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THE AUTHENTICATION AND CHARACTERIZATION OF GLASS OBJECTS EXCAVATED FROM TELL ES-SUKHNAH, JORDAN

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ABSTRACT

A sample of 29 glasses uncovered from Tell Es-Sukhnah, Jordan, has been subjected for XRF analysis. The group of sample consisted of two main categories: samples from glass vessels and glass bracelets. The main aim of this analysis is to identify and authenticate the raw materials used in glass production, manufacture technology and the technical choices related to glass objects from the Roman to Byzantine and Islamic occupations at the site. Chronologically speaking, the chemical analysis of the samples enables the distinguishing between Roman soda natron glass and Islamic soda plant ash glass at this freshly excavated site. The most important observation was that the transition in the use of traditional methods and of the same sources of raw materials for glass-making occurred, with obvious modifications, from natron to plant ash and from calcium-rich sand to calcium -free sand through the period from 1st to10th century AD at this southern Levantine site.

KEYWORDS: Tell Es-Sukhnah, glass vessels, bracelets, chemical analysis, Roman and Islamic periods

1. INTRODUCTION

Glass production can be considered as an international cultural phenomenon that expands geographically the whole Antique world. The characterization of the chemical composition of ancient glass highlights some aspects of production system such as sources of raw materials or/and the technological choices undertaken by the producers in the production process (Schibille et al., 2012). Both aspects of production can provide with cultural information on location of raw materials and the socio-economic status of consumers. Moreover, fine technical aspects of production can be identified with respect to characteristics such as sources of lime, crushed shells or calcareous sand (Brill, 1988; Freestone et al., 2002a).

Glass production has been subjected to numerous studies in the Eastern Mediterranean. These studies showed that soda natron-type glass (Na_2O-CaO-SiO_2) was predominant from the mid to first millennium AD. That is, from Roman to early Islamic periods. The glass collection dated to this time span has been identified into five major compositional group of natron glass. Differences between these groups have been attributed to factors such a chronology and geographical distribution. However, these groups can be a source of reference to make comparison with unidentified glass collection. In Jordan, for example, studies of the Roman and Early Byzantine glass from sites such as Bait Ras / Capitolias, Umm Qais/Gadara and Jerash/Gerasa in Northern Jordan revealed that these glasses were classified as soda - lime- silica with natron as a flux. Based on that, glass from these sites assumed to belong to what is called and defined as Levantine 1 group (Abd-Allah 2010-2012; El- Khouri, 2014; Arinate et al. 2014).

Major changes in glass production took place with the outset of first millennium AD. In the Levant, plant ash was replaced by natron as flux. Such a transition in glass production has been an indication of pure Islamic glass industry. It refers to what is called Levantine II group.

In this study, a new data regarding the production of the Roman and Islamic glass in Jordan will be presented. This study analyzes the chemical compositions of selected glass and jewelry objects (bracelets) uncovered from the archaeological site of Tell Es-Sukhnah. The site is situated c. 25 km north -east of Amman and about 7 km to the west of Az-Zarqa city (fig.1). The Tell is measuring about 7.5 acres, and ranging in height about 12m.

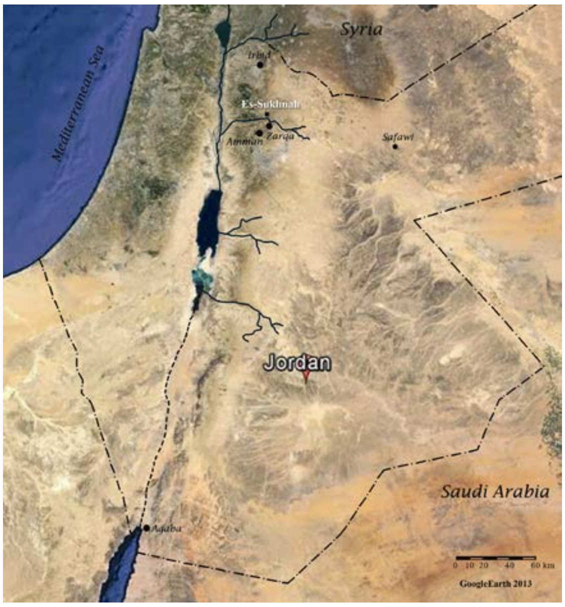

Figure 1: Map of Jordan showing the location of Tell Es-Sukhnah archaeological site

2. EXPERIMENTAL PROCEDURES

2.1. *Analysed samples*

The glass objects uncovered from Tell Es-Sukhnah can be classified into two main groups. These are domestic glass vessels and the second group represented by glass bracelets. The analyzed sample in this study includes 9 samples related to the glass bracelets group and 20 samples related and part of the glass vessels group. Glass vessels were selected based on both morphological and technical, especially the color factor, criteria. Morphologically speaking, the glass vessel samples have been chosen to include different parts of the vessels such as the rim, the base or the body (Table 1). Furthermore, the color of the glass has been considered as classificatory factor, which would be having technical implications. The glass vessel group includes different colors such as green, yellow, blue and black (Fig. 2).

