A GLIMPSE INTO THE ORIGINS OF ROMAN CONCRETE DOMES

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Abstract

Structures have been covered with concrete domes for ages. Before building concrete domes, corbelling was developed gradually during the Roman Empire. This technique was crucial for building arches and vaults. Domes appeared significantly thanks to arch and vault architecture. However, corbelled domes were insufficient for large spans. Also, lime mortar or adobe was not durable against moisture. Although timber provided a large span, it was vulnerable to fire and fungi. Romans solved those problems by inventing concrete domes. Pozzolana was one of the more important raw materials; it played an essential role in this innovation. Consequently, typology and technique used in concrete domes spread all over the Mediterranean basin. So, this development was a quick response to the needs of ancient societies. These concrete domes were very common from the first century BCE until the end of the first half of the second century CE. Although there are comprehensive studies on domes, the origins and evolution of concrete domes were not researched thoroughly by scholars until very recently. In this article, we will focus on the origin of concrete domes and the origin of the dome architecture to understand the appearance of concrete domes. In conclusion, based on the available archaeological data, we can discern that the construction of concrete domes emerged after that of arch and vault structures. The Roman concrete (opus caementicium) produced using the available supply of pozzolan allowed the construction of concrete domes to become widespread, like this providing a practical solution to the needs of society.

Keywords: Dome, Vault, Pozzolana, Concrete, Opus Caementicium.

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ROMA BETON KUBBELERİNİN ORTAYA ÇIKIŞ SÜRECİ ÜZERİNE BİR DEĞERLENDİRME

Öz

Beton kubbeler yapı mimarisinde asırlardır kullanılagelmiştir. Bunun yanı sıra beton kubbe inşalarından önce bindirme tekniği Roma İmparatorluk Dönemi'nde kademeli olarak gelişmiştir. Bu teknik kemer ve tonozların inşasında uygulanmıştır. Kemer ve tonoz mimarileri sayesinde ise beton olmayan kubbeler inşa edilebilmiştir. Ancak bindirme tekniği ile inşa edilmiş bu tip kubbelerde kiriş açıklıkları oldukça sınırlı kalmıştır. Ayrıca beton olmayan kubbelerde kullanılmış kireç harcı, kerpiç gibi malzemeler de neme karşı dayanıksızdır. Kereste kullanımından dolayı geniş kirişleri olan ahşap kubbeler ise yangın ve mantara karşı savunmasızdır. Bu tip problemler Romalılar tarafından geliştirilen beton kubbeler sayesinde çözülmüştür. Puzolan, beton kubbe inşasında kullanılan bir hammadde olarak önemli gelişmelere neden olmuştur. Sonrasında beton kubbelerdeki tipolojik ve teknik gelişimler antik toplumların ihtiyaçlarını karşılayacak şekilde kısa sürede tüm Akdeniz Havzası'na yayılmıştır. Bahsi geçen beton kubbeler MÖ birinci yüzyıl ile MS ikinci yüzyılın ilk yarısı sonları arasında oldukça yaygın olarak kullanılmıştır. Kubbeler üzerine çeşitli çalışmaların olmasına rağmen beton kubbelerin kökeni ve gelişimleri üzerine güncel bir araştırma mevcut değildir. Bu makalede beton kubbelerin ortaya çıkış sürecine dair bir değerlendirme yapılacaktır. Bu sürecin detaylıca anlaşılabilmesi için beton öncesi kubbe mimari tarihine de kısaca değinmek gerekir. Sonuç olarak beton kubbe mimarilerinin kemer ve tonoz yapılar sonrasında ortaya çıktığı anlaşılmıştır. Puzolan tedariki ile elde edilen Roma betonu (opus caementicium) beton kubbe inşasının yaygınlaşmasına neden olarak toplumsal gereksinimlere pratik bir çözüm sunmuştur.

Anahtar Kelimeler: Kubbe, Tonoz, Puzolan, Beton, Opus Caementicium.

Introduction

Since the settlement is one of the essential things in human history, different kinds of structures have been developed by people in line with their needs since the beginning of the Neolithic Revolution. Domes are one of the roofing systems of these structures erected and developed by Romans. At the beginning of this article, the key elements of dome architecture will be shown. To understand the development of domes over time, the historical process of the development of arches and vaults should be conducted. Next, the geographical expansion of the raw material, pozzolan, comes to the fore to understand the locations of the structures all over ancient Rome. Pozzolan is an indispensable material for constructing domes using *opus caementicium*, and it provided the development of the dome's design and functionality. Although previous studies have been conducted on Roman concrete domes, their origins and evolution have not been researched efficiently (see Rasch, 1985). This is the main aim of this study. Lastly, the author concludes how the social need of people caused different kinds of constructions of concrete domes and how the raw material helped the development and design of the domes.

