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Impact resistance of archaeological ceramics: The influence of firing and temper

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ABSTRACT

This work considers technological choices in the manufacture of utilitarian archaeological ceramics, in view of their role in the ceramics' physical properties and affordances. In this paper we present results of an experimental study which examined the influence of processing parameters on mechanical properties of clay-based ceramics. The influence of firing temperature, amount and grain size of aplastic inclusions on a ceramic's response to dynamic loads were determined experimentally, taking into consideration how this compares to the materials' response to static loads. Results show that the fracture strength under quasi-static loading increases with increasing vitrification and decreases with increasing amounts and size of aplastic inclusions. In contrast, while the presence of aplastic inclusions does reduce impact resistance, the amount and grain size of aplastic inclusions do not seem to play a significant role, both in terms of a ceramic's impact strength and fracture energy. This highlights the importance of considering the likely sources of mechanical stresses when assessing the affordances of a ceramic vessel.

1. Introduction

Ceramics are an abundant find at countless archaeological sites from many regions, dating to various periods. While in the past archaeological research has frequently placed more emphasis on the finer, highly decorated pottery, more recently there is a growing interest also in utilitarian pottery, which is usually coarser and in many cases undecorated. Such ceramics not only took part in many facets of every-day life in the past and may shed light on aspects not amenable through the study of luxury or elite products, but, moreover, utilitarian pottery can be highly specialised, requiring selection of particular raw materials, raw material treatment or manufacturing processes.

It is not surprising that pottery products were employed widely, on an everyday basis, for many different functions until very recently: raw materials are widely available and they can readily be formed in many shapes before being transformed into finished products by firing. Pottery has many desirable material properties: it is highly durable, heat (and fire) resistant, chemically inert, as well as strong and tough enough to survive frequent handling. Very different (and often divergent) demands are placed on storage jars, transport vessels, cooking pots, or pyrotechnical ceramics. For example, thermal properties are of crucial importance for pyrotechnical ceramics or cooking ware, while for transport vessels their ability to resist to mechanical stresses is essential. For transport amphorae, for example, mechanical stress can be static stress, arising from weight loads from overlying vessels when densely packed in a ship hull, but also impact stress, arising from vessels bumping against each other during rough seas is important. Indeed, the enhanced ability of archaeological ceramics to withstand mechanical (or thermal) stresses during daily use is frequently argued to be important for the selection of particular manufacturing practices.

Ceramic products gain their characteristic properties in manufacture. Different steps in manufacture such as refining of the raw clay, clay mixing, addition of temper material or firing conditions influence the texture and microstructure of the ceramic material, and consequently the mechanical properties of the finished product. For this reason a main concern of the study of mechanical properties of archaeological ceramics is the assessment of the influence of ceramic manufacture on the physical properties of these ceramics.

Mechanical and thermal properties of archaeological ceramics and the question of whether they have been the driving force behind potters' technological choices in the past or if they influenced technological changes observed in pottery production over time, have attracted research interest and debates for quite some time. Shepard (1956) provides probably the first discussion of the potential importance of strength measurements for archaeological ceramics, pointing out that these would afford a means of judging and comparing serviceability of wares. She discusses strength data obtained on a series of archaeological ceramics (correlating an observed progressive increase in strength with improvement in firing methods), but – overcoming limitations of testing archaeological material – also examines the influence of different temper types on prepared briquettes. It was, however, a paper by Braun (1983), which emphasised that pots are made to be used for certain activities and that their morphology and composition would be constrained (and therefore to some extent dictated) by their intended

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contexts of use, which gave the impetus to an increased preoccupation with the subject. Subsequent publications examined how different manufacturing technologies influence the material properties of archaeological ceramics, and explained technical variations and changes over time in the manufacturing processes of utilitarian ceramics in terms of their impact on material performance (e.g. Steponaitis, 1984; Feathers and Scott, 1989, Hoard et al., 1995). However, it has also been noted that the factors affecting and dictating potters' choices are many and varied, and that it is imperative to include in such considerations the social context of production and consumption (Sillar and Tite, 2000). Even for contemporary products, after all, “fashionable” material choices do not always correlate with functionality or quality very well. In this sense, rather than explaining technological choice, the study of physical properties provides a baseline against which the role of cultural and a host of other possible factors can be examined.

During daily use, pottery vessels are exposed to a multitude of stresses. The ability to retain their contents and to survive loads without losing structural integrity is a prerequisite for many ceramics. When considering mechanical stresses in archaeological ceramics, it is their response to static loads that is usually examined (e.g. Tite et al., 2001). The response of a material to static loads is an indication of its behaviour when exposed, for example, to weight loads, such as those that arise when piling ceramic vessels during transportation or storage. A very different, and often much more damaging, case is the response of a material to dynamic loads, when forces are applied over a very short time period and a material is forced to absorb energy very quickly. This is what is referred to as impact. In any case, fracture occurs – often in a quite spectacular way – if a material is not able to absorb the applied energy.

