FEVE report

Glass recycling, an activity that continues for millennia

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Abstract

Recycling glass is a topical issue in modern societies all over the world given the continuous increasing consumption and the recyclability of glass. Efficient glass recycling, however, is not a present-day achievement. Historical and archaeological evidence demonstrate that in antiquity glassworkers already collected and reprocessed broken glass into new consumer goods. Nonetheless, a historical study of glass recycling remains complicated as the contextualisation of the archaeological and historical data is not easy to grasp nor to fully understand the economic and social meaning of such finds.

What was the benefit of recycling glass in ancient times? What must have triggered people to recycle glass, assuming they were neither conscious of, nor concerned about the impact of environmental pollution created by pre-industrialized production activities and their substantial waste dumping? Most importantly, why does the recycling of glass in ancient times only occur during the Roman imperial period?

A historical background

Bronze Age

Questions pertaining to where and when exactly glass was invented, or how the invention was developed, remain to this day not fully answered. It is likely that these questions will never be answered accurately even though there is extensive evidence that the ancient Near East is considered to be the cradle of glass craftsmanship and its creation occurred at the start of the Bronze Age, sometime in the 3rd millennium BC. From the 2nd millennium BC, Egypt was the leading player in glass production controlling a major part of the eastern Mediterranean's glass distribution, but leading up to Scandinavia. The socio-economic organization of pharaonic Egypt engendered a system of palace-controlled, highly skilled and diverse glass workmanship supplying the various powers in the eastern Mediterranean, e.g. the Mycenaeans in Greece, the Canaanites on the Syro-Palestinian coast and the Hittites in Turkey.

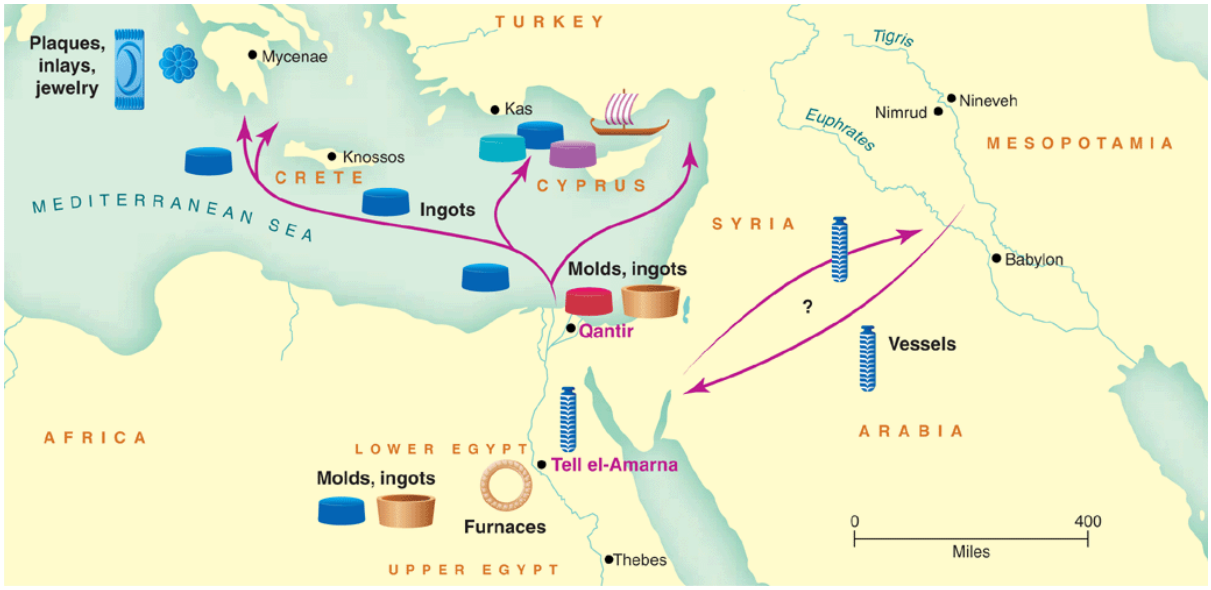

Figure: Map showing glass production and trade around the Mediterranean in the Late Bronze Age (Credit: Preston Huey/Science)

