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A POWDER WHICH PRODUCES ASTONISHING RESULTS – THE PHENOMENON OF ROMAN CONSTRUCTIONS PERSISTENCE

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A b s t r a c t

The oldest vestige of concrete application has been found in the Galilee village Yiftah El, which dates back to 7000 BC. Its prevalence as a building material appeared several centuries later in ancient Rome, from which come great buildings like the Pantheon or Coloseum, existing for hundreds of years without the need for complex repairs. Vitruvius did not fail to mention its excellent characteristics in his famous treaty. Concrete is, however, generally considered as a material of modern civilization, very "trendy" both in architecture as well as in interior design. The aim of the article is to overview the concrete's technology used by the ancient Romans, famous for its resistance and compactness. The author analyses the process of its production, paying attention to the aspect of ecology, multi – century life and compares its features with the characteristics of modern building materials.

Keywords: concrete, roman cement, Portland cement, ancient Rome, Vitruvius

S t r e s z c z e n i e

Najstarsze ślady zastosowania betonu odnaleziono w galilejskiej miejscowości Yiftah El datowane na 7000 r. p.n.e. Jego rozpowszechnienie jako materiału budowlanego nastąpiło kilka stuleci później w starożytnym Rzymie, z którego pochodzą tak znakomite obiekty jak Panteon czy Koloseum, istniejące setki lat bez potrzeby kompleksowych napraw. O jego doskonałych właściwościach nie omieszkał wspomnieć Witruwiusz w swoim słynnym traktacie. Beton uznawany jest jednak powszechnie za budulec współczesnych cywilizacji, bardzo "modny" zarówno w architekturze jak i we wnętrzarstwie. Celem artykułu jest omówienie technologii wytwarzania betonu stosowanego przez starożytnych Rzymian, słynącego ze swojej odporności i zwartości. Autorka analizuje proces jego produkcji zwracając uwagę na aspekt ekologii, uzyskania wielowiekowej trwałości i porównuje jego cechy z właściwościami współczesnych materiałów budowlanych.

Słowa kluczowe: beton, cement romański, cement portlandzki, Starożytny Rzym, Witruwiusz

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„For there is no kind of material, nobody, and nothing that can be produced or conceived of, which is not made up of elementary particles; and nature does not admit of truthful exploration and accordance with the doctrines of physicists without an accurate demonstration of the primary causes of things, showing how and why they are as they are."[1] Elementary particles, which are mentioned by Marcus Vitruvius Pollio, an architect who lived during the reign of Julius Caesar and Augustus, in his famous treaty, are undoubtedly one of the most common modern building materials – concrete. This artificial stone is formed from a combination of a fine filler with a binder, and creates a type of composite material, in which a leaven is a matrix and an aggregate is an inclusion. The characteristics of the used aggregates, binders and additives influence concrete properties. The so-called "regular concrete" is formed from mineral rock aggregates joined by cement while maintaining conditions that its apparent density is at least 2000 kg/m^3, and aggregates reach over 8 mm. In order to achieve additional properties such as water resistance, frost resistance, heat resistance, acid resistance or weight reduction (the so-called lightweight concrete with a density of volume under 2000 kg/m^3), the appropriate admixtures, liquids, steel fibres, foaming agents, etc., are added, and the resulting material is known as "special concrete"[2].

Mortar, a concrete component, is a mixture of sand, binder and water, which has accompanied the development of civilization since ancient times. Its name reflects the nature of the binder (lime, cement, gypsum, clay). The oldest are limestone and gypsum, evidencing the use of lime in construction, coming from 12 Millennium BC from destinations in today's Turkey, where it was discovered in the construction of floors and terraces[3]. The first traces of concrete – a mixture of lime mortar and limestone, were found in the floors and parts of walls in Galilee village Yiftah El. They date back to 7000 BC. A similar type of concrete was discovered in the Serbian village Lepenski Vir in the floors of a fishing cottage from 5600 BC and in South America in Mexico in the roofs of buildings in the town Veracruz from 1100 BC[4]. The lime mortar was also known to Egyptians who towered the pyramid of Djoser stepped in Saqqara, the builders of the Great Wall of China and the ancient Greeks, who used it to seal water tanks (in the Temple of Athens on the island of Rhodes, and in the harbour of Piraeus), the construction of waterworks, or interior finishing[5]. In Greece, there were attempts to modify it by adding the ground of Santorini, cracked tiles and volcanic ash from the island of Nisiros and Puccoli (Putteoli – Greek colony in Italy). The largest deposits of volcanic tuff were at the foot of Mount Vesuvius in the village of Puccoli, hence the name for this material was adopted – pozzolana[6]. After the Greeks, the use of lime mortars was taken over by the Etruscans and the Romans, who initiated a further improvement process.

