5 PHYSICAL PROPERTIES OF POTTERY

Generally, pottery analysis is based on three main parameters: functional, technological and stylistic. Within each of them there are several variants significant for the classification of pottery forms. Many authors have dealt with the analysis and classification of ceramic objects, but Anna O. Shepard has left the biggest mark; she was the first to approach systematically the issue of pottery analysis and description (Shepard 1985). In her view, the subject of pottery analysis and description is treated from four angles: *physical properties, composition of materials, technique* and *style.* Understanding of the physical properties of ceramics is necessary if we are to analyse and process pottery material, and understand the technological choice and circumstances of the pottery production. The physical properties of pottery include its colour, hardness, strength, porosity and texture. Those properties are interrelated, and they affect the vessel's quality and lifespan.

COLOUR

Colour is the first feature that we notice on a pottery sherd. When we try to put together fragments that belong to the same vessel, colour is generally the first criterion applied for selecting such fragments. However, there are several factors that can influence the colour of a vessel. The primary factors include clay composition and firing atmosphere, temperature and duration. The secondary factors stem from the post-firing conditions, such as charcoal deposition during the vessel's exposure to fire (visible especially in the lower parts of vessels), deposition of substances from the soil after the pottery object had been discarded, wear after long use, leaching by soil waters, overexposure to high temperatures in the case of a house fire, etc. All the secondary factors should be recognized before the pottery colour is described.

Pottery colour has been regularly specified using the *Munsell Soil Color Charts*, which provide us with three interrelated visual variables. Those are: *hue*, or the position of the colour in the spectrum; *value*, or the intensity of light and dark tones, and *chroma* or *brightness*, that is, the purity of the colour (Shepard 1985: 103–113). However, it should be pointed out that colour reporting using the Munsell system is used primarily to define the colour of the geological layer, rather than of fired soil/clay. The colour can undoubtedly say a lot about the clay and firing method – that is, whether reduction or oxidation firing was applied – but the question which is always raised is whether it is necessary to describe the colour of a pottery sherd in detail, without any further analysis, and how important the colour criterion is for the classification of the pottery. Pottery colour is important only if considered together with other variables.

The firing atmosphere is typically divided into oxidizing, reducing and neutral. If the flow of air is unobstructed and there is sufficient free oxygen which bonds easily with elements present inside and on the surface of the clay objects, this is an oxidizing firing atmosphere. The colours obtained by this firing method are nuances of red. If a vessel fired by oxidation firing contains iron, it will oxidize, and the ceramic vessel will be yellowish (firing at less than 850°C). However, if fired at a higher temperature (above 850°C), more oxidized iron ions will render the pottery yellow or red. An atmosphere in which there is not enough free oxygen (which contains gases that extract oxygen from the clay) is called a reducing atmosphere, and it results in black or grey pottery. Reduction firing depends entirely on the quantity of organic substances in the clay mixture, which turn into charcoal due to the insufficient oxygen necessary for oxidation. This transformation leaves black traces within the pottery pores, and the resulting reduction-fired pottery is grey (if the quantity of organic material is small) or black (because of soot, i.e. unburnt carbon). Ceramics that contain primary clays (such as kaolin) will be white if heated at high temperature. However, the majority of ceramic wares have a specific colour which is primarily a result of the use of secondary clays that contain colouring minerals. For example, iron oxides will render pottery yellow, brown or red, and manganese oxide will make it dark or black (Goffer 2007: 242–245). As we can see, the colour of the surface of fired clay depends entirely on the firing atmosphere and iron compounds in the paste. Thus, when describing objects and their colours, we can only talk about the post-firing surface colour, and not about the clay colour (Horvat 1999: 46–55).

The pottery's surface colour cannot always be easily established, especially if the vessel has been exposed to sudden and frequent changes in temperature (during the firing, or deliberate or accidental incineration in a house fire). Such secondary factors can often be observed on prehistoric pottery, making colour reporting using the Munsell system unreliable for determining the firing atmosphere (*Fig. 1, p. 37*).

