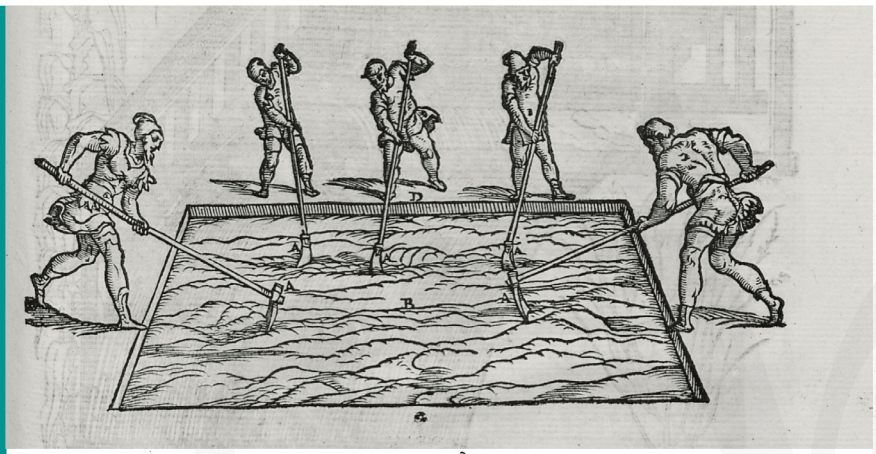
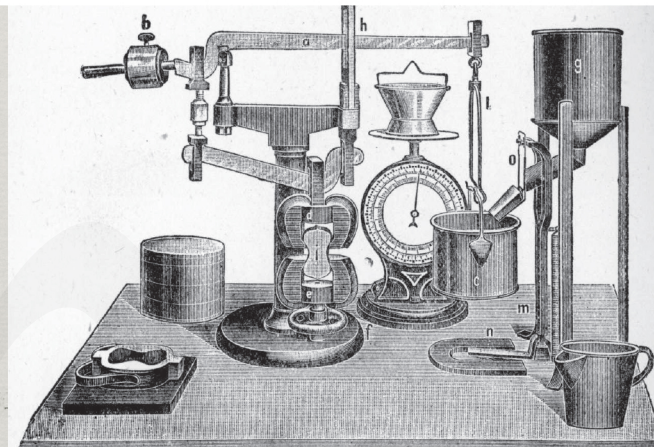
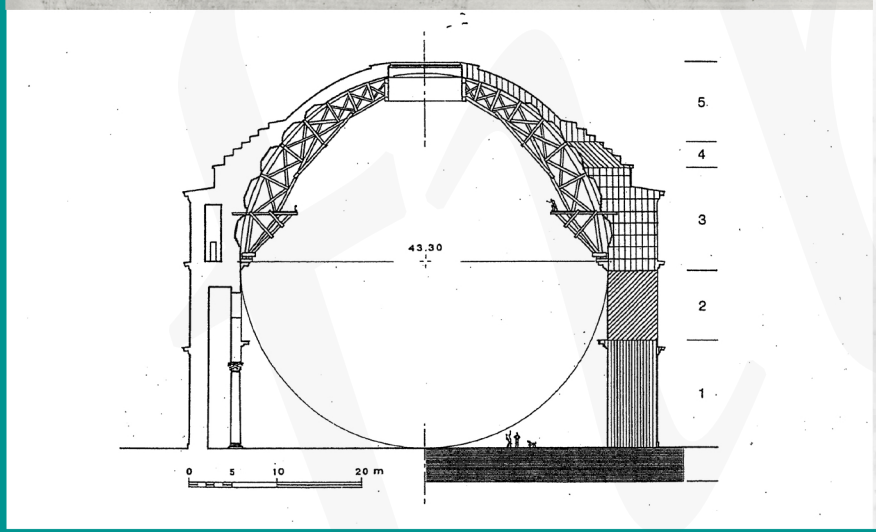
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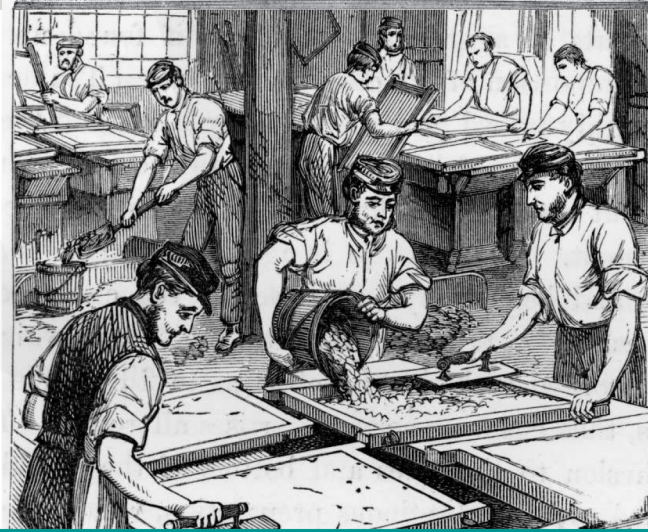
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Bulletin 107









An Introduction to the History of Structural Concrete

Vol. 1: From Antiquity to the 19th Century

Manual

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fib CEB-FIP Bulletin 107

An Introduction to the History of Structural Concrete

Vol. 1: From Antiquity to the 19th Century

Manual

Task Group 1.6

March 2023

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Any publication not having met the above requirements will be clearly identified as a preliminary draft.

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Foreword

This bulletin is a Manual, the first Volume of a series on the History of Structural Concrete prepared by Task Group 1.6. This first Volume follows the Structural Concrete evolution from Antiquity to the 19th Century.

The argument of this document represents a novelty for *fib* and it is very important for disseminate the knowledge to the community. In particular, it is important to disseminate the information presented in this manual to students and young engineers.

The historical analysis of the past is essential for the conceptual design of new structures. In addition, the historical knowledge is important when engineers should approach existing structures: a critical historical analysis is the base for the correct structural assessment.

Finally we can consider this Manual, and the future Manuals (the following Volumes on the History of Structural Concrete) important and useful documents at different levels: students, engineers and all person interested on this topic.

As Commission 1 chair, I'm very grateful to Manfred Curbach, to Michel Moussard and to all members of TG 1.6 "History of Structural Concrete", for having produced this document that I consider very interesting not only for the *fib* members, but also for the concrete community.

Alberto Meda

Chairman of *fib* Commission 1 *Concrete structures*

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Preface

On the occasion of Barack Obama's speech to the UK houses of parliament on the 25th of May 2011* the Commons Speaker, John Bercow said some remarkable sentences about history and cement in his welcome address: "History is more than the path left by the past. It influences the present and can shape the future…" and later, he added: "It is my honour, Mr President, to welcome you as our friend, and as a statesman. Statesmanship is the cement which seals our shared idealism as nations."**

History of concrete is more than stories about the past. It shows where we are today and where we are able to go. Cement is a binder of the whole story.

The history of concrete - and above all, that of building and construction research in the broadest sense – has been a subject of interest for a very long time. As engineers, architects or builders, there is no need to reinvent the wheel. Rather, the work of predecessors can be continued. Analysis of past abnormalities and understanding of historical developments are worth being used as the basis for the solutions of the future. Above all, being involved with concrete in today's world means dealing with building materials, aesthetic principles, construction methods, and computational techniques of the past and present so as to identify starting points which can be used in the future to save not only materials and energy but also working time.

In most ground breaking research projects, in the beginning, researchers found themselves looking into the past. Who was the first person to conduct research on a topic? What is the stage of development today? What questions remain unanswered? This approach is nothing extraordinary, but rather self-evident, and has been the guiding force behind the evolution of structures, materials, and methods of construction. An inevitable sense of admiration arises, not only when we look at structures, but also when we look into the story of their builders, who showed great courage by bringing their ideas to life, one structure at a time.

The history of this book - in a bulletin format of three volumes - goes back to a conversation between Michel Moussard and me during the 11th *fib* symposium in Stockholm in 2012. One year later, in Tel Aviv, a task-group on concrete history was formed and the work began. Then, we decided to write a book that could accompany the lectures of a one-semester course, each lecture having a duration of one and a half hours per week. There are 10 chapters corresponding to 10 lectures organized in three separate bulletins. This reflects our hope that more universities will add lectures on the field of civil engineering history because knowledge of the past is really an important matter.

Thank you to all members of the task-group. First of all, I would like to thank Michel Moussard most sincerely for his intensive cooperation as Co-Convenor, which was characterized by warm friendship and great understanding. A big help was the ongoing support by Michel Moussard, Edwin Trout, David Fernández-Ordóñez and Patricia Garibaldi as members of the editorial board. Both this work and the two volumes still to follow could not have been completed without the extensive and knowledgeable work of the respective authors. The entire editorial board would like to express its sincere thanks to the respective authors. During the ten years of development, both the people within the task group and the intensity of their collaboration have changed. We would therefore like to thank all the people who were involved – even if only temporarily – in the creation of these volumes. A very special thank you goes to Patricia Garibaldi, who has done not only the work of a secretary of the group but also made substantial input to several chapters of this book.

We hope that this book finds increasing interest within the concrete history community and among readers.

Manfred Curbach

---

* This remarkable speech can be seen on youtube: https://www.youtube.com/watch?v=fp85zRg2cwg and can be read on http://edition.cnn.com/2011/POLITICS/05/25/obama.europe.speech/index.html

** Can also be seen on the youtube-link shown above and can be read on https://www.parliament.uk/business/news/2011/may/us-president-address/speaker-bercow-speech/

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1. The Beginning

1.1 History of the Earth

Scientists estimate the age of the Earth to be about 5 billion years, or 5'000 million years: an enormously long time!

The Precambrian spans from the formation of the Earth to the first development of the animal world about 560 million years ago. There is evidence of earlier bacterial, unicellular organisms that did not have a cell nucleus (so-called blue-green algae), but multicellular organisms did not yet exist. The evolution of land plants began about 475 million years ago, and the first animals still lived exclusively in water. At first there were only jellyfish and sponges, later also more highly developed marine animals. It is assumed that the first land animals evolved during the Devonian Period about 370 million years ago.

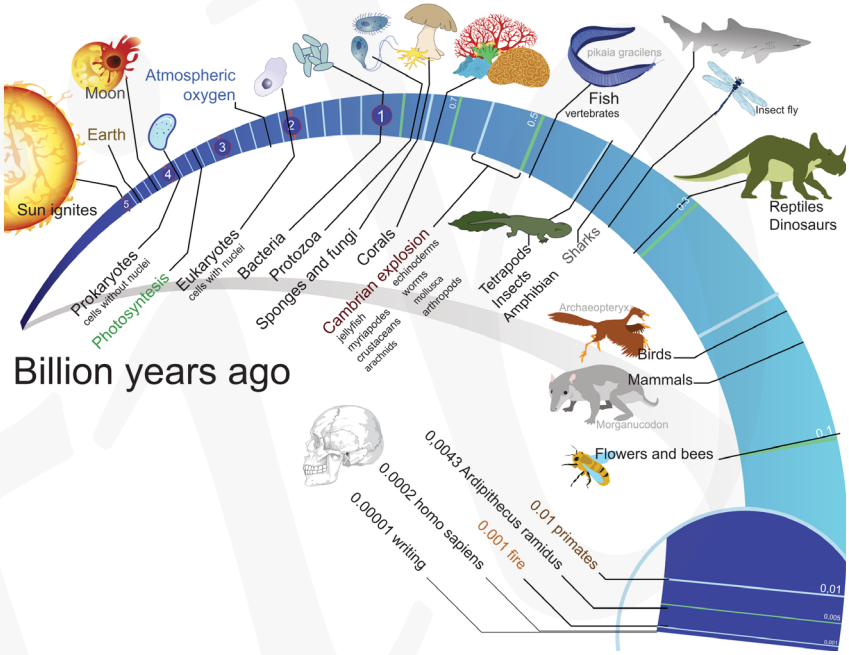


Fig. 1-1 Evolution of the Earth and its flora and fauna (Wikipedia commons).

Residues of this early flora and fauna formed huge geological formations of limestone, gypsum, hard coal, gas, and petroleum, which we use today as fuels and as raw materials for building materials.

1.2 Evolution of Mankind

According to Charles Darwin, humans developed through evolution. This probably began about 2.5 million years ago from the Australopithecus, or "southern ape" species, the group of extinct primates closely related to modern human beings. Their fossil remains have been found in eastern, north-central and southern Africa. About two million years ago, early humans left their ancestral homeland in East Africa and made their way to the regions of Europe and Asia. This is also the time when the first crudely carved stone tools emerged and gave rise to the name Homo habilis.

This chapter was mainly authored by Nobis.

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Adapting to different living conditions, several different human species developed from these prehistoric people. Of these, Homo sapiens prevailed and displaced all other human species[1-1]. For many thousands of years, they hunted small animals and ate what they could capture or gather. At the same time, they were still on the menu of the large predatory animals. They were still in the middle of the food chain.

It was not until about 400'000 years ago that the first humans began to hunt larger prey as well. It is not known exactly, but science believes that they tamed fire about 300'000 years ago and thus took an important step towards further development. Humans probably developed their first cognitive abilities around 200'000 years ago. Today it is assumed that it was only about 100'000 years ago that Homo sapiens, the human species, managed to reach the top of the food chain.

During the Middle Palaeolithic period, lasting till about 50'000 BC, people still lived by hunting and collecting wild berries, roots and seeds. To protect themselves from wind, cold, sun, rain and dangers they lived in natural caves. Their inhabitants were not yet sedentary, but followed the migration of animals, visiting warmer regions according to the seasons. Slowly they were able to produce more sophisticated stone tools (Figure 1-3).



Fig. 1-2 During the so-called Stone Age, people were mostly not sedentary. They lived in natural caves or simple huts or tepees and were hunters and gatherers following the seasons or animals or waterholes (Carl Arriens, AKG Images).

1.3 First Permanent Dwellings

After the end of the last ice age, the Sahara region dried up and northern latitudes were freed from the ice. The transition from the Palaeolithic period into the Neolithic period started about 12'000 years ago, and a period of extensive innovation took place over the next few millennia.

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Fig. 1-3 At the end of the Palaeolithic Period around 10'000 BC people started to learn how to work stone to produced more sophisticated tools and weapons (Photo R. Nobis).

People began to live in larger settlements, build permanent dwellings and protect themselves against enemies by means of defensive structures.

The majority of today's prehistorians believe that these beginnings of urban life and the cradle of settled humanity lie on the western slopes of the Taurus and Zagros mountains in south-eastern Turkey up to the border of northern Iran. According to current knowledge, the first known permanent settlements were established here. It was the time when primitive agriculture began. At first, wheat and goats were domesticated and the first woven fabrics were produced. Humans also learned to make pots and other utensils of fired clay[1-2], [1-3].



Fig. 1-4 The first centres of Early Neolithic cultures were located around the so-called "Fertile Crescent". People began to live in larger settlements, build permanent dwellings and protect themselves against enemies by means of defensive structures (flickr, Prince Arthur, open source).

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The further development of the first sedentary peoples soon concentrated specifically on the region of the so-called Fertile Crescent. More and more people evolved from hunters and gatherers and began to form fixed social structures. This region includes the present-day countries of Syria, Iraq, Lebanon, Jordan and Israel, along with parts of Egypt and south-eastern Anatolia. According to today's knowledge, the first artificial building materials were also produced here. They consisted not only of clay and loam, but in rare cases of man-made materials[1-4].

The new ways of life reached the Aegean around 8'000 BC and reached Central Europe around 6'400 BC. The new sedentary lifestyle now required solid dwellings especially in rainy and cool regions. What they all had in common was that they initially consisted exclusively of natural materials that were available in the region in question.

Independently of each other, other cultures around the world developed between 7'000 and 2'000 BC. Dwellings consisted mostly of natural materials such as tree trunks, branches, reeds, leaves, grasses and animal skins. Spaces between trunks and branches were often filled with earth, clay or dung. Despite their simple construction, they gave people and animals considerable protection against wind, rain and frost.



Fig. 1-5 The first permanent settlements in Central, Central and Northern Europe were built between 6'400 and 5'000 BC. Mostly natural materials were used, as they were available on site (flickr, Rob Hudson, open source).

1.4 First Evidence of Monolithic Masses, Mortars and Plasters

The later broad development of artificial building materials cannot be attributed to any single culture. Rather, it took place independently on the various continents of the earth. Clay and loam played a special role in almost all regions; they were available almost everywhere and could easily be processed into solid dwellings.

Since there was no concrete in today's sense in the time before the Romans, we define "concrete" here as a monolithic, solidified mass of man-made and natural materials. Clay and loam can be included.

Mortar or plaster, on the other hand, have existed since the earliest times. These are not made into monolithic structures, but having an adhesive effect are used to join building components together.

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The first known early monolithic masses and mortars were based almost exclusively on clay and their mixtures, rarely on gypsum and lime. Very early on, bitumen was also used as a mortar in some regions.

1.5 Clay and Loam, a Versatile Building Material

The world's early human cultures often developed in large river valleys where loam and clay are abundant and readily available.

The use of loam and clay as building materials was therefore common all over the world since the time that the first permanent dwellings were built. These materials were easy to use and became hard when dried by the sun. Their use was not only simple and almost free of cost, but offered ideal physical properties, especially in arid climates. Used in massive walls they had great insulating effects and a strong regulating effect on humidity.

Loam and clay were, and continue to be, very widespread and preferred building materials, which have maintained their position in many regions of the world to this day. In highly industrialised countries, they are currently even gaining in importance again as particularly ecological building materials.

Loams and clays are generally formed by weathering of rocks such as granite, which is rich in quartzite, feldspar and glimmer, containing mostly silicates and aluminates. Over long distances, when transported by wind and glaciers, and especially water, they were ground to extremely fine particles.



Fig. 1-6 Riverbeds often consist of large deposits of loam and clay. The sediments are mostly formed by weathering of silicate- and feldspar-rich rocks. Such as granite. The constant flow of water ground those minerals into extremely fine mud (bigstock foto, 122211242).

The proportion of sand, silt and clay in loam can vary very widely. The various loams are therefore suitable for a wide variety of applications. Clay-rich loams are described as fat, clay-poor as lean. The richer the loam, the more plastic it is and the more suitable it is for use as a building material. It can absorb up to 70% of its volume of water and thus transform into a plastic, formable mass. The colour of the raw clay or loam varies between ochre and brown in many shades. It is strongly dependent on the iron content and its organic components. Pure clay or loam, without the addition of water, is solid and cannot be formed. Therefore, it needs water to become malleable. Often it is also necessary to

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"degrease" clay and many fat loams with sand, crushed stone or organic matters. The extraction of clay and loam usually takes place in open pits, but in rare cases also in underground mines.

The production of mud bricks, also called "adobe", is simple but needs some knowledge and experience.

The loam or mud is collected first from their deposits. When producing adobe, the mud needs to be intensively kneaded and most of the time mixed with other materials. Depending on the consistency, fat or lean, sand or gravel is added. Sand or fine gravel increases the strength of the dry adobe but makes it also more susceptible to erosion. Too much sand causes the adobe to decompose quicker, while too little sand promotes cracking. In almost all cases straw, dry grass, cereal husks, or sometimes animal dung is added. This material makes the adobe lighter, more flexible and improves thermal insulation. The lighter it is the less likely the walls will compress under their own weight. But the greatest advantage of the addition of straw and similar matter is that adobe bricks crack less. When dried in the sun, adobe bricks shrink by up to 30% in volume. When the outer surface dries faster than the inside, internal forces create cracks, letting water easily penetrate later. Straw or similar matter improves the permeability and lets the drying process be more uniform. Air can penetrate the adobe through little tubes and thus promotes the drying out of the inner part of the brick[1-5].

The addition of straw, however, does not in any way contribute to a longer durability of the adobe brick. Straw accelerates the penetration of moisture and thus the softening of the brick surface.

The precursor of the adobe brick was the so-called hand-shaped clay pat. To build walls, from pure loam, hand-shaped flat pats or bread-like shapes were made and laid on top of each other in a damp state. The walls were then compacted and the surface smoothened.

When producing adobe bricks, the carefully kneaded, viscous clay mixture is put into a rectangular wooden mould. After the top is smoothed, the frame is removed. The wet brick remains on the floor. Once the brick has dried somewhat and has reached a certain hardness, it is turned. After about a week, the raw brick is hard enough and can be stacked. It generally reaches its final hardness under the sun after a few months (Figure 1-8).



Fig. 1-7 Simple walls can be constructed from clay mud bricks, stacked on each other. Later the surface is smoothened using various tools and often white washed with lime milk to make the surface more resistant against wind and rain (bigstock photo, 190547995).

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Fig. 1-8 Mixing, mashing and spreading clay and straw into adobe bricks is still common practice today in many regions of the world (bigstock photo 190547995).



Fig. 1-9 A stock of adobe bricks dried in the sun. After about a week the bricks are strong enough so they can be stacked. To reach maximum strength, they have to be stored in the sun for at least half a year (bigstock photo, 210703906).

When constructing a wall, the individual dried bricks are either placed on top of each other in a dry bond or bound with mortar made of mud. Such a wall is enormously strong, but also very heavy. It stores cold and heat very well[1-6], [1-7].

In most cases the raw adobe brick wall is finally smoothened and often covered with a "plaster" made of mud. Nevertheless, rain and wind make the unprotected clay surface weather quite fast. In these cases, the mud plaster needs to be regularly replaced. But the eroded surfaces of ancient structures have formed over the years the well-known settlement mounds, which today provide archaeologists with treasure chests of finds.

A certain protection is possible by whitewashing the mud wall surface with a thick lime wash. It protects against erosion as the lime reacts with the damp mud surface and carbon dioxide in the air to form a hard white layer resisting weathering quite well. If regularly repeated, adobe brick walls can survive hundreds of years. In addition, the white colour reflects the sunshine reducing the temperature of the building.

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In ancient Greece, often the limewater was mixed with fine pozzolana from the island of Santorini to give the surface a very dense texture, improving further water impermeability and durability.



Fig. 1-10 A city built of Adobe in today's Yemen. Single buildings made from Adobe have up to eight stories (bigstock photo 77780369).

Due to its simplicity and durability, adobe is the oldest man-made building material. Its use in construction has been around for thousands of years and even today, in many areas around the world, it is still very commonly applied. Especially in arid areas, where wood is scarce and expensive, it is part of daily life. Over thousands of years, it has proved its worthiness. Buildings with up to eight floors can still be seen in some Arabian and African countries.

Mud in the right consistence can even act as mortar. It keeps regular and irregular natural stones quite well together. If the top of a wall constructed of clay mortar is given a watertight cover, the wall will endure for a long time (Figure 1-11).



Fig. 1-11 In arid regions clay can serve as mortar and keeps strong for a long time (photo R. Nobis).

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1.6 First Sights of Adobe Construction

All early civilisations around the world developed adobe and applied it independently as their first building material. However, the early Neolithic cultures in river valleys between the Euphrates and Tigris probably were the first to develop and refine the clay construction method. In these alluvial, humid lowlands, their inhabitants relied entirely on adobe to build their houses. The area has scarce reserves of stone and wood, but is full of river loam and clay.

However, the people of Mesopotamia not only built their houses, palaces and holy places from mud bricks; the earliest ancestors of the mosaic tradition emerged in ancient Mesopotamia as well. Their mosaics were formed by small, burned clay cones which, pointed end first, were pressed tightly together into a wall coated with a thick layer of wet plaster, mostly mud. (Cones similar to Figure 1-23, but laid in clay.) The flat ends of the cones were painted in different colours. Such mosaics originated in southern Mesopotamia and were used to decorate monumental mud-brick cult and palace architecture during the second half of the fourth millennium BC. Some of the most impressive examples are found at Uruk. The sheathing of outer walls and pillars made of mud bricks with mosaics of harder materials was not only decorative but also functional, as the cones protected the core of sun-dried bricks from rain and wind.

Some of the first evidence of the use of adobe is found in Jericho, Palestine. Its origin is dated to around 9’000 BC (Figure 1-12). It has been established that circular buildings, measuring approximately five metres in diameter, consisted of a mixture of clay and straw. Adobe bricks were dried in the sun and were bonded together with mud. The roofs consisted of grass and reed, and cooking hearths were located outside the dwellings. Massive settlement walls up to a hight of 3.60 metres and 1.80 metres thick at the base probably served as flood protection and defence. It is assumed that up to 3’000 people lived in this settlement[1-8].

Other excavated archaeological sites in today’s Anatolia showed similar building techniques. They are even dated back to around 10’000 BC.



Fig. 1-12 Tell es Sultan in Jericho, Palestine, was long considered one of the oldest man-made settlements. Archaeologists date its origin to the years around 9’000 BC. Buildings were made from adobe and mud as mortar (Wikimedia commons, MPCA Photos, open source).

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The adobe building technique was also common and well recorded in ancient Egypt. Mud from the River Nile was plentiful and wood very expensive, especially as fuel. The Bible reports of the Jewish slaves in Egypt, who were forced to produce mud bricks. When the work became unbearable, the Jews under the leadership of Moses and Aaron went on strike and finally left Egypt for good around 2'000 BC.

The early Etruscans and Romans, in what is now Italy, built their first large constructions around the 7th century BC, mostly made from shaped tufa stone placed without mortar. But until around 100 BC the common practice in the Roman territories was for private dwellings to be built in wood with adobe bricks. The Romans called the technique "*Opus latericium*". Houses had in general only one storey. For large buildings, however, the construction technology did not provide sufficient load-bearing capacity and, in addition, service life was too short for large investments.

With the improved wealth within the Roman empire, burned clay bricks became one of the preferred and optimized building material together with natural stone and *Opus Caementitium* (as recounted in Chapter 2).

But in other parts of the world, too, people began building permanent settlements early on. It is believed that in the region of present-day China, people began to settle down around 7'000 BC. They also began to domesticate animals and cultivate crops. The first permanent settlements in what is now China were found in the Yangzhou culture in the northern, central and coastal regions. They are dated 5'000 to 2'000 BC. Permanent buildings were round and consisted of wooden posts, straw and mud. In the Shang Dynasty between the 16th and 10th century BC, adobe was the common building technique. Especially between the Yellow River and Yangtze, loam and clay were plentiful. As in other regions of the world, the abundant "yellow mud", mixed with grass and straw, was a perfect raw material to form sun-backed adobe bricks[1-9].

It is assumed that people migrated from East Asia to America probably around 10'000 BC via the still closed Bering Strait. However, archaeologists assume that Aztecs in what is now Mexico were the first to settle around 4'500 BC. They also used natural materials to build their shelters. Initially they were probably primitive huts made of mud, straw and branches, but their building techniques developed continuously. The famous pueblos, made of mud and tree trunks, often whitewashed with lime milk, still bear witness today to their building techniques, which were adapted to the climate. They gave and still give protection against the elements.

1.7 Gypsum

Gypsum, calcium sulphate dihydrate ($CaSO_4 \cdot 2H_2O$), was mostly formed by crystallisation from calcium sulphate in supersaturated seawater. It was chemically precipitated analogous to salt in confined ocean basins or inland lakes where the supply of fresh water is less than the evaporation over a long period of time. As it was covered by other sediments, the gypsum was transformed into anhydrite ($CaSO_4$) by drainage. The gypsum rock ($CaSO_4 \cdot 2H_2O$) found near the surface today was formed by renewed water absorption of the anhydrite rock.

However, gypsum can also occur in the vicinity of volcanic activity during the reaction between limestone and sulphuric acid.

The geological age of gypsum varies widely, depending on the deposit; some deposits are two million and others up to 300 million years old and can be found in many places worldwide. The colour of the gypsum can vary , but is mostly in shades of white to grey. In most cases the gypsum stone is soft, having a Mole hardness of only 2.

When heated (fired) to temperatures of 120-150 °C, gypsum rock releases part of its crystalline water and changes into the hemihydrate $CaSO_4 \cdot 0.5\ H_2O$.

$$CaSO_4 \cdot 2\ H_2O + \text{heat} \rightarrow CaSO_4 \cdot 0.5\ H_2O + 1.5\ H_2O$$

If the process is reversed again and water is added to the hemihydrate, dihydrate is formed again within minutes with the release of heat. The gypsum sets again and hardens to calcium sulphate dihydrate.

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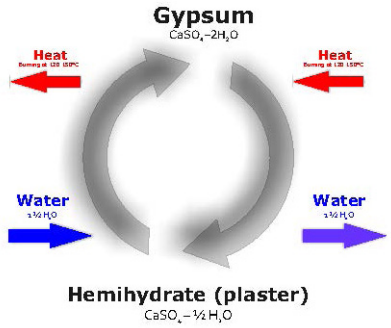


Fig. 1-13 The Gypsum cycle shows that gypsum plus heat becomes plaster and plaster plus water becomes gypsum, the original gypsum stone (Drawn by: R. Nobis).

The production process is therefore an endothermic reaction that requires suitable furnaces and fuels. The heat required to produce gypsum is significantly less than that for lime.

Gypsum as a building material is not resistant to moisture or frost. It cannot be exposed to normal weather conditions. Thus, for thousands of years, it has been used almost exclusively as plaster, and sometimes also as mortar. How humans discovered the production of gypsum and its properties is, of course, not known. The chemical process could have been discovered by chance at some fireplace in the distant past. Probably chunks of gypsum lay lined up in a round to secure a campfire. When the gypsum was exposed to the fire, parts of the crystalline water were expelled. The gypsum thus dehydrated disintegrating into a white powder. Perhaps it started to rain during the night and the powdery gypsum turned into a mud. Then, when the sun rose the next morning, the white mud had already solidified again and regained its original state.



Fig. 1-14 A fire pit of wandering nomads as it might have looked when the properties of gypsum were discovered (flickr, MPVA Photo, open source).

The earliest evidence of the use of plaster can be found in the Çatalhöyük excavation site in today's eastern Anatolia. Here, gypsum was used in combination with loam, as early as 9'000–7'000 BC to model animal reliefs, construct strong, compacted floors and much later decorative mosaics[1-10].

Many other archaeological finds indicate the use of plaster in very early cultures. Near the Sea of Galilee in present-day Israel, plaster was used in house floors in around 7'000 BC. Excavations carried out in Jericho indicate the use of gypsum in around 6'000 BC, and it was also mentioned in the cuneiform scripts of the Assyrians, Sumerians and Babylonians.

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Thus, over the course of thousands of years, gypsum was used as plaster, mortar, grout, as mosaic base and in fresco paintings. It was probably a very valuable building material, since wood was scarce in the arid regions of Mesopotamia and Egypt and needed to be transported over long distances.

The Egyptians probably became aware of gypsum and its uses in around 3'000 BC, but then they used it extensively as mortar and plaster. It was used in their graves, buildings and monuments, often combined or extended with finely ground limestone. Countless beautiful tomb paintings can still be admired in Egypt thousands of years later.

One example of the extensive use of gypsum grout is the construction of the great pyramids of Giza. The blocks of stone, each weighing several tons, were made to a perfect fit and laid without mortar. However, narrow vertical joints and small cavities were often filled with a gypsum slurry containing calcareous material, given that Egypt's gypsum deposits are often amalgamated with limestone. Since the firing techniques used at that time were still very primitive, firing temperatures were undoubtedly also subject to fluctuation.

Thus, as was apparently the case at higher temperatures, not only the gypsum stone dehydrated, but also the limestone impurities were deacidified. This explains why the gypsum used back then reached very high strength and, in many places, was able to survive for thousands of years.

It is not known whether the knowledge about gypsum was transferred from the Assyrians or the Egyptians to the Minoan culture in today's Greece. Whatever the case may be, the fact is that the Minoans, and later the Hellenes, made considerable advances in plaster technology and working with plaster. Gypsum was already used on Crete in the 3rd millennium BC as mortar, plaster and as a basis



Fig. 1-15 Fresco from the palace of Knossos, painted about 4'000 years ago. The fact that the pigments of the paint and plaster became one assured the longevity (Wikimedia commons).

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for magnificent frescoes, of which the palace of Knossos (built between 2'100–1'800 BC) is just one example. The reason why the paintings could survive for such a long time is that the paint was applied directly onto the wet, dump plaster. Thus, the paint penetrated deeply and became part of the plaster.

As in many other examples of knowledge transfer, one can assume that the Romans learned from the Hellenes. The south of present-day Italy was teeming with Hellenic settlements in the few centuries before Christ. (24–79 A.D.) writes in his natural history, "De re rustica", 36th book, chapter 59[1-11], about plaster as a building material:

> Gypsum has a close affinity with limestone, and there are numerous varieties of it. One kind is prepared from a calcined stone, as in Syria, and at Thurii (antique town in Southern Italy), for example. In Cyprus and at Perrhæbia (town in Macedonia), gypsum is dug out of the earth. The stone that is calcined for this purpose, ought to be very similar to alabastrine, or else of a grain like that of marble. In Syria, they select the hardest stones for the purpose, and calcine them with cow-dung, to accelerate the process. Experience has proved, however, that the best plaster of all is that prepared from specular-stone, or any other stone that is similarly laminated. Gypsum, when moistened, must be used immediately, as it hardens with the greatest rapidity.

However, gypsum gained little importance for use in mortar in the Roman Empire as its physical properties were inferior to those of lime. Instead, gypsum was widely used for stucco, plaster, and frescoes. It was known for the ease with which it could be produced, the fact that it was easy to work with in liquid form and was extremely durable when dry.

1.8 Bitumen and Asphalt

Bitumen and asphalt are, of course, extremely widespread building materials in road construction today.

However, it is comparatively recently that asphalt, a mixture of bitumen and aggregates, gained this importance. When in 1712 the Greek doctor Eirini e'Eyrinys discovered the gigantic asphalt deposit in the Val de Travers in western Switzerland, the bitumen extracted from it was initially not used as a building material, but in medical applications[1-12]. It was not until the 20th century, after extensive research, that the excellent properties of asphalt were recognised in road construction, and its use accelerated after the Second World War. In the broadest sense, it is also a monolithic building material that can be shaped according to need.

Bitumen, however, has served as an almost indispensable building material in certain regions since prehistoric times. Not only does it have sealing and adhesive properties, but it also becomes very hard and durable after degassing.

It is not surprising that bitumen was first widely used in regions where it was easily available, especially in today's Iraq. In the area of the Euphrates and Tigris rivers, it comes to the surface in very many places and even forms natural bitumen lakes. It is actually crude oil that loses its volatile components when it reaches the surface and solidifies into a sticky mass. Bitumen could thus be scooped from the surface by the simplest of means and processed and used to make various products.

Initially, it served in the lowlands of southern Mesopotamia as a sealing material for boats, walls, roofs, baths, canals or bank reinforcements. The region is low-lying and has a high-water table; it is humid and threatened by frequent floods[1-13], [1-14], [1-15], [1-16].

Early on, bitumen was also mixed with clay, sand and even gravel. This resulted in an excellent artificial asphalt, which, when compacted, produced an exceptionally hard surface in buildings or on paths.

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Fig. 1-16 Surface deposit of natural bitumen. When oil roses to the surface volatile components evaporate and developed into bitumen (Wikimedia commons).

Bitumen or asphalt was often used as mortar in important roads or building projects. Depending on the consistency, the asphalt was poured or applied with a trowel. Porous bricks or stone blocks absorbed parts of the bitumen in the asphalt and formed an enormously strong bond after solidifying and ageing. However, it was very expensive and was only used in larger quantities in extraordinarily important projects. These included processional roads, embankments, public buildings or mausoleums. Impressive evidence of its durability can still be admired today (Figure 1-17 and 1-18).

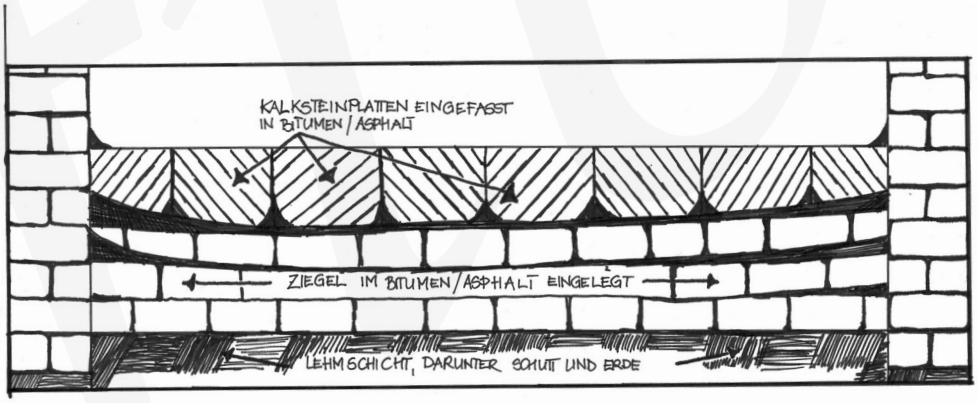


Fig. 1-17 A processional street in Babylon and embarkments on the banks of the Tigris consisted of natural stone blocks and burnt clay bricks laid in bitumen mortar. They were built around 1'300 BC. Remains can still be seen today. (Kastl, J. Entwicklung der Straßenbautechnik. Vom Saumpfad bis zur Autobahn, (Copied and drawn by: R. Nobis)

A famous example is the ziggurat of Ur in central Mesopotamia. Ziggurats, massive stepped towers, probably served as places of prayer and mystical practice. Usually, they were built entirely of sun-baked mud bricks, in some cases just the outer walls of baked bricks. Depending on their size, ziggurats testified to the prosperity and strength of a town or region. For stability, the bricks were sometimes mortared with bitumen. Even today, 4'000 years after their construction, impressive examples of bitumen-based mortar can still be admired.

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Fig. 1-18 Bitumen mortar after 4'000 years. It consists of bitumen plus sand as aggregate (Wikimedia commons).

1.9 Limestone

Limestone consists of varying amounts of lime, or more precisely calcium carbonate ($CaCO_3$). We use it today to produce cement, mortar, plaster and concrete.

Like gypsum rock, limestone is a natural rock that occurs on all continents of the earth in large deposits and in various forms and qualities. It is part of the Earth's evolution, the residue of seas that have long dried up.

Its formation is a long geological process and can date back to the Palaeozoic Era, 400 million years ago. The calcareous sediments were formed from mussel shells, corals, sponges or skeletons of microorganisms that inhabited the seas. After their death, their remains were deposited on the seabed and formed calcareous muds. The formation of calcareous deposits was also promoted by crystallisation of dissolved calcium carbonate, carried in from the land. Through pressure, drainage and often increased temperatures caused by overlying younger sediments, the subsoil solidified into massive lime deposits. The introduction of fine sands or clays by wind and rivers often created less pure limestone deposits. They contain a larger proportion of silicates and aluminates introduced by clay and, when properly mixed, often developed into valuable marl limestones, an ideal raw material for cement production.



Fig. 1-19 Typical lime deposit and mine. Its formation can date back hundreds of millions of years. Huge deposits, hundreds of kilometres in diameter, are quite common (Wikimedia commons).

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1.10 Chemical Reactions

The formation of lime can be explained very concisely by the so-called lime cycle. First of all, quicklime - CaO - is burned from limestone, the calcium carbonate - $CaCO_3$. Quicklime is also called non-hydrated lime.

$CaCO_3$ + heat → CaO + CO_2

The burning temperatures are around 950 - 1'100 °C, which is significantly higher than required for gypsum. The pure lime does not yet have a hardening effect. First, considerable amounts of water must be added to it to 'slake' it to calcium hydroxide ($Ca(OH)_2$). Here, too, an intensive exothermic process causes a high temperature development of up to 100 °C.

If as much water is added to it as it just needs to hydrate, the result is a dry powder. If more water than necessary is added to it, a lime slurry is formed. In both cases, hydrated lime, calcium hydroxide, is formed.

CaO + H_2O → $Ca(OH)_2$ + heat

Calcium hydroxide is used to make mortar or plaster and for the Romans also "lime concrete", by adding water (if it has been slaked dry) and sand or fine rock chippings. After it has been applied, the lime mortar remains soft for quite a while. Only slowly does it set and harden by absorbing carbon dioxide (CO_2) from the air and releasing water. Since the air is poor in carbon dioxide, the hardening process takes a very long time. It can take months and even many years, depending on its access to air.

Thus, as with gypsum, the cycle closes. The original limestone becomes limestone again.

$Ca(OH)_2$ + CO_2 → $CaCO_3$

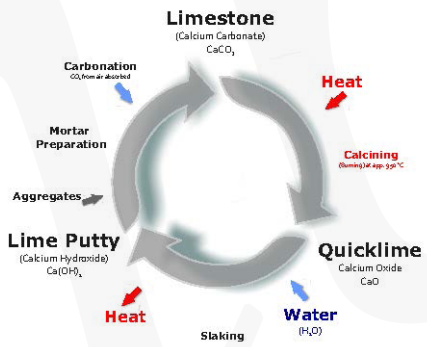


Fig. 1-20 The lime cycle: Under the effect of heat, limestone becomes lime, while under the effect of water and air plus aggregates, lime becomes limestone again (Drawn by: R. Nobis).

As already mentioned, hydrated lime needs air or CO_2 to harden. If this is not present, neither lime mortar nor lime concrete will harden. This means that a lime mortar or lime concrete will not harden under water. This is a major disadvantage, especially when projects are to be realised in water-bearing soils or underwater structures. In cases where limestone contains some clay we might expect to receive a hydraulic lime close to today's hydraulic cements. But this was not the case initially, since it was not possible at that time to create the high burning temperatures required to sinter the mixture. This technology had to wait till the 19th Century.

Of course, it is not known when people discovered the production and properties of lime. Prehistorians, however, assume that this took place 10 to 20'000 years ago.

It might be assumed that wandering nomads discovered the possibilities of gypsum and limestone when they secured their fireplaces with gypsum and limestone.

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If so, hot campfires were followed by rain, which set the reactions of the rocks in motion. However, it is doubtful whether this was the case with lime. The high temperatures needed to calcine limestone is generally much higher than those reached by campfires.

However, archaeologists have uncovered many firepits that were used as hearths for cooking. Often their walls were made of mixtures of limestone, clay and sand. When very high temperatures are applied to this mixture, it can even result in a very solid, fireproof wall as the various components sinter. If we look more closely, the mixture even corresponds to the rough basic recipe of a modern cement. For cement consists mainly of lime and silicates, which are found in clay and sand.

1.11 Production of Lime

The production of lime has hardly changed over the millennia. While today it is fully automated, historically it was a labour-intensive and unhealthy task. Limestone first had to be broken into the size of a fist and heated together with fuel, usually wood or charcoal. In historical times, this was usually done in open pits, later in simple field-dug, stone-built cavities. To ensure that enough air reached the fireplace, the stoves were often built in natural slopes so that their openings faced the general direction of the wind. In these furnaces, the burning chamber was already separated from the limestone chamber.

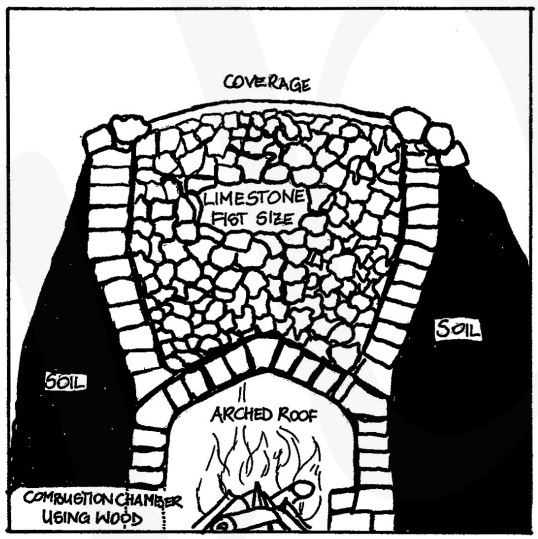


Fig. 1-21 Reconstruction of a very early lime kiln. As so-called field kilns, they were often placed in dug cavities. The construction was complex, since the separation between the combustion and lime chamber had to be made of fireproof dolomite rock using false work. To ensure ventilation, the access had top b placed in the direction of the prevailing wind (Drawn by R. Nobis).