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[1] Witruwiusz, *O architekturze ksiąg dziesięć*, tłum. Komaniecki K., Biblioteka Antyczna, Prószyński i S-ka, Warszawa 2004.

[2] Z. Jamroży, *Beton i jego technologie*, Wydawnictwo Naukowe PWN, Warszawa 2009, p. 4.

[3] J. Katzer, *Zaprawa dobra na wszystko*, Inżynier budownictwa. Miesięcznik Polskiej Izby Inżynierów Budownictwa, październik 2009, http://www.inzynierbudownictwa.pl/technika,materialy_i_technologie,artykul,zaprawa_dobra_na_wszystko,3263 (access: 26.05.2017).

[4] W. Raczkiewicz, *Beton – materiał budowlany znany od wieków*, Przegląd Budowlany, październik 2012, p. 13, http://www.przegladbudowlany.pl/2012/10/2012-10-PB-13-18_raczkiewicz.pdf (access: 26.05.2017).

[5] J. Katzer, *Zaprawa …*, *op.cit.,*

[6] W. Raczkiewicz, *Beton …*, *op.cit.,* p. 13.

The civilization of ancient Rome began the territorial expansion on the lands surrounding the Mediterranean Sea and the Black Sea, hence the demand for building materials resistant to different weather conditions was growing. Lime mortar was modified with volcanic ash, volcanic tuff and brick starch and lime gradually became only a supplement to the mortars, which based on bond called a modern cement[7]. The already mentioned Vitruvius wrote about the appropriate proportions and the origin of the components necessary for the production of lime mortar in his work "The Ten Books of Architecture": " (…) with regard to lime, we must be careful that it is burned from a stone, which, whether soft or hard, is any case white. Lime made of close – grained stone of the harder sort will be good in structural parts; lime of porous stone, in stucco. After slaking it, mix your mortar, if using pit sand, in the proportions of three parts of sand to one of lime; using river or sea – sand, mix two parts of sand with one of lime. These will be the right proportions for the composition of the mixture. Further, in using river or sea – sand, the addition of a third part composed of burnt brick, pounded up and sifted, will make your mortar of a better composition to use. [2]. The reason why lime makes a solid structure on being combined with water and sand seems to be this: that rocks, like all other bodies, are composed of the four elements. Those which contain a larger proportion of air are soft; of water, are tough from the moisture; of earth, hard; and of fire, more brittle."[8]

In the IV Century BC, the Romans erected constructions *opus emplectum*, which can be described as the precursors of concrete structures; they poured between two brick walls (the lost formwork types) a rare mortar and then they threw inside the rubble stone – ceramic. Over time, the mixture of sand, water, gravel and dust ceased to be used only as a binder of stones and bricks and became an independent building material. The name *caementum* was used to call the pulverized fragments of ceramic tiles or bricks and *betonium* was the final effect of the connection of lime, crushed stone, slag and dust[9]. In the III. Century BC, a mixture of stones, water and cement (mortar, limestone and volcanic ash – *pulvis puteolanus*) was used, which, after hardening, gave artificial stone corresponding to the modern concrete[10], awakening the acclaim of Vitruvius: "There is also a kind of powder, which produces astonishing results from natural causes. It is found in the neighbourhood of Baiae and in the country belonging to the towns round about Mt. Vesuvius. This substance, when mixed with lime and rubble, not only lends strength to buildings of the other kinds, but even when piers of it are constructed in the sea, they set hard under water. The reason for this seems to be that the soil on the slopes of the mountains in these neighbourhoods is hot and full of hot springs. This would not be so unless the mountains had huge fires of burning sulphur, alum or asphalt beneath them. So the fire and the heat of the flames, coming up hot from far within through the fissures, make the soil there light, and the tufa found there is spongy and free of moisture. Hence, when the three substances, all forced on a similar principle by the force of fire, are mixed together, the taken in water suddenly makes them cohere, and the moisture quickly hardens them so that they set into a mass, which neither the waves nor the force of the water con dissolve."[11] Information about the volcanic dust from the Bay of Naples used to produce