Table 1: Showing formal and color characteristics of glass vessels from Tell Es-Sukhnah.

S.N.	Season	Square	Locus	Form	Description
1	2009	L26	12	Base	Tint green
2	2009	K25	7	Rim	Transparent
3	2012	JB 23	5	body	Deep Yellow
4	2009	N20	7	Base	Transparent
5	2009	L 26	17	Body	Deep Yellow
6	2009	N20	7	Body	Transparent
7	2009	N20	7	Body	Tint blue
8	2009	N19	3	Base	Tint blue
9	2009	L26	15	Base	transparent \ yellow
10	2009	K25	1	Rim	Tint green
11	2009	N26	8	Body	Tint green
12	2012	M20	10	Rim	Deep Yellow
13	2009	K24	7	Body	Tint blue
14	2009	K24	10	Body	Deep Yellow
15	2009	N19	6	Base	Tint green
16	2009	N19	11	Base	Tint blue
17	2012	L23	10	Body	Tint yellow
18	2012	M20	6	Base	Tint green
19	2009	M19	9	Body	Deep Yellow
20	2009	L26	15	Rim	Deep violet or black

Figure 2: Photographs of a few Roman vessel fragments found at Tell Es-Sukhneh selected for chemical analyses.

The glass bracelets group has been chosen based on color factor (Table 2). Bracelets were either having two mixed colors or more than three colors. The former includes a main color intersected with other one such as brown and yellow band or brown and white band. Others include black and brown colors. However, the multi-color bracelets represented by ones which have three colors such as brown, white and blue, or four colors such as yellow, white, brown and blue (Fig. 3).

Table 2: Showing formal characteristics of glass bracelets from Tell Es-Sukhnah.

S.N	Season	Square	Locus	Description
1	2012	JB25	14	Dark brown with yellow band
2	2009	L24	7	Brown with yellow lines
3	2012	M25	Baulk	Brown and Yellow color
4	2012	M20	0	Mixed color : yellow, white, brown, and blue
5	2012	JA25	14	Brown and white color
6	2012	JB25	9	Dark black, with brown color
7	2013	JB22	9	Brown with white , light blue lines
8	2013	JB22	9	Mixed color : white, brown, and blue
9	2009	L24	7	Brown and yellow lines

Figure 3: Photographs of a few Islamic bracelets (above) and Roman (below) found at Tell Es-Sukhneh selected for chemical analyses.

Archaeologically speaking, both major groups of glasses were uncovered from different archaeological contexts during various seasons of excavation carried out at the site of Tell es-Sukhnah (2009, 2011-2013). Chronologically speaking, the glass vessels were dated back to the Roman period (1st to mid-4th century AD). Meanwhile, the glass bracelets were uncovered from both Roman and Islamic (Ayyubi- Mammluk period) horizons. The dating of glass collection of both types was affirmed by the associated pottery assemblages.

2.2. Methods of analysis

A Bruker S4 Pioneer Wavelength Dispersive X-Ray Flourescence Spectrometer (WDXRF) located at the Laboratories of the Natural Resources Authority of Jordan (NRAJ) was used to determine the chemical composition of the glass samples. The spectrometer uses the high-purity silica BCS-CRM 313/1 standard certified reference material from the Bureau of Analyzed Samples LTD, UK and works under vacuum, voltage 20-60 KV, current 5-150 mA and a Power limit of 4050 watt. This method was the most accurate method available for determining the elemental composition and the concentration of elements in the sample. This technique was preferred since it only required a small amount of the samples (Abd-Allah, 2011-2013. Moreover, an optical microscope (Nikon model H-III) was used for examining the glass samples.

2.3 Sample preparation

For the XFR measurements, the samples were prepared as fine powder, then compressed as disks and fused to identify their compositions and the main raw materials used. It should be noted that the weathering products or crusts were mechanically removed from the areas in which the glass samples were taken. These products have a completely different chemical composition of glass. Therefore, any contamination of these products with the selected samples would have affected the accuracy of the results of chemical analyses. Furthermore, many glass fragments were prepared for microscopic examination to characterise their manufacturing technology.