Archaeological data shows that the development of true arches, vaults, and domes are successive processes. But these three architectural elements were only developed by using corbels (Cowan, 1977, p. 1). One of the earliest uses of corbels dates back to the Tall Halaf period (5900-5300 BCE) in Tall Arpachiyah (Mallowan & Rose, 1935, pp. 30-31). Other earliest known examples in the period of the 4th and 3rd millennia BCE belong to the underground domed tombs of the Royal Cemetery of Ur (Wooley, 1934, pp. 228-237; Mallowan & Rose, 1935, pp. 31). Generally, stones were used for the construction of those tombs. With the development of corbels, vault architecture became more common. Afterwards, the vault's construction has spread from Sumerian cities to Mesopotamia. The Tomb of Ka'a is known as one of the earliest uses of the leaning barrel vault at the Necropolis of Sakkara in Egypt (Emery, 1958, p. 98). This tomb was built in the early 3rd millennium BCE and is concurrent with the ones in Ur. There are also other early examples from Egypt. In Dahshur, corbelled chambers were built in Bent Pyramid and Red Pyramid in the Old Kingdom era. Both structures belong to Dynasty IV, and they date around 2600 BCE (Zupančič, 2010; Nuzzolo, 2015). Bricks, plaster, wood, sand, and gravel were the most common materials used for the construction.

Vault architecture is considered the first stage of dome construction (Tunca & Rutten, 2009, p. 33). Vaulted tombs of Tall Chagar Bazar were constructed with corbels out of clay bricks. Like contemporary Babylonian examples, they built underground houses dated to the early 2nd millennium BCE (Mallowan, 1937, p. 107). Then, the use of vaults reached Anatolia in the 16th century BCE. The earliest examples of such burials were built in the grain silo complexes of Hattusa. Those structures dating from the 16th to early 15th centuries BCE (Seeher, 2006, p. 74). Unlike the use of stone in the grain silo complexes of Hattusa, bricks were used as material for constructing vaults in an Assyrian tomb dated between the 14th-13th centuries BCE (Feldman, 2006, p. 22).

The vault was also used for defence purposes except for tomb or storage architecture. The postern at the city wall of Ugarit is one of the earliest examples of vault architecture for defence purposes. The corbeled, vaulted postern gate served as a passageway dated between the 15th-14th centuries BCE (Yon, 2006, p. 31). Another vaulted corridor built for defence purposes belongs to Yerkapı Rampart in Hattusa. It is 71 meters long and 3-3,3 m high, dated to the 13th century BCE and designed like a tunnel (Nossov, 2008, p. 28). The corbelled masonry is made of successive courses of stone blocks.

Those stone blocks project inward, forming vaults that end with a wedge-shaped keystone. Similar to Hittite corbels, structures can also be seen in Mycenaean architecture. Those corbelled vaults in Tiryns are dated to 1300-1190 BCE, namely to the LH IIIB period (Maner, 2013, p. 421).

Corbelled remains of residential architecture are known from the period of Nebuchadnezzar II (605-562 BCE) at the Southern Citadel in Babylon. It has been written that no other vaulted residence remains have been found yet in Mesopotamia that can be dated before the period of Nebuchadnezzar II (Koldewey, 1914, p. 94). However, as an iconographic architectural reflection, some structures with domes have been depicted on a relief dating to the period of Assyrian King Sennacherib (705-681 BCE) (Paterson, 1913). Additionally, it has been known that the oldest corbel remains of residential architecture belong to Dynasty XII (1991-1803 BCE) from Egypt (Petrie, 1890, p. 23).

Corbelled architecture and domed structures continued to develop in Mesopotamia. The effect of this process reached the Aegean islands and the Greek mainland in the Bronze Age. Early Cycladic vaulted graves were built with corbels. As can be seen with examples from Sire, tombs dated around 2300 BCE consist of a pit lined with stones and roofed with a corbelled structure (Palyvou, 2009, p. 41). In the Bronze Age, vaulted graves are also known from Messara Plain in Crete. Minoan vaulted tombs named *tholoi* from Messara can be compared with Egyptian corbelled structures (Xanthoudides, 1924, p. 128). Because Minoan *tholoi* affected Mycenean architecture, there are Mycenean *tholos* graves dating to 1500-1300 BCE. *Tholos* graves were spread over the Greek mainland, constructed on slopes with stone blocks in beehive form. Grave chambers named *thalamos* were circular and were roofed with corbelled domes (Maravelia, 2002, p. 65).

In the Middle Bronze Age (1700-1365 BCE), some megalithic structures called Nuraghi were built throughout Sardinia. Those structures, including stone towers and giant tombs, were constructed with false-corbeled or true-corbeled chambers. In the Late Bronze Age (1365-1200 BCE), many built *ex novo* using new construction techniques (Holt, 2015, pp. 193-194). They are generally in conical form, and no mortar has been used for their construction. Masonry, which forms the vault, was arranged in line with stability and balance. In terms of building technique, *tholos* graves of Mycenae resemble Nuraghi towers. However, unlike Mycenean tombs erected inside a tumulus, Nuraghi towers rise entirely above ground level (Melis, 2003, pp. 12-13).