Firing atmosphere and temperature can be seen well on thin sections, based on the presence or absence of certain minerals or organic substances, which change their mineral composition and structure when exposed to specified temperatures. Organic substances burn off at temperatures of between 300 and 500°C, calcite disappears at temperatures in the range of 700 to 750°C in an oxidizing atmosphere, and at 750°C in a reducing atmosphere (Spataro 2002: 39).

The vessel's cross-section, i.e. its core, is the least exposed to changes in colour, and it can also reveal a lot about the firing environment and method. Although identifying the firing atmosphere on the basis of the cross-section colour alone is not always the ideal solution, it comes closest to specifying the firing environment, at least if pottery is the only material being processed. Mineralogical-petrological and chemical analyses can provide more reliable data, much as experimental archaeology can. The literature proposes several standards for identification of pottery cross-section colour. One of the first, later taken up by other authors, too, was proposed by O. S. Rye (1988: 116). In the second part of the book, a scale consisting of 5 changes in colour present among Vučedol pottery sherds will be presented.

HARDNESS

Pottery hardness is closely associated with firing temperature, and this variable can reveal the durability of a vessel and its capacity to withstand all mechanical changes during its use. Like the pottery's colour, its hardness also depends on a combination of several factors. Most important among them are the firing temperature, surface treatment, type of temper in the clay, and its microstructural properties. In general, clay hardness increases if firing temperature increases. Clay tempering can also influence pottery hardness, especially if it lowers the temperature necessary for the inception of fusion into a solid mass, which eventually results in a solid surface that resists deformation. On the other hand, salt temper can reduce the surface hardness if it concentrates on the surface, as a soft residue. Microstructural properties, including grain size and porosity, also influence the pottery's hardness. Fine-grained and nonporous materials will be more resistant to deformation and breakage, and they will be harder and more durable (Rice 1987: 354–355).

Mineral hardness is usually measured using the Mohs scale of hardness, established by the Austrian mineralogist back in 1922. The proposed scale of relative hardness consists of 10 minerals, in order from the softest (talc – hardness 1) to the hardest (diamond – hardness 10). Naturally, the scale is not linear in terms of absolute hardness, because the hardness of diamond is many times higher than that of talc (Rapp 2009: 19). Still, it is very important to know what this measuring is being used for and what the results are saying. Measuring hardness using the Mohs scale is done for primary identification of minerals, similar to 'fast scanning', prior to the final identification of the mineral composition of the paste, which is done by optical or chemical analyses in laboratories. Establishing hardness on the Mohs scale actually boils down to a rough estimate of the mineral hardness, which often becomes a purpose in itself (Adams 1966). Nowadays it is often used to establish whether ceramics were well fired or underfired, while archaeometric analysis provides much more precise and reliable results.

STRENGTH

Along with hardness, this variable determines closely-related properties of fired pottery. The strength of pottery refers to its capacity to withstand various types of breakage and mechanical stress. A number of conditions influence pottery strength: its texture, clay structure, porosity, method of preparation, production technique, working technique, firing temperature and duration, size of the vessel and conditions after its discarding (Shepard 1985: 130–131).

One of the most important features of the pottery's strength is its resistance to breakage and cracks during sudden and frequent changes in temperature, and its capacity to withstand blows and pressure. Since the majority of vessels were used for thermal preparation of food, the vessel's reaction to the thermal stresses it would be exposed to was one of the most fundamental features to consider when the clay and temper were chosen. The vessel's capacity to sustain constant heating and cooling can be analysed by various laboratory and experimental methods, which will establish how resistant it was to thermal shock/stress. In cooking vessels, under conditions of high temperature, the outer surface was exposed to stress more than the inner, where the wall was cooler due to the contents of the vessel. This could lead to faster cracking of the vessel, and eventually to breakage or spalling. The external surface could also break during cooling, when the vessel's inner surface was warmer than its outer. A proper choice of clay and temper, increasing the number and size of pores, and of a shape for the vessel that can successfully conduct heat, will lower the stress level and avoid possible damage.