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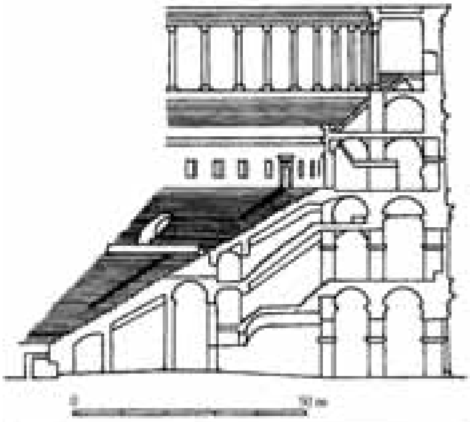
[7] J. Katzer, *Zaprawa …*, *op.cit.,*

[8] Witruwiusz, *O architekturze … , op.cit.,*

[9] http://asocjacje.beczmiana.pl/beton-budulec-naszej-cywilizacji/ (access: 26.05.2017).

[10] W. Raczkiewicz, *Beton …*, *op.cit.,* p. 13.

[11] Witruwiusz, *O architekturze … , op.cit.,*



Ill. 1. The Interior of the octagonal Room in the Golden House of Nero in Rome, source: Watkin D., *Historia architektury zachodniej*, Arkady, Warszawa 1996, p.55

Ill. 2. Colosseum, Rome – section, source: Watkin D., *Historia architektury zachodniej*, Arkady, Warszawa 1996, p.47

Ill. 3. Patheon, Rome, source: Watkin D., *Historia architektury zachodniej*, Arkady, Warszawa 1996, p.58

mortar can also be found in the encyclopaedia of Gaius Plinius Secundus, called the Eldler – Roman historian and writer, who was killed during the explosion of Mount Vesuvius.

In the 1st Century BC, concrete was already widely used to build harbours, breakwaters, monuments, temples, aqueducts and roads; however, it was very often finished with natural stone, because its aesthetic appeal was not always enjoyed[12]. When, after 27 BC, Emperor Octavian Augustus decided to renovate the old Roman buildings and elevated new ones, he gave an order to build the most important buildings with concrete from ash from the volcano Albano from Pozzolane Rosse, a few kilometres away from Rome, considering it as extremely resistant and durable[13].

Many ancient buildings have been preserved to modern times; there you can find concrete based on pozzuoli concrete in foundations, walls, and even in the domes. It was used to build roads and streets, among others, in the oldest Roman road Via Appia Antica from Circo Massimo in Rome, close to Capua in Naples up to Brindisi on the Adriatic coast[14], as well as in the construction of aqueducts troughs. Aqua Appia is the oldest of them, established in 312 BC. supplying water to Rome from the river Anio, which is about 11 km away, and among the most impressive aqueduct is the Pont du Gard in today's France territory, built between 26 – 16 BC and leading water from sources in Uzès to Nîmes[15], inscribed on the UNESCO World Heritage list.

Concrete often cracked and leaked, as is clear from the surviving notation from the I AD aqueduct supervisor Frontinus. This was probably caused by a lack of the necessary dilatation in the long distance construction[16].

Two important buildings, entirely made of concrete faced with brick, should be qualified an octagonal hall covered by dome in the middle of the east wing of the Golden House of Nero (Domus Aurea) (ill. 1). The room was entirely monolithic, walls passed smoothly into the dome, had no windows, and the only illumination from above by was a wide *oculus*. From its five sides, it opened to rectangular vaulted rooms with skylights around the inside edge of the dome. The walls of the hall were reportedly decorated with marble pilasters and stucco, and even gold, jewelled and pearl mass. The construction technology of the Golden House using concrete made it possible to be built very quickly between the year 64 after the great fire of Rome and 68, when Emperor Nero committed suicide. The whole project of more than 120 hectares was created in conjunction with engineers – architects, Severus and Celar. Besides the previously mentioned Golden House, there was a park with an artificial lake, temples, baths, pavilions and arcades. After Nero's suicide, the elements of the Golden House, hated by the Romans, have been absorbed by the Flavian Palace, which was built for the emperor Domitian (inauguration of the 92 A.D.). Architect Rabirius designed a building of an enormous size, whose significant height was possible thanks to the use of concrete walls and columns finished with marble[17].

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12 W. Raczkiewicz, *Beton …*, *op.cit.,* p. 14.

