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The contribution of colour measurements to the archaeometric study of pottery assemblages from the archaeological site of Adulis, Eritrea

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ABSTRACT
Colorimetric evaluation was applied on archaeological pottery from the ancient port city of Adulis in the Red Sea coast of Eritrea. Pottery samples belong to the Ayla-Aksum typology, Late Roman Amphora 1 and *dolia* classes, which had never been analyzed by means of this approach. The survey consisted of colorimetric measurements from different parts of the ceramic bodies, to comprehend how these data could be related to the overall fabric classification. Differences in the colorimetric parameters provided helpful information on both technological manufacturing processes and fabric classification. Subtle variations in the colour coordinates were detected and aptly interpreted, so as to ascribe the related differences. Such an approach proved that the information provided by colour measurements can be partially correlated to observations from stereomicroscopy and optical microscopy, allowing a more in-depth description of the fabrics in the study of archaeological pottery.

Section: RESEARCH PAPER

Keywords: Colorimetry; pottery; fabric; Adulis

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1. INTRODUCTION

Colour is an important characteristic of archaeological materials and yet quantitative and reproducible measurements are needed for a meaningful analysis and classification of artefacts. Review of works on the colorimetric study of ancient ceramics pinpoints to the versatility of this method over traditional and yet solely qualitative description of colour using the Munsell colour charts [1]. The International Commission on Illumination; L*, a*, b* (CIELAB) colour space has been mentioned as a suitable system aimed at standardizing and comparing colorimetric features, and its utility demonstrated in many studies of different ceramic objects. Colorimetric surveys on pottery objects that range from the evaluation of colour of the exposed interior and exterior surfaces as well as their core, and colour measurements on powdered samples and based up on the collection of CIELAB colour data from digital photographs, have been extensively reported in the literature [2], [3]. In general, the archaeometric study of ancient pottery mainly aims at locating the production centres, the specific technology involved in pottery production and understanding the distribution patterns. Provenance is often tackled by determining the chemical and/or mineralogical compositions. and by comparing them with the composition of reference groups. Mirti and Davit (2004) demonstrated that colour measurements may help in assessing provenances and/or production technologies. The general agreement is that sherds made from different clays - or even from the same clay but processed in different ways - would show different colour curves, while ceramic materials obtained from a single clay and processed following a similar procedure should display a similar curve [4]. Colour measurements on archaeological pottery have been applied particularly for the evaluation of the original firing conditions [4]-[16]. On the other hand, the colour of ceramic bodies is not only affected by temperature, but also by firing duration and atmosphere, as well as by the final porosity, the mineralogical composition of the raw materials used and the nature of inclusions. Experimental analyses, aimed at evaluating the colour change with temperature by re-firing, allowed the detection of colour alterations in a specific clay body, and thus enabling an evaluation of the possible behaviour of different sherds. [3-4]. It is also noted that colorimetry, when coupled to other characterization techniques, can provide important results for examining raw materials and artefacts variability. The nucleation, growth, and grain size of hematite during firing as well as the redox reactions inherent to firing process and the influence of mineralogical composition, are all parameters that contribute to colour in ceramics, the consequences of which can be inferred by using mineralogical, micro-structural and chemical approaches [7]-[10] and [13]-[16]. Therefore, the complexity of mineralogical and physical-chemical factors influencing the colour of ceramics requires that colorimetry should be coupled to other archaeometric techniques. In this respect, the dynamics of firing and changes of microstructures affecting colour variations in ceramics can be understood through detailed analytical approaches, colorimetry can be useful to determine colour parameters of the paste allowing preliminary fabric determination.

In this study, pottery assemblages from the archaeological site of Adulis, the primary port of the Aksumite Empire in late antiquity in the Red Sea coast of Eritrea, were investigated by means of colorimetry. The site of Adulis was principally involved in the major developments in the history of the northern Horn of Africa from the first millennium CE [17]-[19]. The long - standing trade relations and cultural interaction with the Romans and the Mediterranean is attested in later periods during first millennium CE, through the Red Sea. Comparative analysis of architectural and ceramic typological sequences attest that the site was continuously inhabited from the first-second up to the sixth and early seventh c. CE and intensely occupied in the 5th-6th c. CE [18], [19]. The Ayla-Aksum, Late Roman Amphora 1 as well as *dolia* samples considered in this colorimetric survey indicate imports from the Mediterranean world in the later phases of the occupation of the site. Studies on these pottery assemblages from the northern Horn of Africa are rare [20]-[22] and colorimetric studies have never been applied previously. In this work, we highlight the evaluation of colorimetric parameters on different parts of ceramic bodies and their treatment in the form of powdered samples to assess the usefulness of colorimetry in pottery studies. The aim of this survey is to establish a preliminary fabric classification, possibly to be used for provenance determination. The results and limits of colorimetric evaluation are also reported here. The following sections provide a look into colorimetric assessment (considering different sampling procedures) and the use of such data to define the variability existing among the different classes.