Our current knowledge on the discovery of glass production shows that glass was slowly introduced throughout the Bronze Age in conjunction with several factors: (1) the continuous technological innovations in metallurgy, (2) the increasing knowledge of mineralogy, and, not in the least, (3) the ongoing improvements of skills in all categories of fire-related crafts. As a by-product of other fire-related crafts developing in this period, the introduction of glass production is generally believed to be related to advances in ceramic production and glazed ceramics, in particular. When bearing in mind that the first glass objects were small, simple beads similar in shape, size and colour to glazed ceramic beads, this hypothesis seemed likely, but it is now recognized that the technological innovations connected to metallurgy appear to have contributed more to the elaboration of glass production. While ceramics were already produced from the 7th millennium BC onwards, it is only about 4.000 years later, by the end of the early Bronze Age, that glazed pottery and faience were introduced. This technological advance in clay processing was the result of the developments in metallurgical production techniques. Increased geological and chemical knowledge, in combination with advances in heat control due to improved furnace construction, led to the introduction of copper and bronze smelting. In some cases, this progress in fire craftsmanship most likely caused coincidental production of an almost pure glazed material with nearly no clay core, that we can consider as the creation of glass metal.

Striking too, is that the first glass items produced remained limited for many centuries to plain blue beads and pendants, which remarkably resemble those made of faience. The confusing similarity continues today even among museum collections, but the most eye-catching example comes from the late 14th century BC Ulu Burun shipwreck found near Kaç (Turkey). Part of the cargo of this trading ship sailing from Egypt to supply the eastern Mediterranean market was a huge amount of identical blue beads in glass and faience mixed together in one jar, separately 9.500 glass beads and 75.000 faience beads.

Figure: Reconstruction of the Ulu Burun shipwreck cargo showing the area including the glass ingots (credit: Panegyrics of Granovetter, Bodrum Museum of Underwater Archaeology, Turkey)

It is clear from this large quantity of indistinguishable beads in both materials that, even a millennium after production of the first glass jewellery, glazed ceramic and glass beads not only appeared similar, but were traded and consumed together. Aside from a cargo of finished products, the Ulu Burun shipwreck also shipped approximately half a ton of deep blue glass cakes which were produced in glass workshops in Tell el Amarna (Egypt). Sailing towards the Aegean Sea, these glass cakes were destined to provide the glass workshops established in various Mycenaean palatial towns, although considering the many stops in between Egypt and the Aegean, the ship most likely delivered glass cakes throughout the eastern Mediterranean.

Figure: Glass ingots found in 2014 at the M50.16 site of Tell el-Amarna (Credit: Amarna project funded by Egypt Exploration Society – EES)

Aside from the unavoidable and ubiquitous blue glass, all sort of opaque glass hues such as white, black, red, yellow, turquoise and green were produced by the transition from the Middle to Late Bronze Age (late 17th – early 16th century BC). Concomitantly, the first glass vessels started to be produced by combining very colourful glass hues in garish polychrome ways. To produce these variegated closed vessel shapes, glass was applied around a clay core modelled into a desired shape and size. The impact of applying hot glass on the clay resulted in a porous core that could be removed easily after cooling down. This **core-formed technique** was used exclusively for the production of closed vessel shapes and remained in use for about 1500 years until the technique of glassblowing was invented sometime in the 1st century BC. To make polychrome open vessel shapes, the **fusion technique** was used by fusing glass pieces of various shapes, sizes and colours into a particular design. Sometime after, the **casting technique** was introduced to produce open and closed monochrome vessel shapes. This technique involves the use of a mould, which seems in the beginning to have been made for single use, while moulds for multiple use were introduced in the Hellenistic period to increase the production capacity.

Figure: Ancient Egyptian core-formed glass krateriskos (credit: Brooklyn Museum 37.340E)

Figure: Ancient Egyptian fused glass mosaic dish (credit: Brooklyn Museum 48.162)

Figure: Cast Mycenaean relief beads in blue glass (credit: Metropolitan Museum of Art 23.160.49)

Up to this time, glass production appears to have been controlled by the ruling class based on the location of glass workshops within palatial spaces and also because glass containers functioned as royal gifts to the upper class. Almost exclusively limited to the royal elite, glass consumption remained at a reduced scale during the entire Bronze Age. The collapse of the palatial redistribution economies at the end of the Bronze Age, causing the disappearance of its privileged consumers, reduced glass to a rare product all through the early Iron Age (c.1100-700 BC), which was more or less restricted to the production of simple jewellery such as beads.