It is worth emphasizing that the vessel's resistance to thermal stress is not a property of the material, but rather a complex parameter which depends not only on the material's physical characteristics – such as thermal-expansion coefficient, mechanical strength and resistance – but, more importantly, on the conditions of the thermal stress (Müller et al. 2014). Experiments conducted have demonstrated that limited thermal stress can be beneficial for vessels that are constantly exposed to such conditions, because the energy of crack propagation increases around temper particles (Müller et al. 2014). Furthermore, it has been shown that vessels containing larger amounts of temper are more resistant to thermal stress. The reason for this lies in the fact that, in a cooking vessel, the temperature inside the vessel will reach 100°C, while that on the external surface will be between 500 and 600°C, which causes thermal stress and results in micro-cracks. If such cracking is not prevented, the cracks will soon spread to the whole vessel and cause irreparable damage. Vessels with low or no thermal stress resistance will break with their very first exposure to a fire. Anything that prevents the appearance of micro-cracks – such as selected type and quantity of temper and surface treatment – increases thermal stress resistance (Skibo 2013: 40). For this reason, cooking vessels contain a high quantity of temper in their paste (up to as much as 40%), as confirmed by archaeometric, ethnoarchaeological and experimental investigations (Plog 1980; Bronitsky & Hamer 1986; Skibo et al. 1989; Skibo & Schiffer 1995; Tite et al. 2001; Pierce 2005; Tite 2008; Skibo 2013; Albero 2014; Müller et al. 2014). Furthermore, fine-grained clays have been shown to conduct heat more slowly, resulting in the external surface heating up faster than the interior. This would cause high thermal stress, in contrast to those clays in which large grains allow for a faster and more even heat absorption. For this reason, the texture of cooking vessels is mostly course-grained (Skibo et al. 1989; Spataro 2003; Skibo 2013).

When it comes to temper selection, it is generally considered very important to use those minerals and other admixtures that have lower or similar coefficients of thermal expansion (such as feldspar, calcite, plagioclase and mica), and grog and crushed shells. However, some of those tempers would have negative impact on the vessel's quality and cause cracks and damage. It is also believed that tempering with calcite and grog results in significant decrease in the thermal stress of vessels constantly exposed to quick heating. However, some properties of those tempers can have both positive and negative effects (Schiffer et al. 1994; Skibo & Schiffer 1995).

On the one hand, calcite tempering increases the plasticity of the wet clay, but on the other hand its presence can cause problems when pottery is fired at intermediate temperatures. When fired in an oxidizing atmosphere, at temperatures above 600–870°C, calcite turns into lime. When cooled, the lime reacts and forms calcium hydroxide, and this process is accompanied by a volume expansion, causing cracks and spalling, which in extreme cases can destroy a vessel (Müller et al. 2014).

Another type of temper often mentioned in relation to cooking vessels is grog, whose features were described in the previous chapter. Given that grog's coefficient of thermal expansion is similar to that of clay, it actually provides very little thermal stress resistance. The reason lies in the fact that a high quantity of clay minerals is not efficient in reducing fracture propagation, and it causes cracks in the particles (Albero 2014: 154). Still, adding a smaller quantity of grog temper will improve the vessel's thermal stress resistance, in comparison to vessels that contain no temper (Skibo et al. 1989; Skibo 2013). Experimental analyses have shown that tempering with 5% grog is optimal for pottery production, while the inclusion of more than 5% grog is harmful for the vessel's mechanical strength, regardless of the temperature of its firing (Vierira & Monteiro 2004).

Quartz, one of the most frequent natural clay inclusions and deliberate tempers, has high capacity for thermal expansion, making it unsuitable for use in cooking vessels. Nonetheless, if used in small quantities and very fine-grained, it can make pottery more resistant to changes in temperature. Moreover, fine quartz particles will make vessels stronger (Bronitsky & Hamer 1986). Quartz passes through its first phase at 573°C, and thus changes which occur at this temperature will cause some stress in the pottery, if this mineral is present in significant amounts, causing crack propagation in the vessel walls. However, smaller quantities of fine-grained quartz will reduce the negative effects of differential thermal expansion of the temper and the paste, thus preventing the initiation of fractures (Albero 2014: 154). Experiments have demonstrated that tempering clay with more than 10% quartz causes individual damaged zones to interact and produce extensive micro-crack networks that cover the entire vessel. During fracture, this micro-crack network encourages crack deflection, thus increasing energy dissipation and contributing to the strength of the material, or vessel (Müller et al. 2014). When the vessel is exposed to a fire, the micro-cracks will allow free space for unimpeded shrinkage.