After the limestone was finally deacidified, it had to be cleared out of the kilns manually. Since burnt lime is very caustic and the firebox certainly still very warm, it was a very unhealthy and even painful activity. Eyes, damp skin and lungs were badly affected. It is generally assumed that in many regions the activity was mostly performed by slaves. Life expectancy was probably quite short.

Slaking the lime is also a very unhealthy activity. It was usually done in simple pits or slaking pans. Since the fresh lime paste is also very caustic and generates temperatures of up to 100 °C during slaking. To avoid injuries, it was usually done with long wooden poles.

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SETTIMO. 101

IL Secondo Capitolo c'insegna à macerar la calce; la quale oltre l'esser attuffata, & mollificata nell'acqua, vuole che con vna cazzuola, ò zappetta, ch'altri la chiamino, sia bene rimescolata, & che il segno della sua bontà sia questo, che essa calce sia come cera appiccaticcia, & non si spicchi così facilmente dalla zappetta: questo particolarmente, si come diligentemente ci viene auuertito da Vitruuio, così minutissimamente l'habbiamo ancora nella nostra seguente figura.

SEguita il Terzo Capitolo: & con esso ci dà Vitruuio la regola del fabbricare i volti in questo modo. E prima che siano dissposti gli Asseri, ò trauicelli diritti, distanti più di due piedi l'vno dall'altro, & quando saranno così ordinati in forma rotonda, che si congiungano alle traui, & siano conficcati con chiodi di ferro. Poi vi si leghino delle canne greche piste, come ricercarà la forma del volto con reste di Sparto Spagnuolo, che nella nostra figura è segnato con la lettera H. & sopra la curuatura vi sia indotta materia di calce, & d'arena mescolata per difenderla da quello, che potesse cadere dal tauolato. Se non vi sarà copia di canne greche si piglierà di quelle de' paludi sottili, & se ne faranno matasse, & legheransi, si che tra due legamenti non vi sia distanza più che di due piedi: & esse matasse legate (come s'è detto) a' trauicelli haueranno conficcati le loro spatelle di legno per maggior vnione, & fermezza, il che tutto ci si mostra diligentissimamente espresso nella seguente figura.

Architett. del Ruscani. Cc Quest'

Fig. 1-22 Slaking lime in a slaking pan. The process is strongly exothermic and produces temperatures of up to 100 °C. The lime slurry must be extensively agitated to produce a uniform, good-quality lime sludge (Giovanni Giocondo, "De architectura libri decem" 1511, University of Heidelberg).

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The production of lime was not only extremely unhealthy and arduous, but also expensive. The amount of firewood and limestone needed to burn lime was enormous. Modern tools for cutting the wood or extracting the limestone did not yet exist, of course. Everything was hard manual labour. Because of the decarbonation process about 1.7 tonnes of limestone is needed for each tonne of lime. Recent burning tests have shown that for 100 tonnes of burnt lime at least about 300 tonnes of firewood were needed. These are huge quantities. This is one of the reasons why even before the Romans, and certainly by the late Middle Ages, whole regions of land in Europe and elsewhere became treeless.

Moreover, either the firewood or limestone (or both) had often to be transported over long distances with only simple carts available for the purpose.

1.12 The Early Use of Lime

The early use of lime was to whitewash the inner and outer walls of caves or shelters built of clay. This was later followed by tamped floors made of a mixture of lime, clay or sand. The first evidence comes from the region of eastern Anatolia or Palestine. The first uses of lime mortars to produce mosaics and frescoes were documented as early as the 3rd millennium BC in Mesopotamia[1-17]. The Bible (Book 5, Chapter 27, Verse 2) mentions the use of lime after the crossing over the Jordan: "large stones are to be erected and whitewashed with lime".



Fig. 1-23 Lime mortar were used in Mesopotamian to produce first cone type mosaics (World History Encyclopaedia).

According to current knowledge, the first evidence of man-made building materials in central Europe comes from the settlement of Lepenski Vir on the banks of the Danube in what is now eastern Bosnia. Excavations revealed the remains of a settlement with dwellings, tools and sculptures that could be dated to around 5'600 BC. Individual soils consisted of a mixture of lime, sand and gravel about 25 cm thick. It could even be established that the lime came from a deposit 300 km upstream. The floors are considered by building historians to be the oldest "concrete-like" constructions in central Europe[1-18].

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Fig. 1-24 The settlement of Lepinski Vir on the banks of the Danube in eastern Bosnia is believed to be the oldest known permanent settlement in Central Europe. Here the first "concrete"-like soils in central Europe were discovered (Wikimedia commons).

The first known use of lime in today's China is recorded in the Yangzhou Culture in the Neolithic period, 5'000 – 3'000 BC. So-called "white ash" was used to whitewash or plaster cave walls. The material was called white ash since a white powder is formed after the burning and grinding of ginger stones. The ginger stones, which look like ginger roots, were hardened marls made up of loess and river mud with a high lime content.

A typical Chinese monolithic building material worth highlighting is the so-called "San-He Tu" material. It has an extraordinary strength and durability and was especially used for heavy walls. The San-He Tu earth consisted of a mixture of lime, clay or loam, sand and organic additives. Its walls often survived for centuries.

The material "tabia" is also noteworthy. This is an admixture of lime, sand and so-called rice water and cooked rice[1-19].

It is said that the rice and rice water gave mortars and plasters but also massive constructions an outstanding strength. If applied in massive walls the mixture contained about one third lime, two third loess and sand, and boiled rice and rice water. The natural concrete was used extensively in the construction of numerous fortifications, tombs, and dams. According to ancient writers the material became "as hard as stone". Chinese scholars even claim that adding boiled rice to mortar was one of the most important achievement of the time.

Greece is a region where high quality limestone is found extensively in the form of marble, and thus marble was also often the raw material for lime.

The Greek philosopher Theophrastus spoke of lime in his treatise on stones in the 4th century BC: "Some of these stones melt and become fluid when subjected to fire.... And some go so far as to say that all of them melt except marble and that this burns up and lime is formed from it".

The ancient stucco or fresco paintings in Greece are famous. The exact terminology for plaster and stucco is not clearly distinguished, but in archaeology, plaster is based on lime and sand, while stucco is based on lime, gypsum and marble or limestone dust. Stucco is a rougher texture and plaster is a smoother texture.

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The oldest examples of stucco in Greece are known from the Minoan and Mycenaean cultures after their civilization emerged on the Mediterranean islands in the 2nd millennium BC. They were greatly influenced by the still flourishing Mesopotamian and Egyptian culture. Early on they covered rough surfaces of tuff and limestone in large temple buildings with stucco; this gave the surfaces a pleasing appearance. Somewhat later followed fine plaster and colourful frescos.

However, the Minoans were able to distinguish themselves by the extensive use of frescos in their interiors. In contrast to formalized Egyptian motifs the Minoans made an exuberance use of colours depicting pleasant motifs.

Until the 4th century BC, almost all public and private Greek buildings that were not built in marble had a plaster and stucco interior[1-20].

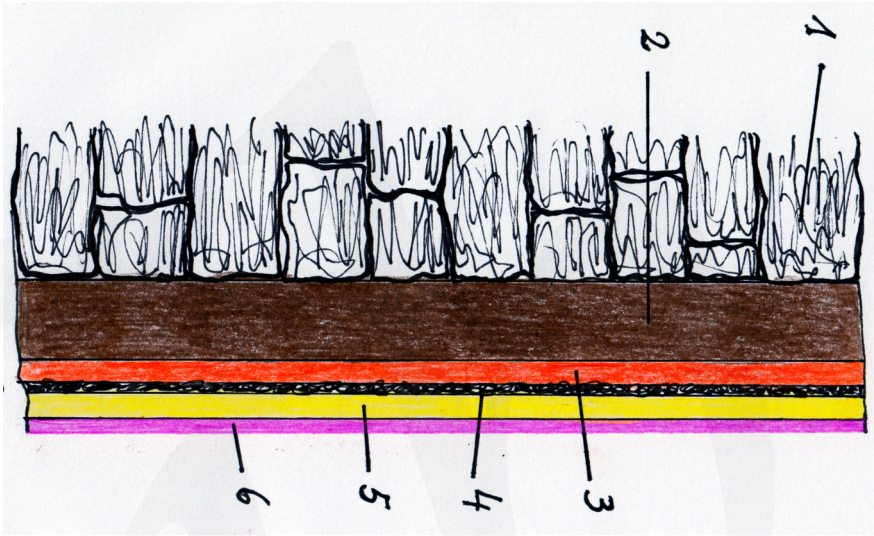


Fig. 1-25 Typical layers of Greek or Roman frescos. The overall structure of a fresco consists of the load-bearing wall (1), mortar of lime and sand (2), damp and fine plaster (3), the preliminary drawing or lime milk (4), marble dust and lime (5) and the paint (6). Up to seven layers of finer plaster were laid on top of each other (Drawn by R. Nobis).

First, the rough surface of the load-bearing wall was smoothed as much as possible; then an initially rough stucco was applied and covered with other finer plasters of fine sands and sometimes pozzolana. Finally, an even finer layer of very pure, creamy slaked lime and marble dust or gypsum was applied. Now the surface was smooth, but still without colour or lustre. Up to seven layers of increasingly fine layers were typical of high-quality frescoes.

The fresco technique in general refers to painting on fresh lime or gypsum plaster that is still damp, in contrast to painting on dry plaster. In fresco painting, lime whitewash was usually applied first on the final smooth surface, which, instead of a grey plaster surface, offers a radiantly bright painting surface. The paints or pigments that had previously been soaked in water or limewater were then applied to the fresh lime surface and were able to bind stably into the plaster during the carbonation of the lime. Thus, the colours became an integral component of the plaster and were able to survive thousands of years[1-21].

Good lime for mortar was also essential for the mosaic technique. This technique, in which specially cut stones or small fired clay cones are laid raw or glazed in a mortar bed, was particularly popular very early on in the cities of southern Mesopotamia. They generally depicted scenes of war and victory.

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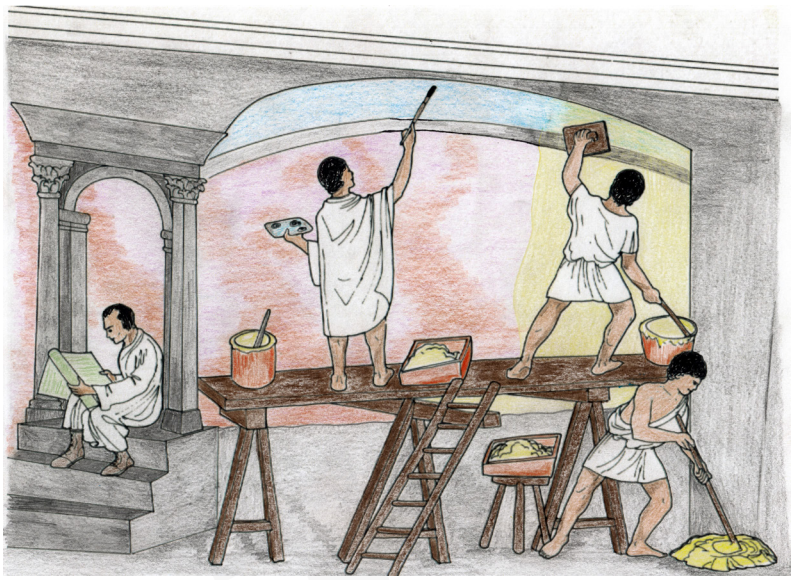


Fig. 1-26 The fresco technique uses the still moist plaster to bind pigments. It absorbs the pigments deep into the plaster. Thus, they become an integral part of the plaster. In this way, the colours can survive thousands of years (Artist unknown, coloured by R. Nobis).

Later, the mosaic technique reached Greece, where at first, however, it was mostly small pebbles that were placed in a bed of mortar. Mosaics achieved an especially high level of quality in the Roman Empire. Not only floors, but also walls were decorated with mosaics in homes of the higher social classes.

Here, too, the work was carried out with the utmost care. The construction of a high-quality mosaic followed strict rules. A coarse base was followed by various layers of finer mortar until the individual tesserae were laid in a fresh mortar bed.

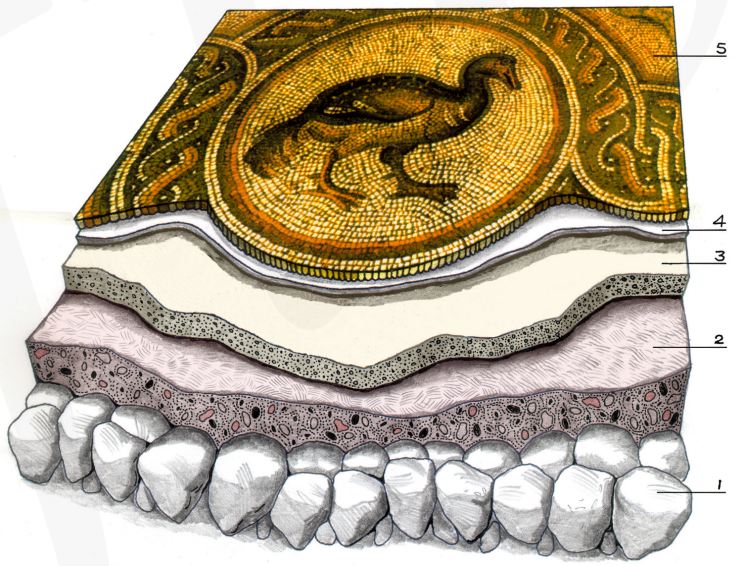


Fig. 1-27 Typical structure of a Greek and Roman mosaic: 1 - first coarse layer of gravel on levelled and compacted ground, 2 - mortar applied with coarse aggregate, 3 - mortar with fine aggregate, 4 - very limy mortar, applied thinly in sections in which the mosaic stones are laid, 5 - Surface cut stones. Joints are filled with fine lime mortar (The Getty Construction Institute, Elsa Bourguignon, J. Paul Getty Trust).

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1.13 The Birth of Hydraulic Lime, also called Water Lime

As already described, lime and its products, be they mortar, plaster or the later lime concretes, do not harden in the absence of air. Lime hardens only very slowly, which is why it can only be loaded gradually, though it attains considerable compressive strength after the passage of time. Furthermore, a plaster or mortar made of aerated lime has a certain water permeability and is not very suitable for sealing cisterns or other drainage or water supply infrastructure.

The setting behaviour of the lime mortar was of course a considerable disadvantage because underwater works – whether they were harbour facilities, foundations in groundwater, or watertight aqueducts – were not possible with it.

A fundamental discovery was the possibility of adding volcanic ash or crushed fired clay products to the lime to create a mortar that not only sets under water, but also hardens much faster and is almost impermeable to water. This new lime is called hydraulic lime or water lime.

It is not known when this final discovery was made. However, many prehistorians assume that the Phoenicians from what is now Lebanon and Syria first discovered this possibility. Their region is full of extinct volcanoes and volcanic ash is abundant.

During the 1st millennium BC, the Phoenicians maintained extensive trade around the Mediterranean basin and were highly respected and welcomed for their craftsmanship. Legend has it that parts of King David's residence in Jerusalem were built by Phoenician craftsmen. Cisterns in particular were covered with plasters made from a mixture of lime and powdered clay shards and dust. They were almost watertight and had considerable strength. Cisterns from the period can still be seen in Jerusalem today.

It is not known when the knowledge of the new mortar mixtures reached Greek regions. It is assumed, however, that the Phoenicians settled on the Aegean islands around the 7th century and brought with them their knowledge of metalworking in particular, but also of hydraulic mortar. Many Aegean islands are of volcanic origin. They thus often consist of volcanic lava, tuffs and ashes.



Fig. 1-28 The Santorini archipelago in the Aegean Sea north of Crete was formed by a gigantic volcanic eruption. It is thought to have been settled by Phoenicians around 800 BC. It can be assumed that they knew the knowledge of the mixture and its effect of lime with volcanic ashes and were the first to apply it in Greek-controlled regions (Wikimedia commons, Nasa, Landsat).

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But what do ground clay dust and volcanic ashes have in common and why can they turn a non-hydraulic lime mortar into a hydraulic mortar? The secret lies in their similar chemistry, formation and mineralogy.

Both volcanic ashes and clay are usually composed of ancient geological rocks, often molten or weathered granite. And granite is rich in silicates (SiO_2), a prerequisite for their reactivity.

Lava in volcanoes, as well as clay products in kilns, is heated to high temperatures. This melts or sintered the SiO_2 component in the rock or clay. In both cases, rapid cooling then often occurs. In the case of volcanic lava by ejecting fine lava dusts, in the case of clay products by venting the kilns.

With this rapid cooling, the silicate molecules could not transform into crystals, but formed amorphous, non-crystalline minerals. Their lattice structure is considerably coarser than that of crystalline minerals.

As a result, the finely digested, amorphous SiO_2 component has significantly more space in the lattice network of molecules. The lime component ($Ca(OH)_2$) is thus able to occupy these lattice networks in the silicate structure during a reaction and form an intimate bond. In some cases, the water-soluble glassy silicate components in the volcanic ash (pozzolan) also dissolve and combine with the calcium hydroxide of the slaked lime, forming new calcium silicate compounds. This reaction is called the "pozzolanic reaction"[1-22], [1-23].

The fundamental chemical and mineralogical processes involved in the hardening of the mixture of lime and pozzolan are extremely complex. The knowledge of why they bind together when water is added was, of course, unknown at the time. A broad knowledge of the interrelationships could only be developed more than 2'000 years later in the late Nineteenth Century.

One of the first proven plasters to possess these hydraulic properties is found on the island archipelago of Santorini, in the Aegean Sea. The islands of the archipelago were formed from several large volcanic eruptions about 3'600 years ago. Thick layers of lava, pumice and ash cover the entire archipelago. The assumption is that Phoenicians brought the knowledge in the Seventh Century and produced the first plasters and mortars from a mixture of lime, sand and volcanic ash. Remains of former cisterns from this period still exist today, which were covered with waterproof plasters. Analyses show that processed mortar consisted of about 43% slaked lime, 47% sea sand and only 10% volcanic ash.

This proves that the volcanic ashes were not used by the craftsmen as a substitute for sand, but to achieve special properties in the plaster. It shows that the Greeks were already aware of the influence of volcanic ashes at that time.



Fig. 1-29 Santorini cistern, built hundreds of years BC. They were plastered with a mixture of lime, sand and volcanic ashes. It made the cisterns waterproof (Photo: Astrid Scharlau and Nikos Mandilaras).

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The volcanic ashes from the Aegean region were called “Santorin-soil”. In antiquity, it achieved considerable importance as a lime admixture and export hit to the entire Mediterranean region. Even today, Santorin-soil is ground to a fine powder and mixed with cement, thus not only achieving good hydraulic properties, but also saving considerable quantities of cement. Because this also means that less cement can be produced, the savings in CO_2 emissions are considerable. For this reason, the use of volcanic ash will also increase significantly in importance in the future. Corresponding cement and concrete standards have been established in all countries of the world for a long time.

The Hellenic Empire in the centuries before the birth of Christ was large and extended throughout the Mediterranean and Black Sea regions. Settlements were founded, trade was brisk and local cultures were significantly influenced. Especially in the region of today’s southern Italy and Sicily, Greek colonies were founded early on, around the Six Century BC. The Gulf of Naples was one of the early centres. And this region is exceedingly dense with volcanic activity, especially the northern-eastern part of the Gulf with Mount Vesuvius on the outskirts of the city of Naples. Former volcanoes in the north, around the city of Pozzuoli, are covered with huge ash fields. As early as 194 BC, two of these Greek colonies, the city of Misenum in the south and Pozzuoli (Latin Puteoli) in the north of the Gulf, were given the status of Roman colonies.



Fig. 1-30 The Gulf of Naples with the "Phlegraean Fields" in the north around Puzzuoli and Mount Vesuvius in the east. Many large volcanic activities left large volcanic ashes in the region (Library of the city of Naples).

It is generally assumed that Greek settlers brought the knowledge of hydraulic lime with them and explained it to the Romans. This is because the extremely extensive volcanic ashes in the region are very similar to those of Santorini-soil. This is how the knowledge and the possibility of using the volcanic ash from the “Phlegraean fields” around Puzzuoli, the Pulvis putoelanis, came to produce a hydraulic mortar and later concrete.

From the port of the city of Pozzuoli, it became famous not only in the Mediterranean region, but throughout Europe. It is now called “pozzolana” after its place of origin. Today, the name is generally synonymous with volcanic ash.

But that’s not all. In the Naples region, but also around Rome, there are huge deposits of tuff. Tuff consists of solidified volcanic ejecta that cooled rapidly during their flight from the volcanoes, also with the help of rainfall during the eruptions, and filled lowlands and valleys as mud. Over thousands of years, these muds have solidified into what is known as tuff. Tuff is an extremely durable rock that can be worked well when wet. When it is crushed and ground into powder, it is called trass. This fine trass has the same properties as pozzolan and can transform non-hydraulic lime into hydraulic lime or mortar or concrete.

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In surface and underground mines in the areas of Naples or Rome, this tuff was extracted in very large quantities. Formed into blocks, it served as a common building material for thousands of years. The resulting waste was further crushed, ground, sieved and mixed with lime. The result was an excellent binder with which the Romans learned to make monolithic concrete.

But more about that in the next lecture.

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2. From the Roman period to the Renaissance

2.1 The Roman period

2.1.1 General historical context

The Roman Republic and later the Roman Empire lasted over a millennium, from the foundation of the Republic until the final collapse of Rome, evolving from a small territory in central Italy to an enormous expanse encompassing all Mediterranean coasts, large inland territories of Europe and the Middle East, and the southern part of Britain. Figure 2-1 shows the Roman empire at its apogee at the early stage of the Second Century AD, at the end of Trajan rule.

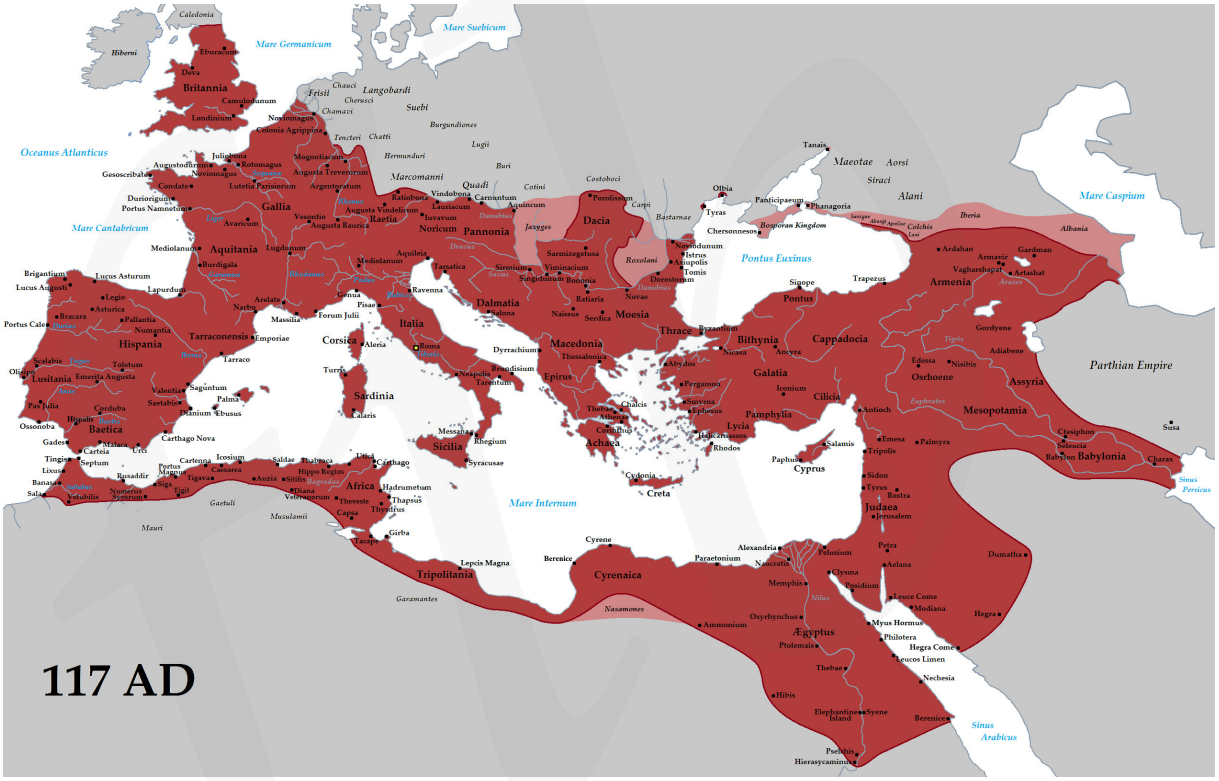


Fig. 2-1 The Roman Empire in 117 AD, under Trajan Rule (Wikimedia Commons).

The evolution of the Roman territories from 510 BC to 530 AD is presented in a series of maps at the following site: Roman Republic Empire map - Empire romain — Wikipédia (wikipedia.org).

The history of Rome started with a partially legendary dynasty of seven kings, founded by Romulus, of supposedly divine descent, in 753 BC. It ended with the reign of Tarquinius Superbus in 509 BC, when the Roman Republic was created. During this early period, particularly between the Seventh and the Sixth Centuries BC, the Romans were strongly influenced by their northern neighbours and often enemies, the Etruscans.

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The Roman Republic lasted from 509 BC until 27 BC, when Octavius received the name of Augustus and became the first Roman emperor. During this period the Romans created a very strong and stable political and social organization, that favoured the development of arts, literature and technology. In addition to the influence of the Etruscans they received the influence of the Greeks, who had established colonies in the south of Italy and in Sicily. The legendary Romans Legions allowed them to conquer or subordinate all the countries around the Mediterranean Sea, which became for them the *Mare Nostrum*. It is during this Republican period that the first structural concrete technology was developed, between the Third and the First Centuries BC. As we will see, this concrete formulation differed significantly from that of our modern concrete. Although Romans often referred to it simply as *caementa,* we will refer to it as *opus caementitium,* a term that is now commonly used by historians and archeologists.

The Roman Empire lasted from 27 BC to 480 AD with a division in two empires in 395 AD, the Western Empire with its capital city in Rome, and the Eastern Empire with its capital city in Constantinople, the ancient Byzantium. After the fall of the Western Roman Empire in 480, the Eastern Empire lasted another millennium, until 1453 AD. The development and use of *opus caementitium* technology continued during all the Imperial period, until the end of the Empire.

2.1.2 Sources of historical knowledge on *opus caementitium* technology

The two main sources of our knowledge of these periods are literature, in the Greek and in Latin languages, and archaeology. As we know, they are inseparable and complete each other in a kind of dialogue. Two other sources, although less important, deserve to be mentioned. One is to actually build test elements in the manner and with the materials that were available to the Romans; as an example, such an experiment was conducted in the framework of the ROMACONS project[2-1], with the construction of an 8 m^3 *pila* in the harbour of Brindisi in September 2004, that led to a number of interesting comparisons, on the one hand with Vitruvius's recommendations, and on the other hand between the works' results and the remains of Roman constructions. Another source of knowledge is the observation of traditional construction methods still in use in Mediterranean countries, that were inherited from the Romans. JP Adam in particular made such observations and refers to them in *La construction romaine, matériaux et techniques*[2-2].

As compared to the bibliography available in modern times, Latin or Greek literature available to us to-day is very limited. Except from Vitruvius *De Architectura libri decem*, the famous, very complete and detailed manual of architecture that was miraculously transmitted to us in its quasi-integrity, we have limited passages of literature which, although devoted to other topics, treat incidentally of materials, construction methods or specific structures. J.P. Oleson[2-1] provides a list of 32 literary passages that he has identified on the basis of a previous publication, *Greek and Roman Technology: a sourcebook* [2-21]. We have reproduced below some parts of these passages, which appeared most important to us. The translations in English that we propose are therefore taken from JP Oleson[2-1].

2.1.3 Materials and formulation. The invention of *opus caementitium*

As indicated in Chapter 1, it is generally assumed that Greek settlers brought the knowledge of hydraulic lime with them and transmitted it to the Romans. Cato the Elder gives, in chapter 19th-38 of his treatise on agriculture *de Re Rustica*, a clear description of a lime kiln, under the heading: "de furnace calcaria". Jean-Pierre Adam gives[2-2] a restitution of Cato description which is shown on figure 2-2.

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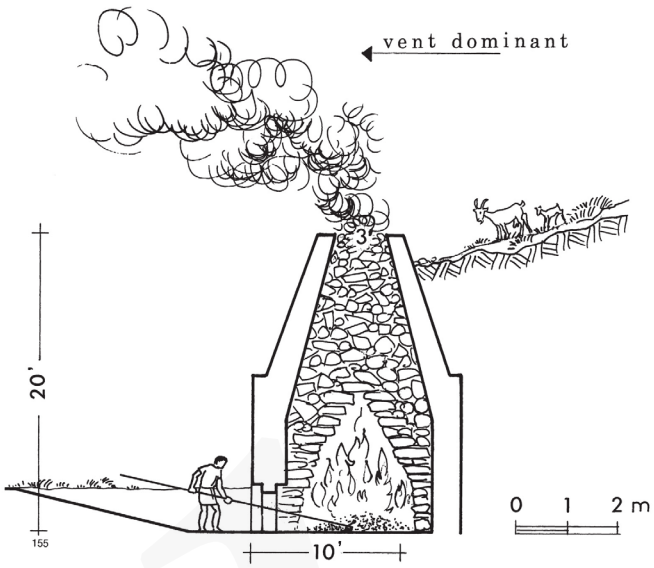


Fig. 2-2 Cato lime kiln restitution (figure 164 page 74[2-2]).

This type of kiln is still in use in countries around the Mediterranean Sea for the fabrication of lime, and also of bricks or ceramics.

Among the limes, "fat" limes with a percentage of clay lower than 1%, that could be obtained from marbles, were much appreciated for bedding mortar. Because of their very long hardening process through the recombination of lime and carbon dioxide, they allowed settlement to be gradual and flexible.

The Romans developped the technology of hydraulic mortars that they inherited from the Greeks (who had inherited them from the Phenicians), by associating lime and either pozzolana or clay powder, called "tuileau" in French, obtained from the pounding of bricks or pottery. This process is described by Vitruvius in detail in famous parts of his *De Architectura Libri Decem*, or Ten Books on Architecture[2-5], that were edited between 33 and 22 BC, according to his own testimony. Book II is related to materials and their general usage. In Chapter 5: *de calce* (about lime), he indicates the importance of preparing a proper lime for mortar mixes and describes the formulation of mortars:

> once the lime has been slaked, mix the mortar (*materia*) according to these formulae: if it is quarry sand (*harena fossilica*), mix three portions of sand to one portion of lime. If it is river or beach sand, mix two portions of sand with one of lime. These are the approximate ratios for the mix. As concerns river or beach sand, if one adds an additional third part of crushed and sifted ceramic (*testam tunsam et succretam*), it will bring a proper temper to the mix and increase its utility.

In Chapter 6, *de pulvere puteolano* (about pozzolana powder), Vitruvius gives the description of what could be referred to as historical Roman concrete (as opposed to that was in modern times called Roman concrete):

> There is a kind of powdery earth (*pulvis*) that by its nature produces wonderful results. It occurs in the neighbourhood of Baiae and the territory of the municipalities around Mount Vesuvius. This material, when mixed with lime and rubble (*calce et caemento*), not only furnishes strength to other buildings, but also, when breakwaters (*moles*) are built in the sea, they set under water (…) Thus when these three substances (ash pozzolan, lime and tuff) formed in a similar manner by the strength of fire [in this volcanic environment] are

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> brought together into one mixture, and suddenly they are put in contact with sea-water, they cohere into a single mass, quickly solidifying, harden by the moisture, and neither the force of the waves nor the effect of water can dissolve them.

And in Book 5, Chapter 12:

> Those concrete structures that are to be in the water must be made in this fashion. Pumiceous volcanic pozzolan is to be brought from the region that runs from Cumae to the Promontory of Minerva and mixed in the trough in the proportion of two parts to one of lime

Adam summarizes as follows the composition of ancient mortars according to Vitruvius[2-2]:

Lime	Sand	Crushed tiles	Pumiceous volcanic ash	Water
1 volume	3 v (Quarry)			15 to 20%
1 volume	2v (River)			15 to 20%
1 volume	2v (River)	1v		15 to 20%
1 volume			2v	15 to 20%

However it will not be until the early 19th Century that lime hydraulicity be scientifically described by Vicat, and progressively explained with the help of modern chemistry. The Romans made an extensive use of them, for terrestrial as well as maritime construction. For the latter, pozzolanic mortar that could set under water, was extensively used.

The main contribution of the Romans was the development of the ancestor of our concrete, by associating hydraulic mortar with large size aggregate. As it appears in Vitruvius' descriptions, Roman concrete was made of mortar (from the latin word *mortarium* which designated first the trough and later its content) and aggregate in the form of decimetric size stones called *caementa.* Mortar and aggregate were not mixed prior to placement, but blended in situ, forming what may be referred to as *opus caementitium.* As we shall see, there should not be any confusion with our concrete and our cement. Adam[2-2] refers in French to "maçonnerie concrète", which we could translate as "concrete masonry".

Aggregates (*caementa*) could be of different natures. Tuff that was available in volcanic areas was extensively used, but in other regions other types of rocks have been used. Advantages of tuff were its lightness and its excellent bond with mortar.

Sea water was used for marine structures, without adverse effects in the absence of iron reinforcement.

Figure 2-3 shows a typical example of a section of a sample of concrete taken on the site of Portus (the major harbour built by Emperors Claudius and Trajan near Rome), one of the many results of the Roman Maritime Concrete Survey (ROMACONS project) that between 2002 and 2009 yielded 36 cores totalling 36.55 m in length, from 11 Roman harbour sites and one fish pond, in Italy, Greece, Turkey, Egypt and Israel. A wide variety of physical, chemical and microstructural analyses was carried out on those cores. The output of this project is presented in: "Building for eternity – the history and technology of Roman concrete engineering in the sea"[2-1]. The purpose of this publication is to present literary, archaeological and analytical data concerning Roman concrete structures built in the sea, with particular focus on the highly specialized marine concrete developed for that purpose. Among many other results, this project has confirmed what previous archaeological works had shown, ie the pertinence of Vitruvius's descriptions and specifications. On these topics one may refer to *Building for Eternity – The History and Technology of Roman Concrete Engineering in the Sea*[2-1] - 7.5 page 175 – Material properties of the maritime concretes.

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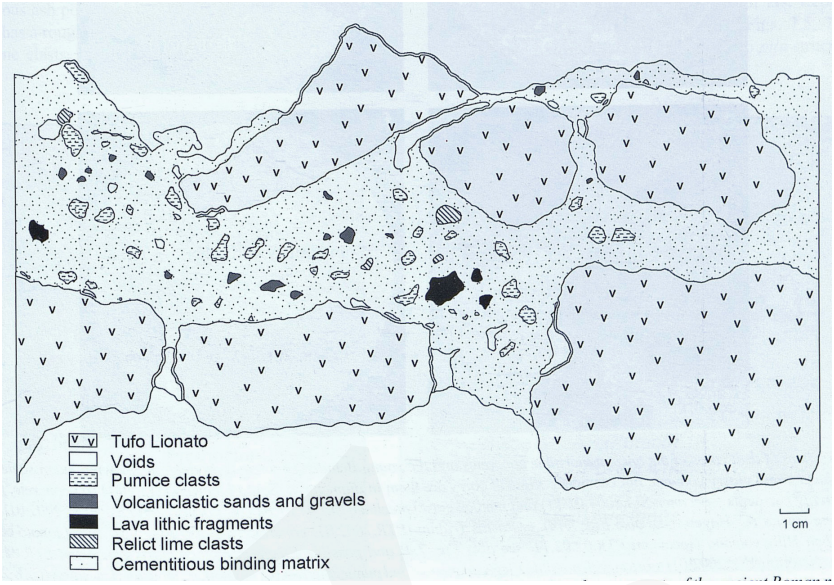


Fig. 2-3 Macroscale map of a segment of the Portus Traiani concrete, showing the principal components of the ancient maritime concrete fabric (figure 7.5 page 145[2-1]).

In a manner similar to that of the ROMACONS team, Heinz-Otto Lamprecht proceeded with investigations of numerous Roman constructions in Germany, Italy, Turkey, Austria and Hungary. In *Opus Caementitium – Bautechnik de Römer*[2-6], he reports on testing results from 42 concrete samples from different Roman building types. In terms of strength, he measured values ranging from 5 to 40 MPa, and concluded:

> With Roman concrete, the history of construction reaches a climax. For example, the compressive strength values of samples 41 and 50 mean that one square centimetre of the surface withstood a load of about 400 kg before the sample broke. This is equivalent to the weight of five to six people; a postcard-sized surface would therefore take the weight of a locomotive of 50 to 60 tonnes. Today, about three quarters of all new concrete buildings have strength values in this range or lower. For reasons of cost, the Romans preferred locally available material as aggregate. Grain composition was based on similar criteria as in our time. The determination of two ancient grading curves showed that this Roman grain composition also fulfils our present-day building regulations.

Among the samples shown by Lamprecht[2-6] some of them seem to indicate an evolution of the concrete formulation during the Imperial period, long after Vitruvius wrote his treatise. In these samples the aggregate size is much smaller than the decimetrical size usually found. This appears for instance in his sample no 25, taken from a harbour storage building (*Horreum*) in Martinsviertel, Cologne (Figure 2-4), dated from the mid-Second Century AD, where the aggregate is described by Lamprecht as "Continuous grading curve approx 0/32 mm, quartz and brick chippings".

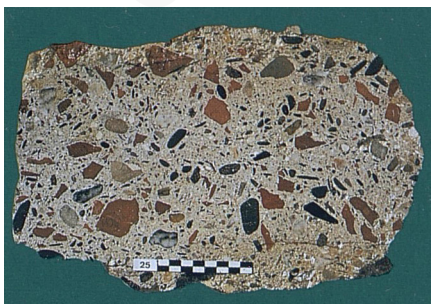


Fig. 2-4 Sample from a harbour storage building in Cologne (Page 63[2-6] – sample no 25).

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It is usually agreed that *opus caementitium* appeared progressively at the end of the Third and during the Second Century BC. Use of lime mortar as a binder for wall construction is mentioned by Cato the Elder in chapter 15 of *de Re Rustica*[2-4], edited in 160 BC (Cato the Elder lived between 234 and 149 BC). In Rome itself, according to Adam[2-2], the first occurrences of *opus caementitium* proven by archaeological investigations and literary references are the Temple of Magna Mater on the Palatine, dedicated in 204 BC, and the great stores of the *emporium,* an early Rome harbour known as *Porticus Aemilia,* built between circa 193 and 174 BC. Improvements were brought to this technique at least until the Second Century AD, two centuries after Vitruvius's treatise. This has been discussed by Lancaster[2-16], [2-17] and summarized as follows by Cellauro and Richaud[2-15]:

> From a rough and unpretentious association of stone and mortar in ancient times, building in concrete was perfected by the Second Century AD. Those employing it knew precisely how to lay aggregate, had full knowledge of *arena fossicia* [excavated (volcanic) sand] – the basic material of ancient Roman buildings in the City of Rome – and were experts in their use of brick facing on both flat and curved surfaces.

As we know Romans developed the art of construction in a manner that would not be surpassed until modern times, and *opus caementitium* played a major role in this development, for terrestrial construction as well as construction under water - the latter mainly in the open sea but also in rivers. One of the main reasons for the success of this type of construction, along with monolithism, strength and durability, was its economic advantage as compared with stone construction, the art of which they had inherited from the Greeks and the Etruscan.

2.1.4 Roman technology of *opus caementitium* for terrestrial constructions

2.1.4.1 Foundations and walls

Opus caementitium was first applied to the construction of walls and foundations, as parts of buildings or as defensive or earth-retaining stand-alone structures.

According to Adam[2-2]: "When the Romans made general use of concrete masonry, they abandoned the construction of *opus quadratum* foundations, especially when these had to occupy a large volume, to build them in *opus caementitium*, whatever the nature of the construction in elevation". These foundations could be cast either directly into a trench, or inside wooden forms made of horizontal planks and vertical post, as shown on Figure 2-5. Evidence of this type of form appears on a number of remaining structures, like the foundations of Titus Arch built by Domitian after 81, where the vertical wooden post left their imprint (Fig. 2-6).

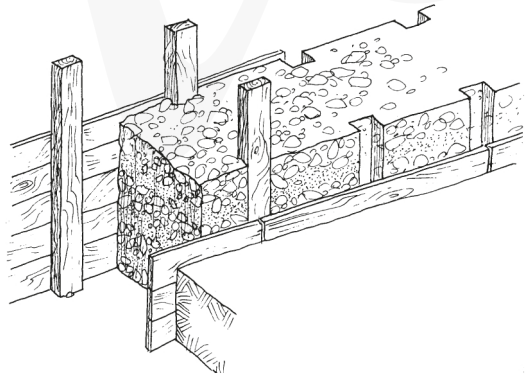


Fig. 2-5 Reconstruction by JP Adam of Foundations forms (Figure 255 page 116 in[2-2]).

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Fig. 2-6 Titus Arch foundations (figure 254 page 116[2-2]).

In most cases *opus caementitium* walls were not cast between shutters, but between facings of different types, that we still know under their Latin names: the main ones were *opus incertum, opus reticulatum, opus vittatum* and *opus testaceum*. These different types appeared progressively. As a consequence of being enclosed between facings, *opus caementitium* does not usually appear on the faces of the walls. (We will see that it is not the case with vaults where it was often cast directly on shutters, and in that case had an external aspect similar to that of our modern concrete). However, in most cases those surfaces were coated with protective and decorative layers of plaster.

In Book II, Chapter 8, of *De Architectura decem libri:de generibus structurae,* Vitruvius describes the different wall construction methods, that coïncide with the observations of today's archaeologists.

The construction site organization of these walls was similar to nowadays installations to build walls with cinder blocks. This is illustrated by drawings by JP Adam shown on Figure 2-7. As it appears on this document notches were left by the scaffolding supports. These notches appear on the faces of a number of remaining Roman walls, as illustrated by Figure 2-8.

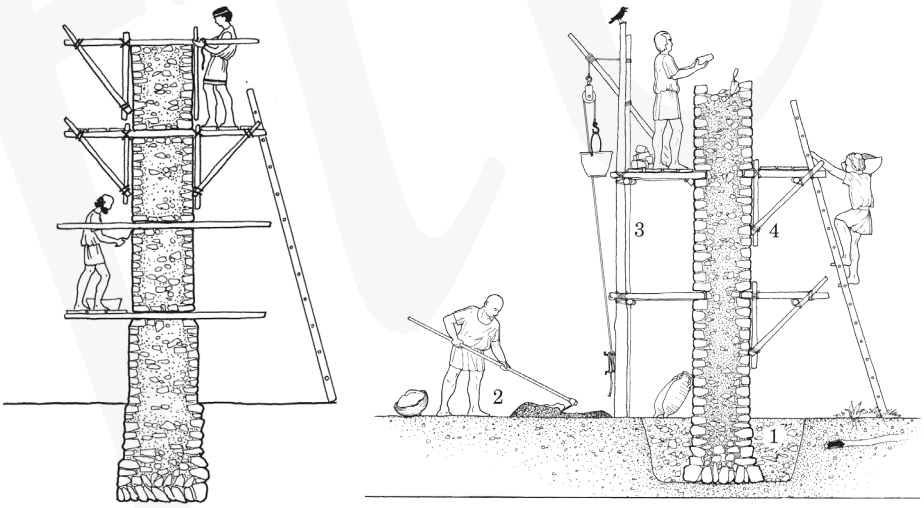


Fig. 2-7 wall construction (figures 195 page 88 and 202 page 90[2-2]).

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Fig. 2-8 notches in a wall in Pompei. *Opus incertum* with brick layers (figure 197 page 88[2-2]).