2. MATERIALS AND METHODS

The colorimetric survey adopted for this study included different sampling procedures to evaluate the colorimetric parameters on archaeological pottery representing the Ayla-Aksum, Late Roman Amphora 1 and *dolia* classes. All the samples considered in this survey were collected in the 2019 fieldwork of the ongoing Italian-Eritrean excavations at Adulis [23]-[25]. On one hand, a set of samples was selected among a collection of 49 small sherds under archaeometric investigations: part of them were in fact not represented in this survey for being too small or showing colour variations after possibly post-depositional alterations. For the examined samples, colorimetric evaluation was done both on the interior and exterior surfaces of the ceramic bodies. The analysed surface was about 8 mm in diameter; thus, the detected coordinates relate to an average area of about 50 mm^2.

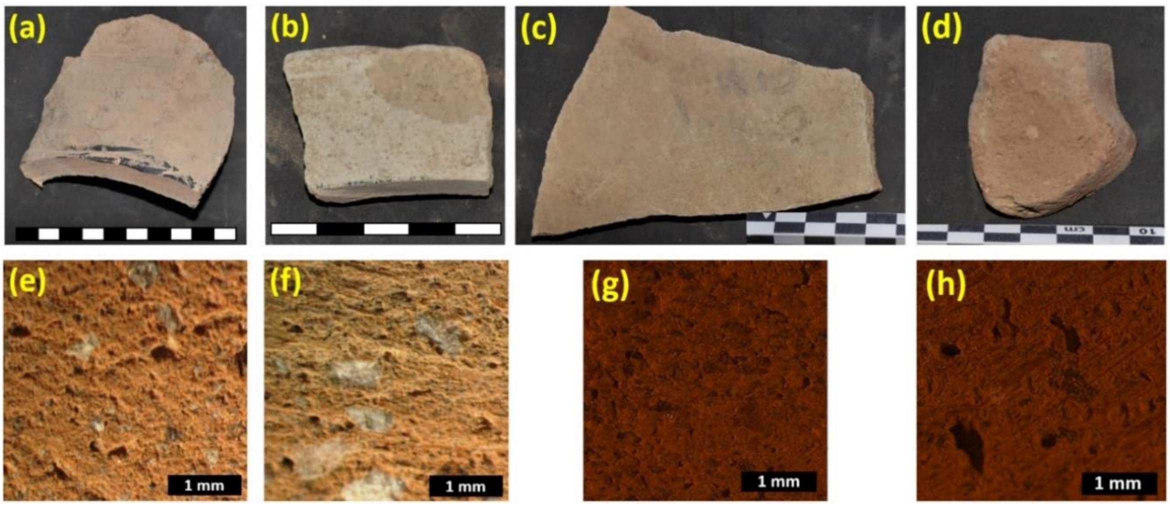

Figure 1. General view and Stereo-microscope images of some Ayla-Aksum: (a), (e) sample 1.3(2); (b), (f) sample 2.0, Late Roman Amphora 1 (c), (g) sample 3.9 and *dolia* sample (d), (h) sample 4.9.

Table 1. All colorimetric values (L*, a*, b* respectively) for exterior and Interior surfaces as well as cross-sections and powders on Ayla – Aksum and Late Roman 1 typologies.