It has been demonstrated by experiment and analysis that the potter's technological choices can increase the vessel's resistance to thermal stress, and these include the choice of: *1)* clay and temper, *2)* wall thickness, *3)* shape and size of vessel (with thermal stress sensitivity increasing linearly with the vessel's size), *4)* firing temperature and *5)* treatment of the vessel's internal and external walls (especially in vessels fired at lower temperatures). The transfer of fluids from the internal to the external surface of the vessel during cooking, and the way in which heat is transferred from the fire to the vessel's interior, can be regulated by proper surface treatment.

Polished and burnished walls in the vessel's interior will ensure water-resistance and also reduce possible cracking, because the mean temperature of the vessel's walls is lower, and thus a lower thermal gradient is transmitted to the surface, creating less stress. In vessels whose internal surface is characterized by low permeability, thermal cracking and fracture resistance can be increased by stronger texturing of the external surface (for example, by barbotine) (Schiffer et al. 1994; Skibo & Schiffer 1995).

The vessel's shape can also affect its thermal stress resistance. A uniform wall thickness and absence of sharp edges and sudden changes in the vessel's shape will reduce the vessel's exposure to thermal stress, or cracking. For this reason, cooking vessels most often have a simple forms (Rye 1988: 27; Sinopoli 1991: 14–15; Skibo & Schiffer 1995: 83; Skibo 2013: 52). Vessels with thinner walls are more resistant to thermal stress because they conduct heat faster than those with thick walls. The latter, however, have the advantage of maintaining a constant temperature of the vessels' contents, but they are heavier and less suitable for transport or constant handling.

As we have seen, there is no simple formula that can guarantee both the vessel's hardness and strength, and its resistance to thermal and mechanical stress. Some tempers are good, some are not so good, and it all depends on a number of parameters (the vessel's size, wall thickness, usage, cultural tradition). Some tempers will make the vessel plastic and prevent cracking upon drying, but on the other hand they will increase its thermal stress. Generally, as the temperature rises, the thermal stress resistance falls, so pottery fired at lower temperatures (such as cooking pots) feature higher thermal shock resistance. At the same time, lower firing temperatures will increase the vessel's permeability, so the potter needs to make another technological choice in order to improve the ceramics' properties (such as surface treatment). In all of this, the size of the grains and their quantity in the clay paste will play an important role.

Various tests of pottery strength have long been included in the analysis of ceramic vessels, and they depend on the field of interest. Given that pottery strength is a result of diverse processes taking place during the pottery's production, the analyses also go in different directions. In this area, a major role is played by experimental archaeology, which attempts to establish the importance of the influences of individual variables on the vessel's strength, such as type and quality of temper (Skibo et al. 1989; Cogswell et al. 1998), firing temperature, surface treatment, thermal shock resistance etc. (Schiffer et al. 1994; Pierce 2005; Maggetti et al. 2010; Rasmussen et al. 2012; Müller et al. 2014). When a vessel's strength is measured, one should take into consideration changes that occur in the pottery during its prolonged use, wear and exposure to high temperatures, the environment in which the vessel was discarded in the archaeological context (presence of salts, moisture, soil freezing) and the vessel's morphology (Neupert 1994).

