Mediterranean Archaeology and Archaeometry, Vol. 16, No 1,(2016), pp. 257-268

DOI: 10.5281/zenodo.44776

ANALYTICAL AND TECHNOLOGICAL STUDY OF ROMAN, BYZANTINE AND EARLY ISLAMIC (UMAYYAD) GLASSES FROM AL-FUDEIN ARCHAEOLOGICAL SITE, JORDAN

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Received: 12/11/2015
Accepted: 20/01/2016
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ABSTRACT

The study investigates the chemical composition and production technology of a set of thirty-nine glass samples from the archaeological site of Al-Fudein, northeast Jordan. The samples cover a long span of time dating back to the Roman, Byzantine and Early Islamic (Umayyad) periods. The X-Ray Fluorescence chemical analyses revealed that the samples are soda-lime-silica natron based glasses. The majority of the samples are most probably of the Levantine type I glass, where the silica might come from the Syrian-Palestinian coast. Manganese and copper are the probable generators of the distinguished purple and turquoise colors. The high content of magnesia and potash of 4 Roman and 1 Umayyad samples might indicate the continuity of using plant ash fluxes in certain production centers during the Roman-Umayyad periods or pointing at a possible limited (but not documented before) inter-regional trade of Sasanian glass during the Roman period.

KEYWORDS: Roman glass, Byzantine glass, Umayyad glass, Jordan, Production technology, Natron, Plant ash, Levantine type I.

1. INTRODUCTION

The homogeneity of the composition of the dominant glass in the Mediterranean is considered one of the remarkable characteristics of the glassmaking technology between the beginning of the Roman period and the ninth century AD during the Muslim period (see, e.g., Sayre and Smith 1961; Henderson 1985; Wedepohl 1997; Rehren 2000). Glass production during this period had a relatively stable and fixed recipe based upon silica fluxed with natron (Jackson *et al.* 2009). Natron glass was subdivided into major compositional groups including (among others) the Levantine I and Levantine II groups, where the latter group has higher concentrations of SiO_2 but lower CaO and Na_2O than the former group (Freestone *et al.* 2002a,b).

It is believed that this type of glass was produced in a limited number of primary glassmaking centers which supplied raw glass to numerous secondary workshops that shaped artifacts throughout the Mediterranean as well as central and northern Europe (Nenna *et al.* 1997, 2000; Freestone *et al.* 2002b; Degryse *et al.* 2005). Large glassmaking furnaces uncovered in several archaeological sites in the Levant of the above mentioned period (Freestone *et al.* 2008), large amounts of glass chunks uncovered in several shipwrecks from the same period (Foy *et al.* 2003), and the chemical and isotopic analysis of glass chunks confirm the wide spread of land and maritime trade of unshaped glass chunks (see, for example, Freestone 2006; Arletti *et al.* 2010a). At any rate, based on the analytical data, the majority of the first millennium AD glass has an eastern Mediterranean origin.

Romans and Byzantines produced low magnesia glasses at the Mediterranean coast from beach sand containing shell fragments and natron, Sasanians produced high magnesia plant ash glasses further inland in the Middle East (Mirti *et al.* 2009), while Muslims produced natron glasses until about the end of the eighth century, when plant-ash glass largely replaced natron glass across the Islamic world (Gratuze and Barrandon 1990; Henderson 2002; Freestone *et al.* 2005). Plant ash glasses of Syrio-Palestine recipes contained 2-3.5% of MgO and K_2O, while those of the Sasanians and Parthians often contained more than 3.5% of MgO and K_2O (Freestone 2006). These changes represent fundamental developments in raw material use and glass composition; therefore, it is expected that Al-Fudein archaeological glass finds agree with these changes and can potentially reveal patterns of glass production and trade.

Although Jordan is rich in archaeological sites of the above mentioned periods, archaeometric studies of glass finds are few (Al-Ahmed and Al-Muheisen 1996; Schibille *et al.* 2008; Abd-Allah 2010; Rehren *et al.* 2010) and glass finds from some archaeological sites belong only to one of these periods. Excavations at Al-Fudein site uncovered glasses of three consecutive cultures (Roman, Byzantine and Umayyad). An archaeometric study of this collection is therefore of high scientific and historical interest offering an opportunity to investigate glassmaking recipes used by the three cultures and track their development during these three periods.

Al Fudein, with a latitude of 32.35 (32° 21' 0 N) and a longitude of 36.18 (36° 10' 60 E), is located in Al-Mafraq governorate, northeast Jordan (Fig. 1), at the crossroad of the major ancient trade routes passing the area including the King's Highway and Via Triana. Archaeological remains uncovered from Al-Fudein indicate that it has been settled and continuously used from the Paleolithic Age until the end of the Ottoman period (Al-Housan 2002). The site comprises several structures that belong to different archaeological periods including, among others, a fortified castle of the Iron Age, a Byzantine monastery, an Umayyad mosque, auditorium and baths.