Typology	Sample	Powder	Exterior	Interior	Section
AYLA - AKSUM	1.1	64.16; 10.84; 17.28	---	---	---
	1.2	70.06; 1.88; 14.99	62.20; 3.14; 18.12 61.11; 4.11; 19.23	45.80; 3.36; 11.95 47.64; 2.93; 11.11	---
	1.3(1)	66.96; 6.21; 17.60	55.27; 7.77; 21.53 55.30; 7.82; 21.71	56.87; 6.03; 18.54 53.37; 6.15; 17.69	---
	1.3(2)	65.21; 8.41; 17.25	54.62; 6.10; 17.61 54.11; 5.89; 16.94 53.10; 5.70; 17.61	52.77; 7.90; 18.43 52.85; 7.95; 19.14 54.44; 8.26; 19.51	62.05; 10.65; 19.22 60.25; 10.65; 18.94 59.39; 10.52; 18.78
	1.4(1)	68.95; 5.47; 16.53	---	---	---
	1.4(2)	75.10; 1.86; 15.09	63.34; 5.67; 17.02 61.71; 5.39; 17.98 63.21; 5.16; 18.82	66.23; 4.32; 19.75 66.45; 4.74; 20.23	71.91; 1.52; 15.70 67.71; 1.59; 17.04
	1.5	76.53; 2.74; 20.06	---	---	---
	1.6	61.39; 15.35; 20.43	---	---	---
	1.7(1)	63.13; 12.57; 18.44	---	---	---
	1.7(2)	68.47; 3.92; 15.35	---	---	---
	1.8	60.49; 14.40; 19.61	---	---	---
	2.0	69.92; 6.89; 17.29	66.61; 5.15; 19.63 69.84; 3.98; 19.98	68.91; 3.83; 19.42 70.78; 3.36; 19.16 68.65; 3.52; 19.06	---
	3.3	71.59; 1.04; 11.49	---	---	---
	3.4	67.73; 1.27; 14.16	---	---	---
	3.5	69.19; 9.18; 17.87	---	---	---
	3.6	68.51; 10.71; 18.45	66.54; 4.69; 19.69 61.90; 4.18; 18.99 63.35; 4.95; 22.04	61.92; 5.96; 20.94 60.44; 5.48; 20.37	---
	3.7	58.55; 19.19; 22.41	---	---	---
	3.8	57.24; 16.01; 19.36	---	---	---
	C01	65.68; 8.50; 18.00	---	---	---
	C04	67.38; 5.97; 17.24	---	---	---
	C05	67.81; 9.43; 18.40	---	---	---
LATE ROMAN 1	1.9	60.50; 9.70; 16.72	44.77; 5.97 17.34 43.13; 8.32; 17.84 47.34; 8.39; 18.62	51.60; 7.82; 20.66 49.25; 7.93; 16.37 49.69; 8.13; 17.91	---
	2.1	65.58; 6.11; 15.48	53.48; 7.91; 18.10 52.82; 8.30; 17.85 50.37; 8.96; 18.32	45.14; 7.22; 15.89 48.91; 7.64; 17.82	---
	2.2	67.28; 4.56; 13.36	---	---	---
	2.3	65.58; 6.11; 15.48	54.16; 10.87; 21.16 55.82; 11.88; 22.28 55.49; 12.91; 23.16	51.55; 13.11; 24.90 52.26; 13.83; 24.82 53.19; 13.54; 24.78	58.75; 9.16; 18.02 58.38; 9.58; 18.26 58.22; 9.08; 17.70
	2.4	63.69; 12.86; 20.75	---	---	---
	3.0	67.49; 9.55; 18.06	58.75; 5.69; 19.91 58.39; 6.38; 18.95	64.28; 6.87; 21.27 63.50; 6.67; 20.81	---
	3.1	67.97; 8.27; 17.38	64.58; 7.63; 21.78 61.31; 8.23; 21.86	63.10; 6.39; 21.61 61.15; 6.68; 21.58	---
	3.2	67.91; 10.44; 18.81	---	---	---
	3.9	64.34; 3.64; 12.06	---	---	---
	4.1	68.64; 6.54; 16.65	58.44; 7.15; 17.93 58.69; 7.08; 17.20 58.67; 7.19; 19.44	56.15; 7.33; 18.59 58.98; 7.68; 19.15	62.56; 8.25; 20.00 62.01; 8.44; 21.01 59.95; 8.66; 20.50
	C02	67.28; 9.89; 18.40	---	---	---
	C03	67.02; 5.86; 15.75	---	---	---
	C06	62.50; 6.36; 14.56	---	---	58.96; 8.96; 20.01 57.92; 9.61; 19.84 58.22; 9.58; 20.59
	C07	65.99; 7.09; 15.06	---	---	46.31; 9.32; 17.89 47.21; 10.74; 18.50 47.38; 9.91; 18.43
	C08	65.92; 6.97; 14.86	---	---	46.79; 9.10; 17.94 49.51; 8.56; 18.10 48.05; 9.62; 19.02
	C09	71.15; 4.76; 13.40	---	---	46.62; 9.37; 16.14 44.70; 9.26; 15.02 45.52; 9.55; 15.66

Table 2. All colorimetric values (L*, a*, b* respectively) for exterior and Interior surfaces as well as cross-sections and powders on *dolia* typology.

Typology	Sample	Powder	Exterior	Interior	Section
DOLIA	1.0	54.33; 11.66; 13.16	47.46; 12.55; 20.16 47.42; 12.70; 20.20 48.80; 13.01; 20.75	49.76; 12.11; 17.82 49.24; 12.29; 17.32 48.76; 12.61; 17.56	46.20; 15.06; 18.40 47.51; 15.54; 18.76 47.64; 14.99; 17.93
	4.0	59.74; 19.19; 22.41	57.39; 9.53; 22.41 54.48; 9.01; 20.38 55.54; 8.82; 20.30	49.81; 15.14; 19.52 50.40; 15.34; 20.34 50.70; 15.34; 21.16	---
	4.8	66.75; 4.66; 12.72	59.01; 6.75; 16.66 55.63; 7.02; 17.79 56.02; 7.76; 18.99	58.46; 6.53; 17.86 52.99; 6.68; 18.90 55.65; 5.74; 16.75	59.10; 6.11; 15.35 59.11; 5.79; 15.32 59.12; 6.26; 15.24
	4.9	61.15; 6.96; 14.28	43.06; 7.87; 18.66 48.06; 8.65; 19.25	47.06; 8.24; 16.31 50.67; 8.75; 17.63 47.06; 8.24; 17.63	52.44; 12.23; 19.43 55.23; 11.18; 20.83

For some sherds the thickness was also adequate to evaluate colour parameters on their cross-sections. The cleanest areas on the surfaces were selected, to estimate at best the true colour of the ceramic body. In all cases, depending on the dimension of the fragment and on the suitability of the analysed surfaces, 2 or 3 measurements were carried out on different areas of the surfaces to estimate the spread of the data on every considered sample.