If we look at the Iron Age, we see pseudo-domes were built as *tholos* tombs between the 9th-8th centuries BCE in Etruria. Phrygian tombs could have been the model for Etruscan tombs. At the first millennium BCE, the tumulus was a new concept in the eastern Mediterranean basin. Nevertheless, it is impossible to directly compare Phrygian and Etruscan tombs (Cygielman, 2009, p. 53). In masonry, Romans were influenced by Etruscans in the 7th century BCE. Cisterns near the House of Livia at the Palatine Hill and the lower section of so-called the Tullianum (the Mamertine Prison) at Forum Romanum can be shown as the earliest dome examples of Etruscan architectural effects (Boëthius & Ward-Perkins, 1970, p. 80). However, this influence wasn't enough for the beginning of concrete domes. Romans had to wait six more centuries for the invention of concrete domes. In this period, they developed arch and vault architecture.

Background, Design, and Functionality

Adam (1994, pp. 328-329) listed the earliest architecture examples of Roman arches. After the second half of the second century BCE, Romans started to build concrete domes. Pozzolana, volcanic ash, was the main component of early Roman concrete. The earliest concrete domes were constructed in the Campanian Plain (Figure 1). For example, at the Stabian Baths of Pompeii, a conical concrete dome survived as one of the oldest examples of its type. The dome built at frigidarium is around 6 meters in diameter and dates to 120 BCE (Melaragno, 1991, p. 27). In addition to the conical dome, barrel vaults were also built at Stabian Baths (Eschebach, 1979, p. 66; Rasch, 1985, p. 117). Like the conical dome on the frigidarium of Stabian Baths, the same type of dome was built on the frigidarium of the Villa of the Mysteries in Pompeii. This dome is 1,56 meters in diameter and is of the same period. Its section consists of bricks and surfaces plastered with Roman mortar (Rasch, 1985, pp. 118-122).

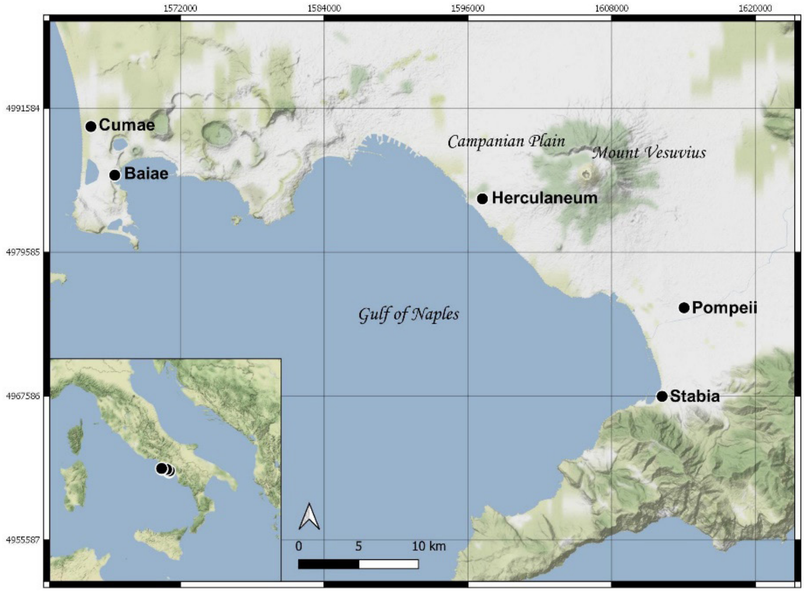

Fig. 1. Map of the Volcanic Areas in the Campanian Plain and the Roman settlements where the first concrete domes were seen. Map prepared by the author (QGIS 3.10).

Parallel to the development of dome architecture, original roof forms started to take shape. The term tent-roof (Zeltdach) suggested the upper part of a round temple dated at the beginning of the first century BCE in Tivoli (Delbrueck, 1912, pp. 11-22). This so-called "Vesta Temple" has been shown with a dome in mannerist architect Sebastiano Serlio's drawings (Serlio 3:4:11). The upper part of the temple has been shown in a tent-roof style on some reliefs and coins from the Roman period. However, Serlio lived between 1475-1554 and he drew the dome with an oculus. So, the temple might have more than one construction phase during that time.

Dome architecture continues to appear around in the middle of the first century BCE at the Forum Baths of Pompeii. The laconicum section of the bath has a dome and the section had been rebuilt as a frigidarium in 60/50 BCE (Eschebach, 1991, p. 272). The plan of the frigidarium in the Winter Palace of Herod (37-34 BCE) is similar to the frigidarium at the Forum Baths of Pompeii (Brödner, 1983, p. 53). In all probability, the frigidarium of the Winter Palace of Herod also had a similar concrete dome. The frigidarium section of the Central Baths (or the Forum Baths) at Herculaneum has a similar round plan like the frigidarium at the Forum Baths of Pompeii and the frigidarium of the Winter Palace of Herod. The frigidarium of the Central Baths at Herculaneum dates to

30-10 BCE and has some sea creatures depicted on the wall of its dome (Deiss, 1966, pp. 112-117).