3. RESULTS AND DISCUSSION

3.1. Chemical characterisation and raw materials identification

The compositions of 20 vessel fragments and 9 coloured glass bracelets from Tell Es-Sukhnah as provided by XRF are shown in Table 3 and 4, and illustrated in figures 2 and 3.

3.1.1. Vessel fragments

According to Table 3 and Fig. 4, the results of the analyses indicate that the major components of the vessel fragments samples are: silica (SiO_2 avg. 68.48%), soda (Na_2O avg. 16.12%), lime (CaO avg. 8.23%) and alumina (Al_2O_3 avg. 2.63%). They were also characterised by low contents of potash (K_2O avg. 0.58%) and magnesia (MgO avg. 0.97%).Therefore, these glasses can be classified as soda-lime-silica (Na_2O-CaO-SiO_2) glass, the common type of ancient glass for more than three thousand years (Degryse et al., 2005; Tite et al., 2006). This composition revealed that the main raw materials from which these glass vessels were manufactured were Levantine coastal sand (calcium-rich beach sand) as a source of silica, natron as a source of alkali soda, and lime (which is already present as impurity or shell fragments in the Levantine coastal sands) as a source of calcium. All the glass samples are corresponding to the previously defined Levantine I glass group, which has a composition characterised by a moderate soda (around 16%), and high lime (c. 8%) and alumina (c. 3%) content relative to the natron-type glass (Freestone et al., 2002a, Abd-Allah, 2010).

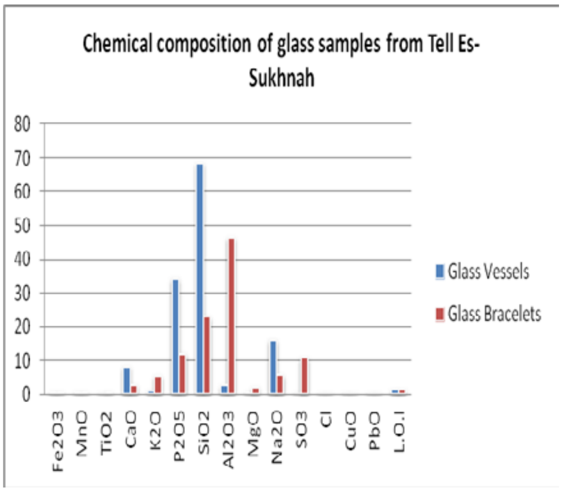

Figure 4: The average compositions of glass artefacts (Vessels and Bracelets) from Tell Es-Sukhneh.

Table 3: Compositions of vessel fragments obtained by XRF.