Finally, colorimetric measurements were performed on the powders of all samples representing the Ayla-Aksum, Late Roman Amphora 1 and *dolia* classes. A fragment was cut from each sample, polished to avoid contaminations, and crushed using an agate mortar and pestle to obtain 100 mg of powders. By doing this, the resulting powders represent a mix of the components of the exterior, interior and cross-section parts of the ceramic bodies, including temper grains, which can also affect colour measurements due to compositional variability and differences in particle size [10]. The measurements were performed by inserting these powders in specific cylindrical cells of optical fused silica with transmittance > 95 % and no features in the whole visible range of the spectrum.

Table 3. Association to fabric groups identified by petrography (FG) and maximum values of Δ*E*ab,Max from colorimetry for each sample. The average for FG is also shown when there is more than one measurement.

Ayla - Aksum				
FG	**Sample**	**Exterior**	**Interior**	**In-Out**
A	1.2 1.3(1) 1.4(2)	1.47 0.19 1.87	0.94 0.86 0.64	8.21 3.34 1.87
B	1.3(2) 2.0 3.6	0.70 1.22 3.15	1.14 0.54 0.75	4.35 1.85 3.15
A	average	1.2	0.8	4.5
B	average	1.7	0.8	3.1

Late Roman				
FG	**Sample**	**Exterior**	**Interior**	**In-Out**
A	1.9	2.74	4.29	4.29
B	2.1 2.3 3.0 3.1	1.07 2.86 1.18 0.61	1.98 0.72 0.50 0.29	2.99 4.71 2.37 1.86
C	4.1	2.24	0.66	2.24
B	average	1.4	0.9	3.0

Dolia				
FG	**Sample**	**Exterior**	**Interior**	**In-Out**
A	1.0 4.0	0.75 2.23	0.56 1.65	3.50 6.58
A1	4.8	2.54	2.35	3.02
B	4.9	0.98	1.42	2.97
A	average	1.49	1.11	5.04

A Minolta CM-508i portable spectrophotometer was used, equipped with a pulsed xenon arc lamp and an integrating sphere to diffusely illuminate the specimen surface, which was viewed at an angle of 8° to the normal (d/8 geometry). The light reflected by the sample surface (specular component included) was detected by a silicon photodiode array, which allowed obtaining the reflectance spectrum in the 400 nm – 700 nm range, with wavelength pitches of 20 nm. The spectrophotometer was calibrated to provide the mean values of three consecutive measurements. Colour coordinates were expressed in the CIE L*a*b* system, using the illuminant D65 (average solar light) and a 10° viewing angle. In this system, the L*coordinate is related to colour lightness, while a* and b* are each determined by both hue and saturation respectively [4], [6]. In Figure 1, representative Ayla-Aksum, Late Roman Amphora 1 and *dolia* samples (scale in cm) and the stereo-microscopic images of their fresh cut are shown. It is worth noting that many factors could contribute to the occurrence of inconsistencies in the data both within the same sample and between different samples, when untreated archaeological materials are analysed. Phenomena such as imperfect geometries of the analysed surfaces, presence of contaminants (not easily detectable to the naked eye), alterations due to post-depositional processes, and porosity can contribute to this variability in the obtained measurements (see Figure 1).

3. RESULTS AND DISCUSSION

3.1. Colorimetric measurements on exterior, interior and cross sections

Table 1 and Table 2 report colorimetric coordinates for all measured samples while in Table 3 the largest values for ΔE_{ab} ($\Delta E_{ab,Max}$) of each sample are indicated, computed according to the following equation:

$$\Delta E_{\mathrm{ab,Max}} = \sqrt{(a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}\,, \qquad (1)$$

where the differences between a_1* and a_2*, b_1* and b_2* represent the colorimetric coordinates showing the maximum differences among the set of measurements for the exterior and interior surfaces, for each sample. Lightness (L*) is reputed to be a less suitable parameter than hue and saturation (a* and b*) and, due to this, it was not considered in this formulation [3].

The reported values of $\Delta E_{ab,Max}$ are quite low in each dataset, indicating that the surface colours of both the interior and exterior surfaces of the pottery samples appear to be quite homogenous. Besides, it seems that data from the interior surfaces are less spread than those from the exterior ones. For example, the average values of $\Delta E_{ab,Max}$ are 1.2-1.7 for exterior surfaces of the Ayla-Aksum -depending on the fabric- and 0.8 for their interior ones, respectively. To highlight this behaviour, the bivariate plot of L*, a* and b* parameters for all measurements is shown in Figure 2 for a selected number of samples (one for each fabric). It is quite evident that differences can arise in colour coordinates depending on which side of the ceramic body surface is being measured (Table 3). For example, in Ayla-Aksum samples $\Delta E_{ab,Max}$ is lower than 3.15 for the exterior and less than 1.14 for the interior surface. A similar behaviour is observed in Late Roman Amphora 1 (with the sole exception of an anomalous interior value for sample 1.9) and *dolia* samples. The measurements on cross-section (not reported in Table 3 but shown in Figure 2) are particularly homogeneous for all classes. This is probably due to favourable experimental conditions, related to the uncontaminated and flat surfaced of the sections. When comparisons are made - based on the values obtained for the exterior and interior surfaces, cross-sections, and powdered samples - the colorimetric values for cross-sections seem to be closer to those obtained for the powders in many instances. However, some discrepancies in the colorimetric measurements of the cross-sections could also be related to irregular geometries.