Classical times

From the 8th century BC onwards, glass vessel production was reintroduced slowly though it remained an exclusive product within royal contexts until the late Archaic period. With the impact of colonization by Greeks and Phoenicians, the Mediterranean gradually evolved into a monetized trade market in the 6th century BC, engendering a flourishing commerce that gave rise to an expanding upper middle class that could afford expensive exotic perfumes packed in exquisite, elitist core-formed glass vessels. A more democratized consumption of glass perfume bottles by the mid 6th century BC onwards can be assumed from the core-formed glass vessels that are regularly discovered in burials and within ritual contexts throughout the entire Mediterranean world.

Figure: Set of various core-formed glass perfume bottles from late 6th-5th century BC; from left to right: oinochoè, alabastron, amphoriskos, aryballos (credit: British Museum 1862,0530.6; 1868,0501.15; 1878,1230.11; 1878,1230.10)

These ubiquitous scented oil containers remained in use until the end of the Hellenistic period when glassblowing, a more efficient way of producing glass vessels, came into use. By the late Hellenistic period, the entire eastern Mediterranean region gradually fell under the control of the Roman Empire resulting in a booming glass industry. This newly created vast market caused a steadfastly growing demand for glass vessels and hence generated the demand to produce much larger quantities of raw glass. Intensifying primary glass production, made an increased supply of a growing number of secondary glass workshops possible and explains the growing popularity of polychrome core-formed closed vessels and monochrome cast and slumped open vessels during the later 2nd-1st centuries BC. On the other hand, the ever-changing market circumstances and the permanent economic stress implicated with it, pushed secondary glass workshops to be more inventive in quickening the production process. Despite the fact that the workmanship of core-formed vessels appears to have declined through time, this observation should be considered to be an inevitable consequence of maintaining a time-consuming, outdated production technique in response to accelerated demand within an extremely flourishing consumer market. In order to produce vessels faster with less glass, and of a satisfactory quality, new advances in manufacturing glass resulted in the rapid development of glassblowing.

The few archaeological remains of glass working for this period attested thus far, were found as dumps in abandoned buildings, or just outside the city along the walls. This pattern of distribution suggests that production waste was never reused, but was instead straightforwardly discarded, excluding any direct recycling.

Roman period

In line with the previous periods, glass consumption in the Roman world consisted of a production system on two levels, namely primary and secondary glass production. Primary production generated raw glass from the principal ingredients of sand and mineral or vegetal soda, whereas secondary production supplied the market with finished glass products. Aside from the familiar vessels and jewellery, the Romans started to manufacture glass windowpanes in the 1st century AD changing the lighting and insulating properties within buildings.

Because combined production facilities have never been attested, we consider that secondary glass workshops were specialized in the production either of vessels, windowpanes or jewellery. Each functional type necessitated a specific technique and consequently glassworkers with precise technological skills needed particular tools and a suitable installation depending on what their speciality was. The primary glass workshops were essentially situated in the south-eastern Mediterranean, along the Egyptian and the Syro-Palestinian coastline. It is, however, likely that primary glass workshops were active in other areas of the eastern Mediterranean as well as in the west. For instance, in the 1st century AD Pliny the Elder (NH, book 36, 194) mentions already that suitable sand was also quarried at the Volturno River not far from Cumae, Italy, to supply primary glass production, and that similar appropriate sand sources were located in Spain and in France. Although it was the Belus River close to Ptolemaïs, present-day Akko in Israel, that was considered the sand source *par excellence* in early Roman times as can be understood from the descriptions by Pliny the Elder (NH, book 36, 190), Strabo (Geography 16.2.25) and Josephus (Jewish War 2.189-190). Conversely, secondary glass workshops have been attested in high quantities throughout the entire Roman Empire. The discovery of various ancient shipwrecks with shipments of raw glass in mainly the western Mediterranean emphasizes the mass distribution of raw glass from Egypt and the Levant to supply the high number of secondary glass workshops.

The introduction of **glassblowing**, both free-blowing and mould-blowing, opened the possibility to produce vessels of any shape and size, not to mention the ability of producing whatever glass hue was required. Moreover, glassblowing not only hastened the production process of glass objects but also decreased the quantity of glass needed to blow vessels. Because more objects could be made from the same mass of glass compared to the older techniques of casting and core-forming, and less time was needed, the improved production capacity caused a price reduction among glass commodities.