Cowan (1977, p. 2) claimed that at the time of Augustus (27 BCE-14 CE) builders were not confident about concrete, because of the common use of concealed voussoirs as back-up reinforcement. However, using concrete became the decisive fact for building domes after the last quarter of the second century BCE. Roman concrete prepared with hydraulic mortar, which consists of the material of pozzolana volcanic ash. Domes made with Roman concrete could be built with larger spans. Therefore, constructing huge arches and domes by Romans in the imperial period was quite possible (Platner, 1911, p. 24). For example, the concrete dome of a bath on the east shore of Lake Avernus had a diameter of 36,2 meters (Clark, 1996, p. 227). This bath from the Augustus period was wrongly described in the literature as the Apollo Temple, however, there was a temple with a concrete dome called the Temple of Mercury (Figure 2), which was built at the end of the first century BCE in Baiae (Rasch, 1985, p. 118).

Fig. 2. The Temple of Mercury (https://goo.gl/maps/sWGaEF519oexD5fe8).

The first rotunda with a dome built in the first century CE at the Baths of Agrippa in Rome (Wulf-Rheidt, 2012). This rotunda's function was considered to be a "waiting or chatting room" by Huelsen (1910, pp. 26-28). During this period, a rounded laconicum was built at the Central Bath of Pompeii a few years before the eruption of Vesuvius in 79 CE (Krencker et al., 1929, p. 256; Kraus and Leonard, 1973, p. 31). This round planned laconicum has four niches and a concrete dome over it (Mau, 1908, p. 215). There is another laconicum dated to the Julio-Claudian period at the Suburban Baths in Herculaneum which is similar to the laconicum at the Central Bath of Pompeii (Pappalardo, 1999, pp. 211-213). Laconicum sections of baths that were constructed between the first century BCE and the first century CE are similar in terms of the architectural design. Vitruvius described architectural features of the laconicum (Vitr. De arch. V.X.5):

> The Laconicum and other sweating baths must adjoin the tepid room, and their height to the bottom of the curved dome should be equal to their width. Let an aperture be left in the middle of the dome with a bronze disc hanging from it by chains. By raising and lowering it, the temperature of the sweating bath can be regulated. The chamber itself ought, as it seems, to be circular, so that the force of the fire and heat may spread evenly from the center all-round the circumference.

From the first half of the first century CE, the construction of octagonal buildings with domes had been started. The Octagon Suite in Domus Aurea (Figure 3) dated to the reign of Nero (54-68) has a dome defined by eight slender piers in its corners (Ball, 2003, p. 209). Piers or buttresses were used to absorb the hoop tension (Cowan, 1977, p. 4). The dome of the Octagon Suite also had an oculus aperture on top. The suite's dimensions and oculus were designed to consider astronomical data and therefore the building was positioned in the direction of the north-south meridian (Hannah, 2009, p. 4). Another octagonal building was constructed at the Baths of Nero in Pisa. The building was defined as a sudatio and its upper part designed as a pavilion vault (Campus, 2016, p. 1; Fabiani et al., 2018, p. 8). A similar octagonal structure, Domus Augustana, was built during the Domitian reign (81-96) by architect Rabirius (Richardson, 1992, p. 115). Its dome design is called a monastery vault (Rasch, 1985, p. 119). Monastery and pavilion vaults have similar designs. Following octagon planned buildings, the domes with pendentives over square buildings were developed in the second century CE. The monumental tomb named c70 Casal de'Pazzi (Sedia del Diavolo) in Via Nomentana is one of the earliest examples of a dome with pendentives on a square building. The dome is 4 meters in diameter (Gallina, 2011, p. 15).

Fig. 3. The Octagon Suite in Domus Aurea (https://goo.gl/maps/EP3UeMxBgK4GUvX9A).

The use of concrete Roman domes was spread all over the empire in a short period. During this period, the dome of the laconicum at the Capito Thermae in Miletus was constructed by using *opus caementicium* in the first century CE and is 9 meters in diameter (Tuchelt, 1974, p. 149; Rasch, 1985, p. 125).

Concrete domes become more noticeable from the beginning of the second century CE. Baths of Trajan, which were completed in 109 CE, is a clear example of this period (Anderson, 1985, p. 505). Structural features like coffered slabs of domes of the Baths of Trajan are similar to those of the Pantheon (Hetland, 2009, p. 115). The Baths of Trajan include sections with half domes that appeared to have been libraries (Bennett, 2005, p. 153). However, as a symbol of revolutionary Roman architecture, the Pantheon has a huge concrete true dome which is a unique structure (Figure 4). It was built under Hadrian's rule and was completed between 118-128 (Mark & Hutchinson, 1986, p. 24). The concrete dome is 44 meters in diameter. The coffered slabs consist of 12 vertical and five horizontal ribs (Altın, 2001, pp. 198-199). To reflect light, perhaps metal plates were inserted into coffers that are divided with ribs (Heilmeyer, 1990, p. 108). The oculus on the top of the dome is nine meters in diameter. The light that comes from this oculus is the same as the cyclical movement of the light on a sundial. According to Hannah (2009, p. 5), we should consider its function as a timekeeper for certain periods of the year. To reduce its concrete dome weight, the upper part of the dome was built with alternate layers of tufa and pumice (Cowan, 1977, p. 2).