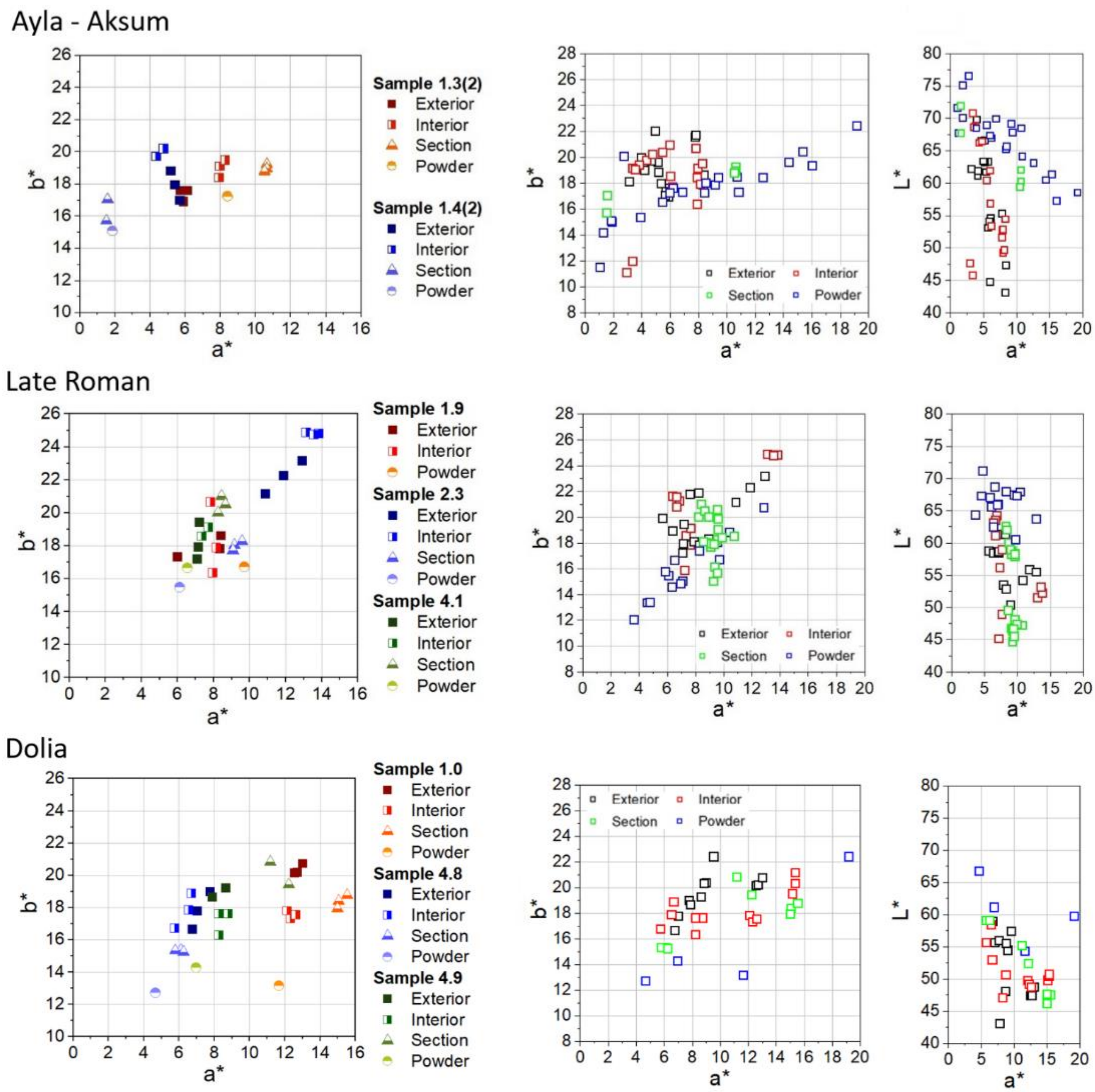

Figure 2. Colorimetric values for selected samples (left); all colorimetric values for exterior and interior surfaces as well as cross-sections and powders (centre and right).