The continually increasing glass production and its inherently coupled glass consumption, also generated a growing mass of discarded broken glass. In urban contexts, in particular, poor people must have seen an opportunity in collecting broken glass. It is very likely that the concentrations of broken glass found in large containers as attested in Pompeii, might have been accumulated by the occupants of houses pending the visit of a hawker. These vendors supplied either intermediate traders or the local secondary glass workshop directly with broken glass that was then used as cullet to lower the melting temperature of the raw glass and accordingly economize on fuel and on working hours. Other material that was used as cullet was the production waste coming from within the workshop itself, such as misshapen objects and moils, knocked-off from the blowing pipe or the punty. Noteworthy, is that Rome already housed an entire neighbourhood of glassworkers, called *vicus vitrarius*, from the 1st century AD which was located between the Aventine and Caelian hills in Regio I.

Written evidence on recycling glass

The first attestations on the recycling of glass in Roman times are essentially restricted to written sources. A number of ancient sources help to better understand when glass recycling was introduced in the Roman world. We can for instance deduce from Pliny the Elder's *Naturalis Historia* —an encyclopaedia he dedicated to emperor Titus in 77 AD— that glass recycling was not yet customary in the Julio-Claudian period (27 BC-68 AD). With his explicit claim that "Heating only causes broken pieces of glass to adhere. They cannot be completely melted again except into distinct drops, as when the little round counters are made which are sometimes called *oculi* (= 'eyeballs'), some of them with various multicoloured patterns." (NH, book 36, 199), we understand that by the start of the Flavian dynasty the knowledge to re-melt broken glass in a batch to produce new vessels was lacking. Glassmakers were familiar only with the fusion technique, which made it possible to reshape fragments into new objects. This application was seemingly exclusively limited to the production of the so-called plano-convex gaming stones or counters.

On the other hand, there is Martial, who wrote epigrams which were collected in 14 books between 85 and 102 AD. Martial referred to glass recycling in an epigram in his first book (1.41.1-5):

Urbanus tibi, Caecili, videris.
Non es, crede mihi. Quid ergo? Verna es,
hoc quod Transtiberinus ambulator
qui pallentia sulphurata fractis
permutat vitreis.

Caecilius, you consider yourself urbane.
Believe me, you are not. What then? A home-born slave,
just like a hawker from Trastevere,
who barters pale sulfur
for broken glass.

Martial indicates that the person Caecilius lived in present-day Trastevere, a district on the other side (west bank) of the river Tiber (Transtiberinus = from across the Tiber) that was known as an undesirable place to live. A contemporary poet, Statius, also mentions the exchange of sulfur for broken glass in his book Silvae (1.76.70-74).

Hoc plaudunt grege Lydiae tumentes,
Illic cymbala tinnulaeque Gades:
Illic agmina confremunt Syrorum,
Hic plebs scenica quique comminutis
permutant vitreis gregale sulphur.

Here are clapping a bunch of disposed Lydian (girls),
there cymbals and bells from Cadiz,
there Syrian crowds raise a shout,
here are plebeians from the theater and those who
exchange sulfur for broken glass.

These references to glass collecting in early Roman poetry imply that glass recycling had become common by the late 1st century AD. Hence, we can conclude that from Flavian times onwards, when glass became a ubiquitous consumer good, written sources indicate the beneficial practise of organized collecting of broken glass from dwellers in large cities to supply secondary glass workshop with cheap, second-hand raw material. It is clear from the written sources that systematic glass collecting arose in an environment where glass started to circulate abundantly. People from the lowest rank of Roman society found a way to earn money to survive, or to improve their living, by supplying intermediate merchants and local secondary glass workshops with broken glass. Hence, in Roman imperial society recycling glass was purely socio-economically driven.

Archaeological evidence for recycling glass

The archaeological evidence of reprocessing broken glass in a successful recycling economy, such as the Roman Empire, is much more difficult to recognize and remains limited because recycled glass material mingles together in the crucible. It is common knowledge that glass is brittle and can break easily into smaller pieces, and that this glass waste could be collected and re-melted to produce new objects. However, the few archaeological examples concur with the written sources and demonstrate that broken glass (cullet) underwent a complex pathway from consumer to glass workshop in ancient times.

The large amounts of broken glass in the house of the Indian statuette (I. 8, 5) in Pompeii and the villa of Pisanella near Boscoreale are considered to be accumulations awaiting the hawker to pass by, but the catastrophic eruption of Vesuvius in 79 AD prevented this ephemeral activity of gathering glass to be recycled from taking place.