As explained by Choisy[2-3], in most cases for the construction of walls the Romans placed mortar between the facings in successive layers, and inserted aggregates (*caementa*, stones of decimetric sizes) in each layer before placing a new one. This method avoided applying pressure onto the facings and simplified the operations. It resulted into the presence of voids between mortar and aggregate, that can be seen in remaining structures. In some instances, the fresh masonry was compacted by pounding in the foundations, where pressure could be resisted by adjacent soil, directly or through shuttering, or when *opus caementitium* was placed between heavy stone walls, in a manner inherited from the Greeks "*emplekton*" and described by Vitruvius in Volume II, chapter 8. It might have also been the case in forms used for maritime construction, and over centerings for the construction of arches, vaults, cupolas or domes.

Opus incertum was first developed during the Third Century BC and was in use until the First Century BC. As we see on Figure 2-8, in this case facings were made of stones of irregular shapes and dimensions, similar to those placed inside *opus caementitium*.

Opus reticulatum appeared in Rome at the end of the Second Century BC, and was developed and used in the central part of Italy and Campania until the First Century AD. Exceptionally, some applications may be found outside Italy. This type of facing was made of chipped square stones with their faces placed at 45 degrees to the horizontal. Such an arrangement was probably the result of several factors: standardization of the elements, speed of placement, quality and aspect of the facing. Although it was often coated with some kind of plaster, it resulted in decorative surfaces, sometimes using different coloured stones, arranged with bricks. An example is shown on Figure 2-9. Adam proposes an interesting restitution of *opus reticulatum* covered with three different layers of coating, as shown on Figure 2-10.

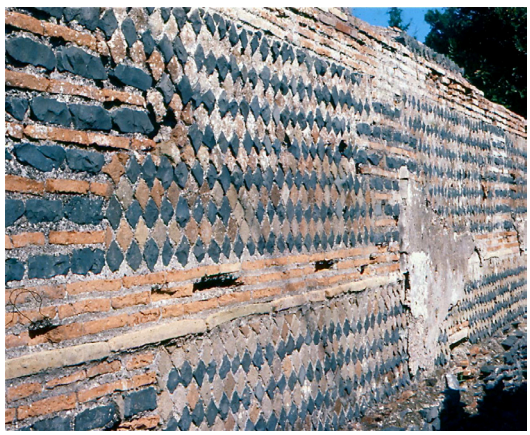


Fig. 2-9 *Opus reticulatum* on a tomb in Ostia (figure 327 page 146[2-2]).

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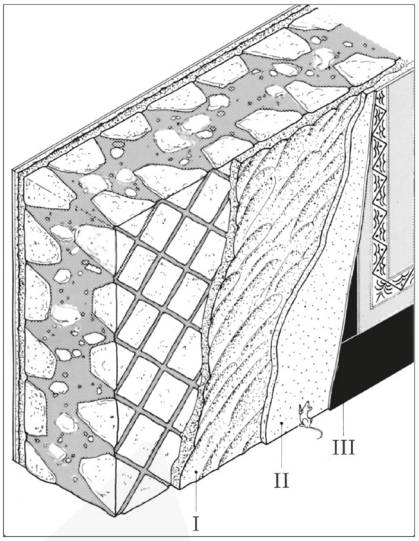


Fig. 2-10 Restitution by JP Adam of *Opus reticulatum* with 3 layers of coating (figure 527 page 236[2-2]).

Opus Vittatum appeared during the Augustinian period and lasted until the end of the Empire and after. It was particularly developed in Roman Gaul. It consisted of chipped rectangular stones of similar thickness in order to form regular layers, with staggered vertical joints. The height of each layer was in the order of 10 to 12 cm, and the horizontal dimension of each stone was in the order of 12 to 20 cm. With such dimensions each element was relatively light and easy to handle. A typical example is shown on figure 2-11. This type of facing was used for the construction of Hadrian's Wall, where the layers either are horizontal or follow the ground slope. This wall was built between 122 and 127 AD approximately along the border between today's England and Scotland, with a total length of approximately 120 km. Figure 2-12 represents two views of this famous wall, which show how *opus caementitium* is somehow enclosed between the facings, which adhere to it.



Fig. 2-11 *Opus Vittatum* – Aquaduct in Metz (figure 337 page 150[2-2]).



Fig. 2-12 Hadrian Wall (figures 342 and 343 page 151[2-2]).

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Opus Testaceum appeared at the end of the Augustinian Period (27 BC – 19 AD) and lasted… for ever! It was indeed based upon brick facings, and bricks, one of the oldest construction materials, are still in use to-day. The Romans had inherited this technique from ancient civilisations in what we would call today the Middle-East, and had created an industry of fired bricks production with high standards of quality. In many of those monuments brick facings were covered with coatings or with marble cladding, but it was not always the case and sometimes different colours and shapes of bricks were used to create elegant "modenatures", as illustrated in Figure 2-13.



Fig. 2-13 *Opus testaceum*. Funeral monument of the second Century AD located between Via Appia and Via Latina (figure 369 page 162[2-2]).

2.1.4.2 Arches, vaults, cupolas and domes

As mentioned earlier, the Romans inherited stone construction techniques from the Greeks and the Etruscans, and they mastered and improved these techniques for the construction of large arches and vaults. But the use of *opus caementitium* brought to these structures the advantages of monolithism and was a great step forward, the importance of which will be matched only by the introduction of reinforcement and prestressing in the 19th and 20th Centuries.

Opus caementitium opened also the way to the construction of large cupolas and domes, with no equivalent in stone construction.

All these structures were built on wooden centerings, in a manner that was in use until the early 20th Century for the construction of large masonry structures.

2.1.4.2.1 Arches

Arch construction found its most significant applications in the construction of aqueducts, a type of structure that is nowadays a symbol of Roman civilization, and in the construction of bridges and viaducts.

Aqueducts

Many aqueducts were built in stone masonry, like the iconic Pont du Gard in the South of France, but many others were built in *opus caementitium.* Among numerous examples we may mention *Aqua Alexandriana,* the last of the 11 aqueducts that supplied Rome. It was built at the beginning of the third Century AD, under the rule of Emperor Alexander Severus (222-235 AD), in *opus caementitium* covered with *opus testaceum* (Figure 2-14). Such aqueducts could be built over very long distances, and their lengths varied from a few kilometres up to 132 km in the case of Cartago aqueduct, in to-day Tunisia. Subsequently they may represent the largest use of *opus caementitium* in public works. Another interesting example is the aqueduct going from Mons to Fréjus in the south of France, where the main supports are transversely tapered to improve stability (Figure 2-15).

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Fig. 2-14 Aqua Alexandriana, at the East of Rome (figure 578 page 263[2-2]).



Fig. 2-15 Aqueduct from Mons to Fréjus (Photo by: Yves Gauthier).

Bridges and viaducts

Roman bridges and viaducts were typically built with stone masonry, often completed above the arches by *opus caementitium*. One of the most famous of these structures, Augustus Bridge in Narni (Umbria) over the Nera River, built circa 27 BC, shows clearly this association. It was 160 m long, had a record central span of 32 metres, and carried Via Flaminia at a height of 30m. Most of it was destroyed in 1053 AD by a flood of the Nera River that scoured the foundations. As shown on Figure 2-16, large remaining parts testify of the long-term solidity of *opus caementitium.*



Fig. 2-16 Augustus Bridge, Narni, Umbria (figure 682 page 311[2-2]).

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2.1.4.2.2 Vaults

At the earliest stages of their history, the Romans mastered the construction of "keyed" stone vaults, that they inherited from previous civilizations. The oldest known vaults of this type are those covering the Three Chapels of the Divine Worshippers of Amon, built in Egypt between 700 and 650 BC, inside the Ramses III Temple enclosure in Thebes.

As in the case of arches, while they developed the technique of keyed stone vaults they also applied *opus caementitium* to this type of structure. Lynne Lancaster[2-16] suggests that the use of *opus caementitium* to build vaults may have been initiated during the Second Century BC, but this is controversial, and the only certitude is that it was well established in the middle of the First Century BC.

These vaults, like arches, cupolas and domes, were built on centerings with wooden shuttering, covered in many cases by layers of bricks following the line of the intrados, in order to provide potential decoration and to facilitate the removal of shuttering planks. In some instances, "caissons" could be modelled inside the vault. These different options are illustrated by Figures 2-17, 2-18 and 2-19.



Fig. 2-17 Imprints of a wide-plank shuttering (figure 451 page 195[2-2]).



Fig. 2-18 Tiles used as shuttering – Ostia 2nd Century AD (figure 448 page 194[2-2]).

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Fig. 2-19 Caissons formed into an annular vault – Praeneste, end of 2nd century BC (figure 454 page 196[2-2]).

The Romans made also use of the vaulting principle for retaining structures with vertical axis vaults, a principle that will be used in modern times for the construction of hydraulic dams. They used these retaining structures either for free-standing earth retaining walls or in the basement of large buildings, like in the case of *caveas* of theatres or amphitheatres, and also to retain water in cisterns. An impressive example is Cistern Fildami in Istanbul, which covered a 127m x 76m rectangle and had a 100'000 m^3 capacity (figure 2-20).



Fig. 2-20 Fildami Cistern in Istambul, 5th Century AD (Figure 72 page 111[2-6]).

The use of *opus caementitium* allowed also the Romans to resolve one of the most challenging construction problems of their times, the crossing of vaults, which they could not resolve with keystone construction (it was only in 530 AD that such a vault crossing was built in Ravenna with cut stones, most probably by an architect from ancient Syria where stereotomy was developed). A remarkable example of such *opus caementitium* vaults crossings, or ridge vaults, covers the Coliseum ambulatory in Rome, built during the Flavian Period (69 to 96 AD). As it appears on Figure 2-21, these vaults were cast directly on shuttering, and the planks imprint can be seen, now that the coating has disappeared.

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Fig. 2-21 Ridge vaults over Rome Coliseum ambulatory (figure 480 page 209[2-2]).

2.1.4.2.3 Cupolas and domes

The distinction between a cupola and a dome is not very clear. We consider here that a cupola is a spherical shell or plate, while a dome is a spherical structure with ribs, often radial or concentric, or both. Domes are in most cases larger than cupolas.

According to Adam[2-2], the construction of cupolas with *opus caementitium* started probably at the end of the 1st Century BC, with a cupola covering a large room in Agrippa's Thermes in Rome. It was followed during the Augustinian period (27BC – 19AD) by a 21.5m diameter cupola covering the main room of Mercury Thermes in Baia, north-west of Naples, (Figure 2-22), then by the cover of the famous octagonal room in Nero's *domus aurea*, built after Rome fire in 65 AD, where horizontal "generatrices" vary progressively upward from an octagon to a circle, as shown on Figure 2-23. As it appears on this axonometric view, the geometry of *domus aurea* cupola allowed the concentration of loads on pillars located under the octagon angles and the opening of large windows in between, an approach that somehow prefigures gothic architecture.



Fig. 2-22 Inside view of Mercury Temple in Baia (figure 466 page 203[2-2]).

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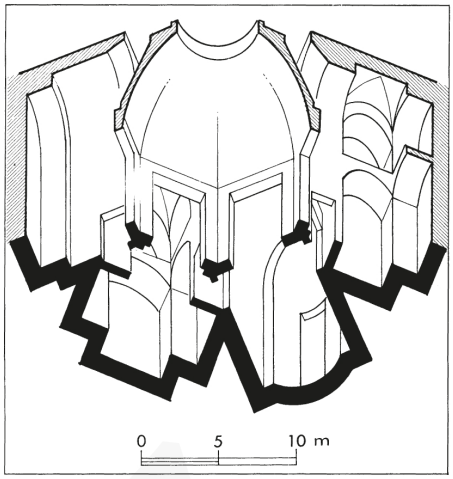


Fig. 2-23 Axonometric view of domus aurea in Rome (figure 467 page 203[2-2]).

Then came the masterpiece, the Pantheon of Rome, built between 118 and 125 AD under Hadrian's rule (117 – 138 AD)

One of the best-preserved Roman monuments, this structure is exceptional by its size, with an inside diameter of 43.3m, that was not surpassed until 1913 and the construction of the 69 m diameter Centennial Hall in Wroclaw, by its architecture, and by the sophisticated way *opus caementitium* was used for its construction.

Its three main architectural features are: its internal geometry, which is perfectly inscribed into a 43,3m diameter sphere (Figure 2-24); the way how, in the lower part of the dome, caissons of variable size delimit radial and concentric ribs (Figure 2-25); and the 9m diameter *oculus* at the top of the dome.

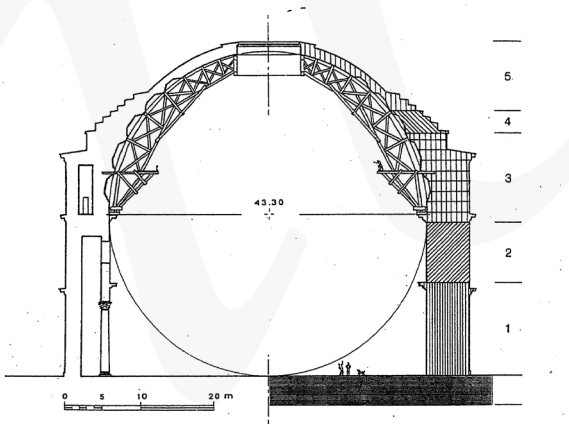


Fig. 2-24 Pantheon cross section, with a reconstruction of the centering (figure 462 page 200[2-2]).



Fig. 2-25 Pantheon ribbed dome and oculus (figure 464 page 202[2-2]).

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This monument was built entirely with *opus caementitium*, of six different types, from the heaviest in the lower parts to the lightest at the top, for obvious structural reasons. These layers, numbered from one to six on Figure 2-24, are described as follows by Adam[2-2]:

> A foundation block consisting of a layer of *opus caementitium* 4.50 m thick, with travertine *caementa*;
>
> 1. A vertical rise to the top of the order of *opus caementitium* with tuff and travertine caementa;
> 2. A second vertical rise until the beginning of the vault in *opus caementitum*, mixing tuff and bricks;
> 3. A first ring of the dome with broken brick only;
> 4. A second ring alternating bricks and tuff rubble;
> 5. Finally, the terminal cap mixing rubble of tuff and alveolar lava.

All six layers were made of *opus caementitium*.

The Pantheon is also a very interesting structure because of its cracked state. Indeed, in a hemispheric shell, tensile hoop stresses are generated in the lower part of the dome. Due to the low tensile strength of concrete, cracks appear when the stresses are larger than this strength. This is the case in the Pantheon where concrete in the lower part has been cracked most probably since its construction. This issue of cracking in the Pantheon dome is analysed by D.P. Billington, and P. Draper[2-8], and by Mark and Hutchinson[2-9]. Both conclude of the positive effect of cracking, which results into a favorable redistribution of stresses.

In *Mémoires d'Hadrien***,** fictive memoirs of Emperor Hadrian written by French scholar and novelist Marguerite Yourcenar[2-7], the author imagined the description by Hadrian of this temple devoted to all gods, which he considered as his own creation:

> I had gone back for the very structure of the edifice to the primitive and fabulous times of Rome, to the round temples of ancient Etruria. I wanted this sanctuary of all the Gods to reproduce the shape of the terrestrial globe and the stellar sphere, of the globe where all the seeds of eternal fire are contained, of the hollow sphere which contains everything. It was also the shape of those ancestral huts where the smoke of the oldest human hearths escaped through a hole at the top. The dome, built of hard and light lava, which seemed to still participate in the upward movement of the flames, communicated with the sky through a large hole alternately black and blue. This open and secret temple was designed like a sundial. The hours went round in circles on these caissons carefully polished by Greek craftsmen; the disc of the day would remain suspended there like a golden shield; the rain would form a pure puddle on the pavement; prayer would escape like smoke to that void where we put the gods.

2.1.4.2.3 Roads

Lamprecht[2-16] provides a clear description of the development of the Roman *vias* across the Empire:

> "All roads lead to Rome" has become a common saying; one could continue it: and meet there at the milliarium aureum (Golden Milestone, image 123). This gilded marble cylinder was erected on the Forum Romanum in 20 BC under Augustus and records the distances to important cities of the world empire. At the same time Agrippa had a large world map compiled in several parts: the commentarii geographici. These "strip maps" were also a prerequisite for the construction of new roads and water pipes. They are also the original version of the "Peutinger's Table" in Vienna, which dates from the 12th/13th century and goes back to a Roman model from the third century AD. The commentarii geographici have not survived. A good road network was an indispensable prerequisite for the domination and administration of the vast *Imperium Romanum*. This network will be planned in such a way that, together with the shipping lines, it forms a meaningful transport system. This is certainly a prerequisite that the Imperium Romanum could be held together for about five centuries. First and foremost are the great trunk roads. The oldest is the Via Appia, which was begun by Appius Claudius as early as 312 BC and initially reached as far as the city of Capua, about 180 km away. It was extended to Brindisi. It has a width of about 8 m. To the north, the Via Aurelia was built in 241 BC and the Via Flaminia in 220 BC. They were followed by the Via Cassia, Via Clodia, Via Salaria and Via Latina. These seven main lines were followed by long-distance connections to all parts of the empire, which, for example, crossed the Alps over five passes. One of them is the long-distance road from present-day Switzerland to the North Sea coast. It follows the course of the Rhine over a length of around 800 km; in Mainz, Xanten and above all in Cologne, crossroads branch off to the west. Its course corresponds today to the Bundesstraße 9. The roads are extraordinarily solidly constructed and, with a total thickness of 80 to 130 cm today, have a layered structure. However, it should be that in the course of time several layers were laid on top of each other (Figures 2-26 and 2-27).

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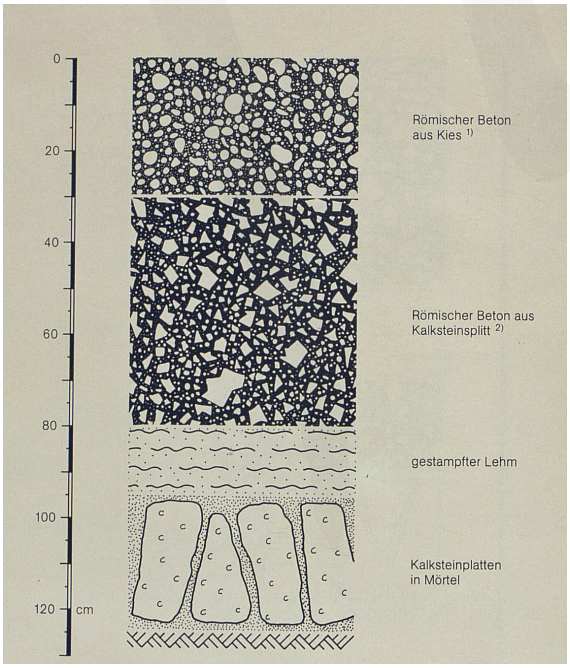


Fig. 2-26 Via Severiana au Sud de Rome – beginning of the 3rd Century AD (Figure 124 page 151[2-6]).



Fig. 2-27 Roman road near Saalburg Roman castle – 2nd Century AD (Figure 125 page 151[2-6]).

Lamprecht provides several typical cross sections of Roman roads located in today's Germany, that include one or two layers of concrete. Figure 2-28 reproduces Lamprecht's cross section of the Roman Trier-Metz road near Bilzingen, with four layers that are described from top to bottom as: Roman concrete (gravel combined with lime); Roman concrete made of sandstone cut into small pieces and bonded with mortar ; tamped clay ; hewn sandstone set in mortar.



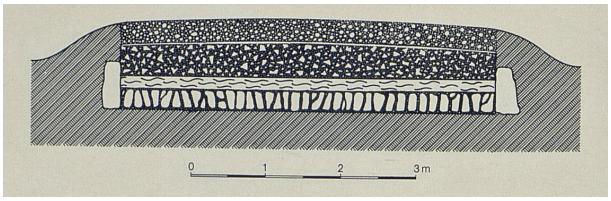


Fig. 2-28 Road Trier-Metz near Bilzingen (Figure 131 page 158[2-6]).

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In a poem written by P Papinius Statius (sometimes referred to as Stace) called *Via Domitiana* (*Silvae, IV, 3, verses 40 to 55*), describing the construction of *Via Domitiana*, a branch route built in AD 95 to replace a poor road along the coast from Rome to Naples, two verses may be interpreted as an indication of the use of pozzolanic mortar for its construction:

Illi saxa ligant opusque tesunt,

Cocto pulvere sordidoque tofo,

JP Oleson[2-1] translates these as: "these workers bind stones together and weave the work with burnt powder (pulvere : pozzolan) and grimy tuff (tofo)". Paul Marie Duval[2-11] gives a similar interpretation, and points out that the use of pozzolan could be explained by the location of the road near Naples, and the fact that this road was built on swampy ground, that could have justified the need of a monolithic structure.

In contradiction with Lamprecht, JP Adam[2-2] dismisses the use of Roman concrete in *vias* and suggests that on this topic a passage of Vitruvius relating to pavements (*expolitiones, in De Architectura, VII, 1*) was misinterpreted. He supported this opinion by three surveys of *Via Flaminia*, *Via Appia* and *Via Aurelia,* that did not show the presence of mortar. This difference may be explained by a specific development of "concrete roads" technology in the part of the Roman Empire corresponding to today's Germany, with an extensive use of concrete layers, including the surface one. We may suggest as a conjecture that the necessity to avoid freeze and thaw deterioration be a reason for that.

2.1.5 Roman technology of *opus caementitium* for underwater, mainly maritime, constructions

Although underwater construction methods developed by the Romans were described in detail by Vitruvius, they have not been given as much attention as conventional terrestrial construction, most probably because of the difficulty of investigating under water, and also because the remains of harbours, even when they can be seen above water, are not as spectacular as those of towns and cities, and do not present such an architectural interest.

While it was not the first investigation project of maritime Roman construction remains, the ROMACONS project and the documentation derived from it, that is presented in *Building for eternity*[2-1], have, because of their amplitude and completeness, brought a new light upon this field of knowledge, and improved it.

According to these recent works and to more ancient sources, it seems reasonable to say that maritime constructions using pozzolanic mortars appeared during the Second Century BC along the western coast of southern Italy, near Naples, with the construction of fish pools by rich owners of *villas,* and the construction of harbours in the Bay of Pozzuoli, conveniently near the places from where pozzolana was extracted.

In Book V of *De Architectura libri decem*, Chapter 12, *De portubus et structuris in aqua faciendis – About ports and underwater masonry construction*, Vitruvius provides detailed descriptions of materials and methods to build in this difficult environment, which show that these methods were well advanced at the end of the First Century BC (Vitruvius *De Architectura* was edited between 30 and 22 BC, during the period of transition from the Republic to the Empire).

CJ Brandon[2-1] proposes the following translation of selected parts of these descriptions, and has reconstructed representations of each of the three methods described by Vituvius (Figure 2-29)

Type A on Figure 2-29 :

> The concrete structures that are to be in the water must be made in this fashion. Pumiceous volcanic pozzolan (*pulvis*; lit. powder) is to be brought from the region that runs from Cumae to the promontory of Minerva [to the west of Naples] and mixed in the trough in the proportion of two parts earth to one of lime. Next, in the designated spot, formwork (*archae*) enclosed by solid (or "oak") post and tie beam (*stipitibus robusteis et catenis*) must be let down into the water and fixed firmly into position. Then the area within it at the bottom, below the water, must be levelled and cleared out, [working] from a platform of small crossbeams (*Ex trastilis or trastillis*). Afterwards aggregate broken in the trough (*caementis in mortario*) and mortar (*materia*) mixed as specified above is to be placed within, until the space inside the form has been filled with the concrete structure (…).

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Type B on Figure 2-29:

> But in locations where pumiceous volcanic ash (*pulvis*) does not occur naturally, one must use the following procedure. Let double-walled formwork (*arcae duplices*) be set up in the designated spot, held together by close set planks and tie-beams (*relatis tabulis et catenis conligatae*), and between the anchoring supports have clay packed down in baskets made of swamp reeds. When it has been well tamped down in this manner, and is as compact as possible, then have the area bounded by the cofferdam emptied and dried out by means of water-screw installations and water-wheels with compartmented rims and bodies. The foundations are to be dug there, within the cofferdam. If the foundations are to be on earth, the area to be excavated and drained must be wider than the wall that will stand above. Then fill the form with aggregate, lime and sand (*structura ex caementis calce et harena*).

Type C on Figure 2-29:

> But if because of waves or the force of the open sea the anchoring supports (*destinae*) cannot hold the forms together, then a platform must be built from the shore itself or from the foundations of the mole, and made as firm as possible. This platform is to be built out with a level upper surface over less than half its area. The section towards the shore is to have a sloping side. Next retaining walls one and one-half feet thick are to be built at the end facing the sea and on either side of the platform, equal in height to the level surface described above. Then the platform section is to be filled in with sand and brought up to the level of the retaining walls and platform surface. Then a concrete block (pila) of the appointed size must be built there, on this levelled surface, and when it has been formed is left at least 2 months to cure. Then the retaining wall that holds in the sand is cut away, and in this manner erosion of the sand by the waves causes the block (pila) to fall into the sea. By this procedure, repeated as often as necessary, the breakwater can be carried seaward.

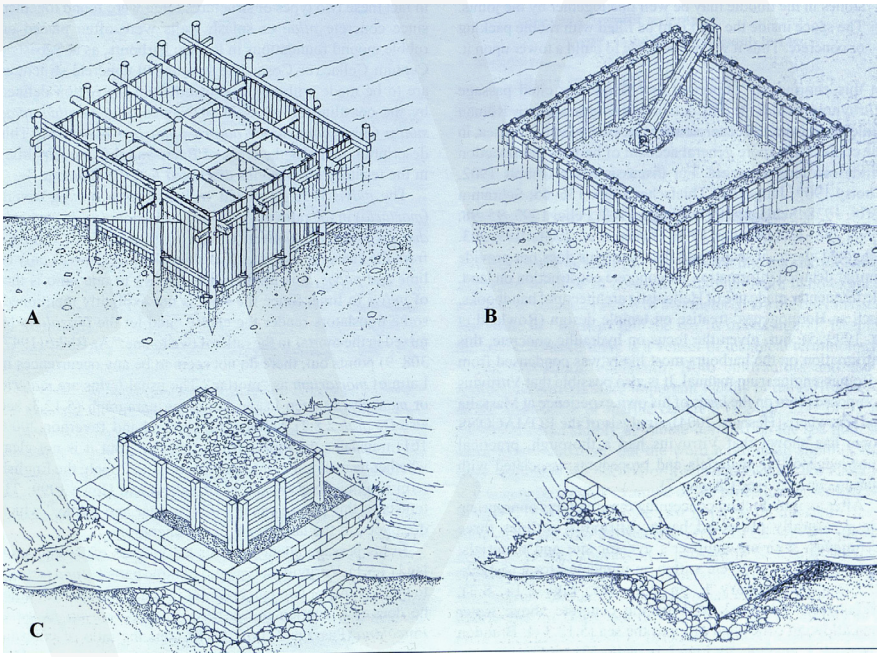


Fig. 2-29 Reconstruction by CJ Brandon of the three types of form mentioned by Vitruvius in Book V, Chapter 12 (figure 2.1 page 21[2-1]).

Archaeological evidence has only partly confirmed Vitruvius's descriptions. Type A and type B have been clearly identified on a number of sites, while Type C has not. However, it appears from archaeological sources that in the situation described by Vitruvius to justify Type C methodology ("But if because of waves or the force of the open sea the anchoring supports cannot hold the forms together"), the Romans developed a method using prefabricated forms that could be launched from the shore. C.J. Brandon has proposed a reconstruction of the floating and setting into place of caissons for the construction of the main enclosing mole at Sebastos, the harbour of King Herod's city of Caesarea Palaestinae (Figure 2-30).

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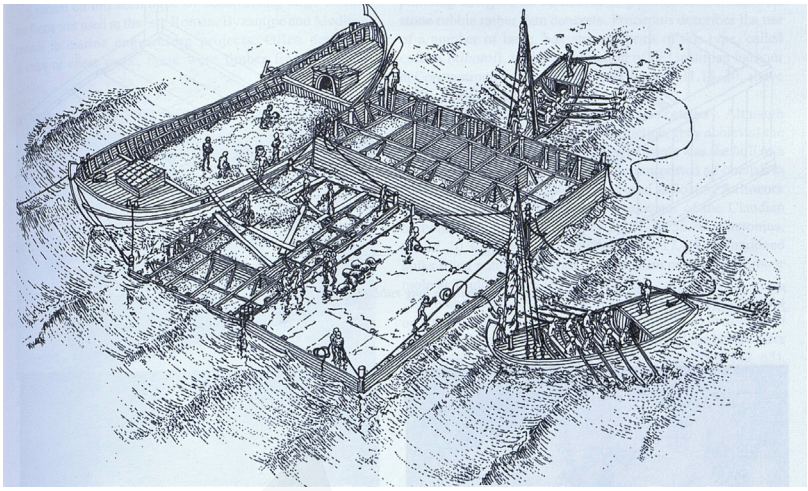


Fig. 2-30 Reconstruction of prefabricated caissons being positioned and loaded with concrete (figure 8.52 page 213[2-1]).

Archaelogical evidence of this formwork technology consists of voids or imprints left by the wooden elements, or sometimes by the remains of such elements. For instance, a picture taken underwater in the harbour of Alexandria (Figure 2-31) shows the remains of the base of a caisson made of wooden planks, that, among many other elements, supports the idea of prefabrication of such caissons.



Fig. 2-31 Base of caisson, Antirhodos Island, within the eastern harbour of Alexandria (figure 8.54 page 213[2-1]).

From all the data collected, C.J. Brandon[2-1] proposes a typology of formwork design for underwater construction:

- Category 1: inundated form constructed in situ, corresponding to Vitruvius type A, as illustrated on Figure 2-29;
- Category 2: cofferdam formwork constructed in situ, designed for dewatering, to be used either with non-pozzolanic or pozzolanic mortar, corresponding to Vitruvius Type B, as illustrated on Figure 2-29;
- Category 3: prefabricated and floating forms, that were not described by Vitruvius, but deducted from archaeological works, as illustrated on Figure 2-30. Falling into this last category are single-walled caissons, double-walled caissons, and redundant ship hulls used as formwork.

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According to Brandon,

> the most famous example of formwork that falls within this category [redundant ship hulls used as formwork] was the enormous ship used by Caligula to transport an obelisk from Heliopolis in Egypt in AD 37 (…). After delivery - the obelisk still survives, moved to the plaza in front of Vatican by Domenico Fontan in 1586 – the ship was laid up in Puteoli (…); Eventually she was towed to Ostia, on the order of Claudius, already loaded with *pozzolana* ballast from Puteoli or its environ. (…) the ballast was probably unloaded at the harbour construction site to allow mixing with lime in the appropriate proportions; then the mortar would have been reloaded in the hull along with tuff or heavier weight aggregate, forming a maritime concrete. When the ship was only slightly buoyant, it was probably towed a few hundred meters to the gap between the two breakwaters and sunk with the addition of more concrete, to serve as the foundation of a large lighthouse.

This exceptional event is clearly described by Pliny the Elder in his *Historia Naturalis*, and by C. Suetonius Tranquillus in his biography of Claudius.

These advanced methods greatly contributed to the expansion of the Roman Empire around the Mediterranean Sea, with the installation of a dense network of harbours associating large "hubs" to smaller installations. Figure 2-32 shows the number and locations of identified Roman harbours around the Mediterranean Sea.

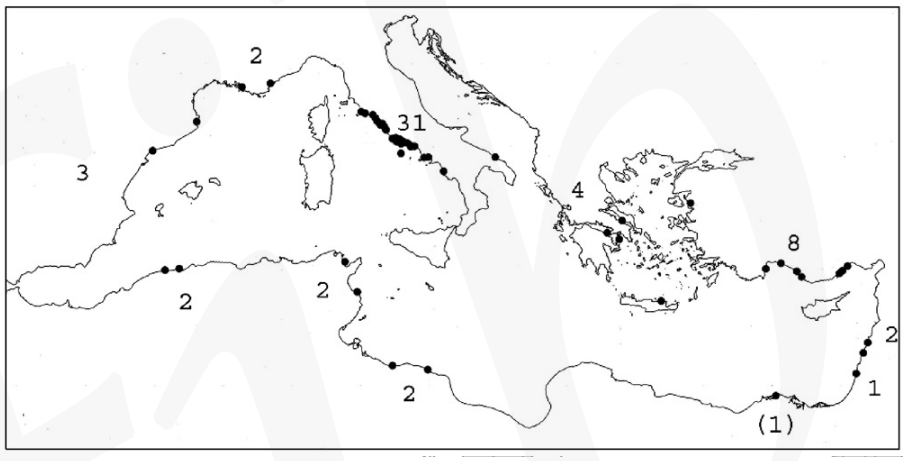


Fig. 2-32 Map of the Mediterranean with the location and number of roman maritime sites, from the 2nd century BC to the Byzantine era[2-10].

This network of harbours was particularly helpful in feeding Rome, a city with a population of one million people at its apogee. The largest of these harbours, Portus, was built near Rome, ca 4 km north of the mouth of the Tiber River, under the rule of Emperor Claudius (AD 41-53) and his successors, to provide the capital city with food and supplies from all the Mediterranean world.

This highly developed maritime traffic allowed the supply of pozzolana to harbour construction sites around the Mediterranean Sea. It appears indeed from the analysis of the cores taken by the ROMACONS team from Roman harbours in different locations around the Mediterranean Sea that the mortars used for their construction contained pumiceous volcanic ash from the area of Naples, and sometimes even aggregates from the same origin. According to R.L. Hohlfelder and J.P. Oleson, "none of the ROMACONS samples so far analysed seem to show characteristics corresponding to volcanic origins from the Aeolian or Aegean Islands, so a hypothesis suggesting export from the Gulf of Naples seems reasonable based on the present evidence"[2-1].

2.2 The Middle Ages

The Middle Ages lasted in Europe from the Firth to the Fifteenth Century AD, and were quite mistakenly considered as a period of darkness and barbarism until the middle of the Nineteenth Century. This might be

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why there is a kind of myth that Roman knowledge of concrete was lost or kept secret in monasteries during this period. The reality is certainly more complex.

As Rainer Nobis indicates in his Illustrated History of Cement and Concrete[2-20]:

> Building methods and rules continued to exist and good building materials and the knowledge of their advantages and disadvantages were still known. So not all knowledge was lost. However, specialist knowledge was mainly applied only in monumental and important projects. Famous examples in Constantinople include the Hagia Sophia (built between 532 and 537) and the Hagia Irene (6th century) and in today's Italy, the great basilicas of Rome: Old St. Peter's (4th century) and San Vitale in Ravenna (early 6th century).

Vitruvius's treatise was not completely forgotten. Georg Germann, in his *Einführung in die Geschichte der Architekturtheorie*, *Introduction to the history of architectural theory*[2-14], wrote:

> (…) the Ten Books will not go unnoticed. Until the Renaissance, they will be mentioned almost in every century, as shown by Herbert Koch in his work 'Vom Nachleben des Vitruv', 'From the afterlife of Vitruvius' (1951). The survival of Vitruvius to the Carolingian and Ottonian eras has been studied by Carol Heitz (1974), while Carol Herselle Krinsky (1967) provides an overview of the 78 medieval manuscripts, complete or partial, of the Ten Books. We owe Luigi Vagnetti and Laura Marcucci (1978) the complete, commented and illustrated bibliography.

A testimony of the transmission of concrete Roman technology are the important concrete structures built in Rome during the second half of the Middle Ages. Louis Cellauro and Gilbert Richaud, in *Palladio and concrete – Archeology Innovation Legacy*[2-15], wrote :

> In fact, rather than suddenly re-emerging in the Renaissance, the ancient Roman tradition of building walls and vaults in concrete continued uninterrupted in the Eternal City during the Middle Ages, as attested to by features in several important Late Medieval churches: the thirteenth-century vaults of the monastery of San Marino ai Monti, the barrel vault of the prothyrum of St Praxedes (eleventh to twelfth centuries) and the groined and barrel vaults of the so-called Chapel of San Giuliano of San Paolo fuori le Mura (twelfth century). It is most probable that what happened in Rome, not only during the Middle Ages but later on during the Renaissance period, happened in other cities of the immense Roman Empire, where the Roman concrete technology had been widely disseminated. It could be the case in particular in the area of the Byzantine Empire. This would be an interesting topic of research, or more simply of information gathering, since documentation most probably already exists.

As it relates to marine concrete technology, R.L. Hohlfelder and J.P. Oleson are of a different opinion[2-1]:

> It is likely that the sophisticated Roman techniques of preparing marine concrete, along with the carefully constructed formwork in which to place it, died out along with the final cessation of major Imperial harbor construction in the later sixth century. When harbor construction commenced once again in the fourteenth or fifteenth centuries, the extraordinary Roman recipe based on the products of pyroclastic volcanism had been forgotten.

2.3 The Renaissance period

The Renaissance marked the transition from the Middle Ages to the Modern Period and comprised the Fifteenth and Sixteenth Centuries. It was characterized by an effort to revive and surpass ideas and achievements of classical antiquity. This is very much the case in the field of architecture and construction. Indeed, during this period, Vitruvius *De Architectura Libri Decem* was not only copied and transmitted, but was commented, revisited and, thanks to the invention of printing in the 1450s, widely disseminated. It became the fundamental reference to all treatises on architecture, a situation that would last until the Ninetheenth Century. The first of these treatises that was printed, *De re aedificatoria,* was written by Leon Battista Alberti (1404 – 1472). His book was printed in 1485, after his death. Similarly to Vitruvius work, it comprised ten books and covered all aspects of architecture and construction technology, with due reference to Vitruvius principles, in particular the three criteria : *firmitas*, *utilitas* and *venustas*. and also to *relevés* from Roman monuments.

This great interest to Roman architecture is also illustrated by a letter to the Pope Leon X, also referred to as *the brief about monuments conservation*, written during the years 1510. According to Bonelli, the authors are Raffaelo Sanzio, known as Raphael, and Baldassare Castiglione, but there is no

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certainty about that. This report to the Pope presents the history of Roman monuments, the reasons in favour of conservation, and a surveying methodology. Complaining about the lack of protection of these monuments during the Middle Ages, the authors wrote[2-14]:

> How many have had foundations excavated only to extract pozzolana, so that the monuments collapsed subsequently? How much lime has been burnt from ancient statues and monuments! Yes, I dare say it: all this new Rome, however great it may be, so beautiful, so rich in palaces, churches and other monuments visible today, is entirely built with lime made from ancient marbles.

Andrea Palladio (1508-1580) is known as a major architect of the Italian Renaissance for the villas he designed and built, mainly in Tuscany. He was, as his contemporaries, deeply influenced by Vitruvius. He collaborated with Daniele Barbaro to publish in 1556 an illustrated and commented translation of Vitruvius, which became a major reference, and published himself in 1570 *I quattro libri de architectura.* According to Louis Cellauro and Gilbert Richaud[2-15],

> "Palladio reconstruction of ancient masonry techniques, and in particular his ideas on the use of removable wooden formworks for the infill walling technique, which he termed *la maniera reimpiuta*, were taken up by later writers, who contributed in varying degrees to their dissemination. Palladio's treatise would become almost the sole source of reference for authors discussing ancient masonry in eighteenth-century France."

Among these later writers and builders, who referred to Vitruvius and Palladio, one may find : Jacques-Raymond Lucotte (c1733-1804) who published an article entitled *Maçonnerie* in Diderot and d'Alembert *Encyclopédie,* Jean Rondelet (1743-1829) in the pages he dedicated to materials and building techniques in his *Traité théorique et pratique de l'art de bâtir,* Claude Fleuret (1744-1817) in his book, *L'art de composer des pierres factices aussi dures que le caillou.* These works inspired in turn people like François Coignet with his *béton aggloméré,* and we can therefore trace a multi secular filiation from Vitruvius to Palladio and from Palladio to François Coignet and later Tony Garnier and his *béton ordinaire* (unreinforced ordinary concrete).

As it was already the case during the Middle Ages, concrete construction in Rome went on during the Renaissance period. We may refer again here to Cellauro and Richaud[2-15] :

> A major early Renaissance example is the *all'antica* coffered barrel vault built by Francesco del Borgo (c.1415-68) in the vestibule of the Palazzo Venezia in Rome (c. 1466) [Figure 2-33] (…) However it was Donato Bramante (1444-1514) who experimented more consistently with Roman methods of concreting, using concrete for the core of the crossing piers and for the large arches of St Peter's (1511-13) (…) It is likely that Bramante also intended the dome of St Peter's to be built in concrete [with reference to the Pantheon in Rome]. There is no evidence for this, but he would certainly at least have envisaged it as a serious option at some stage of his design process.

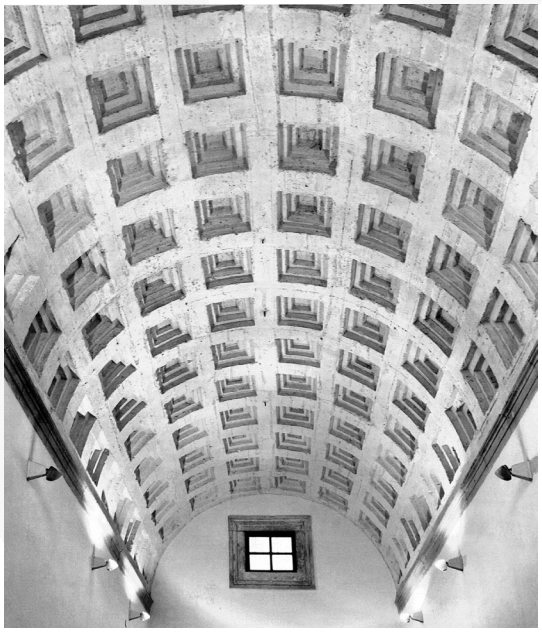


Fig. 2-33 Francesco del Borgo, coffered barrel vault of the vestibule of the Palazzo Venezzia in Rome, c. 1466 (photo Sailko, Wikipedia commons).

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2.4 Conclusion

We may quote here Haegermann[2-13]:

> Kaschnitz von Weinberg paid tribute to the introduction of cast masonry into Roman building techniques in the following way: " . . . All these things (i.e. aqueducts, vaults, bridges), however great they may be, are of lesser importance compared to a technical innovation which, perhaps, in the history of European architecture is equal to nothing in revolutionary importance: the invention, or more correctly, the introduction of mortar work (i.e. cast masonry - author) into monumental architecture"[2-18]. And in 1892, a British author, Middleton[2-19], observed that the "eternal" of the city of Rome had not only a proverbial, figurative sense, but was also based on something purely material: the durability of the buildings erected by means of the pozzolana.

The Romans created what we would nowadays refer to as a concrete industry, with its methods, standards, textbooks and practical manuals, from which unfortunately Vitruvius' *de Architectura decem libri* only was saved. All this knowledge spread across the whole Empire, thanks to the powerful centralized Roman administration. This tradition, saved during the Middle Ages, was revisited, widely commented and illustrated during the Renaissance. Concrete construction went on in Rome during these periods, and most probably not only in Rome but in other cities of the Empire.

Vitruvius treatise describes the "state of the art" at the end of the first century BC. Consequently, it does not include all the evolutions of the Roman concrete technology that must have taken place afterward, during the Imperial period, and we lack ancient documents to fully interpret the progress of this period.

Roman works were not matched in size, quality and complexity until the modern times and the industrial revolution. They remained the main reference for architects and builders for 15 centuries after the end of the Roman Empire, until the early Twentieth Century.