Figure 1 Location map of the site (Drawn by Ali Al-Omari).

2. MATERIALS AND METHODS

2.1. Samples

During archaeological excavations conducted at Al-Fudein by the Department of Antiquities of al-Mafraq, Jordan, between 1990 and 1999, a collection of glass finds was uncovered. Based on the accompanied pottery and/or coins the glass was dated from the Roman (early (63BC-135(or195)AD) and late (135(or 195)-324(or 365)AD) (Freeman 2008)) to the Umayyad (AD 661-750) periods (Al-Housan 2002). The glass fragments analyzed in this study were excavated from a variety of sealed and well stratified contexts from different structures (Table 1). Excavations have not identified evidence of primary or secondary glassmaking activities such as glass chunks, furnaces, or residues of raw materials or production activities.

A set of 39 samples (21 Roman and 8 Byzantine of various artifacts of different shapes, functions and colors and 10 Umayyad window glasses) was selected for the chemical analysis (Table 1). The Umayyad samples were window glasses of different colors mainly purple, dark green, brown and turquoise. The most common colors of the Roman and Byzantine samples were blue and green, which represent the most common natural colors of glass during the periods under investigation.

2.2. *Analytical methods*

Fresh and clean surfaces of the selected glass fragments were sampled after removing the corrosion layers and surface contaminants using a diamond coated wheel. Samples were col- lected by cutting small pieces by means of a diamond saw. The sampled pieces were washed with double distilled water in an ultrasonic bath, dried and ground to a fine powder in an agate mortar. About 1.25 gram of powdered glass of each sample and 10 grams lithium tetraborate (1:8 ratio) were fused. The solid glass disks were chemically analysed for major and minor components using a Bruker S4 Pioneer Wavelength Dispersive X-Ray Fluorescence Spectrometer (WDXRF) at the Laboratories of the Natural Resources Authority-Jordan. The spectrometer uses the soda-lime-silica glass NCS DC 61103 and high-purity silica BCS-CRM 313/1 standard certified reference materials and works under vacuum, voltage 20-60 kV, current 5-150 mA and a power limit of 40-50 watt. Table 2 shows the comparison between the certified compositional values and those recovered by the XRF analyses for the NCS standard.

3. RESULTS AND DISCUSSION

3.1. *Composition of the Glass Samples*

34 of the samples are silica–soda–lime glass produced with natron as the source of the flux, while 5 samples (5,6,7,12,39) are plant-ash based, see Figure 2a. The results of the chemical analysis and averages of both groups are given in Table 1 and presented as bi-plots of some main and minor elements. Based on the chemical results presented in the bi-plot in Figure 2b, most of the samples are most probably of the Levantine glass types (Freestone *et al.*, 2002a: Fig. 7; Arletti 2010a: Fig. 2).

Table 1: *Description, form and context of the samples and Chemical compositions of the major and minor oxides of the glasses.* (1a=West Fudein, Byzantine church, north room, the pavement, second (Roman) layer of, third season, 1995. 1b= West Fudein, Byzantine church, in front of the church, cemetery room, pavement, third (Roman) layer, third season, 1995. 2a= East Fudein, Aramaic castle, sounding #4, south wall, fourth layer, third season, 1995. 2b= East Fudein, Aramaic castle, covered north water canal, second season, 1994. 3= Fudein, In front of the office, Roman-Byzantine cemetery, tomb #3, looted, pavement, Roman layer, fourth season, 1996. 4a= West Fudein, south landfill, fifth layer, fourth season, 1996. 4b= West Fudein, south landfill, fourth layer, fourth season, 1996. 5= East Fudein, baths, throne hall, pavement, north apse, cement layer, fourth season, 1996. 6a= East Fudein, the Tell, Northeast corner of the North room (kitchen), fifth square, pavement, the kiln, third (cement) layer, fourth season, 1996. 6b= East Fudein, the Tell, Northeast corner of the North room (kitchen), fifth square, pavement, the kiln, bottom layer, fourth season, 1996. 7a= West Fudein, west kitchen, southwestern tower, pavement, Roman layer, third season, 1995. 7b= West Fudein, southwestern tower, sounding #4, Roman fill, fourth season, 1996. 7c= West Fudein, west kitchen, southwestern tower, pavement, cement layer, fourth season, 1996. 8a= East Fudein, Umayyad castle, south wall, sounding #5, fourth layer (Roman fill), fourth season, 1996. 8b= East Fudein, Umayyad castle, throne room, pavement, adjacent to the cabinet, Roman layer, third season, 1995. 9= East Fudein, Umayyad mosque, in front of the prayer niche, gypsum layer, first season, 1993. 10a= West Fudein, west the entrance of the west church, north room, paved floor of the cemetery, fifth season, 1997. 10b= West Fudein, west the entrance of the west church, north room, third layer, fifth season, 1997. 11 Umayyad= East Fudein, the Umayyad mosque, window glass, pavement, fourth (mortar) layer, first season, 1993). Chemical compositions of the major and minor oxides of the glasses.