Item	S.ID.	Fe_2O_3 Wt.%	MnO Wt.%	TiO_2 Wt.%	CaO Wt.%	K_2O Wt.%	P_2O_5 Wt.%	SiO_2 Wt.%	Al_2O_3 Wt.%	MgO Wt.%	Na_2O Wt.%	SO_3 Wt.%	Cl Wt.%	CuO Wt.%	PbO Wt.%	L.O.I Wt.%
1	**L26**	0.53	0.03	0.06	4.39	1.63	0.12	71.60	0.48	0.72	16.90	0.11	0.28	0.10	0.50	2.50
2	**K25**	0.40	0.03	0.05	8.01	0.73	0.13	67.3	2.57	0.79	17.60	0.08	0.17	0.04	-	2.20
3	**Jb23**	0.54	1.48	0.06	8.19	0.66	0.20	69.40	2.52	0.52	15.10	0.05	0.16	0.06	-	1.00
4	**N20**	0.44	0.04	0.06	8.78	0.66	0.15	66.70	2.50	0.57	18.70	0.15	0.33	0.05	-	-
5	**L26**	0.40	0.04	0.05	8.32	0.79	0.16	68.00	2.65	0.51	18.40	0.14	0.34	0.03	-	-
6	**N20**	0.52	1.49	0.06	8.29	0.70	0.30	69.50	2.70	0.56	15.30	0.11	0.26	0.06	-	-
7	**N20**	0.83	0.82	0.11	9.08	1.28	0.27	66.80	2.78	0.72	15.90	0.07	0.31	0.04	0.03	0.20
8	**N19**	0.77	0.73	0.09	8.94	1.22	0.33	66.90	2.90	0.61	16.70	0.16	0.36	0.06	0.05	-
9	**L26**	0.66	1.81	0.10	7.11	1.25	0.14	68.40	3.26	0.57	12.70	0.09	0.19	0.04	-	3.60
10	**K25**	0.72	1.15	0.11	9.84	0.94	0.23	66.50	2.88	0.69	14.20	0.06	0.13	0.04	0.03	2.90
11	**N26**	0.71	0.48	0.08	9.15	1.07	0.23	67.50	2.64	0.50	15.10	0.14	0.20	0.05	0.02	1.50
12	**M20**	0.45	0.03	0.06	8.32	0.97	0.12	68.90	2.49	0.38	17.60	0.16	0.36	0.08	-	-
13	**K24**	0.48	0.29	0.07	8.10	0.81	0.16	69.20	2.70	0.42	16.00	0.04	0.30	0.03	-	0.70
14	**K24**	0.54	0.02	0.05	8.45	0.87	0.08	68.70	2.81	0.78	17.30	0.06	0.11	0.07	-	-
15	**N19**	0.55	0.28	0.07	8.20	0.80	0.19	70.40	2.53	0.47	16.00	0.06	0.20	0.04	-	0.20
16	**N19**	0.58	0.30	0.08	8.62	0.96	0.22	69.90	2.61	0.57	15.50	0.05	0.16	0.04	0.02	0.40
17	**L23**	0.75	0.14	0.11	9.31	1.44	0.32	67.50	3.21	0.66	15.10	0.15	0.24	0.07	-	-
18	**M20**	0.58	0.19	0.07	7.78	0.90	0.19	70.00	2.72	0.45	15.70	0.10	0.32	0.06	-	0.20
19	**N19**	0.46	0.06	0.07	7.85	0.90	0.13	69.00	2.75	0.42	16.30	0.09	0.31	0.03	-	1.60
20	**L26**	0.55	1.60	0.06	7.88	0.96	0.29	67.50	2.92	0.56	16.30	0.11	0.17	0.06	-	1.10
Avg. Wt.%%		0.57	0.55	0.07	8.23	0.97	0.19	68.48	2.63	0.57	16.12	0.09	0.24	0.05	0.10	

Table 4: Compositions of glass Bracelets obtained by XRF.

Item	S.ID.	Fe_2O_3 Wt.%	MnO Wt.%	TiO_2 Wt.%	CaO Wt.%	K_2O Wt.%	P_2O_5 Wt.%	SiO_2 Wt.%	Al_2O_3 Wt.%	MgO Wt.%	Na_2O Wt.%	SO_3 Wt.%	Cl Wt.%	CuO Wt.%	PbO Wt.%	L.O.I Wt.%
Group A (SODA- NATRON ALKALI)																
A4	**M20**	0.49	0.04	0.07	5.23	1.99	0.21	68.7	0.69	1.17	18.6	0.09	0.42	0.10	0.37	1.7
A7	**JB22**	0.50	0.05	0.06	4.43	1.69	0.16	73.1	0.51	0.78	16.9	0.11	0.19	0.08	0.45	1.0
A8	**JB22**	0.48	0.03	0.06	4.50	1.65	0.18	72.6	0.56	0.81	17.3	0.12	0.25	0.05	0.44	1.0
Avg. Wt.%		0.49	0.04	0.6	4.72	1.77	0.18	71.4	0.58	0.92	17.6	0.10	0.28	0.07	0.42	
Group B (SODA- ASH ALKALI)																
B1	**JB25**	1.71	0.05	0.45	7.54	4.68	0.50	56.50	2.57	3.13	9.87	0.11	0.19	0.11	0.30	11.80
B2	**L24**	2.48	0.04	0.47	4.73	4.91	0.67	58.9	3.57	2.67	19.0	0.08	0.22	0.15	0.15	1.7
B3	**M25**	1.20	0.08	0.17	2.28	3.44	0.17	70.7	1.46	0.58	17.3	0.06	0.28	0.08	0.71	0.9
B5	**JA25**	0.94	0.03	0.48	4.26	6.27	0.73	61.0	2.66	2.40	17.4	0.09	0.34	0.08	0.45	2.4
B6	**JB25**	1.53	0.06	0.46	6.28	4.89	0.46	58.8	2.76	2.83	13.1	0.05	0.16	0.12	0.20	8.1
B9	**L24**	2.31	0.04	0.47	5.17	4.72	0.65	56.70	3.43	2.70	19.30	0.15	0.74	0.10	0.17	3.50
Avg. Wt.%		1.69	0.05	0.41	5.01	4.81	0.53	60.43	2.74	2.38	16.00	0.09	0.32	0.10	0.33	

3.1.2. Glass bracelets

Due to the the present content of potash (K_2O) is quite not constant and widely ranges between 1.65 and 6.27%, the bracelets samples were divided into two groups as shown in Table 4.