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3. Binders and Cements during the Eighteenth and Nineteenth Centuries

3.1 Renaissance

In 1414, a copy of *De Architectura* by the Roman author Vitruvius[3-1] was rediscovered at St Gallen Abbey, Switzerland, which, with similar finds in the early Renaissance period indicated in Chapter 2, gradually reawakened throughout Europe a residual awareness of classical construction methods and materials. These included the use of pozzolana in lime mortar. Vitruvius's text was first printed in 1486 by Fra Giovanni Sulpitius – but not before Alberti had drawn on the classical work for his *De re aedificatoria*, posthumously published in 1485 – and an illustrated edition was prepared in 1511 by Fra Giovanni Giocondo, a member of the *Frères du Pont* (or order of *Bridge Builders*). The text was translated successively into Italian during the 1520s, German in 1528, French (1547), Spanish (1582) and eventually into English (1692). Architects such as the aforementioned Alberti, the French classicist de l'Orme and above all, Palladio – whose *I Quattro libri dell'Architettura* of 1570[3-2] had such influence on architecture in both Italy and England – all quoted Vitruvius in their writing. Such reference to antiquity was an oft-repeated pattern in the writing of the next two centuries.

Likewise, in a more practical treatise, Joseph Moxon of Wakefield (1627-1691) cited Vitruvius in the vernacular English of his *Mechanick Exercises, or the Doctrine of Handy Works*, 1685[3-3], [3-4] In England, as throughout northern Europe, trass from the Rhineland became an increasingly accepted addition to lime during the seventeenth century, in much the same way as pozzolana continued to be used in Italy.

3.2 The Augustan Age

Indeed, pozzolana was used for what was, at the time the largest English engineering project to have been attempted: the mole at Tangier, constructed between 1663 and 1683, following the city's acquisition on Catherine of Braganza's marriage to Charles II. The works were directed by Sir Henry Shere, advised by Genovese engineers who recommended and supplied pozzolana from Italian sources. As others were to do in future, he experimented with a series of formulations to determine the optimum mix for mortar's setting and hardening under water.

In England, the Restoration of 1660 ushered in a new era of scientific experimentation and discovery, with parallels found in the Enlightenment of eighteenth-century France and elsewhere in Europe, and the search for a hydraulic lime as an improved binder was among the many subjects of enquiry[3-5]. An early authority was Bernard Forest de Belidor whose *Science des ingenieurs* of 1729 discussed mortar[3-6], but although he promoted the use of trass, he also perpetuated the widely held error that the purer the limestone the better the lime. In his later four-volume *Architecture hydraulique* of 1737-53[3-7], he described harbour works at Toulon in which he used a combination of 12 parts of pozzolana or trass, with 9 of quicklime and 6 of sand. This use of pozzolana was the subject of a later study published in 1778 by Barthelemy-Fauja de Saint-Fond.

Similar aims were attempted by George Semple in 1752, when reconstructing the foundations of Essex Bridge across the River Liffey in Dublin, Ireland[3-8]. Here Semple filled a cofferdam with "small stones, grave, sharp clean sand and finely powdered lime, thrown in promiscuously so as to mix equally together"[3-9]. But like Belidor, he accepted the belief that the best limestone yielded the best building lime.

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In England, the late seventeenth century and the reign of Queen Anne to 1714, saw a considerable increase in the use of brickwork for domestic building, and the adaptation or replacement of earlier half-timbered buildings. Not only was lime mortar used for hydraulic engineering, but increasingly for bricklaying and stucco – render marked to look like dressed stone. Demand for the latter led to the development of a class of material known as oil cement, which enjoyed a brief vogue in the later Eighteenth Century.

Table 3-1 British Patents for Oil-Based Cements[3-9]

Date	Name	**Medium**	**Possible Fillers**
1737	Alexander Emerton	Pail and oil	Stone dust, powdered glass, sand
1765	Rev Dr Daniel Wark	Oil	Stone dust, marble drift sand, clay, brick dust, brown sugar, lime, various calcareous earths
1772	Charles Rawlinson	Linseed oil	Whiting, sea-coal, brick dust, white & red lead
1773	John Liardet	Drying oil	Any absorbent matter, lead, sand, gravel
1776	John Liardet	Oil	Calcined and pulverised calcareous matter, white or red lead, sand, marble, mineral powder
1777	John Johnson	Oil	As above but with the addition of serum of blood

Though the medium was oil, the purpose to which these cements were put acted as a stimulus to the later development of Roman and Portland cements. But the great advance in this period was the investigation into hydraulic limes conducted by John Smeaton in the 1750s.

3.3 John Smeaton, 1756

Smeaton was the first to undertake a scientific investigation into why certain limes would set under water and what it was that affected its rate of hardening. Commissioned to replace Rudyard's wooden lighthouse on the Eddystone Rocks, he commenced a series of experiments in 1756 to find a suitable masonry mortar that would withstand the frequent drenching of this storm-swept location off the English coast near Plymouth[3-10]. It has been said of him that in doing so, "the results he arrived at were very remarkable not only for their practical utility, but also as an illustration of the ease with which a very acute observer may stop short of the attainment of a great truth"[3-11].

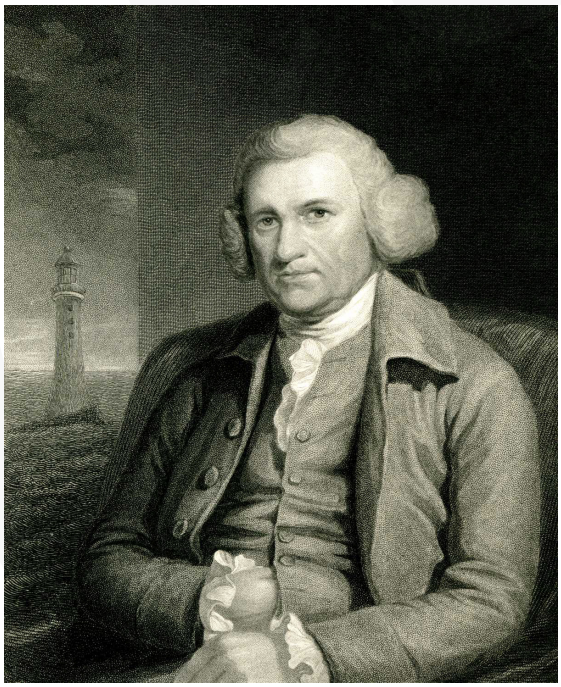


Fig. 3-1 John Smeaton (Photo: The Concrete Society).

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Contradicting the contemporary belief that the hardest stones yield the best limes – "Its acquisition of hardness under water did not depend upon the hardness of the stone; in as much as chalk lime appeared to be as good as that burnt from Plymouth marble" (Smeaton quoted by Pasley[3-12]) – Smeaton discovered that the best raw material for a 'water lime' was, in fact, impure limestone. Those limes that did set underwater all contained a naturally occurring quantity of clay, varying between 6% and 20%: "The fitness of lime for water-building depended on the amount and composition of clay impurity." Smeaton tested 300 limestones and the best of these appeared to be Aberthaw Blue Lias, which occurred on either side of the Bristol Channel and typically contained 86.2% calcium carbonate and 11.2% clay. Added to this, he reaffirmed the Roman practice of combining pozzolana – finding a consignment from Civita Veccia gave the best results for his purposes, though he also considered trass and "some ferruginous substance of a similar nature" as alternatives. He even tried burnt ironstone and forge scales. His preferred proportion of pozzolana to calcined lime was 50:50[3-11].

This hydraulic combination was used to seal the 1493 interlocking granite blocks with which the Eddystone Lighthouse was eventually completed in 1759, resisting the constant spray over the foundations. The construction was so successful that the lighthouse survived until its replacement by a larger structure in 1882 and relocation to Plymouth Hoe, where it remains to this day. Smeaton's hydraulic lime mixture was specified for British Government contracts until as late as 1867 when Portland cement was finally substituted during the extension of the Chatham Dockyard (Bernays quoted by Spackman[3-13]).

Although he established how limes would set under water, Smeaton hadn't quite discovered cement. He did, however, point the way for others to follow, and his findings – which were finally published in 1791 – directly influenced the subsequent development of both natural and artificial cements.

Until Smeaton's *Narrative* appeared in 1791, however, other investigators remained unaware of his conclusions. Notable among these was 'Bry' (Bryan) Higgins[3-14] whose *Experiments and observations made with the view of improving the art of composing and applying calcareous cements and of preparing quick-lime* was published in 1780, just months after obtaining a patent for hydraulic cement-based stucco. His experiments were to investigate the principles governing the "induration" (or hardening) and strength of cements in order to produce a mortar that was better than the Roman equivalent. He prepared mixtures from various sources of lime and sand, recording their characteristics, and subjected the resulting specimens to a range of exposure conditions. The data thus obtained enabled Higgins to comment on the choice of constituents and the optimum proportions when mixed. He also examined the effects of organic admixtures such as ox blood and linseed oil, and additions including various types of ash. The specification he finally patented was for a mixture of quartzitic sand with a binder that combined equal quantities of bone ash with a finely ground lime that "heats the most in slaking and which slakes the most when watered"[3-9]. According to Spackman[3-13], although Higgins appears to have been unaware of Smeaton, he did cite other researchers of the day – including a Monsieur Loriot whose *New discovery in the art of building* was published in 1774 and quoted from the classical authority, Vitruvius[3-15].

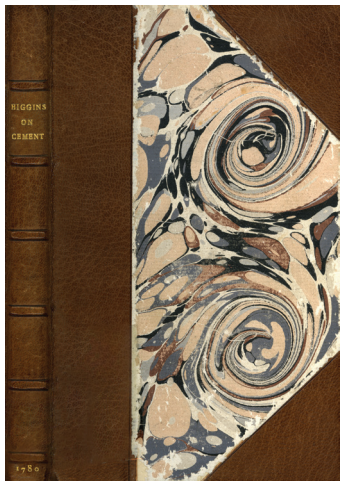


Fig. 3-2 Bry Higgins's Experiments and observations of 1780[3-14] (Photo: The Concrete Society).

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Despite his experiments, the stucco Higgins patented proved unstable in practice, and the conclusions of other investigators, such as Perronet and Fourcroy de Ramecourt in France, remained ephemeral. Commercially successful cement finally came onto the market in 1796 with the patenting of 'Roman cement' by the Revd. James Parker.

3.4 James Parker's discovery of Roman Cement, 1796

In 1791, the year of Smeaton's eventual publication, Parker was a leaseholder of land on the riverside at Northfleet, and from 17 May, the patentee of a process of calcining chalk and limestone. In 1796, having been in business at Northfleet and Lambeth during the intervening years, he took out another patent for "a certain cement or terras to be used in aquatic and other buildings and stucco work"[3-16] a material we would now describe as a natural cement. An account of Parker's discovery was published retrospectively, describing it as "purely accidental":

> "When on a visit to the Isle of Sheppey, he was strolling along under its high cliffs on the northern side and was struck with the singular uniformity of character of the stones upon the beach and which were also observable sticking in the cliffs here and there. On the beach, however, the accumulation of ages, they lay very thick. He took home with him two or three in his pocket and without any precise object in view, threw one onto the parlour fire from which in the course of the day it rolled out thoroughly calcined. In the evening he was pleased to recognise his old friend upon the hearth, and the result of some unpremeditated experiments with it has been the introduction to this country of a strong, durable and valuable cement.
>
> (Anon[3-17] quoted by Francis[3-16]).

Parker's patent[3-18] specifies the reduction to a powder of "certain stones or argillaceous products called noddles of clay" (quoted by Francis[3-16]. These, known today as septaria, he described as "concretions of clay containing veins of calcareous matter …," traces of iron oxide giving the resulting cement its characteristically brown colour. Once ground, the cement was mixed in proportions of two measures of water to five of powder, the mixture setting within 10 to 20 minutes, either in or out of the water.

In March and April 1796, just prior to the grant of patent on 28 June, the eminent engineer Thomas Telford tested the new material and wrote to a client that he considered himself "fully justified in recommending to the Directors to use Mr Parker's Composition, in place of Dutch Tarras, in constructing of the Pier at Lochbay in Skye" (quoted by Blezard[3-19], [3-20]). Besides marine applications, Telford also proposed its use for cisterns, arches, flat roofs and, when mixed with lime, as stucco.

Bringing his new material to market, Parker named it "Roman cemen" in a promotional pamphlet headed *Roman cement, artificial terras and stucco*[3-21], presumably for the hydraulic qualities which enabled it to take the place of the pozzolanas used since antiquity. Certainly the precedence of classical Rome was widely appreciated at the time, and previous investigations into cement production had cited the Romans' example, such as Loriot's *Cement and artificial stone: justly supposed to be that of the Greeks and Romans* in 1774[3-15], and de la Faye's *Recherche sur la preparation que les Romains donnoient a la chaux* in 1787[3-22].

However, despite Telford's endorsement and the protection afforded by his patent, Parker found business sluggish and he soon sold his rights to Samuel Wyatt, who traded henceforth as Parker & Wyatt.

Septaria – the cement stones used as the material for Roman cement – were to be found around the British Isles, particularly in the Thames estuary at Sheppey and Harwich, and off the Yorkshire coast. When Parker's patent expired in 1810, a considerable industry developed in these and other locations, and Roman cement became the leading cement of the first half of the nineteenth century. The first new entrant was James Frost at Harwich in 1807 – government contracts protecting him from

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prosecution for breach of patent – followed in 1810 by Messrs Francis & White at Blackfriars, in 1811 by James Grellier at Sheerness and William Atkinson at Sandsend, Yorkshire, and by Samuel Shepherd at Faversham in 1813. Sundry other companies were established in Kent, Essex and along the Thames during the 1820s, as well as on the Humber, and in Derbyshire and Glasgow in the 1830s. Manufacture of Roman cement commenced in Somerset and Staffordshire in the 1840s. The Roman cement industry in England, at that time, is described by Francis[3-16], Gooding & Halstead[3-23], and Thurston[3-24].

Mr J. Mitchell of Sheerness Dockyard conducted a series of experiments on the various sources of Harwich and Sheppey septaria[3-12]. But perhaps the best-known demonstration of the qualities of Roman cement was a test to the destruction of an 'Experimental Brick Beam' erected for the Southampton Railway near its London terminus in Vauxhall. This brickwork beam had an unsupported span of 21 feet 4 inches between piers (Figure 3-3). Burdened with a suspended cradle loaded with pig iron, it bore nearly 11 tons without deflection or cracks for almost two years. *The Civil Engineer & Architect's Journal* described it as "a surprising proof of the strength of adhesion of Roman cement" (according to a letter, quoted by Francis[3-16]). Eventually, in February 1838, it was loaded as an experiment witnessed by the Council of the Institution of Civil Engineers and many Fellows of the Royal Society. It broke only when the suspended weight reached about 30¼ tons.

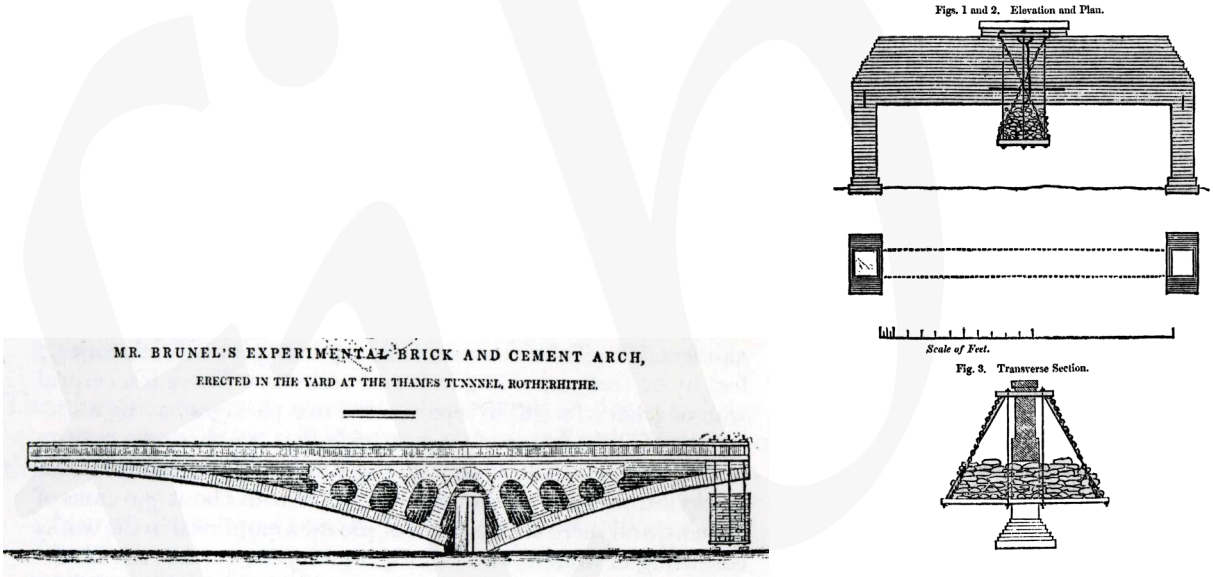


Fig. 3-3 Experiments with bricks and cement in 1832 and 1838[3-16], [3-12].

Parker was not the only pioneer at the turn of the century, however, and nor was British industry alone in manufacturing cement. Developments in Britain had parallels in America and France too. In 1796 a French military engineer named Lesage discovered the hydraulic properties of pebbles on the beach at Boulogne-sur-Mer and commenced production, and across the Atlantic, in 1817, Canvass White found a natural cement rock in the state of New York. By 1818 natural cements derived from argillaceous magnesian limestone were being produced at Rosendale in the USA and were used initially in building the Erie Canal. An American industry developed and from an output of 300'000 barrels in its first decade, production rose to an annual peak of 9'868'179 barrels in 1899[3-25]. Likewise in Europe, the manufacture of Roman cement was gradually taken up during the century, especially in the German states, Switzerland and the diverse provinces of the Austro-Hungarian Empire, as indicated in (Figure 3-4)[3-26].

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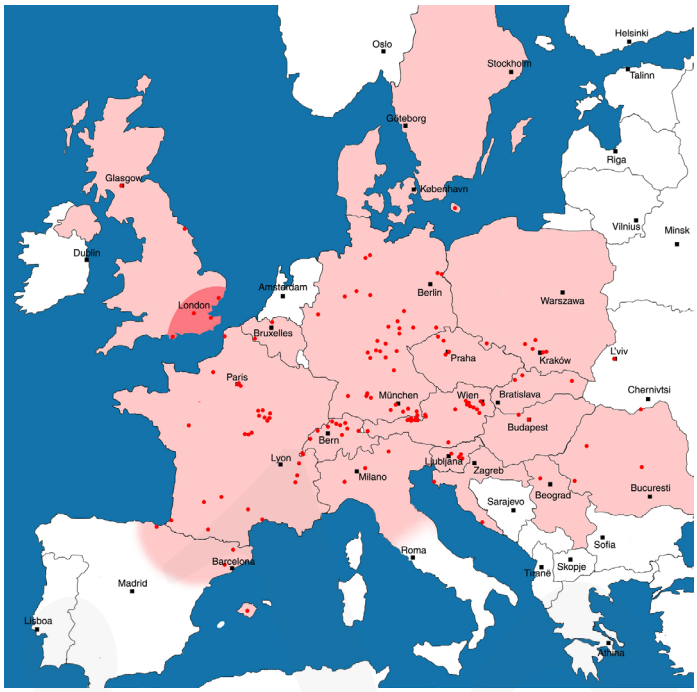


Fig. 3-4 Location of the principal Roman cement plants in nineteenth-century Europe[3-26] (Map: J. Weber).

3.5 French investigators, 1805-1813

As Enlightenment gave way to the Revolution in France, the emerging Napoleonic Empire encouraged the practice of scholarship and practical experiment, given greater urgency by the demands of war and the requirements of naval and military engineering. Among the most prominent investigators were the following (compiled from[3-12], [3-13]):

1787. Jean Antoine Chaptal, ***chemist*** – experimented in making artificial pozzolana by calcining clays and schists found in Languedoc, and tested at the harbour of Cette.

1805. M. Gratien le Père, ***Engineer-in-chief at Cherbourg*** – experimented with calcined shale, especially of Haineville, to replace the wartime shortage of pozzolana needed for works at the port of Cherbourg.

1807. J.B. Vitalis, ***Professor of Chemistry at Rouen*** – analysed hydraulic limestone from Sainte Catherine and Senonces – "limestone marls in with the chalk predominates, but where clay plays an important role" and in which manganese was not present – and proposing clay as the source of hydraulicity: "it is this proportion of clay which, according to me, makes the lime of these two types of stone 'maigre' [hydraulic]"[3-27]. He also experimented on local earths to convert to artificial pozzolana and tested in the Seine.

1808. M. Daudin, ***engineer of roads and bridges, engaged on the Canal du Midi*** – investigated the properties of natural and artificial pozzolanas, and proposed the use of calcined siliceous iron ore as a substitute for pozzolana (silica 50%, iron oxide 31%, alumina 16%, and manganese oxide 3%).

1807. M. Fleuret, ***Professor of Architecture at the Royal Military College at Paris*** – used tile dust or iron slag to supplement the lime that he mixed with sand or ground stone when manufacturing artificial stone at his own factory.

1812. Jean Rondelet, ***architect***– drawing heavily on Vitruvius, he described good practice in making and using mortar and offered the results of experiments into crushing strength and adhesion.

1813. Collet Descotils, ***Professor of Chemistry at the School of Mines*** – analysed Senoches limestone and found it contained silica that, after calcination, proved to be soluble in acids. He attributed its hydraulic properties to this combination of soluble silica with lime.

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This period of experimentation culminated in the work of Louis Joseph Vicat, of his contemporaries the one whose name is most readily recalled today, continuing as it does as that of a test apparatus and a cement manufacturing company.

3.6 Louis Joseph Vicat, 1812-18

Vicat trained as a civil engineer and in 1812, just a few years after graduating from the Ecole des Ponts et Chaussées, was commissioned to build a bridge over the Dordogne at Souillac. The challenges of this site, however, prompted him to experiment with suitable materials with which to fulfil the project, and which he wrote up and published in 1818 as *Recherches expérimentales sur les chaux de construction, les bétons et les mortiers ordinaires*[3-28].

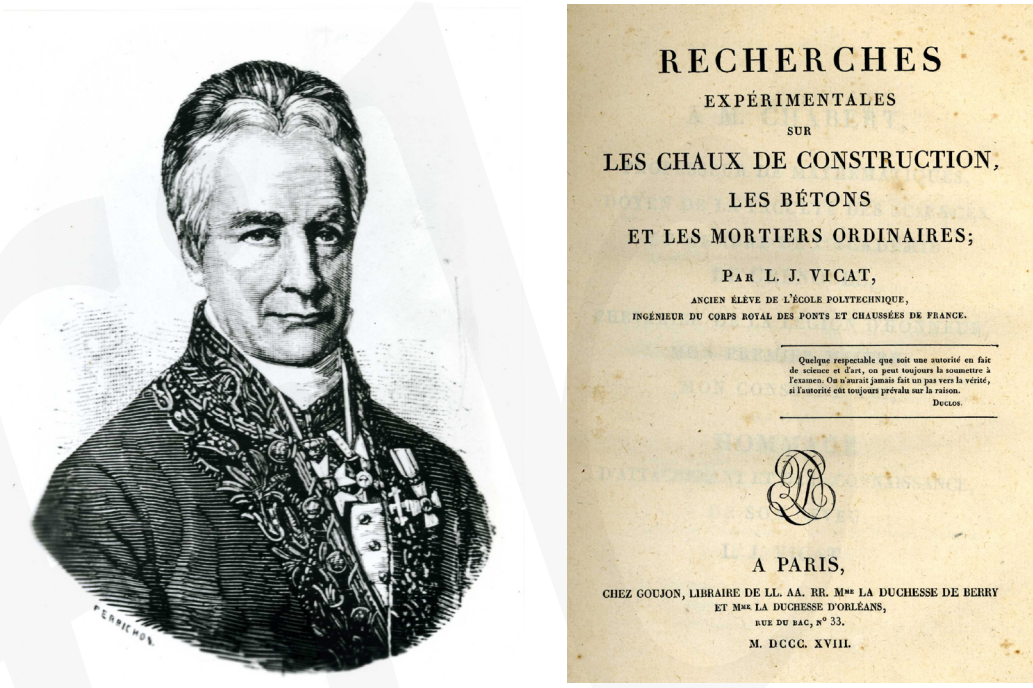


Fig. 3-5 Vicat and his *Recherches Expérimentales* of 1818[3-28].

This work tabulated the results of his tests on 15 sources of lime, and later he set out the first systematic classification of limes and hydraulic limes. Drawing on the data – and referring to the classical authors Vitruvius and Pliny, and the British investigators Smeaton and Parker – he proposed a theory of the setting and hardening of lime mortars in water, even coining the term 'hydraulic'[3-29], [3-30], [3.31]. He directed his conclusions to the invention of an artificial hydraulic lime, a mix of calcined limestone and slaked lime with clay. He experimented with the grinding process and firing temperatures, and established the optimum proportions of his constituent materials. His specification combined limestone (43cu m), slaked lime (34.55cu m) and clay (5.76cu m) – ground in a wet mill and burnt for six days with 150cu m of wood. Having reported his preliminary findings in 1817, he demonstrated his hydraulic lime a year later to the French Academy of Sciences, which approved its use unhindered by patents. His suggestion that hydraulic limes or cements could be produced artificially by firing blends of limestone (or chalk) and clay was taken up by others – including Maurice St Leger at Meudon near Paris, and James Frost and Colonel Pasley in England – and independently confirmed by the experiments of Prof Johann Friedrich John (1782-1847) of Berlin, in his book *Uber Kalk und Mortel* (1819)[3-5], [3-13], [3-32].

On the other hand, practical experiments undertaken during the repair of the French fortress at Strasburg convinced Vicat's contemporary, General Treussart, that the ancient use of pozzolana in lime mortar was a preferable substitute for naturally hydraulic limes than its artificial alternative. The pamphlet Treussart published in 1829 challenged the conclusions drawn by Vicat.

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3.7 Early specifications for artificial cements, 1811-1830

Although the production of Roman cement expanded considerably after the expiry of Parker's patent in 1810, as new producers entered the market, there were several early attempts to artificially replicate the naturally cementitious qualities of septaria[3-33]. Edgar Dobbs of Southwark was among the first in England, filing a patent in 1810 for a mixture of three parts of chalk, one part of clay and one of ash "such as is sold by the dealers in breeze"[3-34], but his business was short-lived. James Frost, having commenced in Roman cement, also turned to the manufactured product. Travelling to France he sought Vicat's advice before bringing his experiments to a commercial conclusion in 1822, with a patent for a material he named "British Cement"[3-35].

> I select such limestones or marls or magnesian limestones or marls as are entirely or nearly free from any admixture of alumina or argillaceous earth, and contain from nine to forty per cent. of siliceous earth, or silica, or combinations of silica and oxide of iron, the silica being in excess and in a finely-divided state, and break such selected materials into small pieces, which are then calcined in a kiln … until all carbonic acid be expelled, and … the calcined material is to be ground to a fine powder …
>
> (quoted by Newman[3-9] and Redgrave[3-36]).

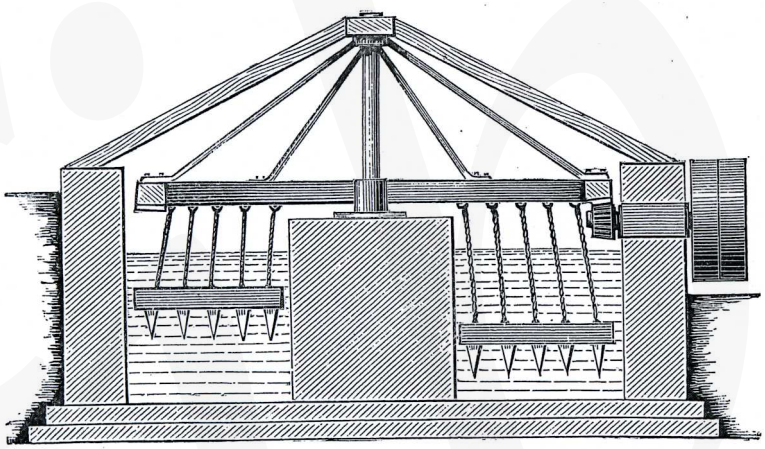


Fig. 3-6 The harrow-type wash mill used by Frost (Reid[3-37]).

Frost ground his materials according to local practice, rather than Vicat's preferred method, though he adopted the Frenchman's use of the wash mill shown in Figure 3-6. He set up a works in 1825 at Swanscombe, on the Thames in Kent, from which he introduced his product to the market. It was first used at Hungerford Market, in the foundations and stucco. British Cement was lightly calcined and sold at a cheaper price than Roman cement, having a "cohesive strength" of about two thirds when tested in 1837[3-12]. Its quality relative to other cements may be gauged by the following tensile strengths at 11 days: Frost's British cement (17.6 lbs/in^2); Francis's Roman cement (30.6 lbs/in^2) – and Pasley's [*see below*] (34.9 lbs/in^2)[3-36].

Experimenting with artificial cements shortly after Frost commenced production was Lt. Col. (later Gen. Sir Charles) Pasley, the officer commanding the Royal Engineers' establishment at Chatham from its foundation in 1812. In 1826, he introduced a course in Practical Architecture and turned his attention to the challenge of making an artificial Roman cement.

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He instigated an extensive series of experiments and visited Frost at Swanscombe in 1828 to compare materials and methods. Eventually he proposed a mixture of five parts of chalk to two parts clay, specifying the blue clays of the Medway mudflats, and published his findings in 1830: *Observations, deduced from experiment, upon the natural water cements of England and on the artificial cements that may be used as substitutes for them*[3-38]. He went on to write in much greater detail eight years later and, by the time of its second edition in 1847, his *Observations on Limes, calcareous cements, etc*[3-12] was the standard text on the subject in English.



Fig. 3-7 General Sir Charles Pasley (Photo: The Concrete Society).

Another of Frost's contemporaries was William Lockwood. With Roman cement being used largely for stucco and architectural modelling, Lockwood – the proprietor of a building firm in Woodbridge, Suffolk, which in 1804 had become agents for Parker & Wyatt's Roman cement – was drawn to the idea of producing a stone-coloured cement by careful selection of the sources of lime used. In 1817 he toured the country for appropriate limestone: to the East Midlands, to Dorset, and to Bristol and South Wales. At some point between 1819 and 1822, Lockwood extended his operations to premises in Spitalfields and, with James Pulham placed in charge, began the small-scale production of an experimental stone-coloured cement for his firm's own use. Swansea lime was considered to combine a sufficient quality with the ease of availability by sea. Joined by his son William Jr. in 1822, Lockwood set up in full-scale manufacture in Woodbridge, using lime from Swansea and Barrow, and a windmill for grinding. Significantly, in view of Joseph Aspdin's patent of 1824, Lockwood was trading – in 1823 – as a "*Portland and Roman cement manufacturer*" as attested by the *Pigot's London & provincial directory for 1823* - a trade directory of that year[3-39] (Cited by Francis[3-16]).

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3.8 Aspdin's patent for Portland Cement, 1824

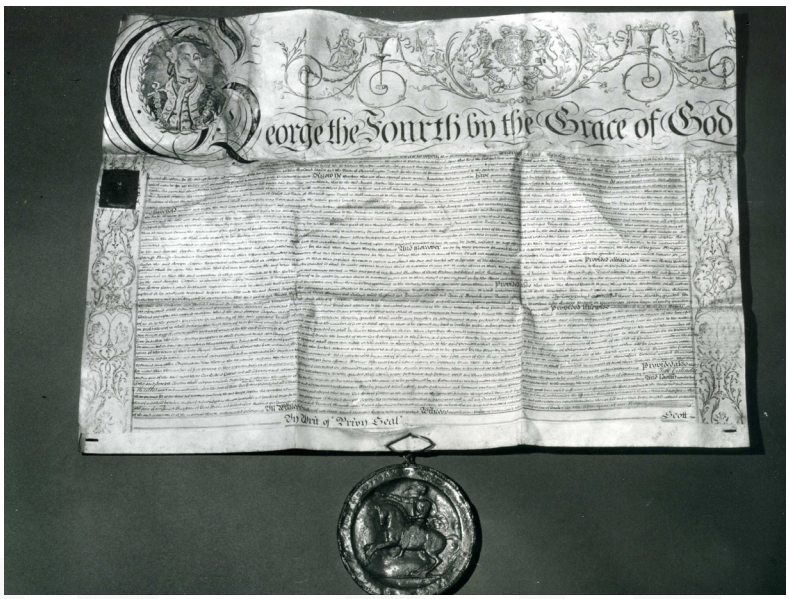


Fig. 3-8 Aspdin's patent for Portland cement, 1824 (Photo: The Concrete Society).

Joseph Aspdin's patent for Portland cement[3-40] is by far the most famous of its kind and the direct progenitor of the present Portland cement manufacturing industry. However, its wording is opaque, either by oversight or design, as no useful information is supplied regarding the relative proportions of limestone and clay, the kiln temperature, the duration of firing or the fineness of grinding.

> I take a specific quantity of limestone such as that generally used for making and repairing roads, after it is reduced to a puddle or powder; but if I cannot procure a sufficient quantity of the above from the roads, I obtain the limestone itself and I cause the puddle or powder, or the limestone as the case may be, to be calcined. I then take a specific quantity of argillaceous earth or clay and mix them in water to a state approaching impalpability, either by manual labour or machinery. After this proceeding, I put the above mixture into a slip pan for evaporation, either by the heat of the sun or by submitting it to the action of fire or steam conveyed in flues or pipes under or near the pan until the water is entirely evaporated. Then I break the said mixture into suitable lumps and calcine them in a furnace similar to a limekiln till the carbonic acid is entirely expelled. The mixture so calcined is to be ground, beat or rolled to a fine powder and is then in a fit state for making cement or artificial stone. This powder is to be mixed with a sufficient quantity of water to bring it to the consistency of mortar and thus applied to the purposes wanted.[3-41]

Although the name 'Portland cement' is introduced – from its association with the qualities and prestige of the then fashionable Portland stone which cement stuccos were designed to emulate, and a comparison also made by Higgins in 1780[3-14] and Smeaton in 1791[3-10] – it is certain that the material differed somewhat from its modern equivalent.

"Nothing more than a hydraulic lime", it has been argued: "its mineralogy was completely different, as was its hydraulic activity"[3-19]. It offered "little evidence of $CaO\text{-}SiO_2$ interaction", as the firing temperature was "too low for compound synthesis"[3-42]. Nonetheless, Aspdin's patent marks an essential step in the development that led to the Portland cements of today. Aspdin's gravestone of 1855 is clearly inscribed "Inventor of the Patent Portland Cement"[3-43].

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Fig. 3-9 Joseph Aspdin's gravestone (Photo: The Concrete Society).

Despite doubts as to the quality of Aspdin's early binders, often expressed by historians of the industry, double-burning the limestone and the fine subdivision achieved by slaking during the intermediate stage, would have represented an advance on the light burning of wet-mixed chalk and clay on which such as Frost and others relied[3-31]. Aspdin is known to have used a kiln of glass-furnace design rather than the traditional limekiln[3-42], [3-44]. The importance of a thorough amalgamation of materials is recognised in the specification of "*a state approaching impalpability*". It is also without doubt that Aspdin and his sons produced cement with commercial success for many years into the Portland era.

3.9 Early Portland cements, 1824-1844

During the early years of production, it seems likely that kiln temperatures failed to reach the point of incipient fusion or vitrification (ie. around 1'450 °C, at which clinker forms[3-19], [3-20], [3-42]. This was a period in which the technology, while constantly improving, had not achieved the characteristics we would recognise today as a true Portland cement, regardless of the name under which it was marketed.



Fig. 3-10 Aspdin's first cement works at Kirkgate, Wakefield (Photo: The Concrete Society).

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Aspdin was a bricklayer and builder from Leeds, whose experiments with cement from 1811 onward indicate a familiarity with the work of fellow Yorkshireman John Smeaton, and his own contemporaries Parker, Frost and others. Indeed, a copy of the 1813 edition of Smeaton remains with his descendants. Having registered his patent on 21 October 1824, and a supplementary one the following year, Aspdin established a factory in Kirkgate, Wakefield – depicted as Figure 3-10 – where he continued to manufacture until 1838. He resumed production at a nearby site in 1839 and relocated to Ings Road in 1848. When the cement industry consultant and publicist Henry Reid visited in the 1870s, he considered the cement had been much improved during these 20 years. However, there is little evidence to adduce for this: Reid was writing many years after the event, having visited replacement works, while the claim by Joseph's son William Aspdin that Brunel had employed Portland cement in repairing the Thames Tunnel in 1828 does not bear scrutiny[3-45].

3.10 William Aspdin and the discovery of clinkering

In July 1841 William Aspdin left the family firm in Wakefield and made his way to London where by the summer of 1843 he had become involved with cement manufacture in Rotherhithe at a works owned by J.M. Maude, Son & Co. An announcement by this firm made it clear that Portland cement was being introduced to the London market, its manufacture locally overcoming the high cost of carriage from Yorkshire. But this same announcement indicated it was a new cement: "as a consequence of improvements introduced in the manufacture … it is stronger in its cementive qualities, harder, more durable, and will take more sand than any other cement now used" (as quoted by Redgrave[3-36]). Clinkering or overburning had been found to improve strength, even if one might presume the discovery was accidental.



Fig. 3-11 William Aspdin (Photo: The Concrete Society).

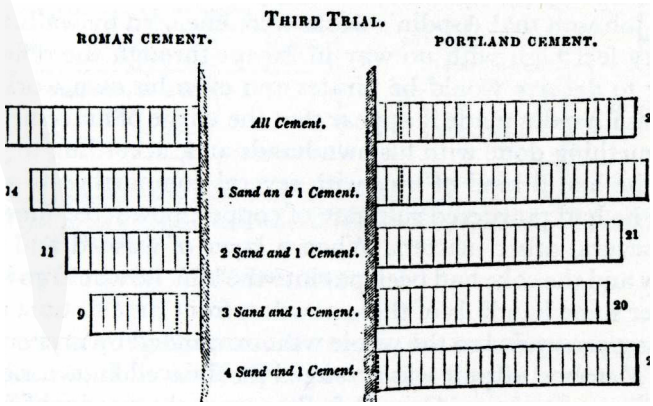


Fig. 3-12 Test results from Grissell & Peto. Contemporary test report, reproduced by Francis[3-16].

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It was not long before this new Portland cement was put to the test. In 1843 the contractors rebuilding the Houses of Parliament, Messrs Grissell & Peto, undertook comparative tests. They summarised the results, illustrated in Figure 3-12, in a letter of 13 November, acknowledging "very satisfactory evidence of the superiority of your cement"[3-36]. Mixed with three parts of sand, Portland cement was more than double the strength of Roman. Positive publicity and some influential advocacy followed shortly afterwards, while the threat of shortages and taxation, and a building site disaster at Euston in 1848, undermined the previous dominance of Roman cement.

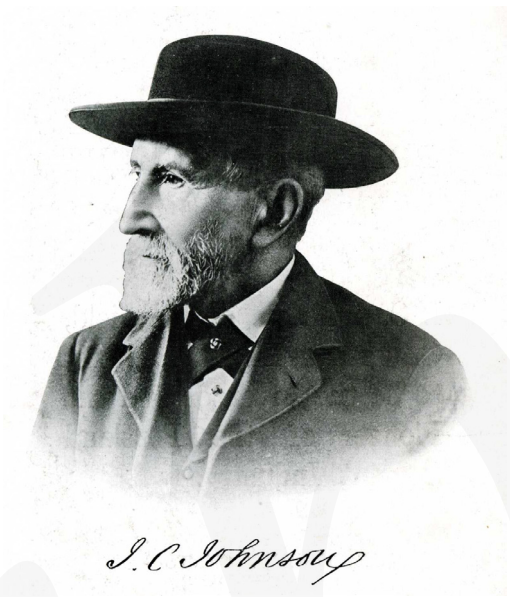


Fig. 3-13 Isaac Johnson[3-46].

Responding to the evident potential of this improvement, and "attracted by the flourish of trumpets, that was then being made about the new cement"[3-47] the long-established Roman cement firm J.B. White & Sons turned to its manufacture in 1844. The company's works at Swanscombe were under the direction of Isaac Johnson who, having studied chemistry in his evenings, attempted to emulate the rival firm's product. First seeking a chemical analysis of Maude and Aspdin's cement, he experimented with additions of bone ash, then with the mineral constituents of septaria respectively from Sheppey and Harwich, before combining chalk and alluvial mud in the way Frost had. Finding material that had accidentally vitrified, probably during the winter of 1844/45 he "pulverised some of the clinker and gauged it":

> It did not seem as though it would harden at all and no warmth was produced. I then made mixtures of the powdered clinker and powdered light burnt stuff and this did set and soon became hard. On examining some days later the clinker only, I found it much harder than the mixture, moreover the colour was of a nice grey.[3-47]

Independently Johnson had discovered the secret of Portland cement, one that the Aspdins had been at pains to protect, and for the rest of his long life – he died in 1911 aged 100 – Johnson claimed to be its true inventor[3-46]. Advertisements in *The Builder* from April 1845 indicate that J.B. White & Sons were manufacturing Portland cement, alongside their existing Roman and Keene's cements (the latter an alum-based gypsum plaster patented in 1838)[3-48].

In early 1846, William Aspdin responded to an opportunity to rent the former Parker & Wyatt works at Northfleet and later entered a partnership with William Robins and his son-in-law, to engage in business there as Robins, Aspdin & Co. An early kiln from these works has been preserved and is illustrated in Figure 3-14. Commercial rivalry between the two enterprises, now neighbours on Kent's Thameside, led to further testing, claims and counter claims, which spurred the development of the product and leave us a record of its progress.

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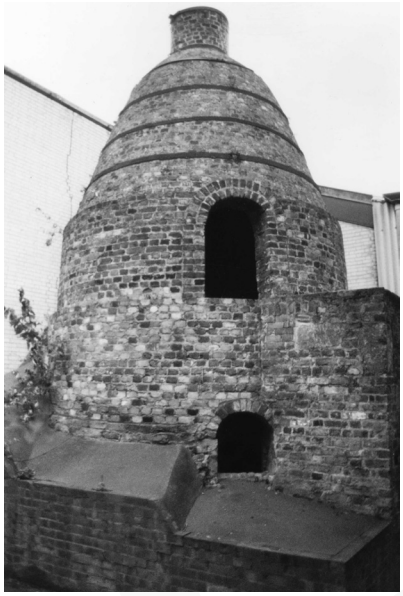


Fig. 3-14 Early kiln at Northfleet (Photo: The Concrete Society).

In December 1847 White's Portland cement was submitted for trials at Messrs. Grissell's works, and the results were published in *The Builder*[3-49]. As in the 1843 tests of Maude and Aspdin's cement, White's demonstrated a clear superiority over Roman cement. Aspdin appears to have been irked by the publicity and in the following September, issued a circular quoting favourable test results and calling for public trials of his cement. These trials were conducted on 18th September and at Messrs. Bramah's works on the 26th. These indicated that Portland cement was 2.4 times as strong as Roman (and double the price). It was also 20% stronger than White's equivalent.



Fig. 3-15 (Left) Barrels of hardened cement used in building the Ship on Shore (Photo: The Concrete Society); (Right) Close view of barrels (Photo: The Concrete Society).

Retrospective microscopical examination of preserved Portland cement made in Aspdin's plant at Northfleet indicates that he had attained a sufficient temperature to achieve vitrification and produce alite crystals. Several investigators independently have examined evidence from the *Ship-on-Shore* public house, constructed from solidified barrels of hydrated cement in 1848, and from mouldings at Portland Hall, erected in Gravesend in around 1850[3-50]. They agree in identifying the material of similar characteristics, rather coarsely ground. D.L. Rayment, for instance, using electron microprobe analysis, has proved that hydrates were identical to the compositions of inner and outer hydrates of modern Portland cements[3.51].