Other evidence comes more than a century later, from the shipwreck Iulia Felix that sunk in the early 3rd century AD in the Adriatic Sea, close to the North Italian coast near the town of Grado. The ship contained over 600 Greek and North African amphoras filled with wine and olive oil, but there was also a wooden cask enclosing 140 kg of broken glass. Considering the ship's load, the location where the ship sank and the prevailing sea currents, the ship must have come via the Ionian Sea to enter the Adriatic Sea, sailing north along the eastern coastline to end up not far from Aquileia. Most likely this barrel full of cullet was meant to supply a secondary glass workshop in Aquileia. As noted above, cullet is useful in secondary glass workshops as adding cullet to the batch lowered the melting temperature of the raw glass which consequently decreased the heating time and reduced the necessary fuel.

Figure: Remains of the late 2nd century AD Iulia Felix shipwreck (credit: "Operazione Iulia Felix: dal mare al Museo. Lo scavo, il recupero e il progetto di musealizzazione della nave romana rinvenuta al largo di Grado", Edizioni della laguna. Monfalcone, 1999)

A much later example comes from the Serçe Limanı wreck, a late Byzantine merchant ship of the early 11th century AD that was excavated by the Institute of Nautical Archaeology and Texas A&M University in the late 1970s. The small two-masted vessel had a glass cargo that consisted of two tons of raw glass broken into chunks and one ton of broken glassware and production waste from an Islamic glass factory on the Fatimid Syrian coast. The ship sailed from the coast of present-day southern Lebanon or northern Israel to supply secondary glass workshops in the Aegean Sea, and most likely the Byzantine capital Constantinople, but was wrecked at Serçe Limanı on the southern coast of Turkey opposite Rhodes. This Byzantine wreck demonstrates the continuation of the bulk trade and intensive distribution of fresh glass in the eastern Mediterranean throughout the Medieval period, while in western Europe glass was reduced to a rare and exclusive commodity by reprocessing old glass from dismantled Roman buildings.

Archaeometric evidence on recycling glass

It is said that glass made from cullet results in a bubbly glass and that recycled colourless glass generally shows a bluish or greenish tinge due to the presence of minor concentrations of colouring agents. In other words, the presence of various oxides can be used as indicator for recycled glass. It remains, however, impossible to recognize recycled glass decisively with the naked eye. Therefore, the most efficient method to distinguish new glass from recycled glass is by means of various scientific analysis techniques which have proven to be useful tools to define the chemical composition of the glass. The occurrence of certain trace elements in the glass metal needs, however, to be considered with care. For instance, elevated concentrations of Cu, Co, Pb and Zn

in decolorized glass —commonly perceived as evidence of recycled glass— could equally be related to specific Mn ores.
Another, presently topical, marker defining glass recycling is the simultaneous presence of antimony and manganese oxides in colourless glass. Both oxides were used in Roman times to decolorize the glass by neutralizing the refraction of light due to the presence of iron oxide in the glass matrix. Because there is presently no evidence of primary glass production where antimony and manganese were added together to the batch, the mixed amount of Mn and Sb in glass is generally considered to be a mixture of specific Mn-decolorized, and Sb-decolorized glass.
Continuing progress in understanding the quantitative data from chemical analyses resulted in the recognition of the importance of ratios of certain trace elements and how they are related to specific sands, such as the Sr/Ca ratio, which can reveal the origin of the sand sources. Therefore, identifying the provenance of ancient raw glass types is essential to characterize recycled glass and the degree of recycling. This research is still a work in progress, but some studies have already indicated that Ti, Cr, Sr, Zr and Ba are useful trace elements to help categorize the different sand sources exploited in antiquity.

For late Bronze Age blue glass, two provenances have not only been attested on the basis of different sands used but more specifically on distinctive colouring agents added to the glass batch. The deep blue glass beads in Mycenaean Greece have been determined to be of either Egyptian or Mesopotamian origin. However, a number showing an intermediate composition can be understood as evidence of mixing Egyptian and Mesopotamian glass in Mycenaean glass workshops. It remains unclear whether these pieces can be considered as the earliest confirmation of glass recycling. Given that the late Bronze Age shipwreck of Ulu Burun yielded glass cakes of both Mesopotamian and Egyptian origin, it cannot be ruled out that an arranged mixing was applied by the Mycenaean glassworkers in palatial workshops before the initial objects were made. Recent research, however, proposes that Mesopotamian glass reached Egyptian glass workshops where it was coloured deep blue with an Egyptian cobalt-copper colorant in order to make beads for trade towards Romania and up to northern Germany and Denmark.