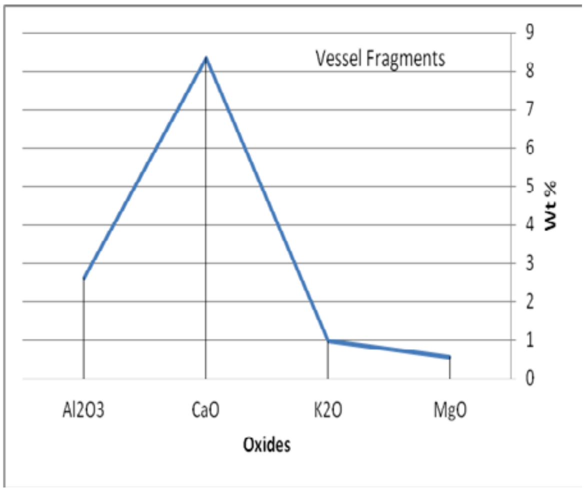

Figure 5: Al_2O_3 vs. CaO and K_2O vs. MgO diagram of the analyzed glass vessel fragment.

3.1.2.1 Group A:

The composition of glass indicates that the major components of these samples are: silica (SiO_2 avg. 71.4%), soda (Na_2O avg. 17.6%), lime (CaO avg. 4.72%) and alumina (Al_2O_3 avg. 0.58%). Therefore, these glasses are also of the soda-lime-silica (Na_2O-CaO-SiO_2) type, with low contents of potash (K_2O avg. 1.77%) and magnesia (MgO avg. 0.92%) (Fig. 6).

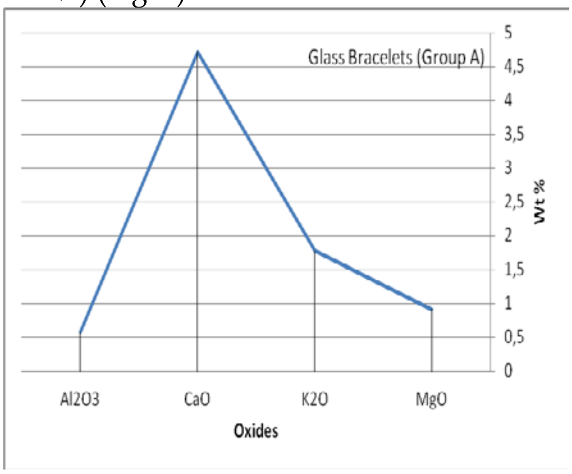

Figure 6: Al_2O_3 vs. CaO and K_2O vs. MgO diagram of the analyzed glass bracelets (Group A: Soda – Natron Alkali)

This composition revealed that these glasses bracelets were not formed from the same raw materials from which the vessel fragments were manufactured and cannot be corresponded to the previously defined Levantine I glass group, which has a composition characterised by a moderate soda (around 16%), and high lime (c. 9 %) and alumina (c. 3%) content relative to the natron-type glass, but probably can be corresponding to the second Levantine group in terms of lower CaO and Na_2O, and higher SiO_2 (Freestone et al., 2002a). It can be emphasize that the main raw materials from which these glass vessels were manufactured were calcium-free sand or crushed quartzite (silica) as a source of silica, natron as a source of alkali soda, and lime stone powder was separately added as a source of calcium and serves as glass stabilizer (Whitehouse, 2002).

3.1.2.2 Group B:

The composition of glass indicates that the major components of these samples are: silica (SiO_2 avg. 60.43%), soda (Na_2O avg. 16 %), lime (CaO avg. 5.01%) and alumina (Al_2O_3 avg. 2.74%). Therefore, these glasses are also of the soda -lime-silica (Na_2O-CaO-SiO_2) type, with high contents of potash (K_2O avg. 4.81%), magnesia (MgO avg. 2.38%) and phosphor (P_2O_5 avg. 0.53%) (Fig. 7).

