technology: Principles and Reconstruction.* Taraxacum Press, Washington, D.C.

SAS Institute, Inc.
1982 *SAS Users Guide: Statistics.* SAS Institute Inc., Cary, North Carolina. Pp. 39–84.

Searle, A., and R. Grimshaw
1959 *The Chemistry and Physics of Clays and Other Ceramic Materials.* 3rd ed. Interscience, New York.

Shepard, A.
1956 Ceramics for the Archaeologist. *Carnegie Institution of Washington Publication* 609. Washington, D.C.
1963 Beginnings of Ceramic Industrialization: An Example from the Oaxaca Valley. *Carnegie Institution of Washington Notes from a Ceramic Laboratory* No. 2. Washington, D.C.

Smith, C.
1977 *The Science of Engineering Materials.* Prentice-Hall, New Jersey.

Speck, F.
1925 The Rappahannock Indians of Virginia. *Museum of the American Indian Heye Foundation Notes and Monographs* 5(3).

Steponaitis, V.
1979 Prehistoric Pottery from Moundville, Alabama—Some Technological Findings. Lecture delivered at National Bureau of Standards, August 14, 1979.
1981 A Possible Technological Explanation for the Distinction Between Coarse and Fine Shell-Tempered Ceramics in Mississippian Assemblages. Paper presented at Annual Meeting, Society for American Archaeology, San Diego, California.
1982a *Ceramics, Chronology and Community Patterns: An Archaeological Study at Moundville.* Academic Press, New York.
1982b Technological Studies of Prehistoric Pottery from Alabama: Physical Properties and Vessel Function. Paper presented at Wenner-Green symposium, "Multidimensional Approaches to the Study of Ancient Ceramics." Lhee, Netherlands.

Stern, T.
1951 Pamunkey Pottery Making. *Southern Indian Studies,* vol. 3.

Weaver, E.
1963 Technological Analysis of Prehistoric Lower Mississippian Ceramic Materials: A Preliminary Report. *American Antiquity* 29:49–56.

Wendorf, F., and E. Reed
1955 An Alternative Reconstruction of Northern Rio Grande Prehistory. *El Palacio* 62:131–173.

Wentworth, C.
1933 Fundamental Limits to the Sizes of Clastic Grains. *Science* 77:633–634.

Windes, T.
1977 Typology and Technology of Anasazi Ceramics. In *Settlement and Subsistence Along the Lower Chaco River: The CGP Survey,* edited by C. Reher, pp. 279–369. University of New Mexico, Albuquerque.