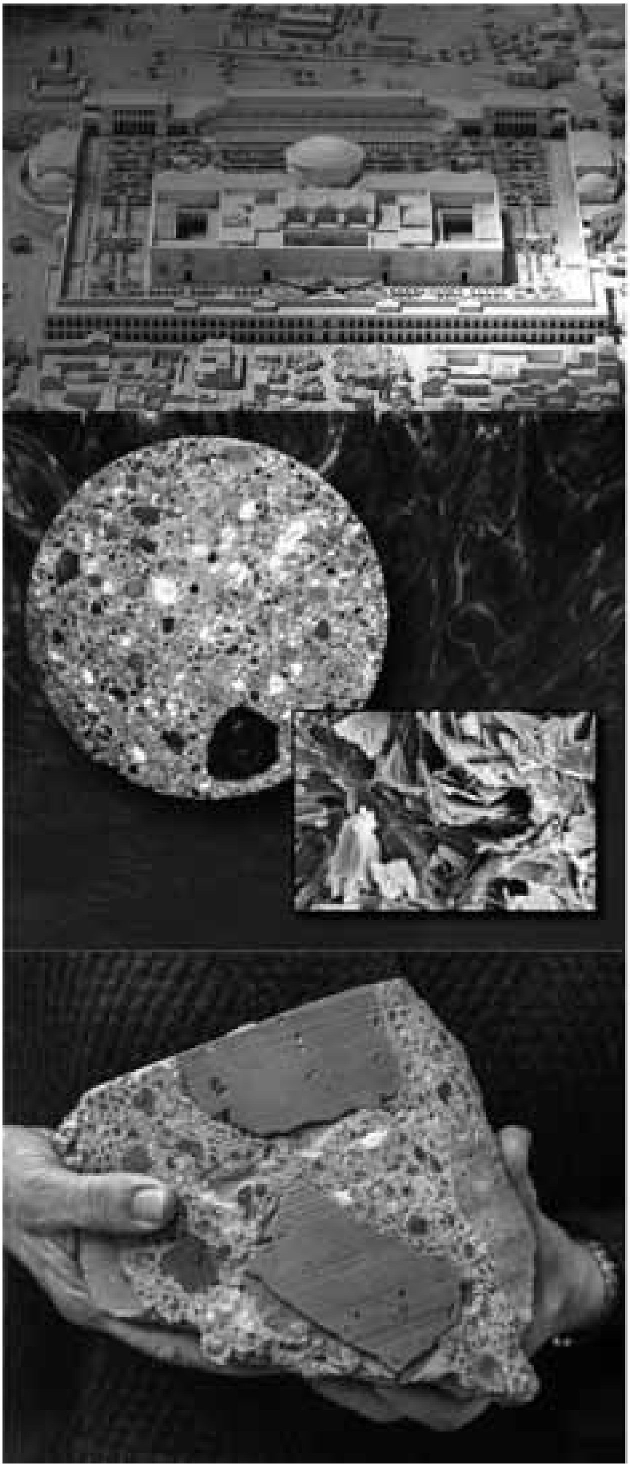
13 http://bywajtu.pl/strony/historia-cywilizacji/notatka/zagadka-trwalosci-rzymskich-budowli/ (access: 26.05.2017).

14 https://pl.wikipedia.org/wiki/Via_Appia (access: 26.05.2017).

15 W. Raczkiewicz, *Beton …*, *op.cit.,* p. 14.

16 *Ibidem*

17 D. Watkin, *Historia architektury zachodniej*, Arkady, Warszawa 1996, p. 54–56.



In the place of an artificial lake neighbouring the Domus Aurea, Emperor Vespasian built the famous Flavian Amphitheatre between 75 and 80 AD, and named it the Colosseum, probably after a colossal statue of Nero standing next to it. It could accommodate 50 000 sitting spectators and 23 000 standing ones. When considering the architecture, it was quite a conservative building whose travertine facades were decorated with rhythmically spaced arcades and half column in: Doric, Ionic and Corinthian orders. However, the construction of the Colosseum was based, to a large extent, on concrete – rising up, mostly marble seats were based on progressively higher, vaulted arch structures of concrete facing brick (ill. 2)[18].