A number of different tests have been used in archaeology to determine the strength of pottery sherds (Munz & Fett 2001: 125–136). Nowadays a relatively new method, *the ball-on-three-balls test* (B3B), is applied because of its simplicity and cost-effectiveness. The method involves putting a sherd on top of three identical steel balls, set at the same distance from the centre of the sherd and in contact with one another, and then placing a fourth ball on top of the sherd. The load on top of the sherd is increased in equal intervals until the sherd breaks. The time elapsed and the way in which the pottery sherd breaks under pressure is used to establish its strength (Neupert 1994; Danzer et al. 2007). This test has proven that grog-tempering, in comparison with sand-tempering, increases the vessel's strength by as much as 70% (Neupert 1994).

POROSITY

Porosity is one of the main properties of pottery, and can also provide useful information on the vessel's structure. Porosity depends on the sizes of pores and pottery vessel, that is, on the conditions which allow gases and liquids to pass through the vessel's porous body. Furthermore, the size of the clay particles and their distribution also affect porosity, as does the form of temper, forming technique and firing method (Velde & Druc 1999: 160).

Pores can be described using their shape, size and place of appearance, and they can also be closed or open to the vessel's external surface. The quantity of pores present in a pottery object determines its porosity. Other factors influencing porosity are the size, shape, grading and packing of particles, the specific constituents of the clay-body mix, and the treatment to which the material was subjected during manufacture (Rice 1987: 350–351). Vessels with polished surfaces and those treated with barbotine will hold liquids more easily, which means that they are impermeable. Vessels with a permeable external wall absorb moisture from the atmosphere; the moisture is retained by the external wall and it cools the vessels' contents. Such vessels are not suitable for storage or consumption of food which does not involve heat-treatment, because after a short period of time the liquids will leak from the vessels.

With a view to reducing their porosity and permeability, vessel walls are often treated with resins, waxes and plant juices (Rice 1987: 231; Schiffer et al. 1994). Chemical analyses have shown that vessels of the Vučedol Culture were also treated with beeswax, which will be discussed in the second part of the book (Chapter 15).

Many ethnoarchaeological investigations testify to the fact that a vessel's impermeability can be increased by a post-firing coating, usually applied to vessels fired at low temperatures. One such example comes from Ecuador, where potters have been coating vessels used for storing, cooking or serving food, to this day, with various organic liquids, such as resins, melted wax, and juices extracted from plant leaves (independently or in combination), with a view to reducing their porosity (Arnold 1985: 140). The Kalinga community of the Philippines (Longacre 1981: 60) coat their vessels with pine resin: they melt a piece of hardened resin on a hot vessel just removed from a fire. The process has been tested in an experiment, and the results have shown that the resin melts on the surface of a vessel removed from a fire at a temperature of 400°C. The melted resin slowly hardens on the vessel as it cools down (Schiffer et al. 1994). With the vessel's frequent use and washing, the resin loses its original function after approximately three months. Thereafter, the women of the Kalinga community stop using the vessel for cooking, because its increased permeability will not allow water to boil. Thus vessels which were originally used for cooking appear in archaeological contexts in their secondary function, when they are used primarily for foodstuff storage (Skibo 2013: 50).

The size and shape of pores, as well as their number, will strongly affect pottery strength: the higher the porosity, the weaker the vessel, which will also diminish its durability. However, sometimes pores may also help to prevent or delay vessel breakage by inhibiting the spread of incipient cracks (Sinopoli 1991: 13–14). This occurs if the pores are large, and a crack in the vessel stops at such a 'void.' This feature is reflected in the vessel's maximum resistance to thermal shocks, and the simplest way to obtain larger pores is by adding of organic temper, which burns up during firing (Rye 1988: 27). When the organic material present in the clay paste oxidizes, the space which was filled with remains of organic matter before firing is left empty, and the pottery becomes porous (Goffer 2007: 242). Furthermore, porosity affects the degree of resistance to disintegration and weathering, various mechanical and chemical changes, discolouration caused by fluids, etc. In addition, porosity increases absorption of carbon, which influences the pottery's black colour (Shepard 1985: 125–126).

TEXTURE

Texture is influenced primarily by clay temper: its quantity, shape and grain size, and by the clay's porosity. Variability of grain size depends on the nature of the tempering material and its preparation. Some materials are used in their natural condition, and others are crushed or pulverized (Shepard 1985: 117–121).