Fig. 4. Pantheon (https://goo.gl/maps/G4aMMsKf1D71gPtMA).

Except for the Pantheon, the development of domes shows diversity in the period of Hadrian. Other buildings with domes were built in the complex of Hadrian's Villa at Tivoli. Those buildings are known as Serapeum, Temple of Apollo, Roccabruna, Hall of the Philosophers, Heliocaminus Baths, Northern Entrance to the Golden Square, etc. The Venus Temple of Baiae was also built in this period. Although the outer plan of Venus Temple in Baiae is an octagon, its inner plan is circular. Most of the 26,3-meter diameter dome has since collapsed. Another building from Baiae the so-called Diana Temple was constructed with a dome which was 29,5 meters in diameter. The dome was designed with an ogival profile (Adam, 1994, p. 387).

During the second century, some smaller domes were not made of concrete. Corbelled vaults and domes in the western bath complex from Gerasa are examples. The diameters of these domes vary between eight and 15 meters. Overlapping wedge-shaped stones were constructed without concrete (Rasch, 1985, p. 126).

The half-dome of Serapeum in Tivoli is 22 meters in diameter (half the diameter of the dome of Pantheon). This design of the vault, named "melon", is not a true dome as its vaults consist of nine radiating segments in a convex curve or flat sections (Tuck, 2015, p. 223). Although it is a half dome, it was built with concrete. Besides, the term of pumpkin vault would fit better grammatically instead of melon vault here because of the dialogue between the emperor Hadrian and the architect Apollodorus of Damascus (Cass. Dio, Hist. rom. 69:4:2); Hadrian dismissively told him, "Go away and draw your pumpkins" (ἄπελθε καὶ τὰς κολοκύντας γράφε).

The function of the oculus of the Temple of Apollo and Roccabruna at Hadrian's Villa was similar to Pantheon's oculus. The light from outside was important. This function might be more important for some astronomical or historical events, such as solstices, equinoxes, the *dies imperii* (11 August), or the *dies natalis* of Rome (21 April) and so on (Franceschini, 2013).

Another structure with domes from the period of Hadrian was built in Pergamon. Round towers of the Red Hall have two concrete domes, each 12 meters in diameter. Each dome has own oculus and was built with *opus caementicium* in a hemispheric form (Bachmann & Steiner, 2013, p. 595). It has been thought that Hadrian's travels impressed him so much and gave him a new architectural perspective. The new style was more Roman and less Greek. He transformed buildings and spaces and according to geometrical order. They must have been domed (Moore, 1960, p. 18). Hadrian's Villa in Tivoli was the most prominent place for this transformation. Dome architecture in the period of Hadrian also might have been influenced by Greek philosophy. Geometric and cosmological properties of the space refer to the universal mechanism of the Stoics, the numbers of Pythagoreans and the harmony of the Platonic spheres (Nicoletta & Virgili, 2016, p. 253). A comparison between the ideal model and the survey model of the dome of the Pantheon might show this influence (Aliberti, Canciani, & Rodriguéz, 2015). The Pantheon became a model for dome construction. Domes at the Asklepieion of Pergamon were imitations of the monumental dome of the Pantheon in Rome (Riethmüller, 2014, p. 503). For the construction of the round Temple of Zeus-Asklepios in the Asklepieion of Pergamon, L. Cuspius Pactumeius Rafinus was selected as a consul in 142 (Halfmann, 2004, p. 523). The temple had a dome 25 meters in diameter and light and rainwater came through the oculus (Radt, 1988, p. 260). Also, the concave surface of the dome was covered by splendid mosaics. According to Deubner (1938, p. 54), we can only compare its splendor with the Pantheon. A Healing Building was also constructed to the south of the Temple of Zeus-Asklepios. The Healing Building dated to the second half of the second century CE and it had a concrete dome 27 meters in diameter built on 8 pillars (Ziegenaus et al., 1968; Friese, 2006, p. 6).

After the second half of the second century CE, oculus apertures built not just for supplying rainwater or astronomical purposes, but also simple functions like getting sunlight. For example, the Baths of Antoninus in Carthage built between 145-162, have oculus apertures with glass windows on its domes which they designed to provide sunlight inside (Lézine, 1968, p. 25).