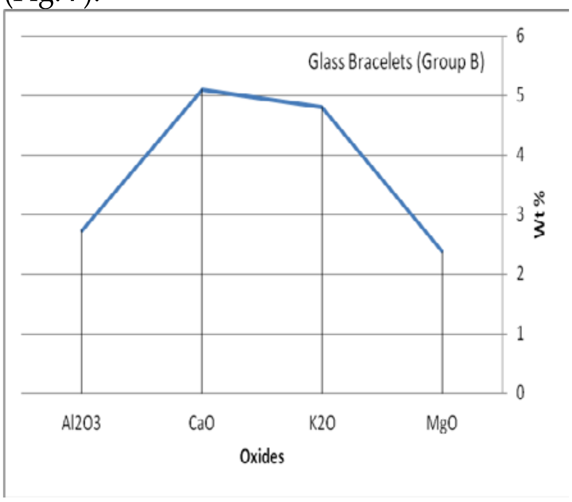

Figure 7: Al_2O_3 vs. CaO and K_2O vs. MgO diagram of the analyzed glass bracelets (Group B: Soda – Ash Alkali).

This composition revealed that these glasses bracelets were not formed from the same raw materials from which either the vessel fragments or the glass bracelets group A were manufactured. It can be confirmed that the main raw materials from which these glass vessels were manufactured were calcium-free sand or crushed quartzite (silica) as a source of silica and calcium-rich plant as a source of alkali soda.The use of coastal plant ash is suggested by the relatively high content of MgO, K_2O and P_2O_5, as well as by the presence of chlorine. This glass bracelet can be corresponding to the previously defined early Islamic glass group (between 8^{th} to 10^{th} centuries AD) in terms of lower CaO and higher Al_2O_3 and MgO (Whitehouse, 2002; Lima et al., 2012).

The results of the analyses comparatively indicate that all glasses (vessel fragments and bracelets) are soda-lime-silica glasses typical of the Roman glasses from other sites in Jordan. They are characterised by Al_2O_3 contents of about 2.5%, which are relatively similar to those of most of the Roman glass samples. Lime is typically in the range of 8.5-9%, and silica is typically about 70.5%. Alkali content (soda and potash) content generally is about 16% and 0.97% of vessel fragments, which is very normal of natron-based alkali, but important changes were observed in the bracelets samples.

Some common observations regarding all the analysed glasses from all contexts in Tell Es-Sukhnah could be inferred from the average compositions presented in Table 5 and illustrated in Figure 10. It also becomes apparent that the sands used for making glass in Jordan during ancient times were most likely obtained from the Syro-Palestinian or Levantine coast. This type of sands (and the Levantine I glass group) contain a ratio of lime (CaO avg. 8.7 %) and alumina (Al_2O_3 avg. 3.1%) which is relatively corresponding to the ratio of all the analysed samples (Tables 3 and 4). It should also be noted that lime was not intentionally added to the glass batch as a glass stabiliser, to decrease the solubility of soda-glass and improve its chemical durability. However, the sand at the mouth of the river Belus on the Levantine coast was reputed for glass-making across the centuries (Freestone et al., 2002a; Aerts et al. 2003; Rutten et al., 2005; Abd-Allah, 2006).

The low contents of potash (K_2O) and magnesia (MgO) indicate that this is a natron-based glass, where the mineral salt of natron was used as flux for all samples. The high amounts of chlorine (Cl_2O) and sulphur (SO_3) oxides in the analysed samples are also due to natron, which contains halite (NaCl) and thenardite (Na_2SO_4) in various proportions as a contaminant (Henderson, 1985 ; Shortland et al., 2006; Abd-Allah, 2007; Silvestri et al., 2008). According to Shortland et al. (2006), it is generally assumed that Wadi Natrun in Egypt was the primary source of natron during the first millennium BC and the first millennium AD. Natron seems to have been an important resource for the Roman glass industry, and the great majority of Roman glass is of the low-magnesia natron variety, with only a few special exceptions. It should be noticed that natron was related to other Roman centers . Glass continued to be natron-based across the Levant, the Mediterranean and in Europe until a time around the 9^{th} century AD (Liritzis et al. 1997).

3.2. Glass colorants and opacifiers

It was stated that the color of glass is due to the presence of coloring transition elements in the glass batch, most of them are recorded in XRF results of both glass vessels and bracelets as shown in Tables 3 and 4.

In all glass vessels, except sample 20 manganese oxide (MnO avg. 0.55%) is present here as a glass decolorizer and intentionally added to overcome the green tint of iron oxide, where in sample 20 it was intentionally added to color the glass violet. It is also known that an alternative way of producing colourless glass is by adding a "decolorizer". Antimony and manganese both decolorize glass by oxidising the iron which is always present in sands and confers a green tint to glass (Jackson, 2005; Abd-Allah 2009; Mirti et al. 2009).