The best-preserved building of ancient Rome, where you can find the synthesis of creating inner space, closely associated with the development of concrete structures, and respect of the traditional classical forms is the Pantheon (ill. 3). It was built in the years around 118 to 128 AD at the time of Emperor Hadrian in the place were the temple by Marcus Agrippa had been built in 27 BC. Behind the eight – column portico entrance, there is a huge rotunda with niches in the walls 6. 2 m thick. The interior is covered by a dome with a diameter of 43.2 m with the oculus at the top with a diameter of 8.5 m, which covers the interior with light. Coffers, from which the building is mostly constructed, contain a variety of filling materials: travertine, tuff, brick and light volcanic pumice. The materials were used in various combinations to gradually decrease the weight of the building, starting with the heaviest layer in the foundations, and ending with the lightest of pumice stone at the top of the dome. The Pantheon undoubtedly helped to initiate a new phase of architecture, in which a huge emphasis was put on the creation of a vast, unsupported inner space by using a concrete structure[19].

When mentioning the important buildings of ancient Rome, in which concrete was used, it is also worth stopping at the biggest thermal baths of Caracalla of Rome erected at the foot of Aventine Hill from 212 – 216 AD during the reign of Marcus Aurelius Antoninus (fig. 4). Their name comes from the nickname of the Emperor – Caracalla, which means a Gallic coat with a hood, often worn by the ruler of the Empire. The property covers an area of about 20 hectares and is fitted, among others, with a palaestrae, massage rooms, saunas, pools, nymphaeum, and a library. The caldarium (hot water room) was constructed outside on the south-western façade for maximum use of solar heat and was covered with a concrete dome, which is higher than the dome of the Pantheon, but with a slightly smaller diameter[20].

Pozzolana binders used for concrete production in times of the Roman Empire facilitated the creation of durable and extremely interesting architectural objects. Besides the listed temples, amphitheatres also appeared in underwater construction and breakwaters, and as brick faced concrete in residential buildings, warehouses, or storehouses (for example, in Rome or in Ostia).

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[18] *Ibidem*, p. 46–47.
[19] *Ibidem*, p. 60–61.
[20] *Ibidem*, p. 64

Ill. 4. The thermal baths of Caracalla – model, source: http://wikimapia.org/44422/pl/Termy-Karakalli--Thermae-Antoninianae#/photo/515697 (access: 30.05.2017)

Ill. 5. A sample of drill core of volcanic ash-hydrated lime mortar from the ancient harbour of Baiae in Pozzuoli Bay, source: http://newscenter.lbl.gov/2013/06/04/roman-concrete/ (access: 30.05.2017)

Ill. 6. A sample of mixed Roman mortar binds with cobble-sized fragments of tuff and brick, source: http://newscenter.lbl.gov/2014/12/15/roman-architectural-concrete/ (access:30.05.2017)

After the fall of the Empire, they ceased to produce cement, which was probably related to the fact that the main medieval centres occupied areas of today's Germany, France and England were located outside the areas where naturally volcanic ash existed. Mortar for brick or stone masonry was based on lime binders or gypsum, and back to the cement came not until after a few centuries, in the second half of the 18th century, along with the beginnings of the industrial revolution[21].

In the year 1756, John Smeaton, called the father of civil engineering, searching for a suitable mortar for the construction of harbour facilities and the lighthouse in Eddystone Rock, observed that mortar of lime fired from raw material rich in clay substances had better properties, which implied a breakthrough in the manufacture of hydraulic binders. Twenty years later, Joseph Parker discovered that fired solid of marl limestone from the slopes of Mount Kent gives good hydraulic cement, which some years later was called Parker's cement or Roman cement, because it had a colour similar to the ancient Roman cements with lime and pozzolana[22]. In the year 1818, the French engineer Louis Joseph Vicat showed that if there are no loamy substances in limestone, the same quality hydraulic lime can be obtained by mixing mechanical limestone with clay. Firing argillaceous limestone in a fairly low temperature of 500–1200 °C also allowed the production of cement (Roman). It was characterized by a very quick setting and hardening time, which allowed it to reach full strength faster[23].

Intensive development of Roman cement production fell in the second half of the 19th century, because of its warm colour, changing depending on the impurities from yellow to brown, which perfectly harmonized with fashion in architecture for using historical costume on facades. Thanks to the relatively fast and easy production, resistance to atmospheric factors and colour approximate in sandstone became a desirable building material, from which moulding plaster *in situ* were made willingly, as well as plaster cast mounted with an iron anchor. Its heyday ended with the outbreak of World War I, after which there was a decided turn towards Portland cement applied until today[24].