To sum up, the corbelled vault that has been used by architects from the beginning of the sixth millennium BCE, became the core element of dome architecture. Corbelled vaults were used to construct graves, city walls and buildings. Later, the corbelling technique spread from Mesopotamia to the Mediterranean basin. Concrete domes didn't appear until the second half of the second century BCE. Before concrete domes, corbel vaults and arch constructions were also processed in the Italian peninsula. Romans mixed different materials into their mortar and noticed that a material called pozzolana was more resistant to lime. The mortar with pozzolana or *opus caementicium* was an innovation in Roman architecture. So, Romans were able to build concrete domes by using *opus caementicium*. Usually, the first examples of concrete domes appeared in Herculaneum, Pompeii, Stabiae, and Baiae near Mount Vesuvius. Because of the geography of western Italy, volcanic materials were accessible for the preparation of *opus caementicium*. The first concrete domes were built in the baths, especially to cover laconicum sections. After a while, domes were developed with monastery vault or pendentives. Those forms determined the plan of the building, such as rotunda, square or octagon. Then, in a short period, domes were built not only for baths but also for temples, libraries, halls, and healing buildings. Concrete dome architecture increased in Tivoli in Hadrian's period. Oculus was an important feature of the dome. It had been used for astronomical purposes or heat balancing. However, after the second half of the second century, oculus became more of a design element rather than a practical feature. Oculus as a window form on the domes of the Baths of Antoninus in Carthage and can be shown as evidence of this transformation.

Material and Technique

Concrete domes developed in a short period and their styles became quite diverse. Because of this diversity, these domes became popular. This popularity caused economical and technical developments (MacDonald, 1982, p. 166). Technical developments were influenced by geographical location. Raw materials were extracted from volcanic areas like Vulsini, Cimini, Sebatini, Colli Albani, Roccamofina, Campi Flegrei and Vesuvio in western Italy. Tufa, a porous volcanic rock was used for construction. For constructing walls, ashlars were made with heavy tufa. Vaults were built with light tufa. However, the mortar was prepared with the volcanic ash called pozzolana. Lightness was a big advantage for Romans in this case and therefore they were able to construct wider domes. Consequently, large and pillarless interior spaces developed as well. Concrete domes had been built first in baths with a smaller diameter. Later, they were constructed on other building types but with a wider diameter. As domes were becoming wider, their forms became diversified. So, this process which was shaped by architectural development reduced the need for large spaces. So, large spaces under concrete domes were the result of technical development. Normally wooden beams can span much farther than stone beams. However, concrete domes were preferred more than timber, not just because of lightness, but because timber is vulnerable to fungi, insects and fire (Cowan, 1977, p. 1).

Auxiliary construction materials, such as limestone, travertine, clay, and timber were available from central Italy. Tufa was the primary element for constructing concrete domes. The most common type of tufa, *tufo lionato* (1,600 kg/m³), was available in the western region of central Italy. *Tufo lionato* is also known as *Aniene tufa*. This type used for preparing caementa is reddish-brown. *Tufo giallo della via Tiberina* (1,350 kg/m³) as another type of tufa was used less. This yellow tufa was valuable because of its light weight. *Tufo giallo della via Tiberina* was the same weight as another tufa called *Tufo rosso a scorie nere* (also called Fidenae tufa) or black pumice. Additionally, heavier types of tufa were also used for construction. These types are known as *lapis Albanus* and *lapis Gabinus* (2,250 kg/m³) and they were available at the rims of volcanic craters. Although they were heavier than other types of tufa, *lapis Albanus* and *lapis Gabinus* were used for constructions of vaults. *Selce* (2,800 kg/m³), which is an extremely hard lava type was rarely used for vaulting. This type was used primarily for road building or for *caementa* in foundation walls (Lancaster, 2005, p. 16).

Except for tufa, another raw material was used in *caementa* for vaulting. This vesicular scoria called pumice and it was available from Vesuvius on the Bay of Naples. This material is often referred to as pumice in the archaeological literature but it is somewhat coarser and heavier (750-850 kg/m³) than true pumice (600-700 kg/m³) (Lancaster, 2005, p. 16). Although it's commonly reddish to dark brown, some of them can also be white, yellow, gray or black.

Opus caementicium was made with mixing pozzolana and lime. Pozzolana is a type of volcanic ash or dust (Figure 5). It was possible to get pozzolana from tufa and usually came from two regions in Italy. A type which is a light grey color, called *Campi Flegrei Pozzolana* or *pulvis puteolanus*, was available at the Bay of Naples. However, there were several types in the region of Colli Albani such as *pozzolana rossa* (red), *pozzolana nera* (black), and *pozzolanella* (greyish).