On the contrary, TiO_2 present in 0.5% - 0.11%, and hence it is ascribable to be impurities of heavy minerals in the raw sands rather than to be intentionally added as glass opacifier. The lead oxide (PbO avg.0.10%) in all glass vessels was probably present simply as an impurity rather than being intentionally used as a glass opacifier. Iron oxide (FeO avg. 0.57%) is present as an impurity associated with sands, and it is almost exclusively responsible for colouring glass to light green and yellowish green (less than 1%). This suggestion also matches the iron content of the glass bracelets group A where the content of FeO ranging between 0.48-0.50%.

On the other hand, in all glass bracelets group B, iron oxide (FeO avg. 1.69%) it possibly intentionally added to color the glass black or blue (exceed 1%). FeO content, in particular, is the highest among the studied sample B2 and B9 (FeO-2.48% and 2.31 %), suggesting the deliberate addition of Fe bearing materials to the melt, with the aim of preventing copper oxidation (Croveri et al. 2010; Arletti et al. 2011). The relatively high content of copper oxide (CuO avg.0.10%) indicate that it was used as colorant agent to color the glass bracelets blue, green, yellow and black (Di Bella 2013; Jackson, 2005; Mirti et al., 2009; Abd-Allah 2009; Croveri et al. 2010).

Lead oxide contents are very high in the opaque yellow and red bracelets (15-71%) and relatively high in the green and yellowish green ones (20-35%). The relatively high concentration of PbO suggests the addition of lead as a melting agent and to improve the brilliance and chromatic aspect of the bracelets past beside his role as opacifying agent of glass. On the contrary, TiO_2 content in glass bracelets group B ranging between 0.45% -0.48%, and hence it is ascribable to be intentionally added as glass opacifier rather than to be impurities of heavy minerals in the raw sands.

3.3. Technological and cultural aspects

The discovery of considerable collection of glass vessels together with a set of glass bracelets related to glass processing is not sufficient to suggest a local secondary production of glass artifacts at Es-Sukhnah archaeological site in north –east Jordan from the Roman to the early Islamic period. In addition to that, the chemical data provided above potentially confirms this suggestion. The resulting data and archaeological evidence show at least that the majority of the glass vessels (the secondary production) were formed locally in a glass workshop at another site in Jordan or being imported in large quantity from elsewhere, as finished artefacts. In contrast, there is yet no evidence for the primary production of raw glass at the site, because no considerable traces of raw materials and fritting crucibles have been found to date at the site (Freestone et al., 2002a; 2002b; 2003; 2005; 2006; 2008).

The production technology for this type of glass composition has been discussed in some details elsewhere (Al-Ahmed and Al-Muheisen 1995; Freestone et al., 2002a). Certain Palestinian coastal beach sands contain approximately the proper concentrations of quartz and calcite that would allow them to be mixed with soda (probably from the lakes of Wadi Natrun in Egypt) to produce a blue-green soda-lime-silica glass. This procedure was carried out in large tank furnaces of the type excavated at Beth Shearim, at Beth Eli'ezer, and in Apollonia (Arsuf), in batches of 5 to 10 tons (Freestone et al., 2008).

It was stated that glass production in the first millennium AD was divided between a relatively small number of workshops that made raw glass and a large number of secondary workshops that fabricated vessels. During the Roman and later periods, glass was produced from its raw materials in massive tank furnaces in a limited number of glass production centres. The unformed chunks of raw glass originating from these furnaces were then re-melted to produce glass vessels at a larger number of glass working centres (Freestone et al., 2002a; 2002b; 2003; 2005; 2008). The Levantine coast appears to have been the location of large-scale glass making in antiquity. This is evident from the writings of classical authors such as Strabo, Pliny and Josephus, and from the archaeological discoveries of glass-making factories at sites such as Bet Shearim, Bet Eli'ezer (Hadera), and Apollonia (Arsuf), all in Palestine. There is also abundant evidence from glass workshops within Palestine for the distribution of glass in the form of rough chunks. However, it is not yet fully understood how these were traded, over what distances, and what other sources of glass were in competition with Levantine factories (Freestone et al., 2002a). A study on raw materials by Brill (1988) suggested that Levantine I glass was made using coastal sand of the type that occurs around the mouth of River Belus, in the bay of Haifa, used as glass making sand in antiquity. This group appears to have represented the typical glass of the Levant between the 4^{th} and 7^{th} centuries AD. The second Levantine group was a product of the massive glass-making furnaces at Bet Eli'ezer, near Hadera, Palestine. The Bet Eli'ezer or Hadera glass differs from the Levantine I type in terms of lower CaO and Na_2O, and higher SiO_2. This aspect reflects that fact that it was produced in a different location on the Palestinian coast, where the sand is of a different composition, and at a later date, during the early Islamic period. Freestone et al. (2002a) suggested that the furnaces from Bet Eli'ezer, probably from early on during the Islamic period, replaced those producing glass of the Levantine I composition.