Sample N./period	S.ID.	Color	Form	Context	SiO_2 wt%	Na_2O wt%	CaO wt%	Al_2O_3 wt%	MgO wt%	K_2O wt%	Fe_2O_3 wt%	MnO wt%	TiO_2 wt%	P_2O_5 wt%	L.O.I. wt %
Natron glass samples															
1/L. Roman	Rom-1	Yellowish Green	Base /cup	(1a)	69.9	15.5	7.42	2.68	0.55	1.11	0.65	0.02	0.08	0.22	1.2
2/ L. Roman	Rom-2	Yellowish Blue	Neck/bottle	North room of Byzantine church (1b)	75.6	13.3	5.63	2.6	0.39	0.52	0.57	0.02	0.09	0.05	0.5
3/ L. Roman	Rom-3	Yellowish Green	Lower body/ bottle	North room of Byzantine church (1b)	71.5	14.0	8.64	2.64	0.61	0.9	0.7	0.03	0.1	0.17	0.2
4/ L. Roman	Rom-4	Yellowish Green	Base/bottle	Aramaic castle (2a)	72.1	14.5	7.89	2.23	0.41	0.9	0.41	0.25	0.06	0.07	0.4
8/ L. Roman	Rom-8	Yellowish Green	Neck/bottle	Baths (5)	70.1	15.3	8.39	2.4	0.56	0.92	0.55	0.38	0.09	0.11	0.3
9/ L. Roman	Rom-9	Yellowish Blue	Knob/ bottle	Baths (5)	70.3	16.7	7.36	2.4	0.39	0.77	0.44	0.02	0.07	0.08	0.7
10/ L. Roman	Rom-10	Yellowish Blue	Neck and upper body/ bottle	The tell (6a)	75.9	12.7	6.38	2.65	0.39	0.5	0.52	0.02	0.09	0.04	0.5
11/ E. Roman	Rom-11	Yellowish Green	Neck/ bottle	South-west tower (7a)	71.7	13.7	7.82	2.65	0.94	0.99	0.82	0.16	0.12	0.19	0.5
13/ L. Roman	Rom-13	Brown	Upper body/ bottle	Landfill (4b)	70.3	15.1	8.27	2.63	0.42	0.9	0.58	0.03	0.09	0.14	0.7
14/ L. Roman	Rom-14	Yellowish Green	Decorative tape/vessel	Umayyad palace (8a)	71.2	12.6	7.77	3.08	1.01	1.37	1.08	0.12	0.15	0.24	0.6
15/ L. Roman	Rom-15	Yellowish Blue	Base and lower body/ vessel	Fifth square-North room of the tell (6b)	69.7	14.9	8.55	2.45	0.51	0.91	0.55	0.95	0.07	0.13	0.5
16/ L. Roman	Rom-16	Blue	Semi-transparent, body/ cup	The mosque (9)	72.4	14.6	7.7	2.18	0.53	0.47	0.44	0.19	0.07	0.16	0.5
17/ E. Roman	Rom-17	Yellowish Green	Base/ bottle	South-west tower (7b)	71.1	14.1	8.62	2.53	0.68	1.13	0.6	0.03	0.11	0.18	0.2
18/ L. Roman	Rom-18	Yellowish Blue	Base/ bottle	Baths (5)	73.3	13.2	8.11	2.56	0.5	0.89	0.5	0.02	0.09	0.12	0.2
19/ E. Roman	Rom-19	Yellowish Blue	Semi-transparent, Body/ cup	South-west tower (7c)	72.6	11.6	12.2	1.0	0.41	0.5	0.39	0.14	0.06	0.01	0.4
20/ L. Roman	Rom-20	Blue	Semi-transparent, Neck/vessel	The tell (6a)	71.7	13.7	7.89	2.6	0.95	0.99	0.78	0.15	0.13	0.2	0.1
21/ L. Roman	Rom-21	Colourless	Transparent, body, vessel	Umayyad Palace (8b)	71.7	14.7	8.62	2.22	0.38	0.82	0.35	0.06	0.05	0.06	0.3
Average*	**Roman**				**71.83**	**14.13**	**8.07**	**2.44**	**0.57**	**0.86**	**0.58**	**0.15**	**0.09**	**0.13**	**0.46**
22/ Byzantine	Byz-1	Turquoise	Fragment/ Bracelet	Church- north cemetery (10a)	69.8	18.3	5.12	0.43	2.09	0.81	0.74	0.04	0.12	0.15	1.2