By the mid 1st millennium BC, natron glass was established as the standard glass type in the Mediterranean and Europe, however, plant ash glass never disappeared. Despite the fact that this soda glass is more suitable for recycling at lower temperatures, the widespread practice of recycling did not begin until after the compulsory change in furnace technology emerged with the invention of glassblowing in the late 1st century BC. Most likely early furnace technology was not able to reach the required high temperatures to re-melt broken glass. Hence, the introduction of a horizontal heating chamber furnace not only enabled suitable conditions for glassblowing, but also provided the opportunity to re-melt broken glass, thus creating the opening for recycling glass in a more organized way from the Roman imperial period onwards.
When looking at the glass cullet from the late 2nd-early 3rd century AD Iulia Felix shipwreck, the statistical data from chemical analyses demonstrate that the decolourized glasses were the result of two different production technologies. This conclusion was made possible by comparing the ratios of the trace elements Sr, Zr and Ba suggesting the use of two different beach sands (with different amounts of alkali feldspars). Hence, abnormally elevated levels of certain transition metals in archaeological glasses can be interpreted as indicators of the mixing and/or recycling of different glasses.

From the Price Edict of Diocletian (c.304 AD) we know of the so-called Alexandrian glass from Egypt and the so-called Judean glass from the southern Levant, but also of the division between raw glass and window glass. Because the windowpanes were considerably lower in price than new raw glass, the idea arose to interpret the given price for windowpanes as broken window sheets, or in other words, cullet. This theory suggests that in the late Roman period the secondary glass workshops could be supplied with raw glass or cullet from either Egypt or the southern Levant.
From the 5th century AD onwards trade dropped significantly between western Europe and the eastern Mediterranean because of incursions during the Migration Period, making the supply of fresh glass diminish dramatically. New archaeological evidence from the last two decades show that abandoned Roman buildings were systematically dismantled to reuse all available useful material, and particularly all recyclable materials.

Conclusion

From the discussion above, it is clear that part of the complexity surrounding glass recycling in antiquity stems in the first place from defining exactly what is meant by glass recycling.
First, the most elementary form of recycling glass has to be excluded here, i.e. when an object is given a new function different from the intended function it was made for. The possibility of residual use should always be kept in mind, but when deposited in a tomb as burial gift, an older glass item could have been an heirloom that was cherished by the deceased, or simply given a final new function because the object was partly broken or was no longer considered useful. In this way, older glass items were not always present as heirlooms in later burial contexts, but could also have been given a different meaning and use. Many everyday glass storage vessels of the 1st-2nd centuries AD, such as ribbed jars, and square or cylindrical bottles ended up as funerary urns, used to contain the cremated remains of the deceased.

If the definition of glass recycling is limited to the re-melting of glass in order to make new objects, then glass was already being recycled from the Late Bronze Age onwards. However, this kind of glass recycling is not based on the organized collection of broken glass, but rather a reuse of available glass objects for a variety of reasons such as a loss of value, or if an item was considered offensive or taboo because of changed social and/or religious customs. A comparable kind of recycling occurred during late Antiquity and not solely restricted to glass. The aversion of the early Christians towards pagan art that was considered immoral and corrupt provided ready access to large quantities of unused glass material that could be reprocessed, such as glass tesserae and windowpanes.

When considering a definition of glass recycling as an organized process, based on the intentional collection of broken glass to supply glass workshops, it can be argued that glass recycling was introduced in the proto-industrialized Roman economy of the imperial period. However, glass was not systematically recycled in all parts of the Roman Empire, nor was it recycled to the same extent. The practice disappeared in the west with the disintegration of the western Roman Empire, though from the 4th century AD this systematic glass recycling activity slowly changed into the deliberate reprocessing of pagan material before disappearing in the late Middle Ages. In the east, this systematized glass recycling activity remained in use up to at least the 11th century AD as revealed by the cargo of the Serçe Limanı shipwreck.

From the invention of glass, the status of this brittle and shiny material underwent an evolution in different ancient societies. Glass was formerly an exclusive material mastered by the elite and royals, but through the ages, glass gradually evolved from a rare object for the privileged classes to more ubiquitous items for the common people. It would seem therefore that the organization of glass recycling during the Roman imperial period was the closest to our present system of glass recycling with the difference being that the Romans were totally uninterested in the ecological aspects that trigger the present-day global society.

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