In order to assess the behaviour of a material under impact, pendulum or drop weight tests are usually employed. The former are used to assess the material's impact fracture resistance, whereas the latter are often used to study the damage wrought by impact and to assess any remanent fracture strength. Pendulum impact tests are used, for example, in the quality assessment of modern ceramic tableware (ASTM (American Society for Testing and Materials), 2011), using a schedule of increasing impacts. When using a single blow, the difference in the potential energy of the pendulum, before and after breaking a test specimen, can be used to calculate what is called impact resistance. When the tests are instrumented, pendulum tests provide information about the load–time history of the sample during the test, over a period as short as a few milliseconds or less. Such load–time curves provide information on maximum loads and allow the assessment of fracture energies. Drop weight tests on the other hand are ideal for determining the influence of repeated, non-catastrophic impacts, on the remanent strength of the material. This may be used to assess the number of impact cycles that a material may withstand without fracturing and whether a pottery vessel can safely be used in applications where repeated impact may be expected, such as a long journey by boat.

Impact has so far been largely neglected when examining mechanical performance of archaeological ceramics. Exceptions include Bronitsky and Hamer (1986), who used a pendulum type tester to study the influence of temper materials on impact resistance. However, inherent methodological problems in their approach (some of which are addressed by Feathers, 1989) resulted in anomalous results. Mabry et al. (1988) developed a falling weight impact tester to assess impact and examine a series of experimental briquettes to assess the influence of firing temperature on impact strength. They showed an increase of impact strength with increasing firing temperature, but their setup did not allow gaining information on initiation and propagation of fracture. Finally, Pierce (2005) set out to assess the influence of surface topography on ‘impact strength’ not only in falling weight tests, but also in pendulum tests on whole vessels. Although demonstrating some creativity in experimental setup (his ‘pendulum test’ involves the swinging whole pots with a string against a pillar), results are inconclusive due to problems with the experimental setup and insufficient experimental control.

What follows is a presentation of the first results of an experimental study, which examined the influence of manufacturing parameters on mechanical properties of clay-based ceramics, in particular their response to dynamic loads and how they compare to static loads.

2. The response of archaeological ceramics to mechanical stresses

For a ceramic's response to mechanical stresses, both the initiation and propagation of cracks are important. Two relevant parameters are fracture strength and fracture energy. Strength is related to the maximum force that can be applied to a material without a crack initiating. This is, however, not necessarily equivalent to overall material or vessel failure. A vessel will very often remain intact even if a crack starts, if there are micromechanisms that can stop (“arrest”) this crack before it propagates through the material. Such mechanisms may include crack bifurcation, microcracking, crack wandering, grain pull-out etc. The second parameter is the fracture energy which consists of an intrinsic and a dissipation part. This is the energy that is required to both initiate and propagate a crack through the material. The intrinsic part describes the energy needed for the onset of fracture (related to the energy which is required to form new surfaces by breaking atomic bonds), while the dissipation part describes the material's ability to stabilise crack propagation through the micromechanisms described above. In truly brittle materials with unstable crack propagation, the energy is determined only by the intrinsic part. However, clay-based ceramics may exploit energy dissipation mechanisms, and exhibit stable crack propagation during fracture: when any of the above micromechanisms act on the cracks, the energy dissipated increases and the fracture energy measured is higher. Much of our knowledge on the mechanical capability of pottery is based on tests performed under slow static flexure, which are more routinely performed for these materials than impact tests. These provide information about how a ceramic will react when exposed to a static load, as the material is allowed to absorb the load slowly and over an extended period of time (Tite et al., 2001), as would be the case for stacked storage or transport jars.

A crucial difference between such static loading and impact loading is the time available for the activation and action of the micromechanisms that can arrest a propagating crack. Whereas under static loading there is ample time for most such crack arrest mechanisms to act to stop cracks before they lead to final failure, under impact loading there is very little time and these micromechanisms contribute little or no energy to the total fracture energy measured. The current work is a first attempt at measuring such fracture energy under impact loading, relevant for archaeological ceramics, on experimental briquettes.

3. Experimental procedure

Testing of mechanical properties on archaeological material is usually avoided. This is because these tests are destructive and require repetition on several specimens, which usually have to fulfil geometrical constraints not readily met by archaeological specimens. Moreover, potential degradation of the material during use and weathering in burial means that the properties measured on an archaeological ceramic today in a laboratory, are not necessarily the properties the material exhibited in the past. Finally, testing of experimental briquettes is preferred also since it enables to determine the influence of selected manufacturing parameters, e.g. the addition of temper, on mechanical properties under controlled conditions. For the remit of the present study, i.e. in order to investigate the influence of firing and tempering on ceramic performance under impact and to assess how this compares to their response under slow loading, a series of experimental briquettes was manufactured as follows.

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