23/ Byzantine	Byz-2	Light blue	Fragment of decorated vessel with turquoise threads	Church- north cemetery (10a)	71.8	13.8	8.54	2.77	0.51	1.02	0.57	0.02	0.09	0.18	0.3
24/ Byzantine	Byz-3	Yellowish green	Handle/ vessel	Church- north room adjacent to the apse (10b)	73.5	14.0	7.17	2.65	0.5	0.48	0.79	0.02	0.09	0.04	0.4
25/ Byzantine	Byz-4	Olive	Body/ small and pierced	Church- north cemetery (10a)	68.9	15.6	9.35	2.5	0.51	0.8	0.54	0.02	0.08	0.14	0.5
26/ Byzantine	Byz-5	Light green	Handle and upper body/ bottle	Church- north cemetery (10a)	70.3	13.6	10.1	2.7	0.69	0.73	0.6	0.05	0.09	0.15	0.4
27/ Byzantine	Byz-6	Light blue	Handle/ bottle	Church- north cemetery (10a)	75.2	12.8	6.02	2.93	0.46	0.63	0.65	0.02	0.1	0.06	0.4
28/ Byzantine	Byz-7	Blue	Handle/ ware	Church- north cemetery (10a)	74.0	12.3	8.11	2.66	0.51	0.78	0.72	0.05	0.13	0.18	0.4
29/ Byzantine	Byz-8	Blue	Mosaic cube	Church- north cemetery (10a)	71.0	12.9	8.03	3.04	0.52	0.62	1.06	0.02	0.1	0.11	0.3
Average*			**Byzantine**		**71.81**	**14.16**	**7.81**	**2.46**	**0.72**	**0.73**	**0.71**	**0.03**	**0.1**	**0.13**	**0.49**
30/ Umayyad	E.ISL-1	Purple	Window glass	Umayyad mosque (11)	72	13.3	7.38	2.41	0.37	0.86	1.08	2	0.16	0.07	0.2
31/ Umayyad	E.ISL-2	Purple	Window glass	Umayyad mosque (11)	71	12.5	7	2.75	0.73	0.93	0.93	3.37	0.13	0.1	0.1
32/ Umayyad	E.ISL-3	Brown	Window glass	Umayyad mosque (11)	72.5	14.3	7.1	3.22	0.51	0.56	0.74	0.03	0.11	0.06	0.4
33/ Umayyad	E.ISL-4	Dark green	Window glass	Umayyad mosque (11)	68	12.6	7.2	3.35	0.52	0.76	5.55	0.07	0.14	0.1	0.5
34/ Umayyad	E.ISL-5	Turquoise	Window glass	Umayyad mosque (11)	71	14.1	6.97	2.83	0.49	0.8	0.76	0.47	0.09	0.07	0.2
35/ Umayyad	E.ISL-6	Green	Window glass	Umayyad mosque (11)	67.2	14	6.35	2.71	0.61	0.88	3.68	0.04	0.09	0.08	0.1
36/ Umayyad	E.ISL-7	Purple	Window glass	Umayyad mosque (11)	70.4	12.6	6.9	3.11	0.71	0.96	0.8	3.29	0.12	0.1	0.2
37/ Umayyad	E.ISL-8	Turquoise	Window glass	Umayyad mosque (11)	66	11.8	7.26	2.82	1.01	1.05	0.82	0.46	0.08	0.13	0.3
38/ Umayyad	E.ISL-9	Brown	Window glass	Umayyad mosque (11)	74.3	12.4	6.89	3.18	0.51	0.71	0.68	0.03	0.13	0.07	0.2
Average*			**Umayyad**		**70.27**	**13.07**	**7.01**	**2.93**	**0.61**	**0.83**	**1.67**	**1.08**	**0.12**	**0.09**	**0.24**