Nowadays, because of its excellent properties (among other, quick setting time in conjunction with a slight shrinkage, resistance, water vapour transmission), Roman cement is appreciated by heritage conservators. It allows to reconstruct the historical detail from the turn of the 19th and 20th centuries in a material, which is equivalent to the one originally used, it allows to make quick repairs of natural stone, the execution of the decoration carved on the wet, etc.

We owe the appearance of Portland cement, named after the resemblance to a building stone mined in the vicinity of the island of Portland, to the English bricklayer Joseph Aspdin, who patented it in 1824. After arduous research, he appointed, as the first person, competent quantitative ratio of lime and clay, enabling to fire these materials at a high temperature.

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[21] J. Katzer, *Zaprawa …*, *op.cit.,*

[22] H. Szeląg, A. Skorek, *Cement romański – przeszłość, teraźniejszość i przyszłość*, Inżynier budownictwa. Miesięcznik Polskiej Izby Inżynierów Budownictwa, listopad 2009, http://www.inzynierbudownictwa.pl/technika,materialy_i_technologie,artykul,cement_romanski___przeszlosc_terazniejszosc_i_przyszlosc,3308 (access: 26.05.2017).

[23] K. Janicka-Świerguła, M. Iwaniec, *Cement naturalny*, Inżynier budownictwa. Miesięcznik Polskiej Izby Inżynierów Budownictwa, kwiecień 2016, http://www.inzynierbudownictwa.pl/technika,materialy_i_technologie,artykul,cement_naturalny,9023 (access: 26.05.2017).

[24] K. Janicka-Świerguła, Iwaniec M., *Cement…*, *op.cit.,* H. Szeląg, A. Skorek, *Cement romański..*, *op.cit.,*

Portland cement spread after Parker's cement was used to construct a tunnel under the River Thames and proved to be imperfect and the construction collapsed in 1828. William Aspdin (son of Joseph) perfected his father's recipe and offered the use of its product to build the tunnel, displacing Parker's cement, which was used before, out of the market. The optimum composition and roasting temperature was worked out in the year 1845 by Isaac Charles Johnson, who became a pioneer in the industrial production of Portland cement in the world[25].

Portland cement is obtained from natural rocks, such as limestone, marl, clay, chalk, diatomaceous earth, volcanic tuffs, and sometimes quartz sand. After processing (firing), these resources are in the form of baked blocks of up to 20 mm and are called Portland clinker cement. During its shredding, gypsum is added, which regulates the process of setting, and in this way, the mixture creates Portland cement[26].

The main drawback of concrete is its ten times less tensile strength than compressive strength. 19th – century engineers and inventors led their research on improving these properties. The invention of the reinforced concrete is assigned to a French gardener responsible for the maintenance of the gardens of Versailles – Joseph Monier. Over the years, he struggled with the problem of splintered pots for plants during winter. In the year 1849, supposedly by accident, a metal basket fell into a concrete mortar, which, when dry, turned out to be a very durable structure. Monier led further research and experiments. In 1867, he patented the technology of the production of concrete baskets, and then pipes (1868), plates (1869), ceiling (1880–1883) etc.[27] Next years have brought improvements to the way of concrete reinforcement, that is, next to steel, one of the most popular construction materials.

In the middle of the 20th century, concrete structures were designed to last 50 years; nowadays, we design buildings to last between 100 to 120 years. The question therefore arises: how come ancient buildings of concrete structure still exist, despite the fact that centuries have passed? This issue was studied by an international team of researchers led by Paulo Monteiro of the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab), a professor of civil and environmental engineering at the University of California, Berkeley and a professor Marie Jackson from University of Utah Department of Geology and Geophysics. They examined a sample of concrete taken from the ancient harbour of Baiae in Pozzuoli Bay, in the north – western region of the Bay of Naples, which had survived for 2,000 years in an aggressive, underwater environment (fig. 5). Researchers used Berkeley Lab's Advanced Light Source, as well as facilities at UC Berkeley, the King Abdullah University of Science and Technology in Saudi Arabia, and the BESSY II synchrotron at Germany's Helmholtz-Zentrum Berlin für Materialien und Energie, to discover how Roman concrete differs from the modern Portland material[28].

The Romans made concrete by mixing lime and volcanic rock, which they combined with volcanic tuff and packed into wooden forms for underwater structures. After submerging it in seawater, it instantly triggered a hot chemical reaction, whose product was a very durable concrete[29].

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[25] Raczkiewicz W., *Beton – materiał ..., op.cit.,* p. 16.