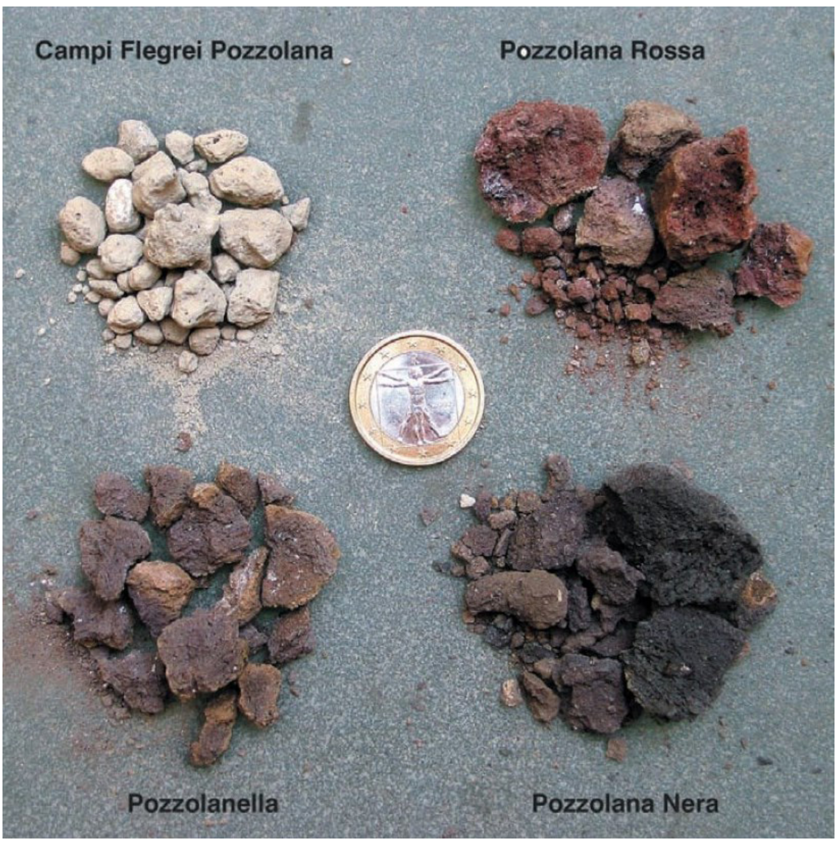

Fig. 5. Four types of pozzolana (after Lancaster 2005, Plate III).

Seneca said if pozzolana touches water, it turns into stone (Sen. Nat. Quest. 3:20:3). Vitruvius mentioned a dust type called pulvis from the region of Cumae. It was possible to make mortar by mixing pulvis with lime and water (lime:pulvis = 1:2) (Vitr. De arch. 5:12:2). Vitruvius explained more in detail. There is a type of dust called *pulveris* available from Baiae and near Vesuvius.

If it is mixed with lime and rubble, we get the concrete which is extra strong if cured underwater (Vitr. De arch. 2.6.1). The chemical reaction in the mortar with pozzolana is different from the lime mortar. Thus, construction made with pozzolana mortar is more resistant against intensive moisture conditions (Sear, 1998, p. 73). This shows clearly why the first concrete domes were built in bath complexes. Dark grey or reddish-grey *opus caementicium* were used by Romans in the Late Republic Age and the reign of Augustus (Van Deman, 1912, p. 251). Consequently, the domes of buildings with large spaces could resist humidity.

It is known that when covering inner and outer surfaces of domes and vaults, flat terra-cotta bricks were used. Those bricks turned bright red when Romans baked them well to make them waterproof. Generally, they were not thicker than 3,5 cm. These roof tiles and bricks had porous surfaces, so they connected well to mortar. There were three main types of tiles (Sear, 1998, p. 77): *bessales* (19,7 cm), *sesquipedales* (44,4 cm) and *bipedales* (59,2 cm). Those square tiles could also be divided into two pieces as triangles to cover walls. Furthermore, a tile could be broken into small squares to use them in arches. *Bessales* were used mostly during Claudius, Nero, Vespasian, Titus, Trajan and Antoninus Pius periods. *Sesquipedales* were used under Domitian and Hadrian. And *bipedales* was preferred only under Domitian. Covering patterns could change according to the surface. For example, between the years of 125-133 *bessales* tiles which were placed in both vertical and horizontal positions on the inner surface of the dome at Heliocaminus Bath in the Hadrian's Villa (Lancaster, 2005, p. 31).

Except for covering material, bricks were used for dome construction. The Temple of Asclepius at Pergamon was built above vaulted substructures of concrete, and its cella was topped by a brick dome (Lancaster, 2015, p. 46). Radially laid bricks were also used for the domed roofs of the Red Basilica at Pergamon. Later buildings followed this technique in the second and third centuries CE. The technique of radial tile covering can be observed at the barrel and sail vaults of Terrace Houses at Ephesus and the sail vaults of the West Mausoleum at Side.

Amphorae were placed into the vaults to lighten the weight of domes (Adam, 1994, p. 374). The best-known examples of this technique were used between the years of 326-330 CE at the Mausoleum of Helena. However, one of the earliest applications of amphorae into dome vaults can be seen at the Villa alla Vignaccia at the fourth mile of the Via Latina. Because of brick stamps, most of the buildings in the region dated Hadrian's period (Ashby, 1907, p. 74). Those structures were built with mortar called *Tufo lionato* and their walls covered with the technique of *opus reticulatum*. A type of amphora which they placed into the vaults has been identified as Dressel 20 (Lancaster, 2005, p. 193).

Consequently, there are two main techniques of dome construction. The first one is the construction of those without using *opus caementicium* (Figure 6). For this technique, ashlars can be used for construction at the vaults of domes. There is no concrete mortar used as connecting material between ashlars. As mentioned before, domes at the western bath complex at Gerasa from the second century are built with this technique. An earlier and different example of this technique can be seen at the dome and vaults of the North Baths at Morgantina. The complex dated to the third century BCE and terracotta tubes were used to form the framework of the domes and vaults. The framework was covered with rough mortar. Lucore (2013, p. 157) concludes from this example that the possible dome at Syracuse was also built using terracotta tubes.