Plant ash glass samples															
5/ L. Roman	Rom-5	Colourless	Transparent, base and lower body/cup	Roman cemetery in front of the office (3)	70.8	12.5	7.22	0.69	2.6	2.64	0.58	1.08	0.09	0.36	0.7
6/ L. Roman	Rom-6	Yellowish Green	Neck/bottle	Aramaic castle (2b)	62.5	14.7	7.31	1.82	7.07	3.33	0.66	0.49	0.12	0.19	0.7
7/ L. Roman	Rom-7	Yellowish Green	Neck and upper body/ large vase	Landfill (4a)	60.3	14.1	10.8	4.15	4.82	2.49	1.77	0.05	0.26	0.41	0.1
12/ L. Roman	Rom-12	Yellowish Green	Base/ bottle	North room of Byz-antine church (1b)	60.8	16.5	6.68	2.07	6.82	3.94	1.07	0.04	0.12	0.21	1.0
Average*	**Roman**				63.60	14.45	8.00	2.18	5.33	3.1	1.02	0.42	0.15	0.29	0.63
39/ Umayyad	E.IS-10	Green	Window glass	Umayyad mosque (11)	62.0	12.5	7.27	2.62	5.34	3.68	1.04	0.77	0.14	0.3	3.4

Table 2. Comparison of certified and measured composition of Reference Material NCS DC 61103. D.a. = Difference (absolute), D.r% = Difference (relative percentage), all values are in wt%.

	SiO2	Al2O3	Fe2O3	TiO2	CaO	MgO	K2O	Na2O	SO3
NCS61103 Certi-fied%	71.25	2.56	0.18	0.057	6.37	3.98	1.1	13.77	0.17
NCS61103 Measured%	71.3	2.6	0.18	0.062	6.8	3.91	1.12	13.6	0
D.a.	0.05	0.04	0	0.005	0.43	0.07	0.02	0.17	0.17
D.r.%	0.07	1.55	0	8.5	6.5	1.7	1.8	1.24	200

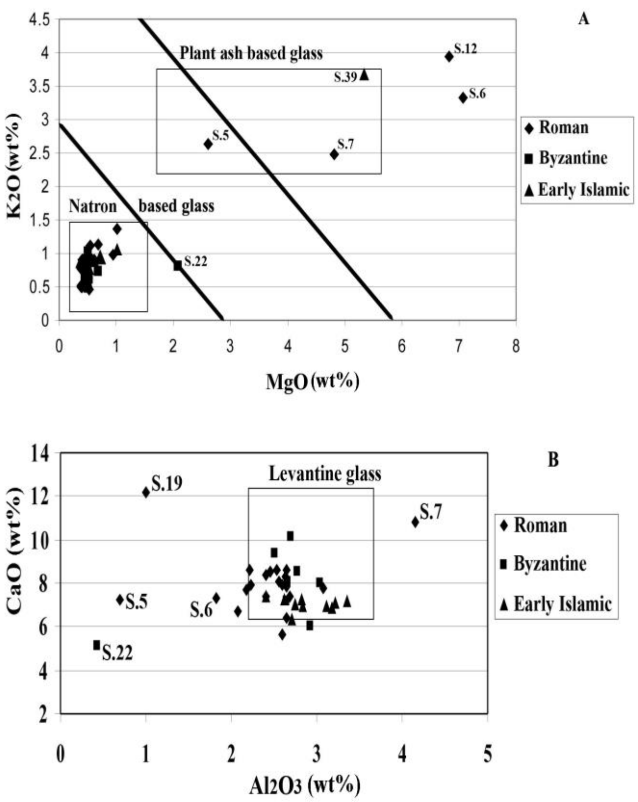

Figure 2 A) Magnesia versus potash distribution showing subdivisions between low and high magnesia (Syrian-Islamic and Sassanian) glasses (after Freestone 2006, Arletti et al. 2010a), B) alumina versus lime for the glass finds (after Arletti et al. 2010a), showing the discrepant samples.

While most of the Levantine glasses are of Levantine I type, seven samples (2,10,18, 24,27,28, and 38) are probably of the Levantine II type (Fig. 3a, Freestone *et al*. 2000: Fig.6). Unfortunately there is a significant overlap between the two groups and it would be difficult to attribute a single analysis to one of them. The authors suggest the area of the trapezoid in Figure (3b) to present the Levantine I glasses depending on their contents of Al_2O_3 and Fe_2O_3. The inclined line of the trapezoid suggests a suitable division between the Levantine I and the HIMT glasses. Regarding these samples, it is probable that the glassmakers used silica for their production somewhere from the coast of Syria-Palestine.

It is probable that leaching caused the low concentrations of soda in some of the samples (Huisman *et al*. 2009). Leaching happens in different mechanisms and affects alkalis of the glass exposed to a continuous level of high humidity inside the monument (Moropoulou et al. 2016). However, one of the possible reasons for the decrease of the amount of natron in the Islamic glass might be the shortage of natron supply and the long distance from Lower Egypt to the Mediterranean coast of the Levant, while sources for sand, such as the River Belus (Fig. 1), were closer and more abundant. Larger amounts of soda and lower amounts of silica makes the glass flow more easily; thus, more suitable for shaping at lower temperatures (Fischer and McCray 1999).