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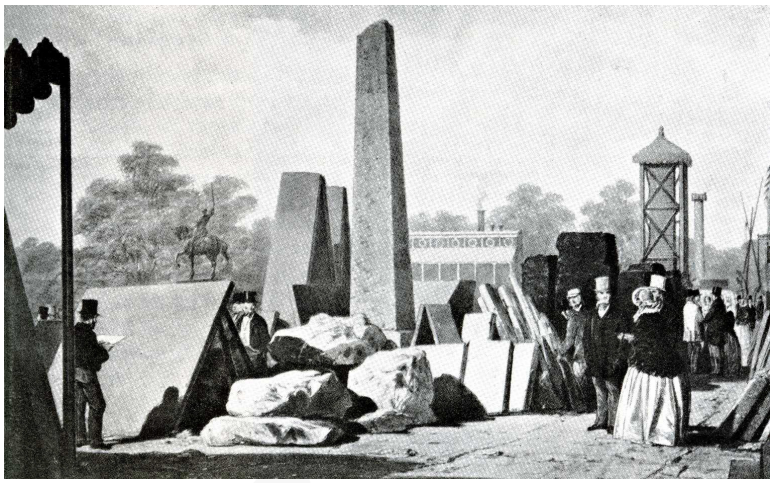


Fig. 3-16 Cement makers' exhibits at the Great Exhibition of 1851 (Contemporary illustration reproduced[3-16]).

Further demonstrations of this enhanced cement were made at the Great Exhibition of 1851. Among the many exhibits from the building industry was a brick-and-cement beam, intended as a replica of the one erected by Francis & White in 1836 to provide a comparison between Roman and Portland cements. Tested to destruction during the exhibition it clearly showed the superior strength of Portland cement, though the last-minute insertion of a hoop iron undermined the value of the result. Several cement makers were represented, including William Aspdin:

> Messrs Robins, Aspdin & Co are exhibitors of a gigantic slab of Portland cement measuring 20 feet by 10 feet and 10 ins thick weighing 15 tons; numerous blocks of cement and concrete proved to various pressures up to 154 tons and showing the strength to be greater than that of Portland stone; of bricks cemented together and placed so as to give a pressure of 3 tons on the first brick; and several other similar illustrations. The Jury has awarded a Prize medal to these Exhibitors [3-16]

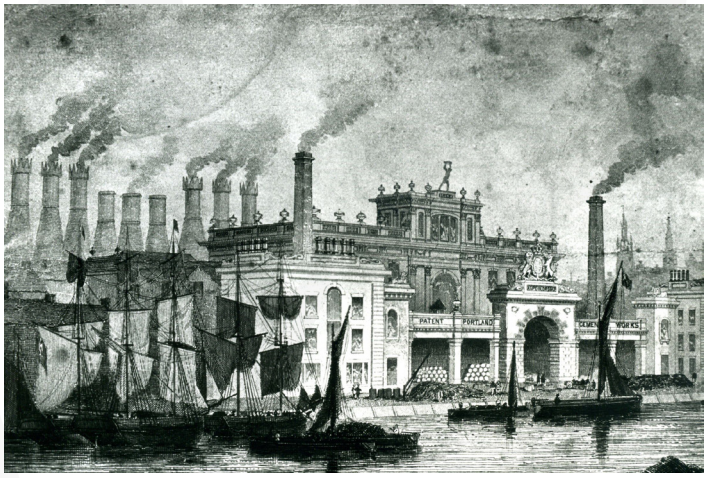


Fig. 3-17 Johnson's Gateshead works in the 1850s (Concrete Society)[3-52].

Shortly afterwards Aspdin fell out with his partners and in 1852 relocated to a new works in Gateshead. Johnson likewise moved on to exploit his discovery, and after a period in partnership with George Burge on the Medway, took over the very works in Gateshead that Aspdin had subsequently abandoned in 1856. Aspdin moved to Germany where he was influential in the early cement industry there, before dying at the age of 48, while Johnson returned to Kent and lived into the next century as the 'grand old man' of British cement manufacture. Meanwhile, this period of rapid improvement in Portland cement manufacture was the subject of a paper read to the Institute of Civil Engineers by George Frederick White in 1852[3-53].

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Based on an analysis of the test results published during the decade 1843-52, Skempton has argued that the "break-through" of clinkering the raw material would seem to have been the Aspdins', and the discovery brought to the Thames-based industry by William by 1843[3-30]. The superior nature of the cement promoted by Aspdin and Maude prompted the more scientific investigation of Johnson in 1844, though despite his claim to be "the inventor"[3-54]- the adoption of the existing name 'Portland' suggests a consciousness that White's new cement was not a different material. As stated in Johnson's letter, quoted by Davis[3-11], Johnson's role was one of "introducing more consistent and rational procedures"[3.30] rather than reliance on Aspdin's more empirical methods, and of putting manufacture on a firmer business footing.

The manufacture of Portland cement was soon taken up on the Continent. In France, for long the seat of scientific study into cements, production of Portland cement is thought to have started around 1850[3-44]. Certainly Emile Dupont obtained a patent (No.796) for his *Provisional specification for the manufacture of cements* in 1854[3-55] and commenced production in Boulogne. Also in the early 1850s cement manufacture took root in the German states; an early factory was established in Buxtehude by Brunckhorst & Westphal, and was producing Portland cement in 1850. Further information on the history of the German cement industry is provided by Quietmeyer[3-56], Riepert[3-57], and Roosendaal[3.58]. The first plant of commercial significance was at Zullchow near Stettin, which was founded by Hermann Bleibtreu in 1853 and came into full production in 1855. Quistorp followed nearby and Gundmann's works at Oppeln in 1857, and by 1864 there were at least 15 works. In 1878 the rapidly growing industry was producing 440'000 tons a year and had achieved an output on 1 million tons by 1887. Portland cement manufacture spread across Europe and America and was introduced to the following countries in turn: Russia (1857), Austria (1860), Denmark (1868), Switzerland (1871), USA (1871), Belgium (1872), Sweden (1873), Netherlands (1875) and Norway (1888)[3-56], [3-59].

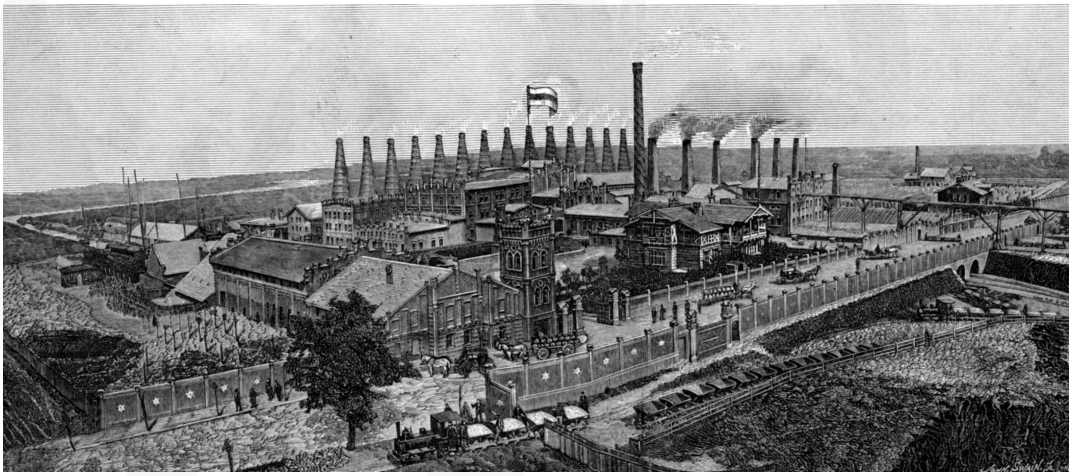


Fig. 3-18 Cement works at Stettin[3-60].

3.11 Adoption of Portland Cement in major projects

While cement in these early years found applications in bricklaying mortar and stucco, its use in civil engineering was limited to the formation of concrete blocks in breakwaters at harbours along the Channel coasts of both England and France. In 1859 it was considered for use in the London Main Drainage scheme.

> Previous to 1859, Roman cement was, with few exceptions, the only cement used for the inverts of the London sewers; the arches being set in blue lias lime; Portland cement was scarcely ever used.[3-61]

Portland cement was largely untried, 50% more expensive than Roman, and sensitive to errors or variation in production "in an industry where production control and quality control process were still rudimentary"[3-62]. However, its hydraulic nature and strength increase over time made it an obvious choice. In 1859, project engineer John Grant made an initial investigation, advised by the cement

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consultant Henry Reid[3-63]. He conducted 302 experiments between January and July on cement supplied by 12 manufacturers. Cubes of neat cement and mortar were immersed for 10-14 days and crushed; other samples were made into briquettes and subjected to tension. The results of this testing again reflect the progress of the material properties of cement at the time and the superiority of Portland over Roman cement.

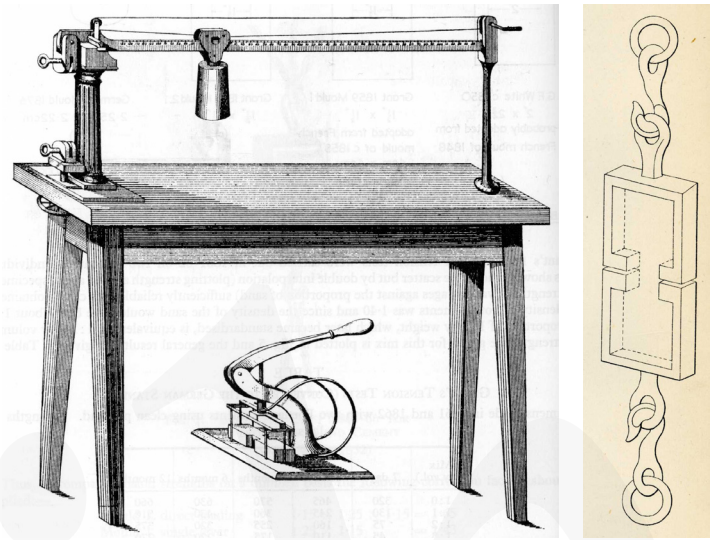


Fig. 3-19 Grant's testing equipment[3-64].

Consequently, Grant recommended its use and Joseph Bazalgette, the Metropolitan Board of Works' chief engineer, authorised its adoption for laying the brickwork for the sewers – the first use of the material in such a large-scale public work. (It wasn't specified for Government contracts in the UK until after 1867, when at Chatham Dockyard it was "found beyond all question, that concrete made of 1 part of Portland cement to 12 parts of ballast was in all respects better and more uniformly trustworthy than the lias concrete of the original specification" (Bernays quoted by Spackman[3-13]).

Crucially, Bazalgette's specification implied ongoing quality control to ensure that minimum standards were being met, and Grant instituted a systematic testing regime to determine the acceptance of materials. Originally few manufacturers could supply at the required minimum strength, but the project spurred improvements in production and new entrants to the industry, and by 1865 a total of 70'000 tons, from 14 manufacturers, had been subjected to 11'587 tests for the 'southern drainage' contracts alone. Test methods and apparatus were improved and Grant's conclusions were thrice published by the ICE. Consequently, the use of cement was extended to concrete pipe manufacture, and to in-situ concrete backfill. The London Main Drainage was Portland cement's first comprehensive large-scale trial, and success had a huge impact on its production and use. Roman cement "gradually succumbed to the merits of the new product, and the impetus given to its use by the London Drainage works in 1859 settled the question of its superiority"[3-37]. Testing became routine and independent test houses were established in the UK by specialists such as David Kirkaldy, Henry Faija[3-65] and his successor David Butler, and later, Bertram Blount with partner Harry Stanger.

3.12 Testing and improvements in quality control

Testing was vigorously and systematically adopted in the German states. Among the pioneers in this field was Wilhelm Michaelis (1840-1911), who wrote extensively on his lifelong investigations into the material, starting with his classic *Die hydraulishen mortel* (1869)[3-66] and from 1872 operated an independent cement-testing laboratory in Berlin. It was his and his partner Fruhling's designs of tensile and compressive strength testing apparatus that became the standard in the German and Austro-Hungarian empires for decades to come[3-67].

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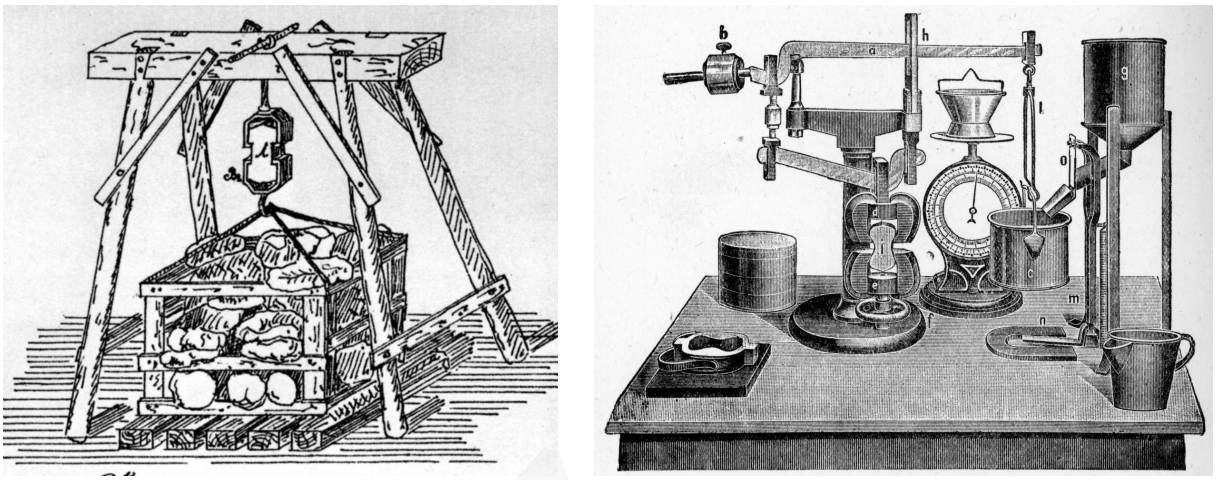


Fig. 3-20 (Left) Traditional testing equipment in 1869[3-68]; (Right) Michaelis & Fruhling's later design[3-69].

Also in the early 1870s Rudolf Dyckerhoff, who had studied chemistry at Heidelberg, introduced systematic quality control processes to his family's cement works; proportioning of the raw meal was henceforth guided by chemical analysis rather than rules of thumb.



Fig. 3-21 (Left) Wilhelm Michaelis[3-57] (Right) Rudolf Dyckerhoff[3-68].

Chemical analysis further improved during the later 1870s and into the 1880s. Professor Bauschinger (1833-1893), who had run the university engineering laboratory at Munich from 1871, undertook a notable series of tests on ten Portland cements between 1876 and 1879. He determined their chemical composition, setting time, particle size, volume change and strengths in tension, compression, bending and shear at different ages. Published in 1879 Bauschinger's results demonstrated the quality and consistency of German cements. Similar consistency was revealed in 1883 when Dr Bohme of the Royal Technical Testing Station published the results of testing a group of 11 types of cement in 1881[3-70]. The CaO content of German cement was generally around 62%; a level that would not be improved until the advent of the rotary kiln in the 20th century permitted levels of 64%. The composition of cements during this period has been compiled in Table 3-2 from selected figures abstracted by Halstead[3-44]; based upon an analysis by Skempton which was reported[3.30].

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Table 3-2 Analyses and Computed Compound Composition of cement

Analysis by % of weight						Compound composition		
Source	**Date**	**CaO**	**SiO_2**	**Al_2O_3**	**Fe_2O_2**	**C_3S**	**C_2S**	**Total**
English	1849-55	58.50	20.40	5.90	3.80	38	30	68
German	1865	59.00	24.10	7.30	2.80	4	66	70
English	1880	59.40	22.40	7.80	4.20	13	54	67
German	1880	60.80	22.10	5.90	3.00	36	35	71
English	1890	59.10	22.80	8.00	3.40	9	59	71
French	1890	60.70	23.20	7.20	2.80	18	53	71
German	1890	61.50	22.50	7.50	3.20	24	46	70
English	1905	60.20	22.30	7.10	4.10	22	47	69
American	1905	61.10	21.80	7.40	3.30	29	41	70

Control of the chemical composition of cements had led to great improvements in quality and strength. German cements of 1885 had strengths about double that of English cements made 20 years previously and three times higher than those made before 1860. Evidence from the early years is fragmentary, but Skempton[3-30] has analysed the surviving data and proposed the following averages:

Table 3-3 Strength (lb/in^2, 1 lb/in^2= 6,894.76 Pa) of Portland cements, 1847-1887[3-30]

			Tension 1:0		**Tension 1:3**		**Compression 1:3**	
Date	**Authority**	**Cement**	**7 days**	**28 days**	**7 days**	**28 days**	**7 days**	**28 days**
1847	G F White	White	-	-	-	-	-	800
1848	W Aspdin	Aspdin	-	-	-	-	-	1’000
1852	G F White	White	250	-	45	-	-	-
1859	MBW Spec.		255	-	-	-	-	-
1859	Grant	6 cements	260	390	-	-	-	-
1860-2	Grant		320	465	50	115	-	900
1860	Leblanc	Boulogne	-	-	55	100	-	-
1864	G F White	White	350	480	75	130	-	-
1865	Grant		-	-	-	-	-	1’200
1868	Grant		420	570	-	160	-	-
1869	Gillmore	Boulogne	310	240	85	155	800	-
1873-5	Bauschinger	Perlmoos	-	-	-	-	-	1’570
1875	Bauschinger	Dyckerhoff	-	-	-	-	-	1’680
1875	Bauschinger	Schiffendecker	-	-	-	-	-	1’700
1876	Bauschinger	5 cements	375	500	115	170	1,070	1’620
1877	Dyckerhoff	2 cements	360	550	110	190	-	-
1878	Barreau	4 cements	-	-	105	180	-	-
1879	Guarantee	Stern	570	710	213	284	-	-
1878	Ger. Stnd.		-	-	-	142	-	-
1878	Aus. Stnd.		-	-	114	170	-	-
1880	Grant’s Sp.		400	550	-	170	-	-
1883	Swiss Stnd.		-	-	-	213	-	2’130
1880-4	Bohme	8 cements	620	740	220	290	1’600	2’100
1881	Bohme	11 cements	625	770	205	295	-	-
1884-6	Bohme	47 cements	-	-	230	300	1’900	2’600
1885	Fr spec		284	498	114	213	-	-
1887	Feret	6 cements	560	680	150	220	1’250	1’550
1887	Ger. Stnd.		-	-	-	228	-	2’280
1887	Swiss Stnd.		-	-	-	228	-	2’280

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In France, quality requirements for cement making were introduced under the control of central administrations like the Laboratoire des Ponts et Chaussées, or city authorities, such as the Direction des Travaux de Paris. In order to comply with demands imposed by the authorities and reduce the cost of poor quality, cement producers developed internal controls all along the production chain, from quarry to delivery. The producers combined as the Chambre syndicale des Fabricants de Ciment Portland de France and in June 1896, this body issued a 42-page document that described not only how to test cement, but how to use it in new applications[3-71].

Progress was also down to improvements in the design of production plant. The Hoffmann ring kiln was one such innovation and the later shaft kiln likewise originated in Germany. Variant designs by Stein and Dietzch (patented in 1884), and later by Schneider, became popular in the British, as well as German, industry. Improved methods of milling to achieve a finer finish were explored, and roller mills developed. In 1880 Dr Tomei of Quistorp Works undertook comparative experiments to establish the strength of the cement obtained by the new and traditional methods, and the roller mill was widely adopted in Germany in the 1880s. The use of fine sieves to ensure consistency of grinding

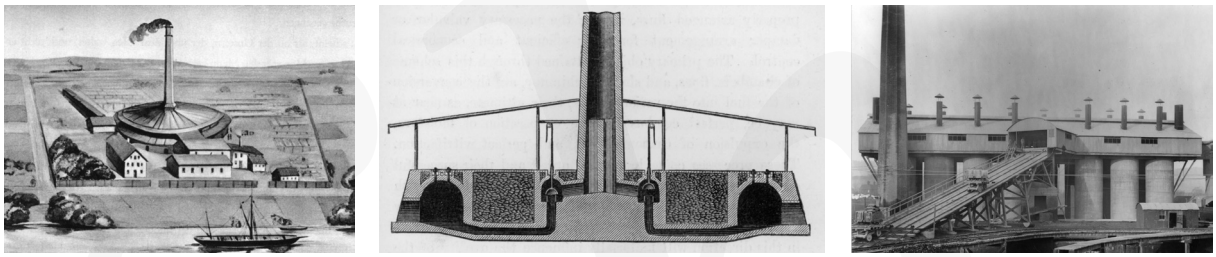


Fig. 3-22 German shaft kilns: (Left) Hoffmann's Kiln (Reid[3-37]); Centre: Dyckerhoff's Kiln; (Right) Schneider's Kiln (Photos: The Concrete Society).

British industry was not unaware of German developments, and many innovations were adopted. Indeed, Reid repeatedly drew his readers' attention to the German example, even publishing a translation of Lipowitz's treatise in his own book of 1868[3-37]. By 1877 he was yet more forthright in his admiration and Grant, in his paper of 1880, also alluded to the German and Austrian rules for testing. However, some years later, Redgrave was to lament the passing of British leadership in cement technology:

> Our own country, the original seat of the manufacture, has been distanced in certain directions in consequence of the superior scientific skill and the energy of foreign rivals. The supremacy we have so long enjoyed has undoubtedly been to some extent wrested from us by the products of Continental industry and enterprise.[3-36]

However, progress was to be found not only in Germany. From the introduction of the Blake stone-crusher onward, American mineral processing equipment became more widely available, as did Danish production machinery. Slag cements were produced in Germany and later in France. In Britain, the dry grinding of limestone was introduced in the 1860s and improved wash mills for the wet process developed by Goreham and de Michele in the 1870s[3-72]. Johnson's invention of the chamber kiln in 1872, that incorporated the drying of slurry before its addition to the kiln by recycling waste gases, was a great improvement on the traditional 'bottle' kiln. Reid (1877)[3-37], and Scott & Redgrave (1880)[3-73] describe the production methods of this period.

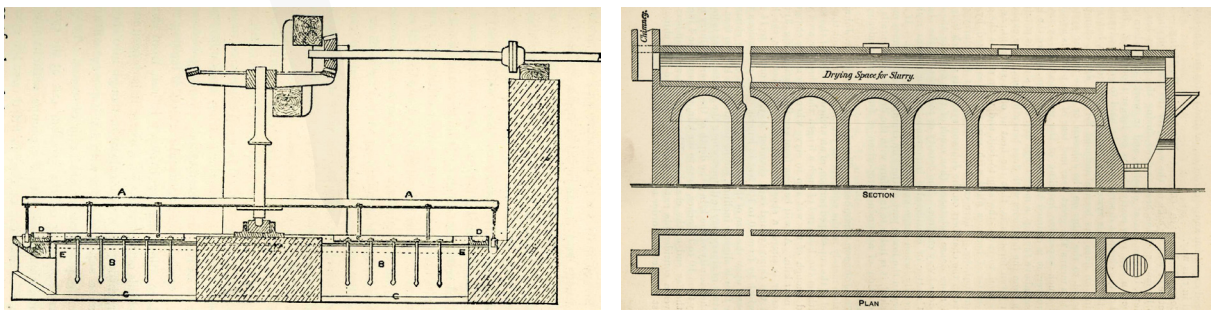


Fig. 3-23 (Left) The "de Michele" wash mill[3-74]. (Right) Johnson's chamber kiln[3-76] (Drawings: The Concrete Society).

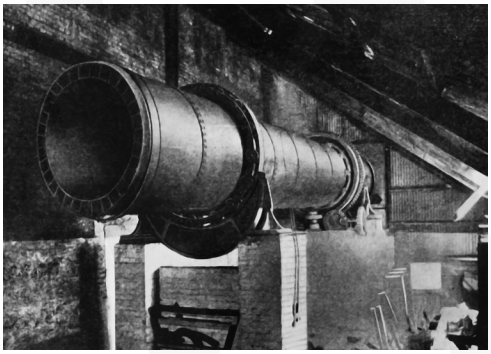
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3.13 The emergence of modern Portland cement, 1887-1904

Several authorities have identified 1887 as a pivotal year in the material development and understanding of Portland cement – a watershed after which it became recognisable as the 'modern' binder we know today. Various criteria are advanced for this distinction: publication of Le Chatelier's thesis in Paris[3-75]; trials of the first practical design of rotary kiln at West Thurrock, and the start of René Feret's comprehensive series of tests on French cement at Boulogne[3-76]. But perhaps the most immediately indicative significance of 1887 was the publication the German standard for Portland cement (a development of the original Prussian standard of 1878[3-77] for which the Verein Deutscher Zement Fabrikanten was originally formed). "The German and Swiss Standard Specifications of 1887 are completely modern in form and required no revision until the first decade of the twentieth century"[3-30].

> The French specification of 1885 marked a further advance in cement testing, but the second German Standard of 28 July 1887 was even more important. … Simultaneously the Swiss regulations were modified and the strength requirements were identical with those given above. The residue on the 900 sieve and the final set were also similar. If we add to the German and Swiss Standards of 1887 the initial set and the 7-day (1:3) tensile strength of the French Specifications, and Grant's 7-day tensile strength for neat cement, we have a set of rules which covers all subsequent Standards until 1901. In other words, by 1887 the pattern of modern cement specifications was already established[3-30].

Arguably the other turning point came at the end of a series of production improvements in the 1890s. These included the discovery of calcium sulfate as a set regulator by Edouard Candlot in 1890 (building on work by Henry Scott[3-78], who patented the selenitic process in a series of patents from 1854 (No.735) to 1870; the development of ball- and tube-mills in Germany and Denmark – by the firms Polysius and FL Smidth in 1891 and 1893 respectively – and the introduction of electrical power for mill drives and other process machinery. These improvements culminated with the introduction of the rotary kiln at the turn of the century.



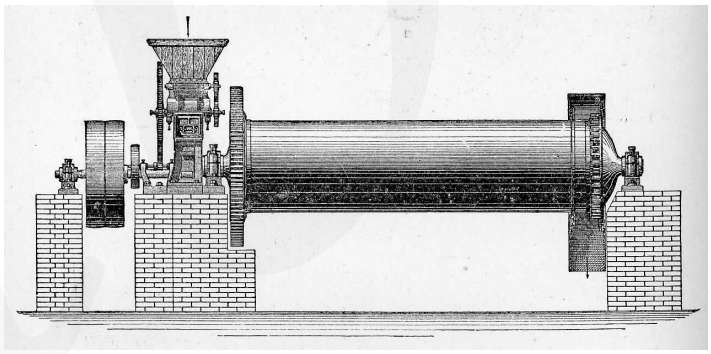


Fig. 3-24 Ransome's rotary kiln (Photo: The Concrete Society) and the FL Smidth tube mill[3-74].

This revolutionary concept was initially patented by Thomas Crampton in 1877[3-79] and prototype kilns by Ransome, such as the one at Arlesey illustrated in Figure 3-24, were brought to practical trials at Mitcheldean and Barnstone between 1885-87. Ransome's patent of 1887[3-80] and further improvements by Stokes led to further experiments at West Thurrock, Arlesey and Penarth. However practical difficulties in achieving sufficient temperature were not overcome until the Keystone (later Atlas) Portland Cement Co. in the USA pioneered to the use of pulverised coal as kiln fuel in the early 1890s. Successful designs by the company's engineers, Hurry and Seaman, and their rivals Lathbury and Spackman at the Alpha Portland Cement co., were patented in 1895[3-81]. Versions of the American designs were adopted in Germany in 1896 and in Britain three years later.

The capital investment required was such that it added momentum to the proposal to consolidate the British industry with the formation of Associated Portland Cement Manufacturers in July 1900, which in turn facilitated agreement on the publication in 1904 of the first *British Standard Specification for cement: BS 12*[3-82]. These changes set the course for the British cement industry until the end of the twentieth century. Similar comments apply to the American industry which, experiencing an explosion

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of output at the turn of the century[3-25]– rising from 250'000 barrels in 1889 to 5'156'064 in 1899 – agreed its own national standard: *Standard specification for cement (ASTM C9)*, 1904[3-83].

Standards such as these required and reflected a strength and quality of cement that permitted its use in the ways demanded of the new century – as a basis of the reinforced concrete then being developed for employment in major structures.

3.14 Acknowledgement

This chapter was adapted from part of a preliminary draft now published as Trout, E.A.R.: 'The history of calcareous cements' in Hewlett, P.C. & Liska, M. Lea's chemistry of cement and concrete[3-84].

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4. Concrete Construction in the Eighteenth and Nineteenth Centuries

> Concrete is a solid mass formed from lime or cement, water, sand and small irregular pieces of stone, brick etc, by their "growing together' (as the word expresses), when brought into contact with each other.[4-1]

4.1 Lime concretes and early cement-based materials

The production of concrete today is inextricably bound up with the use of cement, be it Portland cement or one of its many combinations with supplementary cementitious materials, but early concretes predate the development of modern cements and were based on quicklime mixtures, with or without the addition of trass or pozzolana. The concretes derived from such binders, generally non-hydraulic and invariably weaker than their successors, were of limited structural capacity. They were generally used as fill or for floors, and can be found as far back as the Middle Ages, with examples in England such as the fifteenth floors at Little Moreton Hall and even the twelfth century hearting between masonry walls at Reading Abbey.



Fig. 4-1 Medieval lime-concrete infill at Reading Abbey (Photo: The Concrete Society).

In the modern period, early uses of lime concrete for civil engineering purpose included harbour projects such as the breakwater at Tangier, constructed by English engineers between 1663 and 1683. Likewise, in France, Bernard Forest de Belidor proposed a method of placing foundations under water, which was tried at the harbour of Toulon. After slaking the quicklime, and adding proportions of pozzolana and sand, the constituents were mixed with seawater, and a combination of pebbles and slag or cinders added. Having partially hardened, the concrete was reworked and lowered into the sea in crates. A similar approach was tried by George Semple in 1752, when reconstructing the foundations of

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the Essex Bridge in Dublin. Here he filled a cofferdam with "*small stones, grave, sharp clean sand and finely powdered lime*". He described the mixture's use as follows:

> There are three different methods for making use of lime in such a work as this; one is, to mix the roach lime (made liquid, with its proportion of sand and small stones in such a manner as may clothe every stone and particle of sand with it; the second, to slack and turn them all up together like mortar; the third, to lay each of the three, as it were, in thin layers, still observing the same proportion. … But if they are properly mixed together, the whole stuffing of this coffer will actually petrify, and become one solid compact substance.
>
> (Quoted by Potter[4-2]).

But while concrete was being made with lime, the applications to which the newer cements being developed in the second half of the eighteenth century were put didn't, for the most part, constitute concrete at all. They included such applications as masonry and bedding mortars, stucco and architectural mouldings.

4.1.1 Waterproof mortars

John Smeaton, having been commissioned to replace Rudyard's ruined lighthouse on the Eddystone Rocks, commenced on a series of experiments in 1756 to find a suitable masonry mortar that would withstand the frequent drenching of this storm-swept location. His discovery of the hydraulic combination of Aberthaw lias and pozzolana was used to seal the 1'493 interlocking granite blocks with which the lighthouse was built, despite the constant spray over its superstructure. This is amply illustrated in his book, *Narrative of the building of the Edystone lighthouse*, eventually published in 1791[4-3].

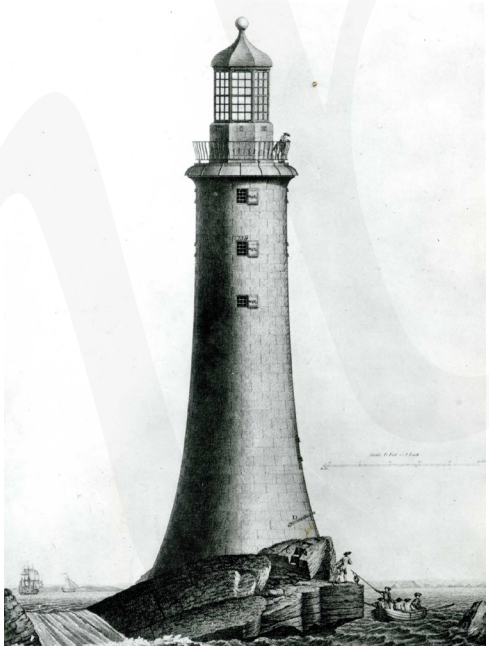


Fig. 4-2 The Eddystone Lighthouse (Smeaton[4-3]).

In Scandinavia there were similar experiments. A cementitious mortar was used for the Farris dam at Larvik in 1764 – the first such use in Norway – and burned alum schist was ground and added to the mortar used in building the locks at Trolltattan, Sweden, in 1779[4-4].

Indeed, it was for use in the waterproofing of locks that a naturally hydraulic cement was introduced into the United States of America, patented by the canal engineer, Canvass White, in 1820. It was "invariably used for the facework of canal locks and arches"[4-5] on the Erie Canal, at a time when similar work in England still relied on lime mixtures.

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4.1.2 Stucco and architectural mouldings

Many of the cements entering the market in the late eighteenth century were conceived principally for use in stucco, and indeed Parker & Wyatt's Roman newly adapted cement factory was described in Hasted's survey of 1797[4-6] as "now used for the making of a composition of stucco for buildings" (quoted by Trout[4-7]). In time, Wyatt, Parker & Co, diversified from the cement business and entered into a partnership with J.M. Blashfield[4-8] to produce architectural mouldings. This was not without precedent as in 1820/21, the firm's agent William Lockwood, based in Woodbridge, Suffolk, developed a 'Portland Stone Cement' which was used by one of his workmen, James Pulham, in a subsidiary business of ornamental mouldings[4-9]. Lockwood's home, the Castle, in Woodbridge, was an advertisement for the business. With battlements and window mouldings, the whole building was stuccoed in Roman cement.

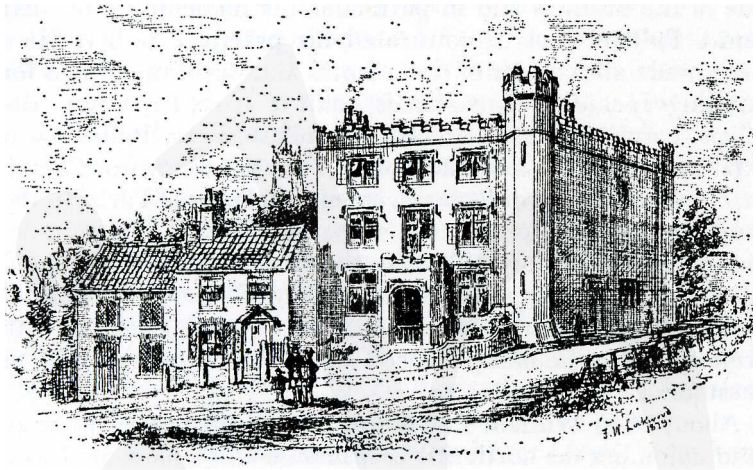


Fig. 4-3 Lockwood's Castle (reproduced by Francis'[4-10]).

4.2 Foundations

Pasley ascribes the introduction of concrete in the UK to Sir Robert Smirke's use of lime-bound concrete for building the foundations at Millbank Penitentiary[4-11] and historians since have followed him in this acknowledgement[4-12]. Certainly, it seems to be the first large scale application and its use soon became standard practice for foundations.

A commission appointed by the Government in 1813, comprising Messrs Rennie, Lewis, Cockerell and Browne, advised the use of concrete, though Rennie appears to have been ambivalent, warning elsewhere against "any artificial or inferior materials, such as concrete"[4-2]. The recommendation was taken up and Smirke's specification required the concrete to "consist of fine gravel or ballast, freed from slime, mud, and sand, except that a small portion of the latter shall be inter-mixed with the other material, in the proportion the architect shall direct, the whole to be well puddled and cast and mixed in lime-water" (Quoted by Sutcliffe[4-1]).

Concrete, defined as late as 1850 as "gravel, sand and ground lime, mixed together with water; the slaking of the lime taking place whilst in contact with the sand and gravel" – without any mention of cement – was characterised by the writer Edgar Dobson as "a valuable material when applied in a proper manner viz in underground works where it is confined on all sides … but it is not fit to be used above ground as a substitute for masonry, and will not bear exposure to water"[4-13]. Confidence in concrete had really to wait until the adoption of Portland cement-based concretes in the late 1850s and 1860s.

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4.2.1 Dock linings

Telford's St Katharine Docks, London, had a 1 ft bed of concrete beneath the wall, as did successive expansions of the London Docks in the 1850s and 60s, for which in 1856-57 steam-powered mixers were employed[4-12]. E.A. Bernays pointed out that lime, rather than cement-based materials remained in Government specifications until 1867 (Bernays[4-14] Quoted by Spackman[4-15]).

4.2.2 Masonry

Lime-based concrete also formed the basis of artificial stone – a type of concrete used as masonry. In the 1830s William Ranger of Brighton patented a type of lime-concrete masonry block, which was described by Reid as representing "the beginning of scientific concrete-making"[4-16]. The concrete was composed of hydraulic lime and gravel, mixed with "the least possible amount" of hot water. A graving dock and sea wall were built at Woolwich in 1835, described by Bernays in 1880[4-14] as "in remarkably good condition" (quoted by Sutcliffe[4-1]). Such blocks were also used at the College of Surgeons, for the porticoes of Wellington Barracks, and the guardhouse in Birdcage Walk[4-12]. Though popular for while, Ranger's blocks were criticised by the early cement investigator, General Sir Charles Pasley of the Royal Engineers, and fell out of favour later in the decade. Like many of his contemporaries, Pasley drew the conclusion that concrete was unsuitable for anything except foundations.

4.3 Early in-situ concrete construction in Britain

While most early nineteenth-century concrete was bound by quick- or hydraulic lime, there were occasional attempts to use Roman cement. In 1827, for instance, John McNeill repaired a section of the Archway road over Highgate Hill, in London, but the rapid set of the material and the labour intensity of the work necessitated the use of small batches, and progress was too slow to warrant repetition[4-10].

Whatever the choice of binder, there was widespread scepticism that concrete might be suitable for anything more structural: "Concrete is not to be regarded as a proper substance with which to form the lofty walls of buildings in towns"[4-17]. But there were exceptions, initially to promote the use of newer types of cement.

4.3.1 Swanscombe 1835

The first concrete house in Britain was built in 1835, at Swanscombe, Kent, for John Basley White, the Roman cement manufacturer. Conceived as an advertisement for his wares, White's house had walls, tiles, window frames and decorative features all of concrete, though not the first floor. Indeed, it was such an imaginative and innovatory use of concrete for buildings that prompted the architect George Godwin to write his seminal paper, *The Nature and Properties of Concrete* in 1836[4-18]. It was the very first paper read to a meeting of the Royal Institution of British Architects and was awarded its Silver Medal.

4.3.2 Other cement makers' houses

White's house was followed by several similar ventures; Pulham House in Broxbourne, built in 1848 by the manufacturer of cement-based artificial rock, James Pulham; the grandiose Portland Hall at Gravesend, started in 1850 by the manufacturer William Aspdin, but never completed[4-19]; and Portland House (known now as 'The Concrete Castle', built in 1851 for John Board of Bridgewater, a Somerset cement manufacturer. It had concrete floors, staircases, door and window frames[4-20].

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Fig. 4-4 Portland Hall in the 1970s (Photo: The Concrete Society).

Also in the 1840s concrete cottages were built at Harwich, where Roman cement was made, and a number of huts were erected for the British Army at Shorncliff encampment in Kent, using locally produced Roman cement and beach shingle for aggregate. And in 1852 two dwellings of in-situ concrete were constructed on the Isle of Wight, near the Medina cement works of Charles Francis, while other houses built of Portland cement concrete on the Isle of Thanet[4-1], [4-10].

4.3.3 United States of America

There were parallels in America, where also in 1835 Obadiah Parker erected an artificial stone house in the Greek Revival style at 107 Amos Street, New York City. It was followed by the octagonal Milton House, Wisconsin, built of gravel bound with lime grout in 1844, and several large unreinforced concrete houses in the Hudson Valley, NY State, in the mid-1850s[4-21].

4.4 The French development of Béton

While concrete with a lime or cementitious matrix developed in England, it followed another course in France, where it was known as 'béton', a term first published by Belidor in 1753[4-22]. Although the respective meanings of national terminology have long since merged, the words originally indicated distinct differences of practice, which remained so well into the second half of the nineteenth century. In 1850 Edgar Dobson was clear in drawing a distinction[4-13]. Concrete, he deposed, was "an artificial conglomerate … in which the pebbles which make up the greater part of its bulk are cemented together by lime mortar (chalk lime or weak stone lime)." The dry constituents are "*m*ixed together with water; the slaking of the lime taking place whilst in contact with the sand and gravel". On the other hand, "béton may be considered as hydraulic concrete; that is, concrete made with hydraulic lime … It differs from ordinary concrete inasmuch as the lime must be slaked before mixing with the other ingredients, and it is usual to slake the lime and sand into mortar before adding the stones." In short, lime concrete was dry mixed and the water added; beton was an hydraulic lime mortar to which, once wet, the coarse aggregate then added. He added that concrete was used hot, while beton was allowed to stand before being used. But he hinted at a future convergence: "Béton, as prepared on the Continent, is seldom if ever used in this country, but concrete is sometimes made with blue lias lime when it, in fact, becomes a species of beton, and must be treated in a similar way."

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Rather than use cement simply as a mortar, or weak lime concrete as a constrained foundation material, the French development of concrete drew on traditional pisé techniques as a source of mouldable construction methods – material rammed between movable formwork that was raised in lifts as the building work progressed. Initially, for compacting earth, the pisé technique was adaptable to improved materials, such as the various mortars that were being developed in the late eighteenth century. Patte, in his continuation of J.F. Blondel's *Cours d'Architecture* of 1777[4-23], advocated the use of 'mortier de Betum' for the foundations of pisé buildings. It didn't take long to extend the idea to 'beton' construction.

4.4.1 Cointeraux

Pisé-type construction was advocated vigorously by Francois Cointeraux[4-24] from the 1780s through to the 1820s. A builder and stone mason, Cointeraux was experienced in the locally established techniques of pisé construction and was energetic in promoting his innovations. Attracted by a competition publicised in 1784, in which the Academy of Picardy competition offered a gold medal to anyone who devised a simple and cheap method of fireproof construction for rural homes, Cointeraux set out his proposals. Unfortunately the Academy did not receive them, so they were published separately two years later. Cointeraux experimented on his own land in Grenoble, and developed proposals for a concrete cistern and serpentine wall, before coming to the attention of Armand-Joseph de Bethune, Duc de Charost and lieutenant general of Picardy. Enjoying his patronage in 1787 he subsequently moved to Paris where he attracted royal, though not commercial, support. Notwithstanding, he did manage to build several cottages and a cemetery wall, and if not a successful exponent of concrete construction in his own right, he did establish a method adaptable to newer materials by his successors[4-25].

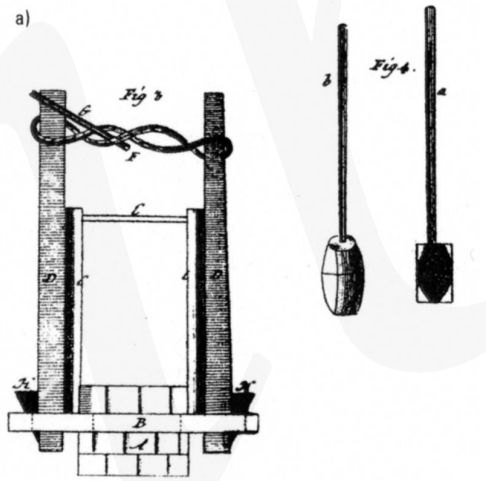


Fig. 4-5 Cointeraux's apparatus[4.26], [4.27].

4.4.2 Lebrun

Most notable of these was Francois-Martin Lebrun, an architect practising in Montauban, who was inspired by Vicat's 1818 publication on hydraulic limes to experiment with béton as an improved and economical construction material. In 1828, with his brother Jean-Auguste as contractor, Lebrun erected two hydraulic lime factories, one at Bouret and the other in Montain, two small towns on the River Tarn. The brothers then built a family home at Marsac, near Albi. It was built entirely of beton: one part hydraulic lime, one part clean sand and two parts shingle[4-12]. The material was thoroughly mixed and pressed into a frame, the walls raised at the rate of about one foot per day, according to the traditional pisé methods. Once erected the walls were plastered with mortar to leave a smooth face and sharp

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arrisses, in all, costing less that half the price of brickwork. Arcades and decorative mouldings were shaped by timber formwork, which was left in place for a month. In this way, a house of six rooms on two floors was completed, plus cellars and ancillary space, with walls, an external staircase and vaults for the floors and roof all in beton[4-24].