[26] Z. Jamroży, *Beton…, op.cit.,* p. 24.

[27] W. Raczkiewicz, *Beton – materiał ..., op.cit.,* p. 17.

[28] S. Yang, *To improve today's concrete, do as the Romans did*, 4.06.2013, http://news.berkeley.edu/2013/06/04/roman-concrete/ (access: 30.05.2017).

[29] P. Preuss, *Roman Seawater Concrete Holds the Secret to Cutting Carbon Emissions*, 4.06.2013 http://newscenter.lbl.gov/2013/06/04/roman-concrete/ (access: 30.05.2017).

As already mentioned, Portland cement is a compound of calcium, silicates, and hydrates (C-S-H). At ALS beamlines, x-ray spectroscopy showed that Roman concrete produces a significantly different compound, with added calcium, aluminium, less silicon and hydrates, and as a result, it is an exceptionally stable binder. In addition, Monteiro's team noticed the additional hydration products in concrete. In theory, C-S-H in concrete made with Portland cement resembles a combination of naturally occurring layered minerals, called tobermorite and jennite, but these ideal crystalline structures are nowhere to be found in conventional modern concrete. However, tobermorite does occur in the mortar of ancient seawater concrete. Al-tobermorite (Al for aluminium) has a greater stiffness than poorly crystalline C – A – S – H and provides a model for concrete strength and durability in the future. It is also significant that the production of Roman cement is much less energy consuming because limestone is baked at 900˚ Celsius, while to burn calcium carbonate (limestone) and clays a key ingredient in modern concrete is a temperature about of 1,450 degrees Celsius. Considering that each year the world produces 19 billion tons of concrete, the manufacturing of Portland cement accounts to 7% of the carbon dioxide that the industry puts into the air[30].

The next analyses were led by a team of researchers from the Lawrence Berkeley National Laboratory (Berkeley Lab) on a sample of concrete walls of Trajan's Markets (mixed Roman mortar binds with cobble-sized fragments of tuff and brick, fig. 6). Its reproduction was made and researchers allowed to cure mortar over a period of 180 days and then x-rayed the mineralogical changes that took place, comparing the results to 1,900-year-old original samples. It turned out that, as in the case of concrete used in the construction of the breakwater, in the mortar was a chemical reaction between limestone and volcanic ash, with the participation of water, resulting in the crystallization of platy strätlingite. They played the role of microfibers responsible for the resistance of ancient concrete. The key to achieving an adequate composition were the proportions: 2 / 3 of ash and 1 / 3 of limestone[31].

Environmentally friendly modern concretes also include volcanic ash or fly ash from coal-burning power plants as partial substitutes for Portland cement, with good results, but their long-term performance could not be determined until the research team analysed ancient underwater constructions. The analyses showed that the Roman recipe needed less than 10 percent of lime by weight, made at two – thirds or less the temperature required by Portland cement and also that lime reacting with aluminium-rich pozzolan ash and seawater formed crystalline structures[32]. However, the ancient recipe concrete may not be applied where quick setting is necessary, hence the works on its improvement are still ongoing.

It is hard to imagine modern architecture without concrete. It is permanently settled in our consciousness. Sometimes, it gains the pejorative connotation in the term "concrete housing estate", and other times, it sparks delight by its simplicity and purity of forms as in the ark of Robert Konieczny. As a construction material, it surprises with its high speed of construction. In interior design, it awakens the imagination of designers. As in every connection of the elements, there is no way to stay indifferent to it. The ancient Romans already knew about this

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[30] S. Yang, *To improve ..., op.cit.,*

[31] L. Yarris, *Back to the Future with Roman Architectural Concrete*, 15.12.2014 http://newscenter.lbl.gov/2014/12/15/roman-architectural-concrete/ (access: 30.05.2017).

[32] http://materialyinzynierskie.pl/starozytny-rzymski-beton-lepszy-od-terazniejszego/ (access: 30.05.2017).

and left a huge architectural legacy. It is worth bowing in front of their beauty and to remind ourselves about the engineering knowledge, from which we can draw upon today, while admiring the monuments.

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[4] Katzer J., *Zaprawa dobra na wszystko*, Inżynier Budownictwa. Miesięcznik Polskiej Izby Inżynierów Budownictwa, październik 2009, http://www.inzynierbudownictwa.pl/technika,materialy_i_technologie,artykul,zaprawa_dobra_na_wszystko,3263 (access: 26.05.2017).

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