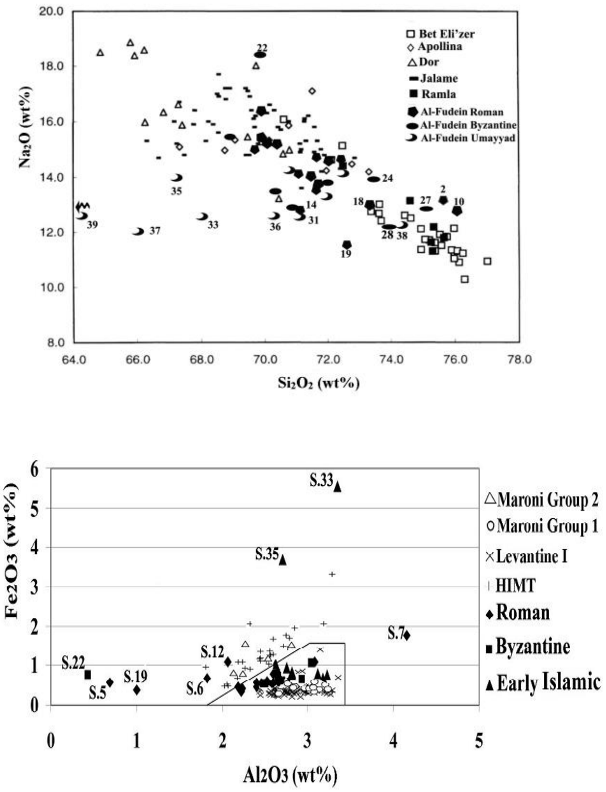

Figure 3 Up) Silica versus soda (after Freestone et al. 2000), down) The Al_2O_3 and Fe_2O_3 contents of Al-Fudein samples compared with Levantine type I including Maroni glasses (After Freestone et al. 2002a).

3.2. Discussion

A division of the Roman and Byzantine from the Umayyad samples could be seen in Figure 2b which shows the Al_2O_3–CaO bi-plot. The Al_2O_3 concentrations of the Roman and Byzantine samples are (in general) lower than those of the Umayyad samples, while the lowest concentrations of CaO are (in general) related to the Umayyad samples. The aluminum and calcium oxides values derive from the feldspathic, clay and carbonate impurities present in the sands (Arletti et al. 2010b). The average of the lime content (around 8%) may indicate the Syrian-Palestine sources of sand, probably the River Belus sands which contain about 15% calcium carbonate and produces, when mixed with alkalis, a soda-lime-glass with 8-9% lime (Freestone 2006). The homogeneity of the CaO and Al_2O_3 of the majority of assemblage of the Roman and Byzantine samples indicates the use of a common silica source, while it might be concluded that different sand sources of the Levant coast were used in the production of the Umayyad glasses (Freestone *et al.* 2000, 2002a; Tal *et al.* 2004).

The very low alumina contents of samples 5,19 and 22 and the low content of lime in sample 5 might indicate the use of a pure sand, relatively poor in the above mentioned impurities. However, the high percentage of lime of sample 19 might indicate that the glassmaker produced this sample by a deliberate addition of lime to the pure sand.

The total mean alkali values (Henderson 2002, p. 598) of the Roman, Byzantine and Umayyad samples are 14.99%, 14.89% and 13.80%, respectively. These results match the trends discussed by Henderson (2002: Table 1); the Umayyad samples have the lowest mean soda and total mean alkali which distinguish the Umayyad from the Roman and Byzantine samples. These values support the above inference that the Roman and Byzantine samples are similar in composition to the Levantine I glass (Freestone 2002a and b). This good correspondence to the Levantine I glass indicates that glass production of this group was active before the 4th century AD. Similarly, few Roman samples are of the Levantine II glass (6th-7th century, Freestone et al. 2000) which might suggest the activity of this group during the late Roman period.

The contents of magnesium versus potassium oxides in Table 1 indicate clearly the use of a single alkali source (natron) as a fluxing agent to produce most of the samples. The groupings sit comfortably within range limits of natron glasses (low contents of potassium and magnesium oxides), as suggested by Lilyquist and Brill (1993). Figure 2a shows an anomalous case of four Roman samples (5,6,7 and 12) and one Umayyad sample (39) in which plant ash was used as a fluxing agent in their production. Few samples (1,14,17,23) have elevated concentrations of potassium oxide (above 1%) compared to those of magnesium oxide which might indicate a contamination from alkali-rich waste gases during burning (Paynter 2008). Tal et al. (2008) explained high levels of potassium oxide in some glass samples from the late Byzantine secondary workshop at Ramla (Fig. 1) to fuel ash contamination.