Lebrun wrote a treatise, *Methode pratique pour l'emploi du béton*, which was published in 1835[4-28], and was awarded the silver medal of the Société d'Encouragement pour l'Industrie Nationale in 1836. Encouraged to try his methods elsewhere, he became an advocate of béton for numerous applications, including prisons, which he considered would benefit from its monolithic nature. Today the house in Marsac survives, as does the town hall of Gaillac (1832) and a 12m span bridge, the Pont de Grisolles (1840).



Fig. 4-6 The Pont de Grisolles, built in 1840 over the River Garonne in 1840 by J.A. Lebrun, with hydraulic cement and bricks used as formwork. It was built in three months.

Lebrun's example found an audience in Germany where soon after the technique of pisé construction was adapted for use with a lean concrete composed of sand and gravel and a minimal quantity of lime. Johann Gottlief Prochnow, a Pomeranian farmer familiar with the experiments of Labrun, and of his contemporary in Sweden, Carl August Ryden, built walls of agricultural structures in this lime-based conglomerate placed within wooden forms. He published a book on his experience in 1842. As the use of this sand-lime combination spread throughout Prussia, Saxony and Bavaria in the 1840s, so eventually did it feature in the literature, with both F. Krause and Friedrich Engel publishing guidance in 1851 – the latter tellingly entitled *Der Kalk-Sand-Pisebau*[4-29], [4-30].

4.4.3 The harbour at Algiers

But, just as would later happen with Portland cement concrete in Britain, the case for beton was most convincingly made in a major scheme of harbour works. As French influence extended into Algeria, improved dock facilities in the harbour of Algiers became a necessity and, from 1834, cast-in-place blocks were used for protective breakwaters by the French engineer, Victor Poirel (1804-1881).

At a proposed 706 cubic feet, a size considered sufficient to resist the action of the sea, the blocks used to form a protective breakwater flanking the existing mole could not practicably be made of natural stone. A cast in situ method was the only feasible option and beton the chosen material. The mortar used in preparing the beton was made of one part of rich lime, slaked and made into a paste, mixed with two parts of Italian pozzolana. This then was added to double the amount of broken stones and mixed.

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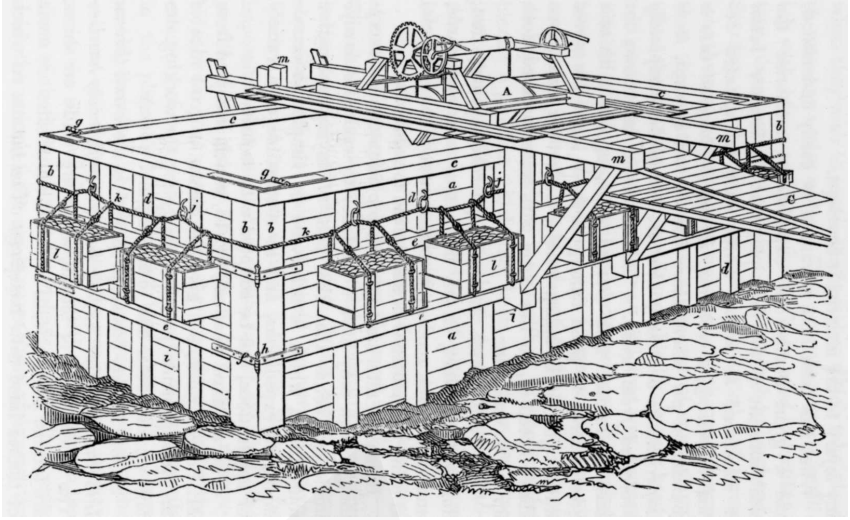


Fig. 4-7 Poirel's caisson at Algiers[4-13].

An elaborate system of tar-lined caissons was developed, each unit cut to fit the profile of the sea bed[4-13]. Once floated out to position and sunk, beton was placed within the liner, which formed a flexible fabric to contain the material and allow it to adjust to the shape of the site. Vitally, it protected the beton from the washing action of the water for the 36 hours required to set and harden before stripping.

In 1838 an additional mole was to be constructed, entirely of béton blocks of 353 cubic feet. These were cast on shore and, after stripping and hardening for a couple of months, moved into place and immersed.

With his work successfully completed, Poirel went on to similar projects at Caen (1840-42) and Livorno (1852-60).

4.5 Early uses of Portland cement concrete

Meanwhile, in England, Portland cement had been patented and, by the 1840s considerably improved, allowing for the possibility of new applications. These did not arise immediately, however. Describing the new cement in his 1852 paper to the ICE, the prominent producer, George Frederick White, referred to its three main uses: as stucco; brick-laying mortar and blocks for harbour walls, piers and breakwaters[4-10]. Not many years later John Grant stated:

> Previous to 1859, Roman cement was, with few exceptions, the only cement used for the inverts of the London sewers; the arches being set in blue lias lime; Portland cement was scarcely ever used. Up to this time Portland cement had been confined to ordinary building operations such as external plastering and a few harbour works on the south coast where it was most used in the form of concrete blocks.[4-31]

4.5.1 Harbour works and blocks for breakwaters

These harbour works, reflecting earlier French experience with beton, included the new Admiralty pier or western breakwater at Dover, that commenced in 1847. White secured a contract to supply cement for the 30-40 ton granite-faced concrete blocks. In the same year work started on a 3'000ft breakwater at Braye Harbour on Alderney, for which Medina cement was supplied by White's erstwhile partner, Charles Francis. In 1848 White persuaded the French bridges and roads administration to test his improved cement for use in building the central breakwater at Cherbourg. It was successful and the 2'000 blocks manufactured between 1848-53 mark the first major use of Portland cement concretes. For each 45-ton block, 4 tons of Portland cement were used, combined with 1.75t of rapid-hardening Medina cement. White later attracted similar business at the harbours of Le Havre, Brest, Lorient and La Rochelle, while Francis found work supplying a 200 ft sea groyne at Sandown in 1852. Such work continued throughout the century, with breakwaters constructed at, for example, Torquay (1867-70)[4-32], Aberdeen (1869-73) and Wick (1870-72)[4-2].

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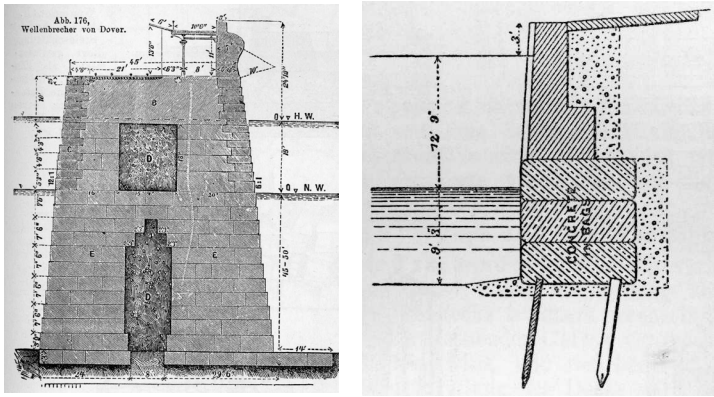


Fig. 4-8 (Left) Harbour works at Dover; (Right) at Aberdeen[4-33].

Thomas Potter observed in retrospect that "the invention of Portland cement, however, no doubt had a great deal to do with the ultimate adoption of concrete for works of this character"[4-2].

4.5.2 The Great Exhibition, 1851

The Great Exhibition of the Works of Industry of all Nations, held in London, was the first opportunity for the manufacturers of the newly improved Portland cements to demonstrate their wares to the general public. Much effort was directed to proving the adhesive qualities and tensile strength that cement conferred to brick-laying mortars, but concrete was exhibited too, including blocks made for Dover and Alderney harbours and the breakwater at Cherbourg. A specimen block measuring 6 ft x 4 ft x 4ft was displayed by Messrs. J. Bazley-White & Bros, consisting of water-worn stones (70.26 %), sand (17.79 %) and "indurated cement" (11.95 %)[4-34]. And while they might not have been conspicuously on show, the foundations of the exhibition hall itself were made of concrete, rather than the wood that might have been expected by contemporaries.



Fig. 4-9 Sample of concrete from an exhibit by Bazley White & Bros at the Great Exhibition of 1851 (Cement Age[4-34]).

4.5.3 Coignet and 'Béton Aggloméré'

The French response to London's Great Exhibition was the Exposition Universelle of 1855, held in Paris, and while 1851 had seen the demonstration of Portland cement as a novel material, it was its use in new methods of construction that was highlighted four years later. Among the many exhibitors was Francois Coignet, a chemical engineer who had spent the late 1840s experimenting with a form of concrete that he eventually termed 'béton aggloméré'. This consisted of hydraulic lime and/or Portland cement, hydrated with minimal quantities of water – 30 or 40 parts to 100 parts of binder – into which was added clean sand and coarse aggregate of various sizes[4-35]. It was then thoroughly mixed and laid between the forms in thin, successive layers, each compacted by iron-shod rammers to about a third of its original depth. He used beton agglomere in the construction of a factory for his chemicals business at St Denis in 1853, and built a house opposite with monolithic walls.

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Coignet's two patents of 1855 were entitled *Béton économique*[4-36] and *Emploi du béton*[4-37] respectively, claiming a 15-year monopoly for monolithic construction. Their value lay particularly in specifying the processes of mixing and compaction. An addendum declared the self-sufficiency of béton aggloméré, claiming "concrete walls need no facing material in stone, brick or any other material whatever"[4-38]. Exhibiting at the Universal Exhibition that year he won a bronze medal.

He built several houses soon after, such as the Stationmaster's house at Suresnes (1856) and another in the Rue de Poissonniers (1857), which demonstrated his confidence in structural concrete. The former he described to the French Institute of Civil Engineers: "This house, constructed entirely in compacted concrete, is a complete monolith from the summit to the foundations: cellers, vaults, slabs, walls, floors, roof (in the form of a dome), cornices and ornaments are all in compacted concrete, without joints or any other material"[4-24].

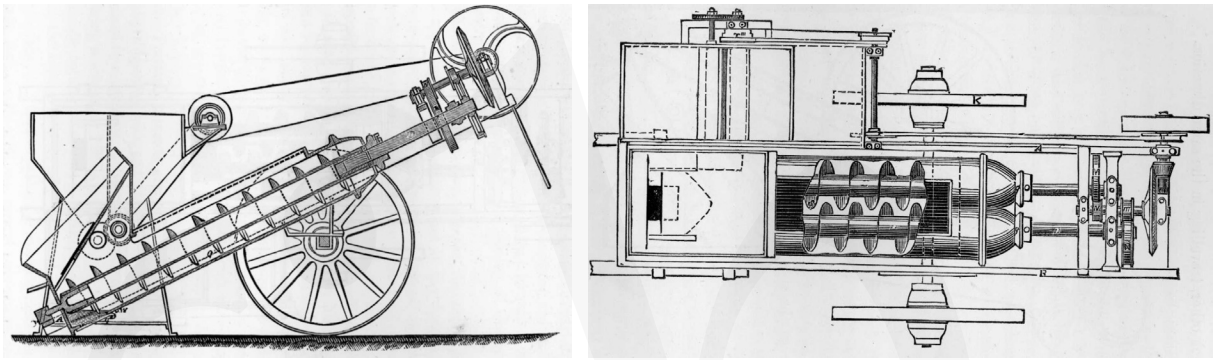


Fig. 4-10 Coignet's Malaxator[4-16]: (Left) Side elevation view; (Right) Plan view.

He went on to become a successful concrete contractor, developed a mixing machine known as the Malaxator, and in 1861 published a monograph entitled *Bétons Agglomérés appliqués de l'Art de Construire*[4-39]. He also captured the attention of Emperor Napoleon III, for whom he worked extensively on the remodelling of Paris in the 1860s, engaged in work on the capital's new drainage and sewerage systems.

His masterpieces were the parish church at Le Vesinet, built in 1864 of concrete around an iron frame; a six-storey apartment block at the corner of the rue Miromesnil and the rue de Naples in Paris, built in 1867; and the Aqueduc de la Vanne, built near Paris between 1866 and 1874. Coignet's prosperity was curtailed by the Franco-Prussian War of 1870-71, though, largely through the agency of General Q.A. Gillmore, his methods were later widely adopted in the USA. Thereafter, if we disregard the artistic use of concrete by the 'Rocailleurs'[4-40], France's principal contribution to concrete construction lay in the development of reinforced concrete in the 1880s and 90s, to which Francois's son Edmond was a major contributor.

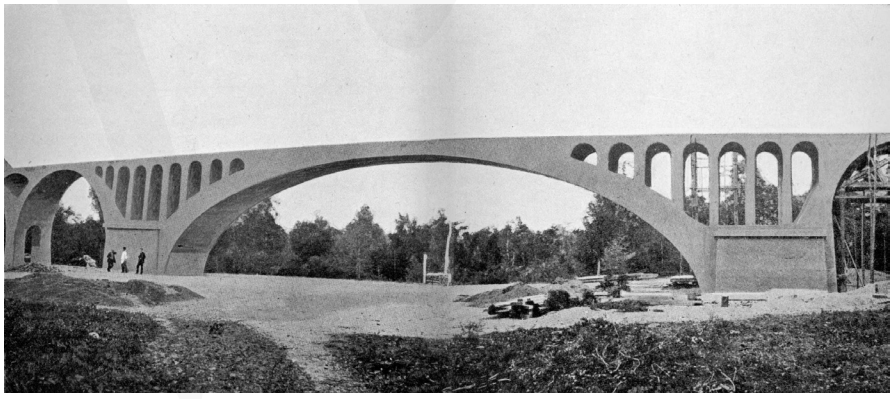


Fig. 4-11 Aqueduc de la Vanne, built in 1866-74 by Francois Coignet.

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4.6 The London Main Drainage and Thames Embankments

Just as Paris accepted the use of new materials for its drainage system, so too did London. Construction of the London Main Drainage system in the 1850s and 60s had an importance far beyond the vast improvement in sanitation it provided: as a proving ground for Portland cement on an extensive scale, and a stimulus to quality control in manufacture. Initially, cement was used in mortar for setting brick sewers, but as the project unfolded, cement-based concretes were used as hearting and for the production of precast concrete pipes[4-41], [4-42].

In 1871 Grant reported that after the successful use of Portland cement in bedding the bricks used for building the earlier sewers, the Board had moved on to making sewers entirely from concrete, and these became standard in Board contracts. Whereas brick sewers cost 16s. 6d per foot, a concrete sewer of 4 feet by 2 feet 8 inches cost 10/-[4-31].

The work rapidly escalated in scale. By December 1863, bills of quantities for constructing the southern low-level sewer specified 57,410 cubic yards of concrete. Raw materials were delivered by barge to Barking, but much, including the concrete, was produced on site. Mixing plants were erected at Crossness and Plaistow, and were described by contemporaries as fitted with expensive and complex equipment[4-16].

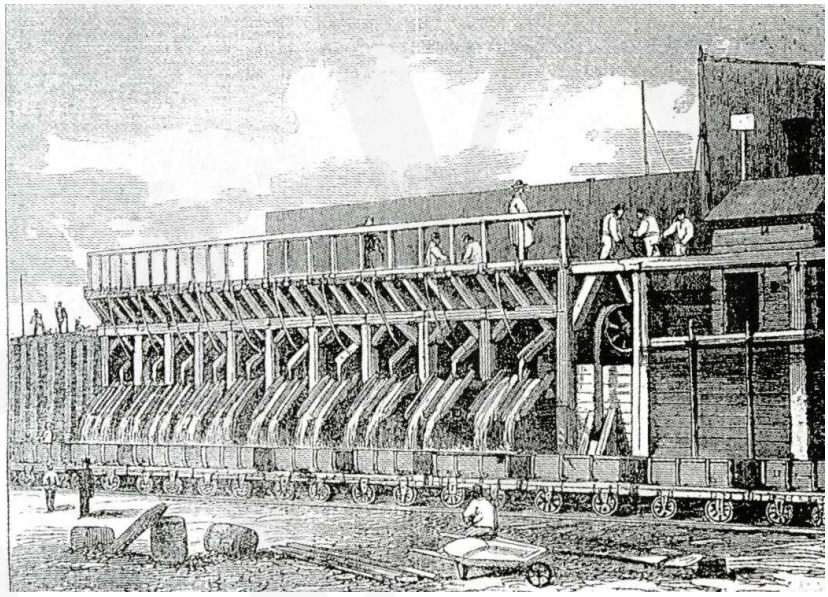


Fig. 4-12 The concrete mill at Plaistow in 1861[4-43].

Overall, the 82 miles of intercepting sewers required 318m bricks and 880’000 cubic yards of concrete, the demand for which caused shortages of supply and price increases in consequence. The use of concrete continued to intensify as the Thames embankments were built, consuming 6m cubic ft of brickwork and Portland cement. Success led to larger quantities being used on the three embankments, amplified by a switch from brickwork with granite facings to concrete with granite, about a quarter of the way into the Albert Embankment contract. At 11/- a yard, compared with bricks at 30/- a yard, 14’300 cubic yards of concrete were employed on those works. Further quantities were then used on the Victoria and Chelsea Embankments[4-42]:

- Albert Embankment – opened 24 November 1869 (cost: £1’014’525)
- Victoria Embankment – opened 13 July 1870, though not yet finished (cost: £1’156’981)
- Chelsea Embankment – started July 1871 and opened on 9 July 1874 (cost: £269’591)

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4.7 Structural concrete in England in the 1860s and 1870s

Potter observed in 1877 that "very little is known, comparatively speaking, about the general application of Concrete to structural purposes." He acknowledged and promoted concrete's expanding role, arguing that "concrete must and will, however, eventually come into general use for building purposes"[4-2]. Indeed it did, but it took several decades, from the mid-1850s to the mid-1870s, to progress from the experimental to the established.

According to Addis & Bussell[4-44], concrete walls for domestic buildings were introduced in the 1850s, and by the early 1870s – though they remained exceptional in a housing stock dominated by brick and stone – examples of houses made substantially with concrete were quite frequently cited in the trade press.

An article in *The Builder* in 1892 paid tribute to three men in particular, as pioneers of concrete construction: Joseph Tall, Charles Drake and Thomas Potter. In fact, Drake had worked for Tall and Potter adopted Drake's methods in his own work, and although relations between the three men were not always cordial, the trio became known to contemporaries as The Patentees[4-45].

4.8 Joseph Tall

Tall, a bricklayer by trade, developed a moveable formwork system similar to that devised by Coignet and, having secured the protection of a patent in 1865, "brought the use of monolithic cement concrete walls into much prominence by the introduction of wood frames or moveable panels for casting the concrete" (Potter quoted in Barfoot[4-46]). Perhaps his best-known memorial is a pair of semi-detached houses at 65-67 Woolwich Road, Bexleyheath, Kent, which he built in 1866 for the use of "agricultural labourers and workmen". It was described as built of "concrete combined with brick rubbish or other hard durable substance" and the walls were erected on "ordinary concrete foundations". (It seems that concrete foundations had been long accepted by this date.) The constituent materials were: 30 cu yd gravel; 3 cu yd Portland cement; 3 cu yd drift or river sand, and the concrete once mixed was cast within the wooden framework, into which recesses and projections could be inserted to form fireplaces and mantelpieces. The houses cost £100 to build, saving half the cost of brickwork walls.

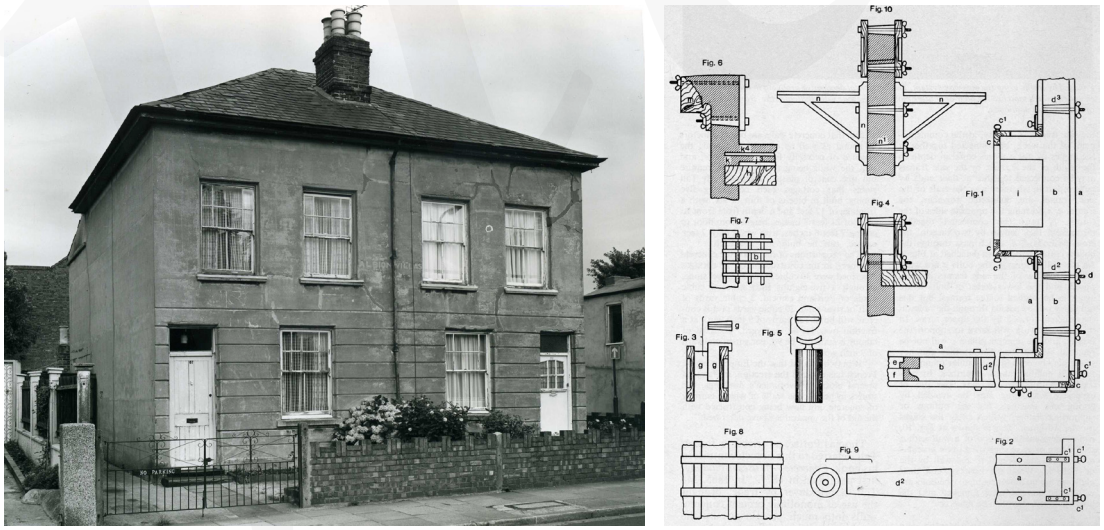


Fig. 4-13 (Left) Joseph Tall's houses at Bexleyheath (The Concrete Society); (Right) Joseph Tall's patent apparatus[4-2].

The houses attracted attention and, after Tall received a gold medal at the Paris Exhibition of 1867[4-47], Napoleon III ordered 40 workmen's houses to be built with walls of concrete in the Boulevard Daumesnil. The work was undertaken by the English contractors, Newton and Shepard – licensees of Tall's apparatus – from plans that included alterations sketched by the Emperor himself[4-2]. "The Emperor of the French has set us a good example", declared *The Builder*[4-48].

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However, despite French approval, the London authorities were not so receptive. The building regulations were founded on the Metropolitan Building Act 1855 which enshrined the established technology of Georgian London: "Walls constructed of brick, stone or other hard and incombustible substances and the foundations shall rest on solid ground, or upon concrete", the regulations required, and while "every wall constructed of brick, stone or other similar substances, shall be properly bonded and solidly put together with mortar or cement", they firmly stated that "all return walls shall be properly bonded together"[4-47]. This was the rub, as officials contended that concrete could not be said to be "properly bonded and solidly put together" Although the Metropolitan Board of Works carried out tests in November 1867 in Gravesend, which clearly demonstrated the superior strength of concrete, buildings with concrete walls were permitted only by special licence. The first was in February 1868 in which the contractor H. Goodwin, using Tall's system, built what he claimed to be the first cement-concrete building in London: a warehouse with walls 60ft high, in Great Guildford St., Southwark.

Tall obtained licences to build other dwellings in the years following, including industrial housing in 1871, in both Great Dover St and Lawson St, Southwark, and six three-storey blocks for the Peabody Estate at East Lane, Bermondsey in 1872. Also in 1872 Goodwin built a concrete property in King St., Borough and Philip Brannon, with another newly patented apparatus, commenced building at New Bunhill Fields, Islington. Disastrously, the roof collapsed and the grudging official approval was rescinded. It was to take almost 20 years for legislation to officially recognise concrete for building purposes in London.

Eventually a test case was brought against Goodwin who had built two five-storey blocks of "artisans' dwellings", in Zoar St, Southward (1884-85), but the presiding magistrate pronounced concrete to be "a good material", adding "and I think that the Metropolitan Building Act ought to have sanctioned it"[4-24]. Metropolitan Board declined to challenge the ruling and reissued amended Bye-laws on 23 June 1886: "Whenever concrete is used in the construction of walls, the concrete shall be composed of Portland Cement, and of clean Thames or pit ballast, or gravel or broken brick or stone, or furnace clinkers with clean sand …" (Bye-laws quoted by Collins[4-24]).

4.9 Charles Drake

As Tall was making a name for himself in London during the late 1860s, his former assistant Charles Drake started out in business on his own account. Having offered Tall the option on an improved design of formwork and been refused, he established 'Drake Bros & Reid, Co Ltd, Concrete machinists and builders' at 208 New Kent Road, just around the corner from Tall in Great Dover Street. From these premises, he supplied builders with his patented equipment. This included a concrete mixer (1869, No.736) a stonebreaker (also 1869) and his signature 2-ton formwork apparatus. This, made of iron, as opposed to Tall's use of wood, with a 24 inches lift compared with Tall's 18 inches, was patented in 1868[4-49]. Clients could rent the apparatus (paying a royalty per foot of construction), or buy it outright (and become an agent).

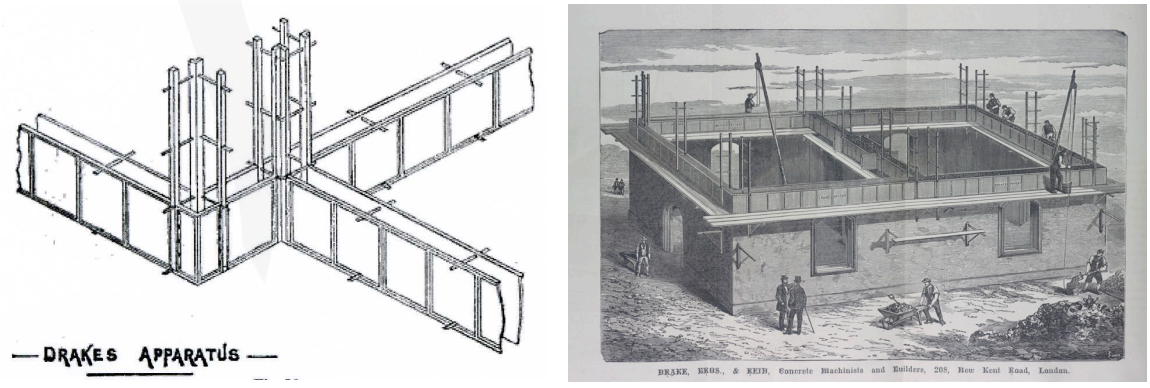


Fig. 4-14 Drake's patent apparatus (Potter[4-2]).

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With his younger brothers John and William he also undertook site supervision, set-up, training and, for the larger jobs, project management, while Drake & Co would also undertake the entire building works as a contractor. In March 1876, Drake himself said of a ten-year career on concrete: "I believe I can claim without exaggeration to have erected more concrete buildings than any other person" (Quoted by Scott Cowan[4-45]). Indeed the total was said to run to thousands.

His first complete building of note was 'Fernlands', in Chertsey, designed by Thomas Wonnacot for the brewer John Maddox. It was heated by a plenum, with ducts cast into the concrete, and the use of concrete extended to the garden's retaining walls. Fernlands became a show house and Wonnacot an effusive champion of the new building method. Within a short span, another three houses were built to Wonnacot's designs: one in Addlestone, another in Tilford, Surrey and one in Wargrave, Berkshire.



Fig. 4-15 Waverley Hydropathic Hotel (Concrete magazine[4-50]).

The Waverley Hydropathic Hotel at Melrose, designed by James Campbell Walker, was built to Drake's system in 1869 and as one of the largest concrete buildings of its day, it represented a considerable investment in concrete construction. It became a flagship for concrete building in Scotland. The Duke of Sutherland was named among Drake's clients in 1870 and it seems that the Duke had bought Drake's apparatus. Sutherland became an influential advocate of concrete himself and on his Dun Robin estate, he had Helmsdale railway station built of concrete in 1871.

Over the ensuing years other houses followed, and of these, perhaps the most distinguished was Down Hall near Hatfield Heath, Essex, designed by F.B. Cockerill in 1873 and finished with stucco and sgraffito panels. Enhancing the utilitarian surface of structural concrete was a preoccupation of the period, and Drake himself argued that finishes such as these were an appropriate treatment of the material itself, and not simply a disguise.

In 1875, in one of his later commissions, Drake built a house at Stapleford, Cambridgeshire, for the Revd. Charles Dawe who, having been burnt in the past, was looking for a fire-proof home. All the walls, floors and flat roof were cast in concrete.

4.10 Other examples

Tall and Drake were not alone and the early 1870s saw a spate of house-building in concrete, largely as private commissions on landed estates, and many examples from this decade could be cited[4-51],[4-52],[4-53],[4-54], [4-55]. Although concrete construction in London suffered in the aftermath of the Brannon disaster of 1872, the commissions that Tall, Drake and others continued to enjoy throughout

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the early 1870s indicate an enquiring interest in architectural circles. This was reflected in some of the papers read to the Royal Institute of British Architects at this time.

- 1871 Thomas Wonnacott The use of Portland Cement
- 1876 Alexander Payne Concrete as a building material
- 1878 Arthur Cates Concrete and Fire Resisting Constructions

Interest appears to have peaked in April 1876 when a debate on concrete was held at the RIBA that the emerging industry must have hoped would confirm concrete's place in construction technology. However, the debate stretched over three sessions, into May, and any such hopes would have been deflated by the increasing evidence of professional antipathy. A paper by Alexander Payne was notably hostile to the Patentees and the summing up by Charles Barry Jr was lukewarm at best. With novelty exhausted, there was to be little further architectural interest in concrete for a generation.

However, those with interest in concrete as a practical medium of construction displayed less ambivalence and where there was freedom to experiment, in agriculture or industry, for instance, there were several prominent developments.

One of the earliest examples of mass concrete wall construction, using concrete made from Portland cement, was the extensive three-storey Kiln Warehouse in Newark. Built in 1857 for John Hole, it was originally a maltings, and is now listed as a significant building[4-56]. A similar, but four-storey warehouse of mass concrete was the wine and spirit store built for H & G Simonds, brewers of Reading in 1870. The walls and floors were of solid, exposed concrete, the latter supported on iron columns capable of 100t loading[4-57], [4-58].



Fig. 4-16 Simonds Brewery (Photos: The Concrete Society).

Early these brewery buildings may have been, but they were far from alone, as several examples from agriculture testify, including the concrete barn on Robert Campbell's industrialised farm in Buscot.

4.10.1 Robert Campbell, Berkshire

When in 1859 Campbell returned from Australia and settled in Buscot near Faringdon (now in Oxfordshire), he ploughed his considerable fortune into experimental agriculture. His estate, with its own light railway and telegraph, contained what was one of the most highly industrialised farms of Victorian Britain in the 1860s. In 1869 he built a large barn in support of a scheme of livestock breeding and intensive fattening; it was 162 ft long, 60 ft wide and 12.5 ft to the eaves, with mass concrete walls and an insulated tile roof[4-57].

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Fig. 4-17 Campbell's concrete barn at Buscot (Photo: The Concrete Society).

Its novelty was highlighted by its inclusion in the Journal of the Royal Agricultural Society of England[4.59]. Others followed his lead.

4.10.2 Thomas Potter, Wiltshire and Hampshire

Thomas Potter worked as clerk of works to Alexander Baring, 4th Baron Ashburton, for the 20 years 1868-1889, and was based at Swarraton, in the parish of Northington, Hampshire. Lord Ashburton had an interest in providing "good and cheap dwellings for the poor" on his estates and, under Potter's administration, concrete became the chosen medium for fulfilling this ambition.

Evidence for his work exists in the Wiltshire villages of All Cannings and Steeple Langford, where several semi-detached houses remain[4-45]. One pair of cottages was built in concrete by Pitt and Drake for Lord Ashburton, along side one of brick, and the price of construction compared. According to a testimonial written subsequently by Potter, the price of concrete was found to be half that of its longer-established rival. A concrete farm and Potter's own house were built at Steeple Langford in 1869, and several additional cottages by 1871.



Fig. 4-18 A concrete cottage at Steeple Langford (left), and the rear of Potter's own house (right) (Photo: David Scott Cowan).

Subsequent concrete works took place Manor Farm at Chilton Candover, which was rebuilt in 1875 with 12 inches thick concrete walls made by crushing and recycling the demolished former buildings[4-60]. Finally, the church of St John the Evangelist at Northington, funded by Lord Ashburton, was built in

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1888. The core was Portland cement concrete "in the proportion of 1 to 7 inches, with much-embedded flint"[4-61]. The outer walls were constructed from precast panels into which Lord Ashburton's labourers arranged decorative flints. Moreover, the churchyard walls, which are now protected in law, are of hollow concrete blocks impressed with flints and embellished with tinted tracery.



Fig. 4-19 (Left) The Church of St John the Evangelist at Northington and (right) detail of the flint embedded concrete panels (Photos: Edwin Trout).

It was in 1877 that Potter wrote the first edition of the book for which he is remembered, *Concrete: its use in building and the construction of concrete walls, floors etc*[4-2]. In this he described the use of concrete, derived from his experience on the Ashburton Estate, as well as providing a fold-out design for a concrete villa. It wasn't the first book on the subject of concrete, though it was a significant early work. As Potter wrote in his preface: "Although technical books on almost every conceivable subject have been written, it is somewhat singular that no practical work of Concrete – besides this – so far as its application to building is concerned, has hitherto appeared".

4.10.3 Andrew Peterson, Hampshire

After a career in the law, in which he served as a judge in the High Court of Calcutta, Andrew Peterson settled in the Hampshire village of Hordle in 1868. Peterson was a man of many interests; he studied and wrote on subjects as diverse as spiritualism, psychology and construction. He became a shareholder in the Isle of Wight Cement Co and experimented with concrete to build various small agricultural buildings locally. During the late 1870s, his attention turned to the project that would later bear his name: a mansion commissioned as his own residence, with a tower that would demonstrate the use of concrete as a versatile new construction material[4-63].

Designed by Peterson himself, the tower was to be made of mass concrete, made of local gravel with – for features such as the window surrounds – the addition of a dry red pigment. Two of Peterson's hand-written diaries survive at Hampshire Record Office and contain a fragmentary record of the construction work, a process that commenced in early 1879 and continued to 1886.

Timber formwork of Peterson's own devising was reused in rotation as the tower progressed upward. Frames were constructed to the dimensions of the tower at each stage and used as a set of three. The three were bolted together, filled with concrete and rammed for compaction. As the concrete hardened, the lower frame was removed and placed on top, ready to be filled again with fresh concrete, which was raised to the working area by bucket and pulley. Construction proceeded from within, without the use of scaffolding, precast concrete steps incorporated into the walls as work progressed.

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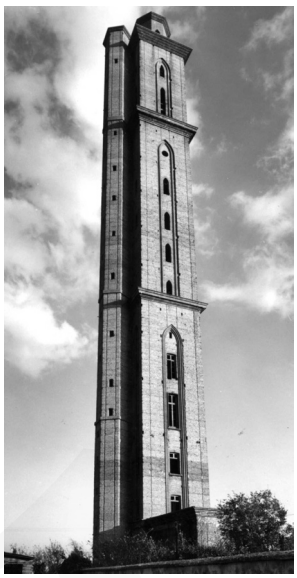


Fig. 4-20 Sway Tower (Photo: The Concrete Society).

When completed the 13-storey structure was 218 ft high: a 198 ft tower, surmounted by a two-storey octagonal observatory and a helical staircase of 330 steps. At the foot were two porches and the whole edifice was built on foundations 9 ft deep. The walls were 2 ft thick at the base, decreasing to 18 feet 12 inches at the top (610 – 360mm), and were pierced by a series of lancet windows in the Gothic style.

4.10.4 Fortifications

The army is often at the forefront of technical development and it was no less so in the evolution of concrete. Just as General Sir Charles Pasley in Britain, and General Treussart in France, had been among those charged with adapting the use of cement and pozzolana to the requirements of "military architecture", so the Royal Engineers continued to experiment with concrete. In a paper published in 1862, for instance, Capt H.Y.D. Scott advocated the use of Portland cement for constructing concrete fortifications[4-64].

Construction of fortifications was recommended in a Report of the Commissioners appointed to consider the defences of the United Kingdom in 1860, and concrete was soon to be one of the materials employed. Newhaven Fort, built in 1866, "may have been the first really large scale use of concrete above foundation level"[4-65]. The concrete at Newhaven was composed of Scott's cement, clean sharp sand and beach shingle, hand-mixed in proportions of 1:1:6, with sufficient water added just before use. It was laid in courses 1 foot high and rammed, with mortar brought to the face with the action of a shovel. It was to last more than a century, despite evidence of vertical shrinkage cracks and some honeycombing.

A further ring of forts around Chatham was started ten years later[4-66]. Originally conceived as brick and masonry structures, concrete was substituted here, as elsewhere, in the 1880s in response to the French development of explosive shells. Concrete was used for the revetments and some of the casemates, but came into its own for caponiers, counterscarp galleries and underground works. Fort Horsted and the redoubts at Twydall were finished in 1889, Forts Borstal, Bridgewoods and Luton in the mid-1890s and Darland in 1899.

Similar concrete fortifications were constructed in Belgium during the 1880s – at Leige, Namur and Antwerp – overlooking the Rhine at Strasburg and along the Franco-German border from Belfort to Verdun. Similarly, the Germans fortified Heligoland in the 1890s, with concrete emplacements up to 8 feet thick. Such work foreshadowed a massive escalation in the military use of concrete during the First World War[4-67].

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4.11 Precast concrete in the 1870s

When Henry Reid wrote his polemic of 1869, he noted that concrete was being used for architectural mouldings in Germany, and – as in London – drains and sewage pipes in France.

"We have been the last to acknowledge the advantages of concrete except for foundations and sea works"[4-12], he claimed and went on to argue for its use in housebuilding in the UK. Just as methods of in-situ concrete construction developed in the 1870s, both for domestic and commercial buildings, so did the production of precast concrete products, even entire systems of building. One of the earliest was the one patented by Matthew Allen in 1862 and employed in London "for the deserving poor"[4-68].

But the best known is probably that of William Lascelles[4-16]. The Lascelles system comprised a timber framework or skeleton, clad in concrete panels. The concrete was made of breeze or "small coke", bound in a matrix of Portland cement, and faced in neat cement, that could be coloured to order by means of metallic oxides. The panels were that of a standard size (3 feet long and 2 feet tall) and of three basic shapes, according to function – fish-tail tile slabs, plain slabs and lining slabs, combined with 8 ft long "studs" used for joists or sills. Each panel was attached to the frame with only four fastenings. Providing architectural ornament, 'patent concrete bricks' were mounded to form quoins, pilasters, cornices and similar features, and 28 designs were commissioned from the eminent architect, R. Norman Shaw.



Fig. 4-21 Lascelles's design for precast houses (Left) in Paris (Photo: Reid[4-16]); (Right) as built in Croydon (Photos: The Concrete Society).

A form of prefabrication, houses built in this manner did away with the need for excavation, bricklaying, timber flooring, tiling, lathing and plastering. They were cheaper to build than brick houses, much quicker to erect and in any weather. They were lightweight and disassemblable, capable of being shipped to distant destinations in kit form, or even relocated after use. One of the first examples built – a Queen Anne house in the Street of Nations at the Paris Exhibition of 1878 – demonstrated these benefits perfectly. Others followed: ten workmen's cottages at Greenhithe, Kent, built over the winter of 1878/79; a 20 ft dome designed for an Indian prince in 1879; a suburban house at 228 Sydenham Road, Croydon (1882)[4-69] and the Buffet, Royal Albert Dock (1883).

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Less systematic, but commercially very successful, was the achievement of Robert McAlpine in Scotland. He won his first big contract in 1872: a hundred miners' cottages in Stonefield, near Hamilton, the profits of which enabled him to expand his business. By 1877 he employed over 100 men and was turning over more than £100'000 a year. During these years of expansion, he leased three brickworks to maintain control of his input costs, and started to experiment with concrete as a cheaper building material. Initially he made lintels and doorsteps, but by 1876 he was building houses with walls of rubble-concrete blocks[4-70].

McAlpine might have acquired a reputation for his use of concrete, but he was just one among many builders at the time who incorporated precast concrete elements in the houses of Britain's booming residential sector. Quite an industry grew up to service the housebuilding industry, turning out lintels and window dressings for houses, and pipes and paving slabs for the streets in which they stood. Concrete block and infill pavement had first been used in 1866, on George IV Bridge, Edinburgh[4-16].

Artificial stone had a long history of architectural use in Britain, based variously on clay, lime and natural cements. Austin & Seeley was the first manufacturer of artificial stone based on Portland cement. Established in the mid 1820s Austin mass-produced fountains and garden ornaments, earning the praise of advocates such as Loudon in periodicals such as Gardener's Magazine, 1834 and Architectural Magazine, 1835. John Seeley entered into partnership in 1840 and Austin & Seeley became one of the largest of several manufacturers of artificial stone in the Victorian period[4-8].

Another of the more important firms in this line during the middle of the nineteenth century was Ransome's Sileous Stone Co. of London. Not strictly concrete, Ransome's material required flints dissolved in caustic alkali to form soda silicate, which was combined with sand and moulded, before being bathed in calcium chloride to form silicate of lime. But it led to the application of a silica treatment for concrete products. Messrs Hodges & Butler established a business on the site of the former Ransome's works during the late 1870s and produced paving slabs, using a machine of their own invention combined with baths of silicate of soda, and pipes of all sizes, using an American impact method. Likewise Victoria Patent Stone was established in London by a Mr Highton and produced Portland cement-based paving slabs and architectural dressings treated with caustic soda[4-16].

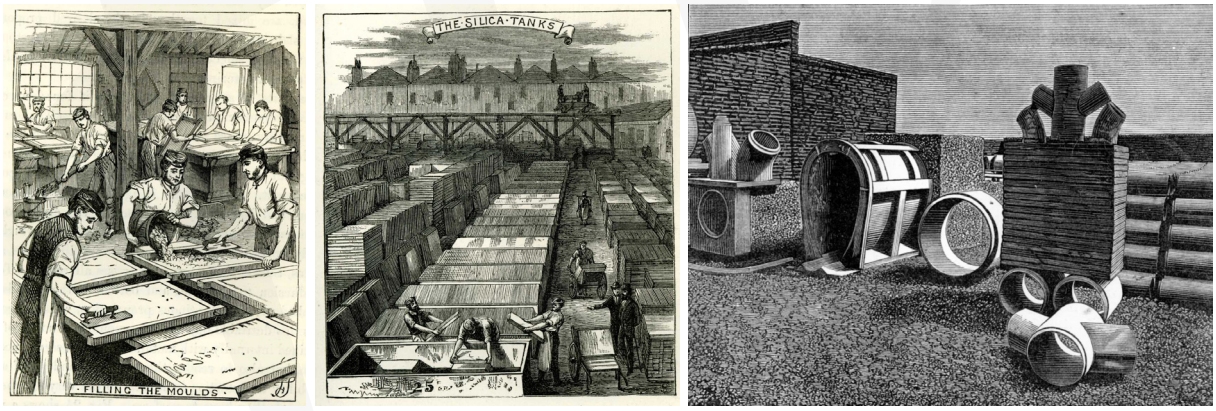


Fig. 4-22 Paving slabs at the Victoria Stone works and pipes at Hodges & Butter (Reid[4-16]).

'Rock concrete' pipes, made with broken pottery as aggregate, were introduced from the USA in 1875 by J.W. Butler, who purchased the British patent[4-16] and granted the exclusive right to manufacture to Messrs Henry Sharp, Jones & Co of Bourne Valley, Dorset. Other enterprises included Lish's patent interlocking 'Z Blocks' and Messrs J. & H. Patteson's concrete tile[4-16].

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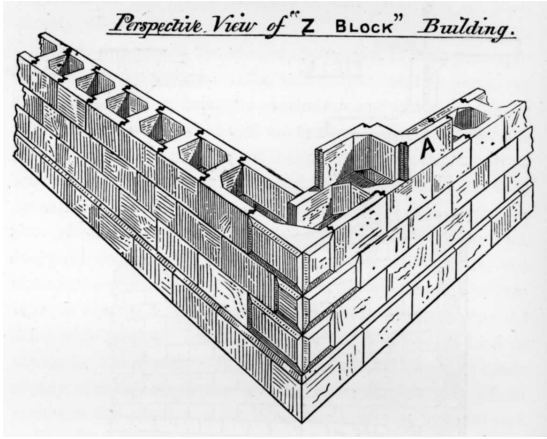


Fig. 4-23 Lish's patent interlocking 'Z Blocks'(Reid[4-16]).