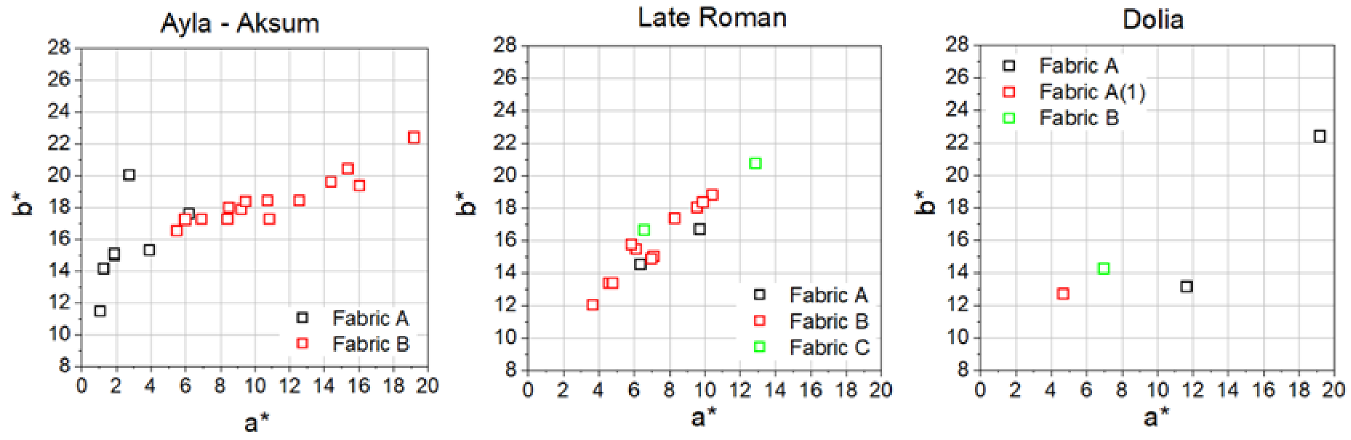

Figure 3. Colorimetric values for powdered samples. Colours refer to the fabric classification as reported in Table 3.

Moreover, in almost all cases, it clearly appears that the colour for the exterior and interior surfaces of the ceramic bodies are darker, i.e., the values of L* are lower than those obtained for their powders.

Such a survey confirms that discrepancies in measurements on both the exterior and interior surfaces – and, in some cases, on the cross-sections – are quite common when untreated archaeological samples are concerned. This sampling problem can be linked to different phenomena. Further treatment of the samples, either by refiring them at different temperatures to evaluate colour changes or by extracting powders from their fragments, however, can sometimes compensate for measurement inconsistencies.

3.2. Colorimetric measurements on powdered samples

For colorimetric measurements on powders, 21 Ayla-Aksum, 15 Late Roman Amphora 1 and 4 *dolia* samples were considered. In particular, the dispersion of the colorimetric values within a specific class of pottery was considered. Such a dispersion for Ayla-Aksum samples (Figure 3) clearly indicates that colorimetric information can be useful for discriminating different fabrics within a given class. Data dispersion in these samples indicates a colour variation from creamy (lower a* value) to a reddish hue (higher a* values). The former is typical of samples belonging to the fabric A of the Ayla-Aksum amphorae; the latter pertains to the fabric B. Such a differentiation might be related to different technologies of production (morphological and/or microstructural changes) and perhaps compositional differences too. The distinction between these samples enabled by colorimetric parameters further complements the observation of different fabrics identified for the Ayla-Axum amphorae by petrography. In this respect, colorimetry can thus be useful to allow preliminary fabric classification when coupled to typological classification, petrography, and stereo microscopy. It should be noted, however, that the colour parameters defined for a homogenised paste (powders) only allows a preliminary fabric determination for each sample, rather than providing information about its composition or provenance.

However, in some cases the fabric classification extrapolated from petrography does not match the distinction made by colorimetric evaluation. This was observed in the trends discerned from the colorimetric evaluation of powder samples from the Late Roman Amphora 1 and *dolia* classes (Figure 4).

Such evidence might indicate that, although the original clay used for manufacturing should be similar, the addition of one or more tempers might account for fabric variability, as defined by petrographic analyses. In this respect the mix design in the production of the ceramics can contribute to colour changes [10]. Therefore, in order to make reliable deductions it is strictly necessary to link colorimetric observations to textural, micro-structural and chemical studies. The results of this study prove that while colorimetry can assist in defining the fabrics and typological classifications, it certainly needs to be complemented with other approaches in order for more detailed information to be achieved. Furthermore, colorimetry can be significantly useful to make deductions about the inter-fabric variability of samples belonging to specific classes. The mere collection of colorimetric parameters for each sample considered in this study could not (if considered *per se)* exclusively ascribe sharp distinctions, when comparison is made among fabrics defined for Ayla-Axum, Late Roman Amphora 1 and *dolia* classes. This limitation is characteristic of colorimetric evaluations as can be seen from Figure 4, where the overlapping of the colorimetric data for different samples belonging to the three classes of pottery considered in this study prevents any feasible conclusions. Nevertheless, the importance of this survey is relevant, as it allows- in many cases - a preliminary distinction of fabric variability within a specific typological class of pottery.