Despite the variability of regional variation of the plant composition and the relative contents of potash and soda in wood and plant ash, the plant ash source can be distinguished based on the Na_2O/K_2O ratio, which is of the range of 2–10 for soda-rich plants, and below 1.5 for mixed alkali ashes (Artioli 2010, p. 290). The Na_2O/K_2O ratios (4.73, 4.41, 5.66, 4.19 and 3.68) of the above mentioned samples (5,6,7,12 and 39 respectively) confirm that they were produced with a plant ash. Although the Na_2O/K_2O ratio of the Roman sample (14) equals 9.19 indicating a plant ash source for the flux, it is located in the MgO-K_2O range of the natron based glass in Figure (3a). On the contrary, the Byzantine sample (22) is located to the right of the MgO-K_2O range of the natron based glass in Figure (2a), while it has a Na_2O/K_2O ratio of 22.59 indicating that it is a natron based glass. In addition, the Ratio of (Na_2O+K_2O) : ($CaO+MgO$) could be used to distinguish between Roman Levantine and Byzantine recipes/workshops (Liritzis et al. 1997). The values of this ratio for samples 5, 6, 7, 12, 14, 22, 39 are 1.54, 1.25, 1.06, 1.51, 1.59, 2.65, 1.28, respectively. They indicate a near eastern influence for all these samples, excluding sample 22 which follows the Roman provincial school recipe.

The introduction of the new Islamic recipe that used a soda flux from plant ash and calcium-free sand or crushed quartz (Whitehouse 2002; Henderson *et al.* 2004) took place during the eighth and ninth centuries (Gratuze and Barrandon 1990, Henderson *et al.* 2004). Nevertheless, Henderson (1995) has shown that certain Islamic vessel fragments from as early as the late eighth century have a composition suggesting the transition to a soda-rich plant ash rather than natron as a fluxing material. The use of soda-rich plant ash appears at first to have complemented the use of natron; however, by the 11th century, the replacement was nearly complete.

On the basis of these hypotheses, it is possible that the anomalies of Al-Fudein glass samples came from vessels made regionally, but with different raw materials from the rest of the samples. Furthermore, it is possible, but needs to be supported by more data, that the Romans continued the use of the plant ash as a fluxing agent in the production of some of their glass; i.e, the use of the plant ash was not interrupted in certain regions. This possibility was not excluded by Sayre and Smith (1961, p. 1826) who claimed that it merits investigation. Inside Jordan, similar results were shown by Al-Ahmed and Al-Muheisen (1996) and Sababha (2000) who analysed Roman glasses from the Yasileh and Hayyan Al-Mushrif archaeological sites, north Jordan, respectively (see Figure 1). The first two authors suggested that the older plant ash recipe did not die altogether although the natron was the major source of the soda during the Roman period.

Outside Jordan, the manufacture of first-century AD emerald green glass at Fishbourne, southern England (Henderson 2013), the manufacture of black glass beakers at Magdalensburg, Austria (Cosyns *et al.* 2006), first century Swiss glasses (Arletti *et al.* 2008), fourth-century plant ash glass at Augusta Pretoria, Aosta, Italy (Mirti *et al.* 1993), and first century AD emerald glass at Frejus (France) and Colchester (England) (Jackson *et al.* 2009) are published examples of producing plant ash during the Roman times. In addition, based on the chemical analysis of several small-volume thick-walled dark green *unguentaria*, which was made of probably Egyptian plant ash glass, Rosenow and Rehren (2014) suggested that the production of plant ash glass persisted in Egypt during the early first millennium AD before the re-introduction of plant ash-based glassmaking in the Islamic period.

The main region where plant-ash glass-making persisted during the entire period is the Sasanian Empire east of the Euphrates (Mirti *et al.* 2008, 2009). Freestone (2006, p. 204) has highlighted the difference in magnesia and potash content between Syrian-Islamic and Sasanian glass, with the latter having systematically much higher magnesia levels. Of the four Roman period plant-ash glasses in our study, three (samples 6,7,12) match the Sasanian composition (Fig. 2a) identified in Freestone (2006), and only one (sample 5) the Syrian-Islamic. Based on the subdivisions of the Sasanian glass by Mirti et al. (2009), sample 6 (MgO=7.07%, K_2O=3.33%, MgO/K_2O=2.12, and CaO/Al_2O_3 > 4.0) can be classified as the Sasanian 2 group, while sample 7 (MgO=4.82%, K_2O= 2.49%, and MgO/K_2O=1.94) and sample 12 (MgO= 6.82%, K_2O= 3.94%, and MgO/K_2O=1.73) can be classified as the Intermediate group. Given the location of Al-Fudein in the eastern edge of the Roman world, it is not unreasonable to suggest that these three glass fragments may belong to artifacts imported from the Sasanian Empire, indicating a little documented exchange of good in this period.