Similar developments occurred in rapidly industrialising Germany, where in the 1870s the underpinning cement industry was overtaking that of Britain in terms of quality and volume of output. Some concrete products had long been on the market. Concrete roof tiles, for instance, were developed in Germany during the 1840s by Adolph Kroher, and commercially available at least since his establishment of Staudacher-Cementfabrik in 1858[4.71].

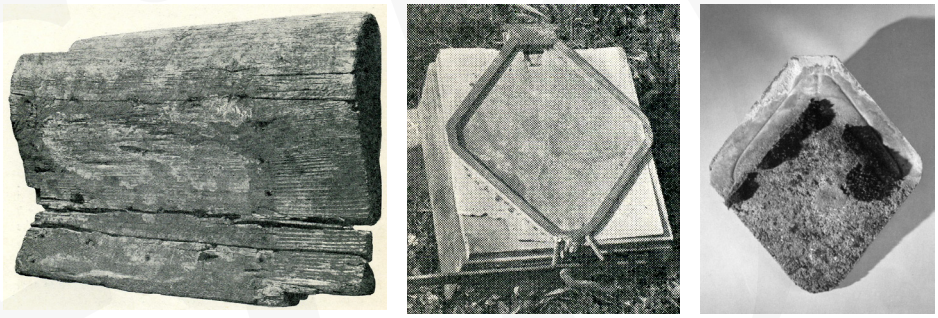


Fig. 4-24 Adolph Kroher's original roof tile and moulds (Dobson[4-71]).

But with the emergence of firms such as Huser & Cie, Gesellschaft fur Zementstein-Fabrikake, and Dyckerhoff & Widmann, the range and sophistication grew rapidly. A glance at photographs of the exhibition displays mounted by Dyckerhoff in the 1870s reveals an abundance of ornamental concrete – statuary and architectural dressings in imitation of stone – as well as the more utilitarian drainage and sewerage pipes[4-72]. (Such combinations of the fashionable and functional were being produced in France and Belgium too, by companies such as Blaton-Aubert in Brussels)[4-73].

Eugen Dyckerhoff was the driving force of his business. A son of the manufacturer Wilhelm Gustav Dyckerhoff, he gained early experience in his father's cement works in Karlsruhe, where his brother Rudolf, a chemist, ran the laboratory. In 1866 he joined the concrete manufacturer, Lang & Cie, which his father and two partners had established a year before to make tanks, pipes and paving products as an outlet for Dyckerhoff cement. In 1869 he took his father-in-law, the Karlsruhe businessman Gottlieb Widmann, into partnership and changed the company's name to Dyckerhoff & Widmann. Inspired by visits to concrete manufacturers in Austria, France and the Netherlands, he experimented with the material to develop what became known in Germany as Stampfbeton – a stiff-mix unreinforced concrete, laid in 6 inches layers and pounded – an evolution of the French béton aggloméré.

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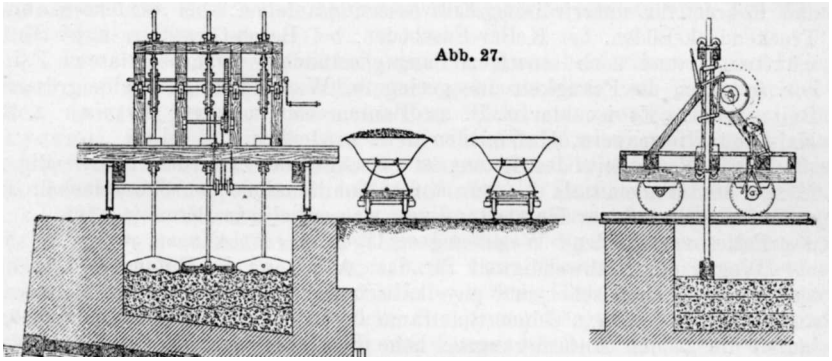


Fig. 4-25 Machine for placing stampfbeton machine (Busing & Schuman[4-33]).

With a rigorous approach to testing and quality control, and an eye for publication and publicity, Dyckerhoff & Widmann's reputation rose rapidly. The company produced artistic products for prestige purposes – architectural ornament and sculpture, such as the famous Galatea fountain in Karlsruhe – and a more utilitarian, but profitable output of concrete pipes and drainage products for which there was a huge demand in the newly unified Germany of the 1870s and 1880s. The company established new factories in Biebrich (1869), Nuremberg (1878) and Chemnitz (1886) – the latter transferring to Dresden in 1890 – to cope with the logistics of supplying heavy goods over long periods to a national market.

Principally a manufacturer, Dyckerhoff & Widmann supplied components, but had little involvement in the underlying structural work. Then in 1880 Dyckerhoff experimented with concrete vaults as the optimal structural form for stampfbeton, and presented a heavily decorated arch footbridge at the Dusseldorf trade exposition. This, in retrospect, was a turning point, combining the company's earlier expertise in ornament with a new focus on structures and construction. It set the direction of the next two decades, building vaulted reservoirs and arch bridges.

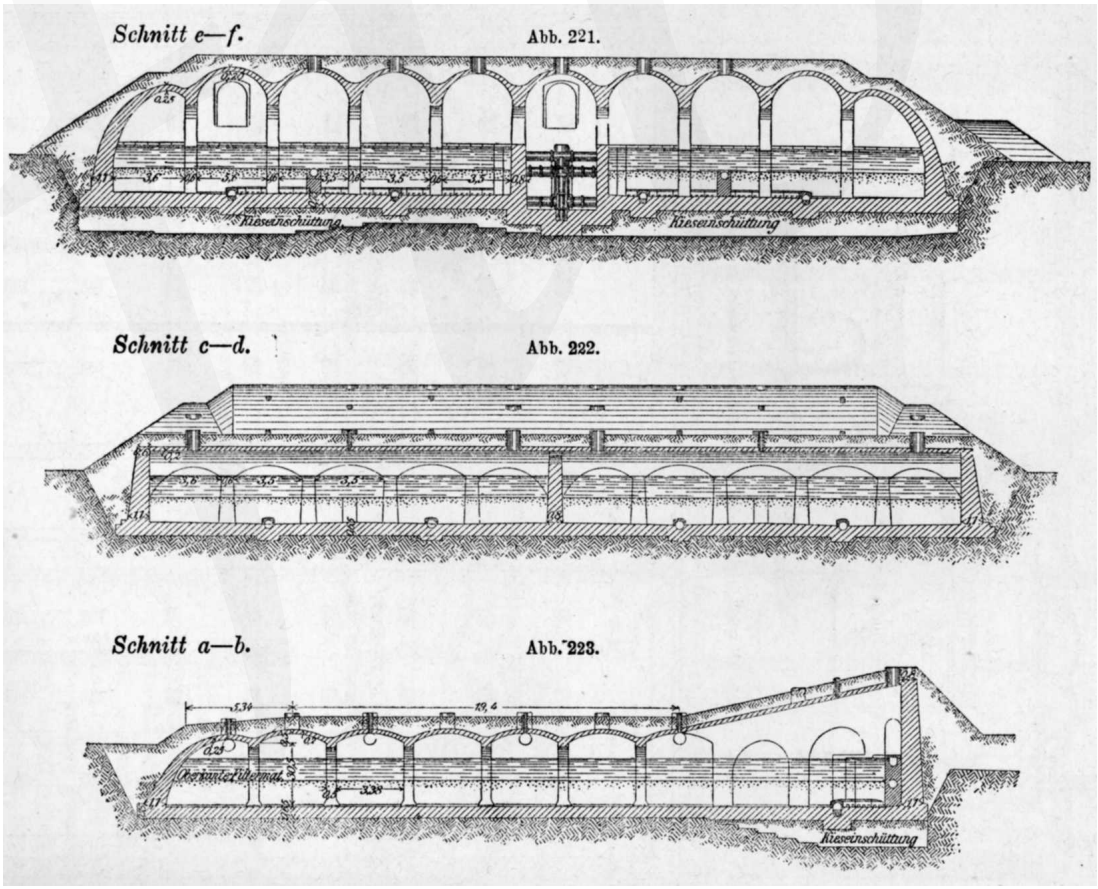


Fig. 4-26 Stampfbeton reservoir at Worms, Germany (Busing & Schuman[4-33]).

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Like Dyckerhoff & Widmann, Huser & Cie started out in precast concrete products and later moved into bridges built in stampfbeton. Established by Hartwig Huser in 1875, from the assets of the pioneering concrete business of August Sadee – who had been instrumental in establishing one of Germany's first cement works at Stettin – the new firm was initially a small workshop in which concrete products were made: pipes, and roof and floor tiles. Huser industrialised the production of sewage pipes, moved into paving slabs and kerbs, and in 1878 took out a patent for diamond-shaped roof tiles. Huser's sons eventually took over the business and expanded into civil engineering, acquiring a reputation far beyond the Rhine both for concrete products and for bridges and viaducts. The company was eventually responsible for 122 bridges built in stampfbeton.

4.12 Concrete construction in the late nineteenth century

Writers of the period, such as Sutcliffe and Potter, would lament the limited use of concrete as a walling material in contemporary construction, and point to its predominant use in foundations and civil engineering works, but there was one structural element for which concrete was embraced enthusiastically: floors.

4.12.1 Floors

"By far the greatest use of concrete in buildings during the last third of the nineteenth century was in the floors of buildings"[4-44], no more so than the so-called 'filler-joist' form of suspended floor. Harnessing concrete's heat-resistant qualities, and building on a tradition of protective fireproof floors originally patented by Fox & Barrett in 1844, these became particularly popular in the 1880s and 90s. The incorporation of coke breeze, cinders, crushed brick, burnt clay or other waste, was considered suitable for this purpose. Indeed, the use of materials that had previously undergone a heat-treatment process was encouraged. The supporting structure was provided by iron or steel joists, which partly fulfilled the role soon to be taken by integral steel reinforcement.

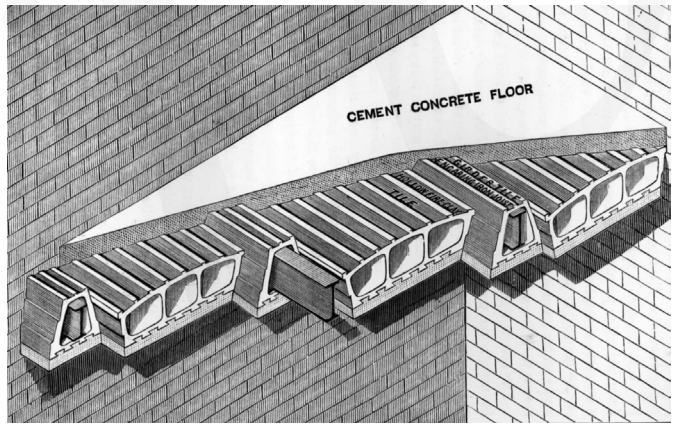


Fig. 4-27 Suspended floors (Reid[4-16]).

Such floors evolved over the century, marketed in numerous proprietary forms – Hornblower's patent fireproof floors[4-16], and from 1888, Stuarts fireproof flooring[4-74] – to reach their peak of popularity in its last two decades:

- 1796-1860s Jack-arch: brick arches between 'I' beams, concrete on top
- 1833-1850s Fox & Barrett: concrete on top of mortar, lathes, plaster on 'T' beams
- 1850s-1870s Fox & Barrett: concrete on top of mortar, lathes, plaster within 'I' beams
- 1870s-1930s filler joist. 'I' beams encased in concrete
- 1890s-1930s King, Fawcett, etc: concrete on top of terracotta tubes or 'pots' set within iron 'I' beams and in-filled with concrete [4.75].

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4.12.2 Civil engineering projects

This was also a time of large civil engineering projects, to which Portland cement-based concrete was increasingly put, of which the following selection of such projects which the recently combined Associated Portland Cement Manufacturers published for promotional purposes in 1907 was indicative[4-76].

Table 4-1 Civil Engineering projects highlighted as exemplars of Portland cement concrete

Date	Project
1879-1881	New Eddystone Lighthouse
1881-1888	Vyrnwy Dam
1883-1887	The Tay Bridge
1892-1897	Blackwall Tunnel
1895	Southampton Graving Dock

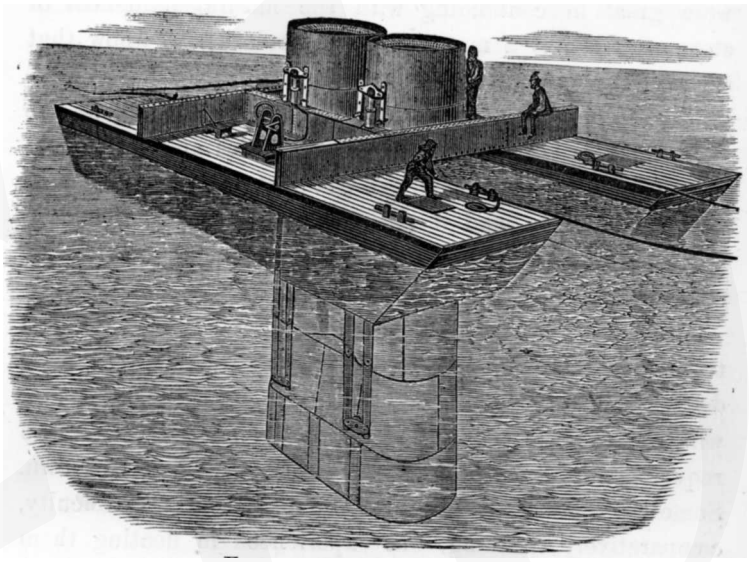


Fig. 4-28 Placing piers for the Tay Bridge (Reid[4-16]).

The Severn Tunnel is another example, for which 36,794t of Portland cement were supplied to[4-77], and the use of concrete as a waterproof cut-offs for dams, rather than the puddled clay of previous practice, led to a boom in water supply projects.

4.12.3 Harbours

There was also a boom in the more established uses of concrete. Concrete had long been the preferred material in harbour works, particularly for the construction of moles and breakwaters, from the seventeenth century works at Tangier, to the use of beton blocks at Algiers in the 1830s and of Portland cement concrete at Dover and Cherbourg in the 1840s. The number and scale of such projects increased as the century progressed and French and British engineering expertise was applied around the world. In India the Madras breakwater was built in 1877 with 33-ton concrete blocks, and rebuilt after storm damage in 1881. The harbours at Colombo and Karachi saw similar concrete block breakwaters built. Sackblocks were used for the breakwater at La Guaira, Venezuela, completed in 1891 by the La Guaira Harbour Corporation Ltd.[4-78].

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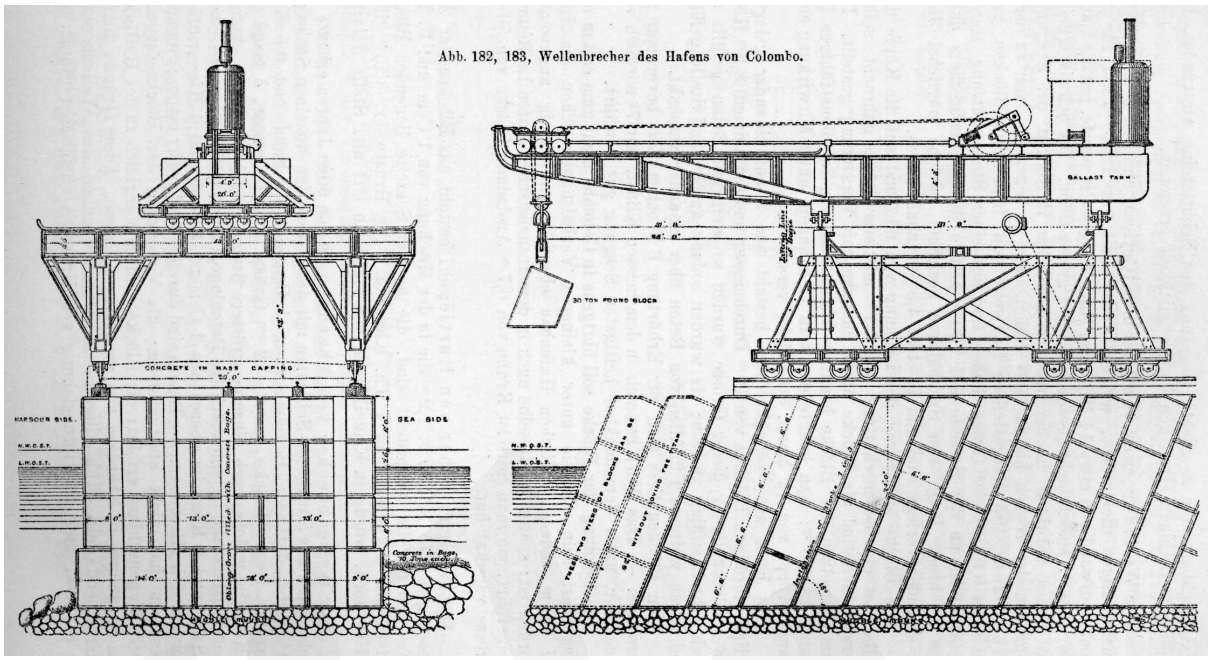


Fig. 4-29 Harbour works at Colombo, Sri Lanka (Busing & Schumann[4-33]).

Various techniques were used, from site-cast blocks manoeuvred into position, blocks cast in situ, to sackblocks (at Newhaven and built in 1878) and hollow blocks floated in to position to be filled in situ (located in Dundee). With its long coast line and prominence in maritime trade, Britain was the centre of the boom in harbour works, with projects carried out in Aberdeen, Buckie, Fraserburgh, Hartlepool, Jersey, Plymouth, Tynemouth and Wicklow (1883-84), to name but a selection.

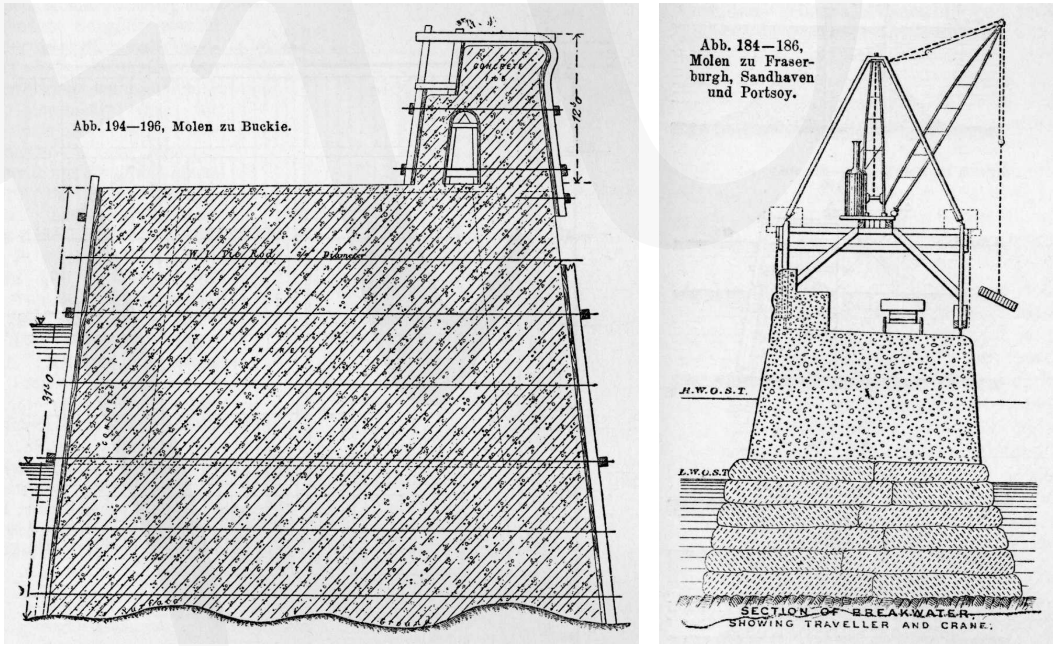


Fig. 4-30 Breakwaters at Buckie and Fraserburgh in Scotland (Busing & Schumann[4-33]).

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French ports that were improved at this time included Le Havre (1880) and Port Vendres, and Germany invested in its naval facilities on the North Sea coast. Other concrete harbour improvements were carried out at Odessa (Russia); Bilbao (Spain); Hanko (Finland, 1889-93) and, at the end of the century, Vardo (Norway, 1896).

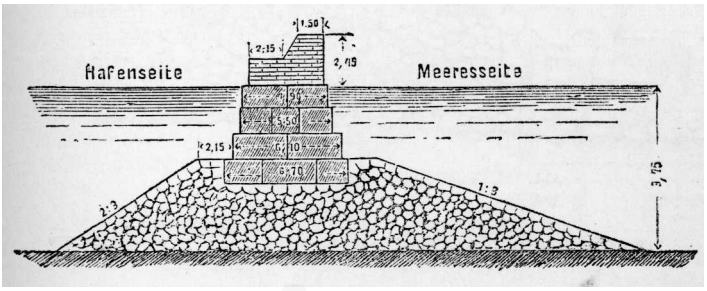


Fig. 4-31 Breakwater at Odessa, Russia (Busing & Schumann[4-33]).

Besides breakwaters, there was a strong demand for sea walls, quays and docks. The switch to concrete made from Portland cement, rather than hydraulic lime, came with the new dock at Chatham, in 1867, and was paralleled by work at Portsmouth that lasted until 1881.

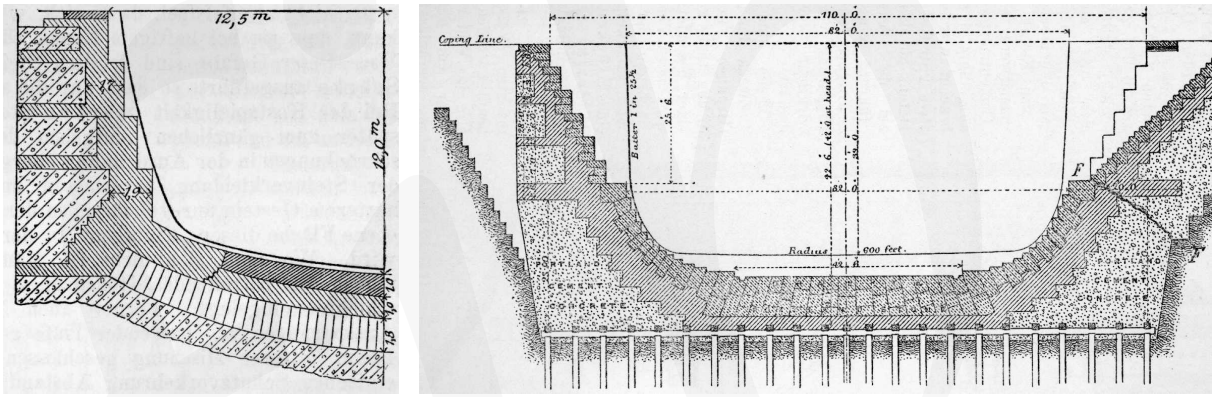


Fig. 4-32 Chatham and Portsmouth docks (Busing & Schumann[4-33]).

By the time the Royal Albert Dock was built, in 1876-1880, mass concrete walls had become established[4-44].

One dock project picked out in the contemporary literature as significant was the expansion of Birkenhead docks on the River Mersey in the 1860s and 70s. Construction of the Morpeth Branch Dock required the replacement of a river lock with a dam, and concrete was selected over the granite used in previous work at Birkenhead. When G.F. Lyster, chief engineer to the Liverpool Dock Board, turned to developing the Wallasey Dock (1874-77), concrete was again the chosen material. In order to ensure water tightness, a series of experiments was conducted to determine the optimum proportions of fine to coarse aggregate for any given quantity of cement, to ensure the filling of all interstices. The results were published in the proceedings of the Institution of Civil Engineers in 1878[4-79]. The specialist consultant Henry Reid also remarked on the innovations at Birkenhead in his book of 1879[4-16], illustrating the concrete mixer devised by a resident engineer, William Henry Le Mesurier. It is perhaps indicative of the importance of harbour works that when a German book sought to illustrate concrete mixing equipment of the 1880s, the machinery used at Newhaven and Tynemouth were among the examples[4-33].

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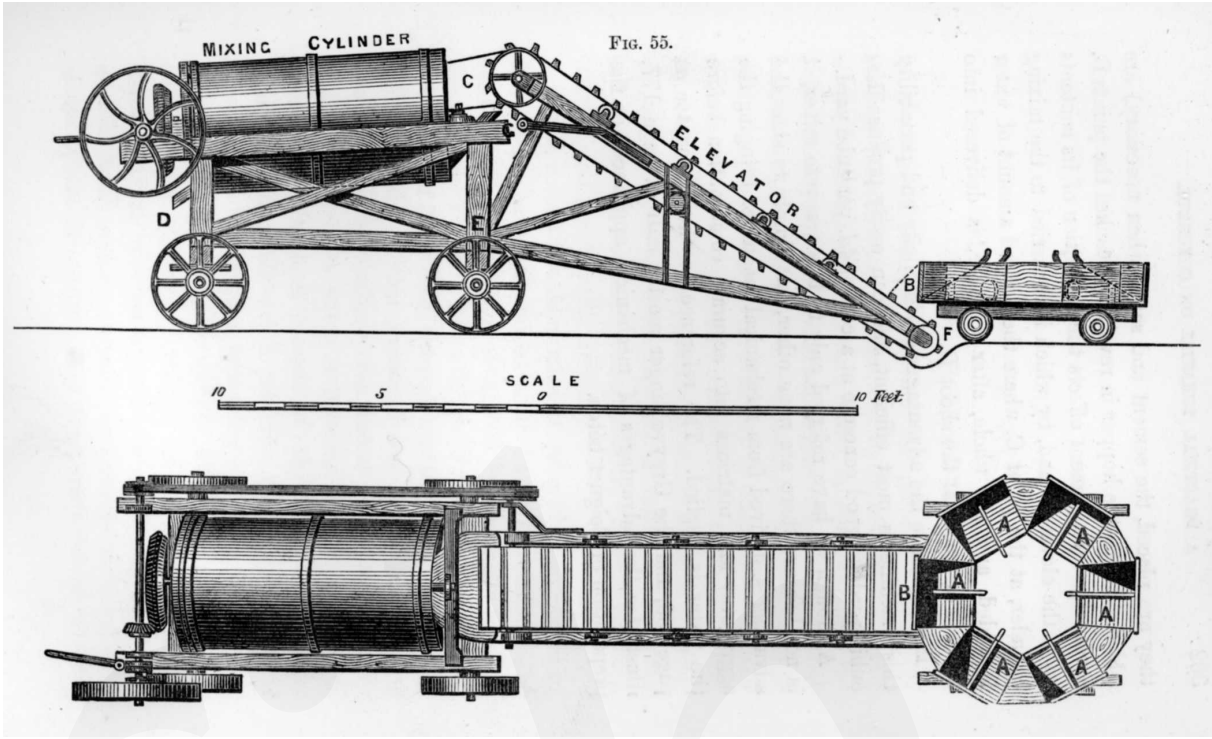


Fig. 4-33 Le Mesurier's concrete mixer at Birkenhead (Reid[4-16]).

At Scarborough, a sea wall was erected in medium-sized concrete blocks. These, while more expensive than in situ concrete, allowed for quality checks and substitutions before use and expansion and contraction while in service. Many such walls, such as the river wall at Fulham, were faced with blocks, bedded into mass concrete infill[4-1].

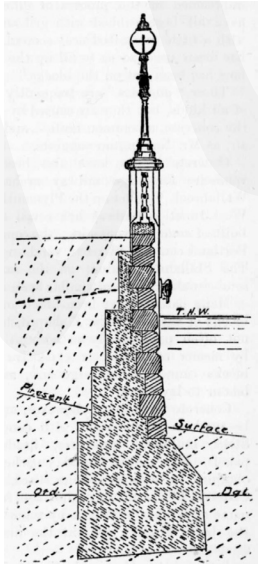


Fig. 4-34 Concrete embankment at Fulham, London (Sutcliffe[4-1]).

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Closely associated with harbour works, and recalling early experiments with hydraulic binders, were lighthouses. The 135 ft tall lighthouse at La Corbiere, on Jersey, was built with concrete blocks in 1873-74, to the designs of Sir John Coode and even in Germany, as late as 1892, was regarded as the exemplar of such structures[4-33]. Possibly La Corbiere inspired the Norwegian, Lt D. Rye – from 1882 the director general of Norwegian lighthouses – who was in Britain in 1874. On his return to Norway, in 1875, Rye published a specification for concrete that ran to 15 pages and contained 19 recommendations. Concrete was adopted for lighthouse construction in Norway and Bogskjaer Lighthouse's repair in 1889 was an early instance of concrete's use in neighbouring Finland[4-4].

While Britain had been the principal cement-making country for decades, servicing the needs of its rapidly growing population and economy, as well as supplying export markets overseas, the 1880s and 1890s saw that situation adjust. The cement industry of the newly unified German empire made huge advances in mechanisation and quality control during the 1870s, stimulating, and in turn feeding, demand for concrete as a construction material.

4.12.4 American expansion

Meanwhile, across the Atlantic, the USA was experiencing an enormous expansion of territory and population. The reconstruction that followed America's Civil War, and particularly after the Jay Cooke Panic of 1873, saw concrete's "growing use in the construction of docks, public works, miscellaneous buildings, sidewalks, etc"[4-80]. Expansion westwards called for bridges – not least for the railways – taller buildings required more substantial foundations, and increasingly towns aspired to have concrete paving and sidewalks. In 1891 the first concrete road open to traffic in America was laid in Bellafontaine, Ohio[4-22].

Growth in concrete construction was rapid and soon outstripped the indigenous cement industry's capacity to supply the required materials, particularly as demand shifted from natural to Portland cements. Taking cement consumption as a proxy for the increase in concrete construction, annual imports grew from 92'000 barrels in 1878, to 106'000 in 1879 and 187'000 a year later. By 1885, 554'000 barrels were being shipped from Europe and the Far East, a volume that was to precipitate the rapid development of a domestic industry in the 1890s to service the huge growth in construction. Though this boom coincided with the development of reinforced concrete, much was still unreinforced, with foundations, paving and masonry the principal applications as the century closed[4-80].

4.12.5 Germany

In Germany during the 1880s, concrete was extensively used for foundations and piling, particularly in hydraulic engineering projects: docks, locks and weirs; reservoirs and pumping stations; drainage, sewerage and water treatment plants.

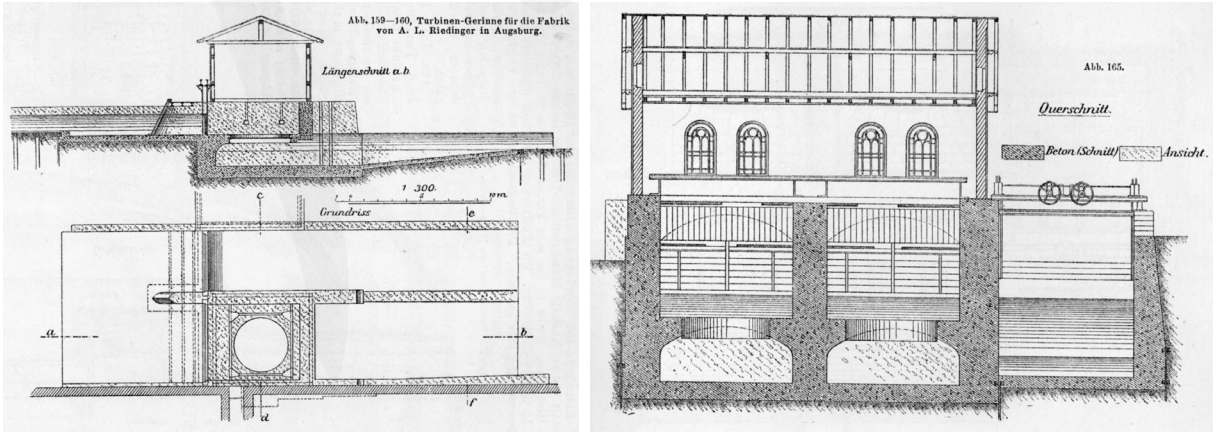


Fig. 4-35 Civil engineering works in Germany: Busing & Schumann[4-33] Riedlinger, Augsburg and Goggingen schleuse.

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Dyckerhoff & Widmann was among the foremost concrete companies in the latter field, having established effective relationships with the public authorities for its supply of concrete pipes during the 1870s, and developed its capability for vaulted construction in the early 1880s. Its first major project was the high-level tank for the Wiesbaden water works in 1882, the company's innovatory approach to which caused considerable attention in the trade press. More than 100 such projects followed during the 1880s and 90s – tanks or covered reservoirs for water works, gas works, even chemical works – with related commissions for culverts and sewers[4-81].

Table 4-2 Selection of commissions for reservoirs awarded to Dyckerhoff & Widmann (Compiled from[4-72])

Water works	Gas works
Nuremburg, 1884	Chemnitz, 1883
Linz am Rhein, 1885	Annaberg-Buchholz, 1884
Porta Wasfalica-Barkhausen, 1887	Emmendingen, 1884
Aschaffenburg, 1888	Krefeld, 1884
Reichenbach, 1888	Bamberg, 1886
Bensheim, 1886	Hagen, 1886
Chemical works	Leipzig-Gholis, 1886
Frankfurt, 1883	Wiesbaden, 1886
Duisburg-Hochfel, 1884	Stolp (Poland), 1887
Worm, 1888	
Bingen, 1888	
Dresden, 1889	

4.13 Unreinforced concrete bridges at the turn of the century

Central both to covered reservoirs and bridges was the vault or arch, and it was in bridges that stampfbeton reached its peak, before being supplanted by reinforced concrete at the end of the century. Amongst the earliest in Germany were the small arch bridges at Vorwohle and Glesse, built in 1877 and 1878 by B. Liebold & Co of Holzminden[4-82]. Dyckerhoff & Widmann followed this lead not long after, in 1880, with the experimental bridge exhibited at Dusseldorf. The company's first essays in bridge building for clients was a modest 9.8 m span railway bridge at Seifersdorf, Saxony and an 11m footbridge at Bad Wildbad, Baden. The experience gained helped the company secure commissions for larger structures, especially in Bavaria and Saxony, such as the bridge over the Pleissebach at Chemnitz (1887) and bridges at Munich (1891) and Dresden (1891-92 and 1894-96). This series culminated in the Chemnitz railway viaduct of 1898-99, composed of 11 arches with spans varying between 28 and 43 metres.

Dyckerhof & Widmann was not alone and other firms such as Diss & Ci (Dusseldorf) and J. Oderico (Frankfurt), attempted arch bridges in stampfbeton. One of the first of any size was 40m long aqueduct over the River Murg between Langenbrand and Weisenbach, designed by Karl von Muller and built in 1885[4-72].

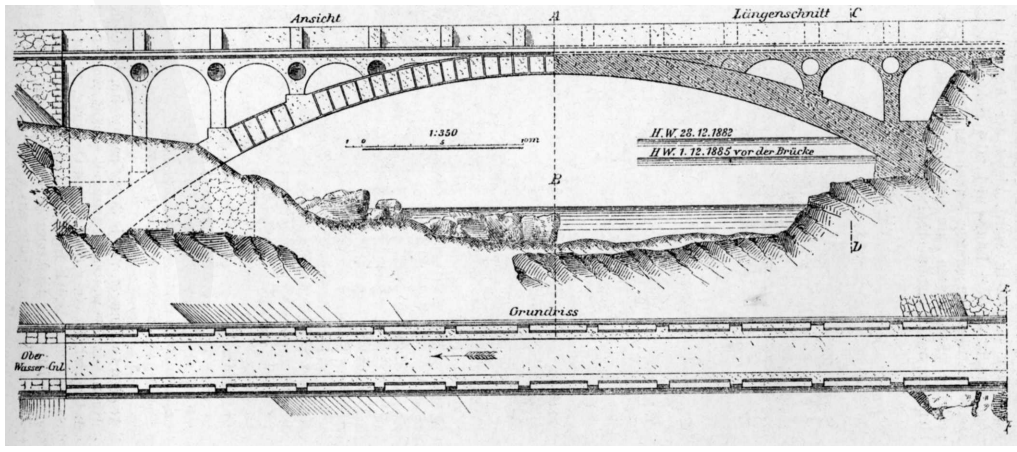


Fig. 4-36 Weisenbach aqueduct in Germany (Busing & Schumann[4-33]).

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The development of bridges followed a similar timescale in Britain, where the first recorded concrete bridge was at Gloucester Road, London, built by the Metropolitan Railway Co. in 1868[4-2]. The river bridge at Homersfield, near Bungay in Suffolk, was built in 1870 with concrete encasing an iron frame [4-83], and the 1877 Axmouth Bridge, Seaton, was an early exercise in cellular construction to reduce deadweight[4-84].



Fig. 4-37 Early bridges at Homersfield, Suffolk and at Axmouth, Devon (Photos: The Concrete Society).

The demand for bridges grew and concrete's use in their construction was encapsulated by Sir Robert McAlpine's career to the end of the century. Diversifying into civil engineering in 1884, McAlpine's first major public works contract was to build the Barrhead to Ardrossan section of the Lanarkshire and Ayrshire Railway, a stretch of line that required 82 bridges and viaducts. The twenty years to 1904 saw the construction of 150 miles of railway in western Scotland and, to a lesser extent, Ireland, during which McAlpine pioneered the use of mass concrete in railway works and earned the epithet 'Concrete Bob'. In 1892-94, for instance, he worked on the Glasgow District Subway, his first tunnelling job, and introduced concrete tunnel linings. On the Bowling to Dumbarton section of the Lanarkshire & Dumbartonshire Railway in 1893-96, the majority of his abutments, viaducts, retaining walls and station buildings were erected in mass concrete tinted sandstone-red. This period reached its peak with the 40-mile Mallaig extension to the West Highland Railway in 1897-1901, a line that featured the famous 21-arch Glenfinnan Viaduct and the remarkable Borrodale Viaduct; at 127 ft 6 in it constituted the longest bridge span in mass concrete ever to have been built in Britain.

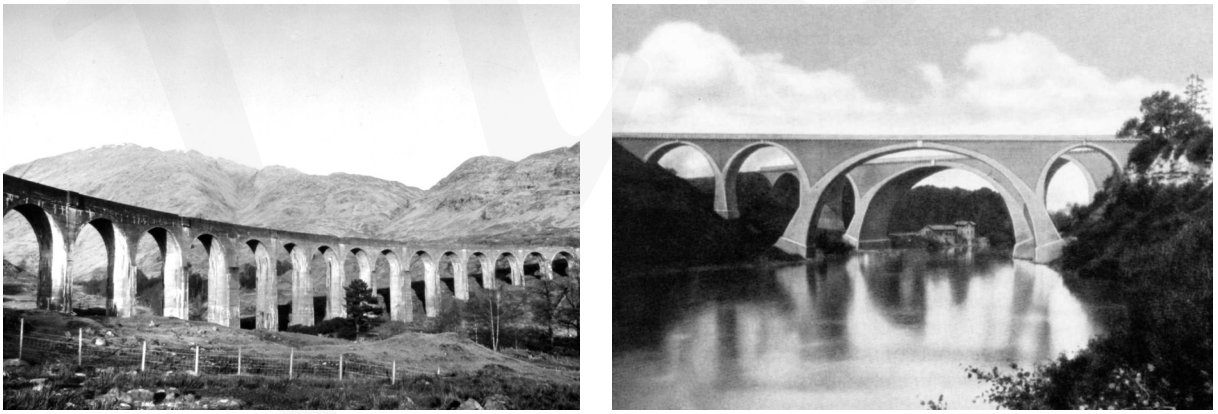


Fig. 4-38 (Left)The Glenfinnan Viaduct in Scotland (Photo: The concrete Society). (Right) The Iller Bridges at Kempten, Bavaria[4-86]).

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Though such prominent projects as Westminster Cathedral (1903)[4-87] and the twin Iller bridges at Kempten in Bavaria (1904-06) – at 36 m tall and 155m long, the largest stampfbeton bridges ever built – indicated a continuing use of mass concrete, the direction of development in the early twentieth century was towards the acceptance and adoption of reinforcement. But reinforced concrete had only become practicable by the development of cements of sufficient strength to combine satisfactorily with steel. The development of Portland cement allowed the weak lime-based concretes of the eighteenth and early nineteenth centuries to evolve into a fully structural material.

> The introduction of Portland cement, which is undoubtedly the strongest cement the world has ever known, contributed largely to spread the use of concrete in building, and although it has not effected that revolution in architecture, of which its enthusiastic admirers dreamed, yet it has proved itself to be an almost indispensable building material, and has, on account of its great strength, and (in comparison with hydraulic limes and natural cements) its reliability, led to the employment of concrete for many purposes, for which lime-concrete was utterly unsuitable.
>
> (Sutcliffe[4.1])

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Glossary

Aerial or air lime
Chaux aérienne
Luftkalk

Lime ($Ca(OH)_2$), obtained by calcining at 900 °C limestone with a clay content of less than 8 % and slaking it with water. It is the basic component of mortars since antiquity, characterized by a slow aerial intake in contact with carbon dioxide (CO_2) from the air.
Chaux ($Ca(OH)_2$), obtenue par cuisson à 900 °C d'un calcaire *contenant moins de 8% d'argile et extinction à l'eau. Il s'agit du composant de base des mortiers depuis l'antiquité, caractérisé par une prise aérienne lente au contact du gaz carbonique (CO_2) de l'air. Appelée aussi chaux calcique.*
Es gibt zwei Arten von Baukalken: Luftkalk und hydraulischer Kalk. Für Luftkalk wird Kalkstein oder Dolomit bei ~900–1'000 °C gebrannt. Durch Zugabe von Wasser wird dieser Branntkalk gelöscht (Löschkalk – Calciumhydroxid $Ca(OH)_2$) und erhärtet durch Zugabe von Mörtelwasser und die Aufnahme von CO_2 aus der Luft (Karbonatisierung) in einer exothermen Reaktion. Luftkalke werden nach ihrem Gehalt an CaO und MgO klassifiziert. Luftkalk wird seit der Antike verwendet.

Blast furnace slag
Laitier de haut fourneau
Hochofenschlacke

Blast furnace slag is a mostly glassy material, produced during the development of the melting resulting from the reduction of iron ores (Hematite Fe_2O_3 or Magnetite Fe_3O_4) by coke (fuel and reducing agent), to obtain melting (iron-carbon alloy, saturated in carbon). Because iron ores are always associated with a gangue of oxides and silicates, they form slag that clumps together under the effect of temperature. Blast furnace slags have a potential hydraulicity that requires calcium (lime) or sulfo-calcium activation and gives cements an increased stability to aggressive chemical agents. Once finely ground, the blast furnace vitrified slag can be either a major component of cement other than clinker or introduced as *an addition* to concrete.
Le laitier de haut fourneau est un matériau majoritairement vitreux, produit lors de l'élaboration de la fonte résultant de la réduction des minerais de fer (Hématite Fe_2O_3 ou Magnétite Fe_3O_4) par le coke (combustible et agent réducteur), pour obtenir de la fonte (alliage de fer-Carbone, saturé en carbone). Les minerais de fer étant toujours associés à une gangue d'oxydes et de silicates, ceux-ci forment des scories qui s'agglomèrent par fusion sous l'effet de la température. Les laitiers de hauts fourneaux présentent une hydraulicité potentielle qui nécessite une activation calcique (chaux) ou sulfo-calcique et qui confère aux ciments en contenant une stabilité accrue aux agents chimiques agressifs. Une fois broyé finement, le laitier vitrifié de haut fourneau peut être, soit un constituant principal du ciment autre que le clinker, soit introduit comme addition au béton.
Hochofenschlacke ist ein Nebenprodukt der Roheisengewinnung. Die leichte Schlackeschicht schwimmt im Hochofenprozess auf dem flüssigen Metall. Sie besteht aus nichtmetallischen Eisenerzkomponenten (Begleitphasen), Bestandteilen des Koks (Brennstoff und Reduktionsmittel) und weiteren Stoffen, die für den Hochofenprozess benötigt werden (z. B. Kalkstein, Dolomit). Nach dem Trennen der Schlackeschicht vom Metall und dem Abschrecken mit Wasser entsteht glasiger Hüttensand (HS). HS ist latent-hydraulisch, d. h. die hydraulischen Eigenschaften müssen aktiviert werden, um sie zu nutzen. Typische „Anreger" sind Calciumhydroxid ($Ca(OH)_2$) oder Sulfate. Fein gemahlene Hochofenschlacke ist ein direkter Hauptbestandteil von Hüttenzementen, kann aber auch als Betonzusatzstoff verwendet werden. Hüttensand bewirkt eine relativ geringe Hydratationswärmeentwicklung. HS-Zemente bzw. -Betone und werden deshalb v. a. zur Herstellung von massigen Bauteilen eingesetzt. Weitere Anwendungsfelder sind Straßenbau und Transportbeton.