Around the beginning of the 1st millennium BC, soda-rich plant ashes were replaced by the natural evaporate, natron, from the Wadi Natrun in Egypt as the flux used in glass production in the Levant and Egypt. Subsequently, by the 5th century BC, natron was the flux used in the great majority of glass produced west of the Euphrates, and fed the prodigious growth of glass production during the Roman period when natron-based glass spread throughout Europe. Glass production across the Levant, the Mediterranean and Europe continued to be based on natron until around the 9th century AD when the pressure on its supply appears to have become such that it ceased to be used as the flux in glass production in the Islamic Near East. Here, natron was replaced by soda-rich plant ash, which had continued to be used as the flux in glass production in Mesopotamia and Iran throughout the period of natron dominance to the west (Tite et al., 2006).

With one exception, the latest evidence for the use of natron by Levantine glassmakers consists of raw glass from the sixth- or seventh-century glass factory at Bet Eli'ezer (Hadera) and 8^{th} to 9^{th} century glass vessels from Ramla, both in Palestine. Similarly, glass vessels from Jordan and southern Syria were made with natron at least until the early seventh century (the date of the latest samples). The transition to plant ash in the Levant, therefore, seems to have taken place in or after the eighth century. The change, it should be noted, was not necessarily universal; glassworkers at Sepphoris, Palestine, are reported to have used natron continuously throughout the Roman, Byzantine, and Islamic occupation of the site (Whitehouse, 2002).

The microscopic examination of the glass vessels from Es-Sukhnah revealed that they are examples of thin-walled glass of fairly good quality. Most of them exhibit blowing marks. This aspect, in addition to the fabric, shape and curvature, indicates that these glasses were made by the mould-blowing technique. Stylistically, these glasses resemble very closely a collection of Roman mould-blowing glasses excavated from other Roman sites in Northern Jordan, such as Beit Ras , Yasileh and Quelbeh, as well as Roman glass from Egypt, Syria and Palestine. It was already established that blown glass was first invented or appeared early in the Roman period (Al-Ahmed and Al-Muheisen, 1995). Pasting or cake-past was the method used for the production and decoration of glass bracelets.

4. CONCLUSION

The above chemical composition results supported the archaeological data with respect to technological aspects of glass production and technological change of production. At the synchronic scale of glass production, the analysis of glass collection from Es-Sukhnah show that the Roman glass vessels and bracelets manufacture was consistent with other Roman sites in the southern Levant. The resulting data showed that both types of analysed samples are examples of soda-lime-silica glass, with natron used as flux for Roma glass vessels and bracelets. Based on that, the Roman glass collection from Es-Sukhnah related to what is called Levantine group I. Furthermore, microscopic examination and technical observation exhibit blowing marks on the glass objects, which indicate that mould-blowing was the main technique used for forming glass from Roman period at Tell Es-Sukhnah. Molding technique was also used in manufacturing Roman glass bracelets.

However, comparing the chemical composition of glass collections from Es-Sukhnah highlights the changing pattern of glass production. The results show that there are significance changes in glass composition between the Roman and Islamic period. The former group of glass related to soda-lime-silica glass, with natron used as flux, meanwhile the second group of Islamic glass related to calcium –rich plant ash soda. This may indicate that transition in the use of traditional methods and of the same sources of raw materials for glass-making occurred, with obvious modifications, from natron to plant ash and from calcium-rich sand to calcium -free sand at this site. Stylistic changes have been observed with respect to colour use in bracelets. The Roman bracelets were characterized by using multi colours as decorative elements; meanwhile the Islamic bracelets decrease the colour of bracelets to two in most cases. The stylistic observation supports the chemical analysis of bracelets group.

At the economic scale, the excavation at Es-Sukhnah did not uncover any installation or feature associated with glass production. The absence of such features highlights the possibility of trade network between Es-Sukhnah and other production or trade locations during the Roman and Islamic period. That is, the mechanism of import or exchange of glass objects to Es-Sukhnah might be related to indirect trade type. The Decapolis site of Gerasa is 22 km to the west of Es-Sukhnah. Therefore, the inhabitants of Es-Sukhnah might purchase their glass objects with Gerasa, which played as market centre or trade station, mainly during the Roman period.

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