3.3. Colouring agents

The Roman samples show low concentrations of iron (average Fe_2O_3 lower than 0.6%) indicating a relatively high purity of the raw materials employed. The average of the iron content of the Byzantine samples (excluding sample 8) is 0.66%. The Umayyad samples show higher iron concentrations ranging between 0.68 and 5.55%. It is worth noting that the major differences in the chemical composition between the glass samples result probably from using more than one silica source (Francesco *et al.* 2010).

The low iron concentrations of most of the samples are the most probable reason for the samples' light blue-green colors. The high concentration of iron oxide in window samples 33,35 and 39 (Table 1) are responsible of the green and dark green colors (Rehren et al. 2012). Lower levels of iron in samples 32 and 38 are most probably the source of the brown color of these two samples. However, under fairly strong reducing conditions a large fraction of the iron (in the presence of sulfate ions originating from natron) is reduced to Fe^{2+} while sulfate ions can become reduced to sulfide ions capable of absorbing Fe^{3+} ions. This process modifies the blue color of the glass to green, olive or brown, depending on relative concentration of the sulfate ions to that of Fe^{2+} (Linden *et al.* 2009). This suggests that the furnace atmosphere and the redox conditions in the melt were properly controlled to obtain selected colors only (Mirti *et al.* 2002). Therefore, the oxidizing atmosphere of the furnace, the sample's low content of iron and the very low content of manganese are the possible reasons of the colourless appearance of some samples.

While some Roman and Umayyad glasses have elevated and slightly elevated manganese oxides, all Byzantine assemblage has very low content of it, suggesting that Byzantine glassmakers did not attempt to decolorize their samples and liked the tints caused by the presence of iron. Samples 6 and 15 show a deliberate addition of manganese oxide (0.49 and 0.95%), more than 0.4% (Sayre 1963, Schibille et al. 2012), but were not enough to decolorize both samples. On the contrary, the elevated concentrations of MnO_2 of sample 5 (1.08%) converted the sample colorless. Other samples (8,11,14,16,19,20) has slightly elevated levels. It seems that high amounts of manganese oxide (>1%) were required to produce colorless glass; therefore, all the above mentioned glasses have tints of yellowish green-blue colors. Decolorizing glass depends on the amount of the decolorant and firing temperature and environment (Jackson 2005).

The highest levels of manganese oxide ($MnO \geq$ 2.0%) present in the Umayyad window samples 30, 31 and 36 produced their purple color. Furthermore, the turquoise window samples (34 and 37) and the Byzantine sample 22 are most probably were colored with high percentages of copper associated with other elements, probably zinc and lead (Jackson 2005).

4. CONCLUSIONS

The absence of production debris, raw glass materials and fuel ash slags at Al-Fudein suggest that the site was not a local secondary production center of glass vessels. The resulting data and archaeological evidence show that the finished glass vessels were probably imported from other secondary production centers rather than formed locally in a glass workshop at the site. Most of the samples are homogeneous in their composition, of green-blue natural colours, and belong to the Levantine I glass. The results agree with Freestone *et al.* (2002a) who labeled most of the Late Roman, Byzantine and Early Islamic glass produced during the AD 4^{th}-8^{th} centuries as "Levantine type I". Al-Fudein glasses present a particular composition of some samples characterized by having higher contents of MgO, K_2O, Fe_2O_3 and MnO_2 and other samples have distinct turquoise and purple colours. Although the natron was widely used as a fluxing agent during the Roman period, plant ash seems to be used during the same period in certain production centers. Of particular interest is the possible identification of three Sasanian glass fragments at Al-Fudein, pointing at the importance of this site for inter-regional trade during the Roman period.

ACKNOWLEDGEMENTS

This research is based upon a thesis submitted for the MA degree at the Department of Archaeology, Yarmouk University by Elham Alama. The research was supported by a grant no. 7/2011 of the Deanship of Research and Graduate Studies at Yarmouk University. We thank the Department of Antiquities of Jordan for their permission to collect the samples. We would like to acknowledge Mr. Ali Al-Omari for the drawings. The authors would also like to thank Prof. Mahmud Wardat for editing the paper and Prof. Julian Henderson and Prof. Thilo Rehren for reading and commenting on the paper.

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