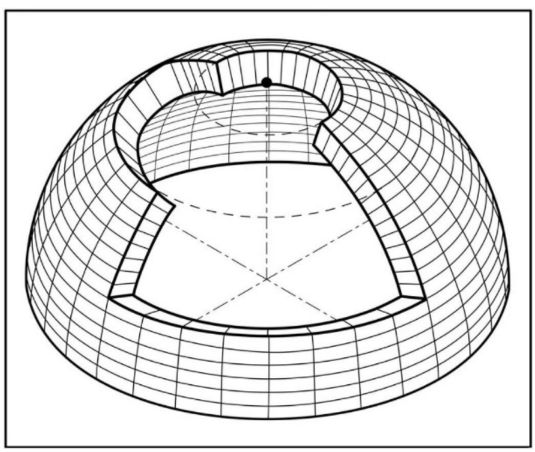

Fig. 6. Drawing of a dome built of radial voussoirs (after Lancaster, 2015, p. 13).

Concrete domes were built with other techniques by using *opus caementicium* (Figure 7). Those concrete domes were built with three architectural elements; with buttresses, ribs, and step-rings. To lighten the weight of a dome those elements were applied to construction. For example, coffer slabs between the vertical and horizontal arch ribs in the Pantheon reduce the weight of the dome. However, cracks can occur in the lower part of the dome due to pressure from the meridian and parallel axes. So, cracks occurred in the vertical direction at the lower part of the Pantheon. Those cracks stopped at a latitude of approximately 57°, where the hoop stress begins to be compressive (Masi et al., 2018, pp. 587-596). Another factor that reduced the weight of the dome is the step-rings on the dome. Those step-rings were designed upwards from the bottom of the dome. One of the earliest domes with step-rings was built on the Temple of Mercury at the end of the first century BCE in Baiae (for the step-rings see Figure 7). We can see step-rings also at the half dome of Trajan's Market in Rome. However, the best-known dome which has step-rings is on the Pantheon. Because the Pantheon had been taken as a model, domes were built with step-rings at the Tempe of Zeus-Asklepios and the Healing Building in the Asklepieion of Pergamon. Step-rings were designed to reduce the weight of domes. There is also another view of the function of step-rings which could be built to help builders construct domes easily (MacDonald, 1982, p. 110). This approach might be true. However, if we take a look at the development of domes, the main reason for constructing domes with step-rings was to reduce the weight (Lancaster, 2005, P. 141). Except for ribs and step-rings, buttresses were used to support domes against the heavy weight. Irregular buttress elements can be seen at the Temple of Mercury. However, buttresses were placed in a certain order at the Octagon Suite in Domus Aurea.

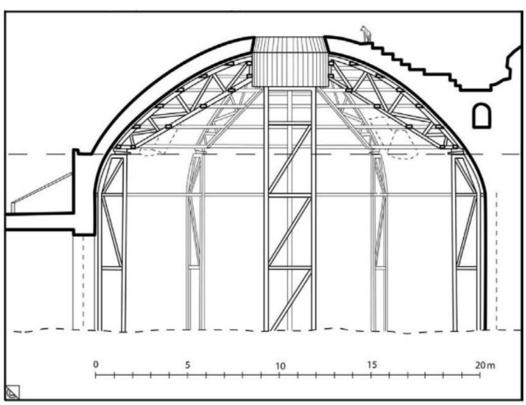

Fig. 7. Reconstruction of the Temple of Mercury in Baiae (after Lancaster, 2005, p. 41).

Conclusion

As seen above, domes emerged after the development of arches and vaults, especially in the grave architecture in the Near East centuries before Roman domes. Afterward, corbelled arches, vaults, and domes had been developed by Romans in the Republic period. After the second half of the second century BCE, concrete domes appeared because of the use of *opus caementicium*. It is not a coincidence that the first concrete domes were built in the baths. Instead of lime mortar which was not resistant to moisture, hydraulic mortar consisting of pozzolana and lime mixture was preferred. The typological development of concrete dome architecture between the 1st century BCE and the 3rd century CE can be followed through archaeological examples. Parallel to this progress, techniques like radial covering or using amphorae in vaults were also developed. Besides, the functionality of the structures was guided by the typological and technical developments of concrete domes. The most decisive factor in the beginning and development of the concrete dome architecture was the use of volcanic ash from the region in the Gulf of Naples to make mortar. In conclusion, the construction of concrete domes came about because of the Romans. Domes for public places like baths, temples, or imperial rooms were erected and used for social, cultural, or religious activities. The other reason was the raw material, pozzolan, which helped to develop the techniques and design around different regions in ancient Rome. Even the huge structures with domes like Pantheon or Hagia Sophia have survived so far, and they show how the importance of using raw materials helped to fulfill the social needs of people.

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