4. CONCLUSIONS

Colorimetric observations were done on Ayla-Aksum, Late Roman Amphora 1 and *dolia* pottery samples collected from excavations at Adulis in order to check potential grouping with

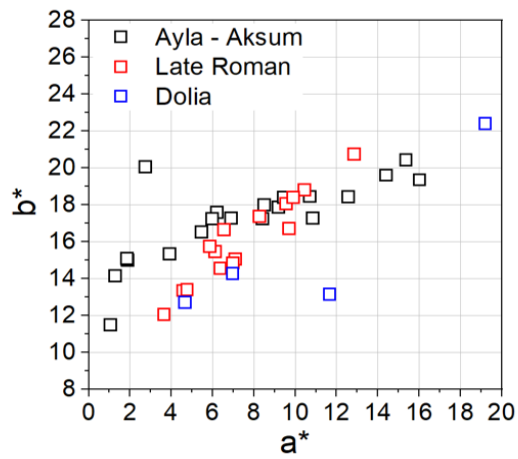

Figure 4. Colorimetric values for powdered samples (Ayla-Aksum, Late Roman and *dolia* classes.

respect to the fabric description obtained by means of stereomicroscopy and petrography. In this respect, this study showed that it is possible to correlate colorimetric values to specific fabric attributions achieved by means of traditional microscopy approaches. Different sampling procedures were adopted to collect colorimetric data, in order to thoroughly understand the limitations and strengths of such an approach. The exterior and interior surfaces of the ceramic bodies, as well as their cross-sections were considered for the untreated samples, while powders were extracted from many samples in order to obtain homogenous samples for the survey. Subtle differences in colour measurements due to these different sampling conditions were interpreted as potential discriminating parameters in order to establish fabrics.

Data variability collected on the exterior or interior surfaces of the ceramic bodies, as well as on their cross-sections or powders, is an indication that various phenomena should be considered while interpreting these data, particularly on untreated samples. The $\Delta E_{ab,Max}$ computation allowed us to understand subtle variations and/or inconsistencies in colorimetric measurements on the exterior and interior surfaces, as well as on the cross-sections. Marked differences in these values have been considered in order to make extrapolations, while feeble differences between samples belonging to the same fabric can hardly be used to postulate a differentiation between them. Yet, the limited number of analysed samples, coupled to the detected measurement discrepancies (due to several factors, such as imperfect geometries of the surfaces, post-depositional alterations and perhaps also porosity), make it necessary to increase the statistical reliability pertaining to the colorimetric approach applied to the classes considered in this study. However, in many cases the attribution of samples to distinct groups was possible based on colorimetric evaluation, which proved to be consistent with previously determined classification by petrography. This observation pinpoints that colorimetric measurements can be useful to complement petrographic studies for in-depth fabric description. The correspondence of the colorimetric groupings with petrographic observations is a further indicator that the information from colorimetry can be useful to support provenance and/or technological studies on archaeological pottery. On the other hand, when colorimetric information cannot parallel petrographic information (as seen in a few cases in this study), a detailed textural and chemical study- as well as a micro-structural understanding of the ceramic body - becomes necessary.

In conclusion, different parts of the ceramic body offer a variety of sampling decisions for colorimetric evaluation with non-invasive procedures, and thus the objective comparison of colour through a quantitative analysis can overcome issues related to typological classification. Moreover, this survey showed that colorimetric measurements could be useful, at least in some cases, to ascribe preliminary fabric determination when coupled to complementary techniques – such as optical microscopy. Such an information could be used to understand – at least partly – the technological processes. as well as to help in tracing the provenance of a given artefact (assuming that objectively attained colour measurements could be correlated to information obtained from these complementary techniques). The inherent limitations of this approach have also been highlighted, particularly to deduce colour variations due to mineralogical, chemical, and micro-structural differences - a subject that needs to be dealt with, in the future direction of this research.

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REFERENCES

[1] M. Giardino, R. Miller, R. Kuzio, D. Muirhead, Analysis of ceramic colour by spectral reflectance, American Antiquity, 63(3), (1998), pp. 477-483.

[2] J. R. McGrath, M. Beck, M. E. Hill, Jr. Replicating red: Analysis of ceramic slip colour with CIELAB colour data, Journal of Archaeological Science: Reports14(2017), pp.432-438. DOI: 10.1016/j.jasrep.2017.06.020

[3] P. Mirti, P. Davit, New developments in the study of ancient pottery by colour measurement, Journal of Archaeological Science 31(2004), pp. 741–751. DOI: 10.1016/j.jas.2003.11.006

[4] P. Mirti, On the use of colour Coordinates to evaluate firing temperatures of ancient pottery, Archaeometry 40 (1998), pp. 45–57. DOI: 10.1111/j.1475-4754.1998.tb00823.x

[5] M. Daszkiewicz, L. Maritan, Experimental Firing and Re-firing, in: The Oxford handbook of archaeological ceramic analysis, A. M. W. Hunt (ed.), Oxford Handbooks in Archaeology, 2016, ISBN: 9780199681532.

[6] M. Bayazit, I. Işık, A. Issi, E. Genç, Spectroscopic and thermal techniques for the characterization of the first Millennium AD potteries from Kuriki, Turkey, Ceramics International 40(9) (2014), pp. 14769-14779. DOI: 10.1016/j.ceramint.2014.06.068

[7] M. J. Feliu, M.C. Edreira, J. Martin, Application of physical–chemical analytical techniques in the study of ancient ceramics, Analytica Chimica Acta 502 (2004), pp. 241–250. DOI: 10.1016/j.aca.2003.10.023

[8] L. Nodari, E. Marcuz L. Maritan C. Mazzoli, U. Russo, Hematite nucleation and growth in the firing of carbonate-rich clay for pottery production, Journal of the European Ceramic Society 27 (2007), pp. 4665–4673. DOI: 10.1016/j.jeurceramsoc.2007.03.031

[9] C. Gernminario, G. Cultrone, A. De Bonis, F. Izzo, A. Langella, M. Mercurio, V. Morra, A. Santoriello, S. Siano, C. Grif, The combined use of spectroscopic techniques for the characterization of late Roman common wares from Benevento (Italy), Measurement 114(2018), pp. 515-525. DOI: 10.1016/j.measurement.2016.08.005

[10] De Bonis, G. Cultrone. C. Grif, A. Langella, A. Leone, M. Mercurio, V. Morra, Different shades of red: The Complexity of mineralogical and physico-chemical factors influencing the colour of ceramics, Ceramics International 43 (2017), pp.8065–8074. DOI: 10.1016/j.ceramint.2017.03.127

[11] Y. Yang, M. Feng, X. Ling. Z. Mao, C. Wang, X, Sun, M. Guo, Microstructural analysis of the colour-generating mechanism in Ru ware, modern copies, and its differentiation with Jun Ware, Journal of Archaeological Science 32 (2005), pp.301–310. DOI: 10.1016/j.jas.2004.09.007

[12] J. Molera, T. Pradell, M. Vendrell-Saz, The colours of Ca-rich ceramic pastes: Origin and characterization, Applied Clay Science 13 (1998), pp.187–202. DOI: 10.1016/S0169-1317(98)00024-6

[13] L. Nodari, L. Maritan, C. Mazzoli, U. Russo, Sandwich structures in the Etruscan-Padan type pottery, Applied Clay Science 27(2004) pp. 119-128.
DOI: 10.1016/j.clay.2004.03.003

[14] V. Valanciene, R. Siauciunas, J. Baltusnikaite, The influence of mineralogical composition on the colour of clay body, Journal of European Ceramic Society 30(2010), pp. 1609-1617.
DOI: 10.1016/j.jeurceramsoc.2010.01.017

[15] R. Mentesana, V. Kilkogolu, S. Todaro, P. M. Day, Reconstructing change in firing technology during the final Neolithic-Early Bronze Age transition in Phaistos, Crete. Just the tip of the iceberg? Journal of Archaeological and Anthropological Sciences 11 (2019), pp. 871-894.
DOI: 10.1007/s12520-017-0572-8

[16] Y. Maniatis, The emergence of ceramic technology and its evolution as revealed with the use of scientific techniques, in: From mine to microscope: Advances in the study of ancient technology. A. Shortland, I. Freestone, T. Rehren (editors), Oxbow Books, 2009, eISBN: 978-1-78297-279-2, pp. 11-28.

[17] C. Zazzaro, E. Cocca, A. Manzo, Towards a chronology of the Eritrean Red Sea port of Adulis (1st – Early 7th Century AD). Journal of African Archaeology 12 (1) (2014), pp.43-73.
DOI: 10.3213/2191-5784-10253

[18] Peacock, D. & Blue, L. (eds.) The Ancient Red Sea Port of Adulis, Eritro-British Expedition, 2004–5. Oxbow Books, Oxford, 2007, ISBN: 9781842173084

[19] C. Zazzaro, The Ancient Red Sea port of Adulis and the Eritrean Coastal Region, BAR International Series, vol. 2569, Oxford, 2013, ISBN 978 1 4073 1190 6.

[20] R. K. Pedersen, The Byzantine-Aksumite period shipwreck at Black Assarca Island, Eritrea, Azania XLIII (2008), pp.77-94.
DOI: 10.1080/00672700809480460

[21] M. M. Raith, R. Hoffbauer, H. Euler, P. A. Yule, K. Damgaard, The view from Zafar - An archaeometric study of the Aqaba pottery complex and its Distribution in the 1st Millennium CE, Zora 6 (2013), pp. 320-350.

[22] S. Massa, A. De Bonis, V. Morra, V. Guarino, in S. Massa (ed.), Adulis Project 2015 Report (2015), pp. 85-90 (unpublished).

[23] Adulis Project 2018 Report (unpublished), S. Massa (ed)

[24] Adulis Project 2019 Report (unpublished), S. Massa (ed).

[25] Adulis Project 2020 Report (unpublished), S. Massa (ed)