This chapter was mainly authored by Acker, Quénée, and Trout. German translation by Curbach and Scheerer.

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Burnt lime
Chaux brûlée
Gebrannter Kalk

An ancient name for cements, meaning high-temperature heating (close to melting at 1'450°C) of lime that is too argileous (limit lime).
Nom ancien des ciments de type portland, désignant la cuisson à haute température (proche de la fusion à 1'450 °C) de chaux trop argileuse (chaux limite).
Alte Bezeichnung für Portlandzemente, die sich auf das Hochtemperaturbrennen (nahe dem Schmelzen bei 1'450 °C) von zu tonhaltigem Kalk bezieht (Grenzkalk).

Calcium aluminate or high alumina cement
Ciment alumineux
(ou Ciment fondu)
Tonerdezement

Slow-acting and fast-hardening cement obtained by heating calcium aluminates (mainly bauxite). Resistant to aggressive environments and high temperatures, it is commonly used for pipes, sewerage works, furnaces, chimneys, and any repair work, seals, etc. Subject to possible losses of strength over time depending on the conditions of initial implementation (alkali, temperature of the constituents in particular), resulting in a change of mineral phase able to cause its initial resistance to drop. Mixing conditions with other cements need to be studied very carefully. Also called melted cement.
Ciment à prise lente et durcissement rapide obtenu par cuisson d'aluminates de calcium (bauxite essentiellement). Résistant aux milieux agressifs et aux fortes températures, il est couramment utilisé pour les canalisations, ouvrages d'assainissement, fours, cheminées, et tous travaux de réparations, scellements, etc. Sujet à de possibles pertes de résistance dans le temps selon les conditions de mise en œuvre initiale (alcalis, température des constituants notamment), entrainant un changement de phase minéralogique à même de faire chuter sa résistance initiale. Les conditions de mélange avec d'autres ciments doivent être étudiées avec beaucoup d'attention. Appelé également ciment fondu.
Tonerde(-schmelz-)- oder auch (Calcium-)Aluminatzement ist ein langsam bis normal abbindender, schnell härtender Zement, der durch Brennen von Calciumaluminaten (hauptsächlich Bauxit) und Kalkstein gewonnen wird. Er ist feuerfest und hat eine sehr hohe chemische Beständigkeit, wird also häufig in aggressiven Umgebungen und bei hohen Temperaturen verwendet, z. B. für Rohre, Kläranlagen, Öfen, Schornsteine; oft Zusatz bei Portlandzementmörteln für (Schnell-)Reparatur und Abdichtung. Die Beständigkeit der Hydratationsprodukte und damit die Endfestigkeit sind abhängig von den Bedingungen während der Hydratation. Aus einer niedrigen Umgebungstemperatur kann bspw. eine anfänglich höhere Festigkeit resultieren, die später durch Änderung der mineralogischen Phase (kubische Umwandlung) auf ein niedrigeres, aber stabiles Niveau sinken kann (Konversion; oft einhergehend mit Erhöhung des Porenanteils).

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Cement
Ciment
Zement

Today, in mortars and concretes, cement refers by default to a hydraulic binder (in terms of material, hydraulic means: able to harden under water), obtained by heating at 1'450°C a mixture of limestone and clays. It has the property of combining and hardening with water (and underwater) by hydration. Standardized current cements are characterized by a resistance class corresponding to the minimum value of their compression strength at 28 days. There are also special cements that have specific properties of setting time or strength, which are covered by specific standards, and white cements made from iron oxide-free raw materials.

Aujourd'hui, dans les mortiers et bétons, le ciment désigne par défaut un liant hydraulique (en termes de matériau, hydraulique signifie : capable de faire prise sous l'eau), obtenu par cuisson à 1 450 °C d'un mélange de calcaire et d'argiles. Il a la propriété de faire prise au contact de l'eau (et sous l'eau) par hydratation. Les ciments courants normalisés sont caractérisés par une classe de résistance correspondant à la valeur minimale de leur résistance à la compression à 28 jours. Il existe aussi des ciments spéciaux qui possèdent des propriétés spécifiques de prise ou de résistance, qui sont régis par des normes spécifiques, ainsi que des ciments blancs composés à partir de matières premières exemptes d'oxyde de fer.

Zement ist ein fein gemahlenes, mineralisches, hydraulisch abbindendes Bindemittel für den standardmäßigen Einsatz in Mörteln und Betonen. Mit Wasser „angemacht", erhärtet Zement an der Luft und auch unter Wasser (Hydratationsprozess: Hydrate sind die sehr festen, kristallinen, wasserbeständigen Hydratationsprodukte); die Endfestigkeit ist (deutlich) höher als bei anderen hydraulischen Bindemitteln. Zement wird durch Brennen eines Gemisches aus Kalkstein und Tonen bei 1'400…1'450 (1'500) °C gewonnen. Erste Versuche zur Herstellung hydraulischer Bindemittel durch Brennen mineralischer Ausgangsstoffe wurden bereits Mitte des 18. Jahrhunderts unternommen. Die Entdeckung des künstlich hergestellten Zements wird in Frankreich Louis Vicat zugeschrieben, der bereits 1818 gezielt hydraulischen Kalk herstellte und dessen Bestandteile und Mengenverhältnisse bestimmte. Einen ähnlichen Ansatz verfolgte zur selben Zeit in Deutschland J. F. John. In Großbritannien sind John Smeaton und James Parker zu nennen. Joseph Aspdin meldete am 24. Oktober 1824 das Patent und den Markennamen "Portlandzement" an. In der aktuellen europäischen Normung sind fünf Haupt-Zementarten definiert, z. B. CEM I – Portlandzement. Zemente werden in eine von drei Festigkeitsklassen eingeteilt, wobei die Zahlenwerte 32,5, 42,5 und 52,5 (N/mm²) dem Mindestwert der 28-Tage-Druckfestigkeit entsprechen. Neben „Normalzementen" gibt es spezielle „Zemente mit besonderen Eigenschaften". Zement ist normalerweise grau, durch Verwendung eisenoxidfreier Rohstoffen und modifizierte Produktionsprozesse kann aber auch Weißzement hergestellt werden.

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Cement clinker
Clinker (de ciment)
Zementklinker

The clinker is the main component of common cements, a granulated product that comes out of the kiln after calcination at 1'450 °C from a mixture of about 80 % limestone and 20 % clay, before being finely ground. It contains 4 major mineral phases C2S (belite), C3S (alite), C3A (aluminate) and C4AF (ferrite), according to oxide cement terminology, with C for CaO, S for SiO_2, A for Al_2O_3, F for Fe_2O_3.
Le clinker est le constituant principal des ciments courants, produit granuleux qui sort du four après calcination à 1'450 °C d'un mélange d'environ 80 % de calcaire et 20 % d'argiles, avant d'être finement broyé. Il contient 4 phases minérales majeures C2S (bélite), C3S (alite), C3A (aluminate) et C4AF (ferrite), selon la terminologie cimentière en oxydes, avec C pour CaO, S pour SiO_2, A pour Al_2O_3, F pour Fe_2O_3.
Klinker ist der gebrannte, ungemahlene Zement und gleichzeitig sein Hauptbestandteil. Er ist körnig/stückig (meist kleiner als Faustgröße). Portlandzementklinker wird i. d. R. bei 1'450 °C im Drehrohrofen gebrannt und besteht zu rund 80 % aus Kalkstein, der Rest sind Tone. Er enthält vier Hauptmineralphasen: C3S (Tricalciumsilikat oder Alit, ca. 65 M.-%), C2S (Dicalciumsilikat oder Belit, ~15 M.-%) und zu je ~10 M.-% C3A (Tricalciumaluminat) und C4AF (Tetracalciumaluminatferrit). Dabei steht C für CaO (Kalk), S für SiO_2 (Silikat), A für Al_2O_3 (Tonerde) und F für Fe_2O_3 (Ferrite).

Ciment fondu
Ciment fondu
Tonerdezement

See *Calcium aluminate,* or *High alumina cement*.
Voir ciment alumineux.
Siehe *Tonerdezement*.

Expansive cement
Ciment expansif
Quellzement

Cement containing an addition of calcium sulfate, which is accompanied by swelling that at least compensates for shrinkage during hardening, or more. It is used for bedding mortars, repairs, underpinning works, *etc*.
Ciment contenant un ajout de sulfate de calcium, dont la prise s'accompagne d'un gonflement compensant au minimum le retrait au cours du durcissement, voire plus. Il est utilisé pour des mortiers de calage, des réparations, des reprises en sous-œuvre, etc.
Zement, der beim Erhärten nicht schwindet, sondern ein gewisse Volumenzunahme (Ettringittreiben) aufweist. Wird in der Regel durch Vermahlen von Tonerde(-schmelz-)zement und Gips oder Calciumsulfat sowie freiem Kalk hergestellt. Er wird z. B. als Quellmörtel für (kleinere) Reparaturen, den Verguss von Fugen oder von Stahlbauteilen in Beton verwendet.

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Furnace Bottom ash
Mâchefer
Bodenasche

Residual from the burning of coal, coke, or the incineration of household waste, sandy-gravel and greyish in colour, used in building blocks or the reinforcement of plaster tiles until the 1970's, and more recently in roads, especially as trench embankment, tracks sub-base, in lieu of more noble materials, such as sand. This material has never been standardized as a building material because it is of very variable composition and toxicity.

Résidu de la combustion du charbon, du coke, ou de l'incinération d'ordures ménagères (MIOM), sablo-graveleux et de couleur grisâtre, utilisé en blocs de construction ou en renforts de carreaux de plâtre jusque dans les années 1970, et plus récemment en voirie, notamment comme remblai de tranchée, sous-couche routières, de pistes, en substitution de matériaux plus nobles, tels que le sable. Ce matériau n'a jamais été normé comme matériau de construction car il est de composition et de toxicité très variables.

Aschen sind anorganische Rückstände, die bspw. bei der Verbrennung von Steinkohle, Erdöl oder Hausmüll entstehen. Bodenaschen sinken hierbei im Gegensatz zu Flugasche auf den Boden des Verbrennungskessels ab. Inerter Kesselsand aus der Steinkohleverbrennung kann als Leichtzuschlag in Leichtbeton/-mörtel verwendet werden. Aschen aus der Müllverbrennung werden bspw. als Sandersatz im Straßen- und Wegebau eingesetzt (Verfüllung von Gräben, im Straßenunterbau, in Fahrbahnen). Holzaschen eignen sich als Füll-, Dämm- und Schallschutzmaterial bei Holzbalkendecken. Nicht jede Asche ist als Baumaterial genormt, da Zusammensetzung und Toxizität stark variieren.

Grappier cement
Ciment de grappier
Grappierzement

Grappiers are the hard elements that the action of water cannot powder when the lime, just out of oven, is extinguished, and that the plant rejected when sifting the powder (through a textile grid). That includes the unburnt, overcooked, lime limits and parts of clayey limestone containing too much clay. As it was a significant loss in the Le Teil plant, the manufacturer managed to take advantage of it by creating the cement of grappier, whose quality could be remarkable. This somewhat bastard product disappeared permanently from the market with the First World War, but it is mentioned in the architectural textbooks of the 1930s, with a production that began around 1870.

Les grappiers sont les éléments durs que l'action de l'eau ne peut faire tomber en poudre lors de l'extinction de la chaux, et que les bluteries rejetaient (tamisage par textile des poudres). C'étaient les incuits, surcuits, chaux limites et parties trop chargées en argile des calcaires argileux. Constituant une perte sensible pour le fabricant, on aboutit au Teil (Ardèche) à en tirer parti en créant le ciment de grappiers, dont la qualité pouvait être remarquable. Ce produit un peu bâtard a disparu définitivement du marché avec la Première Guerre mondiale, mais il en est fait mention dans les manuels d'architecture des années 1930, avec une production qui a commencé aux environs de 1870.

Grappierzement ist ein besonderer (historischer) hydraulischer Kalk, hergestellt in Südfrankreich. Heißer Branntkalk wurde direkt nach dem Entnehmen aus dem Ofen und dann über einen Zeitraum von 14 Tagen mit Wasser benetzt, was ein Zerfallen des Materials bewirkte. Danach wurde der Kalk gesiebt. Grappiers (auch Karne, bis zum Sinterprozess gebrannter, tonhaltiger Kalk) waren die sehr harten, schweren Bestandteile, die zunächst aussortiert wurden. Teilweise stellte die anfallende Masse an Grappiers einen hohen Verlust dar. Im Werk „Le Teil" erfand man daraufhin den Grappierzement. Hierfür wurde das ausgesonderte Material noch einmal gelöscht und gesiebt. Die dann immer noch verbleibenden Grappiers wurden gemahlen und als Grappierzement vertrieben. Er hatte einen erhöhten Gehalt an SiO_2 und einen kleineren Anteil Al_2O_3 im Vergleich zu herkömmlichen hydraulischen Kalken und wurde bevorzugt im Seewasserbau verwendet. Grappierzement wurde in etwa bis zum Beginn des Ersten Weltkrieges verwendet; in Handbüchern der 1930er Jahre wird eine Produktion ab ca. 1870 erwähnt.

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Gypsum
Gypse
Gips

A saline rock of evaporitic origin, most often saccharoidic in appearance, very soft (hardness 2 on the Mohs scale). It can crystallize in many forms – including the well-known *desert rose* – when mixed with sand in desert environments. Its chemical composition of di-hydrated calcium sulfate ($CaSO_4$, $2H_2O$) gives it 21 % water. Its use in the industry is linked to the manufacture of plaster: by moderate cooking around 150 °C, it turns into hemi-hydrate $CaSO_4$, 0.5 H_2O, which after grinding, forms a binder that rehydrates into initial gypsum on contact with water (with the addition of loads, pigments and dyes). It is thus, after the dried or cooked clay and the bitumen of the Persians, the oldest binder, the main component of mortars in ancient Egypt (as evidenced by the coal debris mixed). It is also present in stucco, mixed with marble powder *(plaster stucco)*. Finally, it is also an essential constituent of cements, added to the clinker after grinding as a regulator of their setting time. Highly water soluble, it is the main provider of sulfate ions that will react with the aluminous fraction of cements (causing sulfatic reactions).
Aussi appelé « pierre à plâtre », il s'agit d'une roche saline d'origine évaporitique, le plus souvent d'aspect saccharoïde, très tendre (dureté 2 sur l'échelle de Mohs). Il peut cristalliser sous de multiples formes – dont la bien connue rose des sables – lorsqu'il est mêlé à du sable dans les milieux désertiques. Sa composition chimique de sulfate de calcium di-hydraté ($CaSO_4$, $2H_2O$) lui confère ainsi 21% d'eau. Son utilisation dans l'industrie est liée à la fabrication du plâtre : par cuisson modérée autour de 150°C, il se transforme en hémi-hydrate $CaSO_4$, ½ H_2O, qui après broyage, forme un liant qui se réhydrate en gypse initial au contact de l'eau(avec ajout de charges, pigments et colorants). Il est ainsi, après l'argile séchée ou cuite et le bitume des perses, le plus ancien des liants, constituant principal des mortiers dans l'Egypte antique (comme en attestent des débris de charbon mêlés). Il est présent également dans les stucs, en mélange avec de la poudre de marbre (stuc au plâtre). Enfin, il est également un constituant essentiel des ciments, ajouté au clinker après broyage comme régulateur de leur prise. Très soluble dans l'eau, il est le principal pourvoyeur des ions sulfates qui réagiront avec la fraction alumineuse des ciments (à l'origine des réactions sulfatiques).
Gips, auch „Gipsstein" genannt, ist es ein salzhaltiges Gestein evaporitischen Ursprungs, meist von saccharoidem Aussehen, sehr weich (Härte 2 auf der Mohs-Skala). Es kann in vielen Formen kristallisieren – einschließlich der bekannten Sandrose – wenn es in Wüstenumgebungen mit Sand vermischt wird. Aufgrund seiner chemischen Zusammensetzung aus Calciumsulfat-Dihydrat ($CaSO_4$, $2H_2O$) besteht es zu 21 % aus Wasser. Seine Verwendung in der Industrie ist mit der Herstellung von Gips verbunden: durch mäßiges Kochen um 150 °C wird es in ein $CaSO_4$, ½ H_2O-Halbhydrat umgewandelt, das nach dem Mahlen ein Bindemittel bildet, das in Kontakt mit Wasser (unter Zugabe von Füllstoffen, Pigmenten und Farbstoffen) zu ursprünglichem Gips rehydriert. Es ist damit nach getrocknetem oder gebranntem Ton und persischem Bitumen das älteste Bindemittel, der Hauptbestandteil von Mörteln im alten Ägypten (wie durch gemischte Holzkohlereste belegt). Es ist auch in Stuck vorhanden, gemischt mit Marmormehl (Gipsstuck). Schließlich ist es auch ein wesentlicher Bestandteil von Zementen, der dem Klinker nach dem Mahlen als Regulator für das Abbinden zugesetzt wird. Es ist sehr gut wasserlöslich und der Hauptlieferant von Sulfationen, die mit der aluminiumhaltigen Fraktion von Zementen reagieren (sulfatische Reaktionen hervorrufend).

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Hydrated lime
Chaux éteinte
Löschkalk

Calcium hydroxide $Ca(OH)_2$, obtained from the watering of quicklime (CaO) right out of the oven. Also known as slaked lime. It is supplied as a dry powder before water is added at the time of use.
Hydroxyde de calcium $Ca(OH)_2$ que l'on obtient en arrosant à grande eau (on parle d'extinction ou d'hydratation), au sortir du four, la chaux vive (CaO). Ellel est fournie sous forme de poudre sèche avant l'ajout d'eau au moment de l'utilisation.
Löschkalk ist Calciumhydroxid $Ca(OH)_2$, das durch Wässern von Branntkalk (CaO) direkt aus dem Ofen gewonnen wird. Er wird als trockenes Pulver geliefert. Vor der weiteren Verwendung bspw. in Mörteln oder Putzen muss wieder Wasser zugefügt werden.

Hydraulic lime
Chaux hydraulique
Hydraulischer Kalk

Hydraulic lime, being made from clayey limestone, contains in addition to calcium oxides more than 8% of silicates and aluminates, and therefore is closer to cements, and can harden under water. The hydraulicity index given by Vicat allows to establish a ranking according to their composition and their performance (see term). Carbonation also intervenes, but to a lesser degree, in its hardening process, which remains much slower than cements.
La chaux hydraulique, , étant fabriquée à partir de calcaires argileux, contient en plus de l'oxyde de calcium plus de 8% de silicates et aluminates, et donc est proche des ciments, et peut faire prise sous l'eau. L'indice d'hydraulicité donné par Vicat permet d'établir un classement selon leur composition et leurs performances (voir terme). La carbonatation intervient également, mais à un degré moindre, dans son processus de prise, qui reste beaucoup plus lent que les ciments.
Hydraulischer Kalk ist wie Luftkalk ein Baukalk und wird als mineralisches Bindemittel eingesetzt. Er stellt quasi den Übergang von Luftkalk zu Zement dar. Hauptausgangsstoff ist Kalkmergel bzw. tonhaltiger Kalkstein. Hauptbestandteile sind Calcium-, Magnesium-, Silicium-, Aluminium- und Eisenoxid. Hydraulische Kalke erhärten zementähnlich durch Wasserzugabe und auch unter Wasser und bilden dabei wasserbeständige Reaktionsprodukte. Hydraulischer Kalk wird nach der Festigkeit der mit ihnen hergestellten Mörtel klassifiziert. Sie können mit Zementen gemischt werden.

Keene's cement
Ciment anglais (ou Plâtre aluné)
Englischer Zement

Keene's Cement Plaster or Keene's cement is a hard plaster formulation, primarily used for ornamental work. Alternate names are Martin's cement and Parian cement. It is a calcined formulation of regular calcium sulfate plaster with an alum admixture. The compound gives a hard finish that can be polished. The product was developed by Richard Wynn Keene and patented in 1838.
Plâtre additionné d'alun (un sulfate double naturel, en général d'aluminium et de potassium, hydraté), utilisé avec des granulats pour la réalisation des stucs (synonyme: plâtre aluné). Le composé donne une finition dure qui peut être polie. Produit développé par Richard Wynn Keene et breveté en 1838.
Gips mit Zusatz von Alaun (ein natürliches Doppelsulfat, meist aus Aluminium und Kalium, hydratisiert), der mit Zuschlagstoffen zur Herstellung von Stuck verwendet wird (Synonym: Tonerde-Gips).

Lime putty
Chaux en pâte
Kalkpaste

Quicklime soaked in water, sieved and allowed to settle for at least a month to form a paste. Often stored in pits.
Chaux vive éteinte dans un bain d'eau en excès, formant ainsi une pâte. Souvent conservée dans des fosses.
Luftkalk, der in einem Bad mit überschüssigem Wasser gelöscht wird und so eine Paste bildet. Oft in Gruben gelagert.

Magnesian cement
Ciment magnésien
Magnesiumzement

See *Magnesium oxychloride* or *Sorel cement*.
Voir Ciment aux oxychlorures magnésiens ou Ciment Sorel.
Siehe *Magnesiabinder* oder *Sorelzement*.

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Magnesium oxychloride
Ciment aux oxychlorures magnésiens
Magnesiabinder

In 1855, the French chemist Stanislas Sorel developed a two-component cement, a mixture of zinc oxide powder and a zinc chloride solution, allowing a dense material "harder than limestone" to be obtained in a matter of minutes. This binder can accept a very wide variety of mineral loads, aggregates or dyes. It is originally intended to produce artificial stones and tiles, or to reproduce works of art by means of casts, due to mechanical performance superior to those of Portland cement, but it does not withstand prolonged exposure to water. In 1867, Sorel filed a patent where zinc was replaced by magnesium. The product is more water resistant, but does not support the comparison, in this area, with Portland cement. On the other hand, the resistance to abrasion of Sorel cement is much greater than that of Portland cement. It is this exceptional resistance that lends to its use for the construction or repair of pavements (see also *Sorel cement*).
Le chimiste français Stanislas Sorel mit au point en 1855 un ciment à deux composants, mélange de poudre d'oxyde de zinc et d'une solution de chlorure de zinc, permettant d'obtenir en quelques minutes une matière dense « plus dure que la pierre calcaire ». Ce liant peut accepter une très grande variété de charges minérales, granulats ou colorants. Il est d'abord destiné à produire des pierres artificielles et des carrelages, ou à reproduire des œuvres d'art au moyen de moulages, en raison de performances mécaniques supérieures à celles du ciment portland, mais il résiste mal à une exposition prolongée à l'eau. En 1867, Sorel dépose un brevet où le zinc est remplacé par du magnésium. Le produit résiste mieux à l'eau, mais ne supporte pas la comparaison, en ce domaine, avec le ciment Portland. Par contre, la résistance à l'abrasion du ciment Sorel est bien supérieure à celle du Portland. C'est cette résistance exceptionnelle qui le fait privilégier pour la réalisation ou la réparation de sols (voir aussi Ciment Sorel*).*
Auch Magnesit, Magnesitzement oder früher Sorelzement. Das Bindemittel wurde von dem Franzosen Sorel 1855 entwickelt. Es ergab in wenigen Minuten ein dichtes Material, das „härter als Kalkstein" war. Sorel verwendete zuerst Zinkverbindungen, die er dann im Patent von 1967 durch Magnesiumverbindungen ersetzt hat. Grundstoff ist kaustisch gebrannte oder auch sintergebrannte Magnesia (MgO), die mit Salzlösungen zweiwertiger Metalle (z. B. $MgCl_2$ oder $ZnCl_2$) reagiert und steinartig erhärtet. Freies $MgCl_2$ wirkt allerdings auf Stahl stark korrosionsfördernd. Magnesiabinder kann mit einer Vielzahl von mineralischen, aber auch organischen Füllstoffen, Zuschlagstoffen oder Farbstoffen kombiniert werden. Er hat eine hohe Abriebfestigkeit und schrumpft wenig, weshalb er bei Industriefußböden eingesetzt wird (Magnesiaestrich). Bekannt ist auch der Bodenbelag „Steinholz". Ein weiteres Hauptanwendungsfeld sind Holzwolleleichtbauplatten; hier wird anstelle von $MgCl_2$- $MgSO_4$-Lösung als Reaktionspartner für MgO verwendet. Komposite mit Magnesiabinder sind empfindlich hinsichtlich Wassereinwirkung, weshalb sie vorzugsweise in Innenräumen angewendet werden.

Metal cement
Ciment métallique
Metallzement

Zinc oxide and zinc chloride binder, mixed with stone powder, once used for repairs to stone masonry.
Liant à base d'oxyde de zinc et de chlorure de zinc, mélangé avec de la poudre de pierre, jadis utilisé pour les réparations de maçonneries en pierre.
Bindemittel auf Basis von Zinkoxid und Zinkchlorid, gemischt mit Steinmehl, früher für die Reparatur von Steinmauern verwendet.

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Natural cement
Ciment naturel
Natürlicher Zement

Cement obtained from septaria or cement stone, a marl limestone with naturally adequate clay and limestone proportions, originally patented as 'Roman cement'. It remains essentially used for the manufacture of 'Ciment prompt' in France. Natural cements, obtained with a moderate calcining temperature (1'000 to 1'200 °C), are characterized by a rapid hardening (which starts at 2 minutes and ends at 4 minutes), high mechanical resistance in the very short term but whose progression is then limited, and a low shrinkage. It is resistant to aggressive water (sulfatic water, pure water, acid water). It is standardized for work at sea, as mortar and sometimes concrete. Areas of use: seals, mouldings, screeds, patch repairs and coatings. It should be noted that many quarries throughout France have now disappeared with the industrialization of artificial cement.

Ciment obtenu à partir d'un calcaire marneux ayant naturellement les proportions d'argile et de calcaire adéquates. Il reste essentiellement utilisé pour la fabrication de ciment prompt en France. Les ciments naturels, obtenus avec une température de calcination modérée (1'000 à 1'200°C), sont caractérisés par un durcissement rapide (qui débute à 2 minutes et se termine à 4 minutes), une résistance mécanique élevée à très court terme mais dont la progression est ensuite limitée, et un faible retrait. Il est résistant aux eaux agressives (eaux sulfatées, eaux pures, eaux acides). Il est normalisé pour les travaux en mer, comme mortier et parfois comme béton. Domaines d'utilisation : joints, moulages, chapes, réparations et revêtements. A noter que de très nombreuses carrières dans toute la France ont aujourd'hui disparu avec l'industrialisation du ciment artificiel.

Auch Romanzement oder Romankalk. Zement, der aus Mergel oder Kalk(-ton-) stein mit 22…35 % Tonanteil durch Brennen unterhalb der Sintertemperatur gewonnen wird. Er wurde bereits im 19. Jh. bei Bauwerken eingesetzt. Er ist schnell erhärtend und wird (immer noch) hauptsächlich für die Herstellung von Schnellzement, aber auch für die Nachbildung natürlichen Gesteins verwendet. Es ist anzumerken, dass viele Steinbrüche in ganz Frankreich mit der Industrialisierung des künstlichen Zements verschwunden sind.

Pisé
Pisé
Stampflehm

Traditional raw earth masonry material used for the construction of walls. The earth must be clayey and gravelly and sufficiently moist to be compacted, layer by layer, between the shuttering. It is sometimes amended with a little lime and, more rarely, with cement. Natural fibers, such as straws, are often added to it to increase its cohesion.

Matériau traditionnel de maçonnerie, à base de terre crue, utilisé pour construire des murs. La terre doit être argileuse et graveleuse et suffisamment humide pour pouvoir être compactée, couche par couche, entre deux banches. On y ajoute parfois un peu de chaux, plus rarement du ciment, et souvent des fibres naturelles, comme la paille, pour en améliorer la cohésion.

Massive Lehmbauweise vor allem für Mauern, Wände, Fußböden. Erdfeuchter Lehm wird zwischen Schalwände eingebracht und schichtweise durch Treten oder Stampfen verdichtet. Der Lehm kann mit etwas Kalk (seltener Zement) angereichert werden. Die Zugabe von Naturfasern wie Stroh beeinflusst Wärmedämmvermögen und Rissbildung positiv.

Plaster
Plâtre
Gipsputz

Hydraulic binder obtained by heating gypsum (see gypsum), formula $CaSO_4$, 0.5 H_2O (hemi-hydrate of calcium sulfate). Its application on cement materials is only possible in the absence of water (runoff, projection, infiltration) at the risk of causing a sulfatic attack.

Liant hydraulique obtenu par cuisson du gypse (voir gypse), de formule $CaSO_4$, 0,5 H_2O (hémi-hydrate de sulfate de calcium). Son application sur les matériaux cimentaires n'est possible qu'en l'absence d'eau (ruissellement, projection, infiltration) au risque de provoquer une attaque sulfatique.

Mineralischer Mörtel, bestehend aus Baugipsen, Sand, Wasser sowie weiteren Zuschlagstoffen. Geeignet für das Verputzen von Mauerwerk und Leichtbauplatten im Innenbereich. Anwendung auf Beton nur bei minimaler Restfeuchte, sonst können die enthaltenen Sulfate Treibreaktionen hervorrufen.

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Portland cement
Portland
(ou Ciment Portland)
Portlandzement

Original name of modern cements, characterized by a minimum clinker content of 95 % and a maximum of 5 % of secondary constituents. The name comes from a quarry on the Portland peninsula in England (also named after the geological floor of the *Portlandian,* latest Jurassic Time) from which Joseph Aspdin in 1824 managed to make the equivalent of an eminently hydraulic lime by cooking at high temperature a mixture of limestone and clay, a binder he called "*Portland cement*". Characterized by excellent mechanical strength, it is used for aerial parts of reinforced or pre-stressed concrete structures, but unsuitable for mass or underground work.
Ancien nom des ciments modernes, caractérisé par une teneur en clinker de 95% minimum et au maximum de 5% de constituants secondaires. Le nom provient d'une carrière de la presqu'ile de Portland en Angleterre (ayant donné le nom également à l'étage géologique du portlandien, jurassique terminal) à partir de laquelle Joseph Aspdin en 1824 a réussi à fabriquer l'équivalent d'une chaux éminemment hydraulique en cuisant à haute température un mélange de calcaire et d'argiles, un liant qu'il appela « ciment Portland ». Avec une excellente résistance mécanique, ce ciment est utilisé pour les parties non enterrées des ouvrages en béton armé ou précontraints, mais inadapté aux travaux en masse ou enterrés.
Alte Bezeichnung für moderne Zemente mit einem Klinkeranteil von mindestens 95 % und maximal 5 % sekundären Bestandteilen. Der Name stammt von einem Steinbruch auf der Halbinsel Portland in England (der auch der geologischen Stufe Portlandium (heute: Tithonium; Oberjura) den Namen gab), aus dem es Joseph Aspdin 1824 gelang, durch Brennen eines Gemisches aus Kalkstein und Tonen bei hoher Temperatur einen eminent hydraulischen Kalk herzustellen, dessen Bindemittel er "Portlandzement" nannte. Durch ausgezeichnete mechanische Eigenschaften und hohe Beständigkeit geeignet für Stahl- und Spannbetonkonstruktionen, hingegen nicht für Massenbeton und unterirdische Anwendungen.

Pozzolana
Pouzzolane
Puzzolan

Silica or silico-aluminous material, which has the property, in the presence of water, to react with reactive calcium (lime) and to form hydrates (C-S-H type) with binding properties, properties of most mineral additions added to cement: flying ash, blast furnace slag, silica fumes, gaize, etc. At the origin of the legendary quality of *Roman concrete,* obtained by the addition of volcanic ash (from Pozzuoli, a solfatara close to Vesuvius exploited since antiquity) with slaked lime, volcanic ash that can be replaced by bricks or crushed tiles. Later, in Germany in particular, one will also use crushed tuff (see *trass*).
Matériau de nature siliceuse ou silico-alumineuse, qui a la propriété, en présence d'eau, de réagir avec le calcium réactif (chaux) et de former des hydrates (du type C-S-H) ayant des propriétés liantes, propriétés de la plupart des additions minérales ajoutées au ciment : cendres volantes, laitier de haut fourneau, fumées de silice, gaize… A l'origine de la qualité légendaire du béton romain, obtenu par l'ajout de cendres volcaniques (provenant de Pozzuoli, une solfatare proche du Vésuve exploitée depuis l'antiquité) avec de la chaux grasse, cendres volcaniques pouvant être remplacées par des briques ou des tuiles pilées. Plus tard, en Allemagne notamment, on utilisera également du tuf pilé (voir trass*).*
Künstliche (z. B. Flugaschen, Ziegelmehl, Silicastaub) oder natürliche Stoffe (z. B. Tonerde, Eisenoxid), die zusammen mit Calciumhydroxid und Wasser bindefähig sind; werden als Betonzusatzstoffe verwendet. Benannt nach Pozzuoli, einem Ort in den Phlegräischen Feldern, wo bereits in der römischen Antike puzzolanische vulkanische Aschen gewonnen wurden. Später, vor allem in Deutschland, wurde auch zerkleinerter Tuff verwendet (siehe *Tuff* und *Trass*).

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Quicklime
Chaux vive
Gebrannter Kalk

Quicklime is a calcium oxide (CaO) derived from calcination *(i.e.* decarbonization) out of the oven of pure limestone at 900 °C. Its reaction with water (also called *extinction*), is highly exothermic and will give slaked lime $Ca(OH)_2$. Used, among other things, in earthworks to dry soils and treat clays to make them less sticky or in agriculture to amend soils.
La chaux vive est un oxyde de calcium (CaO) issu de la calcination (i.e. de la décarbonatation) au sortir du four d'un calcaire pur à 900 °C. Sa réaction avec l'eau, ou extinction, est fortement exothermique et donnera de la chaux grasse $Ca(OH)_2$. Utilisée entre autres dans les travaux de terrassement pour assécher les sols et traiter les argiles pour les rendre moins collantes ou en agriculture pour amender les sols.
Auch Branntkalk, CaO; wird durch Brennen von Kalkstein, Dolomit oder tonhaltigem Kalk bei ~900–1'000 °C (Weichbranntkalk) … 1'400 °C (Hartbranntkalk; Prozess unterhalb der Sintertemperatur) hergestellt. Durch Löschen mit Wasser entsteht $Ca(OH)_2$ in einer stark exothermen Reaktion. CaO ist das Ausgangsmaterial von Löschkalk. Es wird aber auch im Erdbau (Bodenaustrocknung), zur Behandlung von Tonen (Herabsetzen der Klebrigkeit) oder in der Landwirtschaft zur Bodenverbesserung eingesetzt.

Refractory cement
Ciment réfractaire
Feuerfester Zement

High-temperature-resistant cement (see also *ciment fondu* or calcium *aluminate cement*).
Ciment résistant aux hautes températures (voir aussi ciment fondu *ou* alumineux*).*
Hochtemperaturbeständiger Zement (siehe auch *Tonerdezement*).

Roman cement
Ciment romain
Römischer Zement

Equivalent of a natural cement, obtained by cooking at 900°C of a local marl, a process discovered by James Parker at the end of the 18th century in England. The name *Roman cement* (not to be confused with *Roman concrete,* see this term) was chosen as the commercial name of its patent filed in 1796. By becoming the basic material for the exterior ornamentation of historicist architecture and *Art nouveau* of the 19th and early 20th centuries, it is very present in the urban centers of many European cities and contributed to the transition from a freestone architecture to that of concrete and then reinforced concrete.
Equivalent d'un ciment naturel, obtenu par cuisson à 900°C d'une marne locale, procédé découvert par James Parker à la fin XVIIIème siècle en Angleterre. Le nom de ciment romain (à ne pas confondre avec béton romain, voir ce terme) fut choisi comme appellation commerciale de son brevet déposé en 1796. En devenant ensuite le matériau de base de l'ornementation extérieure des architectures historicistes et de l'art nouveau du XIXème et du début du XXème siècle, il est très présent dans les centres urbains de nombreuses villes européennes et contribua ainsi à la transition d'une architecture de pierres de taille vers celle en béton puis en béton armé.
Äquivalent zu einem natürlichen Zement, der durch Brennen eines lokalen Mergels bei 900 °C gewonnen wird, ein Verfahren, das von James Parker Ende des 18. Jahrhunderts in England entdeckt wurde. Der Name Römischer Zement (nicht zu verwechseln mit Römischem Beton, siehe diesen Begriff) wurde als Handelsname für sein 1796 angemeldetes Patent gewählt. Er wurde dann zum Grundmaterial für die Außenverzierung der historistischen und Jugendstil-Architektur im 19. und frühen 20. Jahrhundert, war in den Stadtzentren vieler europäischer Städte sehr präsent und trug zum Übergang von einer mit Naturstein zu einer Architektur aus Beton und später bewehrtem Beton bei.

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Roman concrete
Béton romain
Römischer Beton

The ancestor, by its chemical composition, of modern concretes, the binder being obtained by cold mixture of lime either with volcanic ash (mainly extracted from Pozzuoli, a solfatara near Vesuvius, exploited since the high Roman antiquity), or with crushed clay bricks or tiles. Used in all the major constructions of the Roman Empire, some famous buildings in the world testify to the quality and durability of this material: Pantheon of Rome, bridge of Vaison-la-Romaine, the port of Caesarea, *etc*. (see terms: *Roman cement* and *pozzolana*).
Ancêtre des bétons modernes de par sa composition chimique, le liant étant obtenu par mélange à froid de chaux avec, soit des cendres volcaniques (principalement extraites à Pozzuoli, unesolfatare proche du Vésuve, exploitée depuis la haute antiquité romaine), soit, par des briques ou des tuiles d'argile pilées. Utilisé dans toutes les constructions majeures de l'empire romain, quelques constructions célèbres dans le monde témoignent de la qualité et de la pérennité de ce matériau : panthéon de Rome, pont de Vaison-la-Romaine, digues du port de Césarée ... (voir : Ciment romain *et* Pouzzolane*).*
Vorfahre der modernen Betone. Das Bindemittel wurde durch kaltes Mischen von fettem Kalk mit vulkanischer Asche (hauptsächlich in Pozzuoli gewonnen, siehe Puzzolan), gewonnen; später wurden auch zerkleinerte (Ton-)Ziegel beigemischt. Römischer Beton kam in zahlreichen, auch monumentalen Bauwerken des Römischen Reiches zu Anwendung, von denen viele heute noch von der Qualität und Haltbarkeit dieses Materials belegen: das Pantheon in Rom, die Brücke von Vaison-la-Romaine, Deiche des Hafens von Caesarea. (siehe auch: *Römischer Zement* und *Puzzolan*).

Sorel Cement
Ciment Sorel
Sorelzement

See *Magnesium oxychloride* or *Sorel cement*.
Voir Ciment aux oxychlorures magnésiens.
Siehe *Magnesiabinder* oder *Magnesiumzement.*

Stucco
Stuc
Stuck

Coating arranged in flat or relief, imitating marble, white or colored by pigments. It is composed of either a mixture of aerial lime and marble powder *(lime stucco),* or plaster and marble powder *(plaster stucco*).
Revêtement d'enduit disposé en aplat ou en relief, imitant le marbre, de couleur blanche ou colorée par des pigments. Il est composé, soit d'un mélange de chaux aérienne et de poudre de marbre (stuc à la chaux), *soit de plâtre et de poudre de marbre* (stuc au plâtre).
Plastische Anordnung von Mörteln/Putzen verschiedenster Art als Gestaltungsmittel für Wände, Decken, Fassaden; einfarbig weiß, mit Pigmenten eingefärbt, Marmor imitierend. Kalkstuck besteht aus einer Mischung aus Luftkalk und Marmormehl, beim Gipsstuck wird Gips statt Kalk verwendet.

Sulfate-resisting cement
Ciment prise mer, ou PMES (prise mer - eaux sulphatées)
Zement mit hohem Sulfatwiderstand

Cements for work at sea which are subject to standards for work at sea and in waters high in sulfate.
Ciments pour travaux à la mer (nommé PM-ES ou Prise Mer-Eaux Sulfatées) qui font l'objet de normes pour les travaux à la mer et en eaux à haute teneur en sulfates.
Zement mit hohem Widerstand gegen treibenden Angriff durch Sulfate (SR-Zement); geeignet für Bauteile in Gewässern mit hohem Sulfatgehalt, in Meerwasser.

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Sulfo-aluminate cement
Sulfo-alumineux
(ou Ciment sulfo-alumineux)
Sulfoaluminiumzement

Sulfo-aluminous cement or sulfo-aluminate cement (CSA) was invented in 1936 as an expansive additive to compensate for the shrinkkage of Portland cement. Sulfo-aluminous cements are a mixture of sulfo-aluminous clinker and gypsum or anhydrite to activate its setting. The chemical characteristics of these cements are similar to those of aluminous cements and are adapted to the formulation of products for finishing work (special mortars, glues, etc.) and also to the realization of special concretes. The volumes consumed, however, remain anecdotal compared to Portland cement.

Le ciment sulfo-alumineux ou ciment de sulfo-aluminate (CSA) a été inventé en 1936 comme additif expansif pour compenser le retrait du ciment Portland. Les ciments sulfo-alumineux sont un mélange de clinker sulfo-alumineux et de gypse ou d'anhydrite pour activer sa prise. Les caractéristiques chimiques de ces ciments sont proches de celles des ciments alumineux et sont adaptées à la formulation de produits du second œuvre (les mortiers spéciaux, les colles, etc.) ets aussi à la réalisation de bétons spéciaux. Les volumes consommés restent cependant anecdotiques par rapport au ciment Portland.

Sulfoaluminiumzement oder Sulfoaluminatzement (SAC) wurde 1936 als expansiver Zusatzstoff erfunden, um das Schwinden von Portlandzement zu kompensieren. Sulfoaluminiumzemente sind ein Gemisch aus Sulfoaluminiumklinker und Gips oder Anhydrit zur Aktivierung seiner Abbindung. Die chemischen Eigenschaften dieser Zemente kommen denen von Tonerdeschmelzzementen nahe und eignen sich für die Rezeptur von Produkten für die Ausbauindustrie (Spezialmörtel, Kleber etc.), aber auch für die Herstellung von Spezialbetonen. Allerdings sind die verbrauchten Mengen im Vergleich zu Portlandzement nach wie vor vernachlässigbar.

Super-sulfated cement
Ciment sur-sulfaté
Super-sulfated cement

Super-sulfated cement is a hydraulic binder whose hydration process is slowed down due to the particular reactivity of its constituents. It consists mainly of granulated blast furnace and calcium sulfate. Its composition makes concretes of which it is the binder resistant to many aggressive agents, especially sulfates. The properties of super-sulfated cement have led to its use in concrete for foundations and massive structures.

Le ciment sur-sulfaté est un liant hydraulique dont le processus d'hydratation est ralenti du fait de la réactivité particulière de ses constituants. Il est constitué principalement de laitier granulé de haut-fourneau et de sulfate de calcium. Sa composition rend le béton, dont il forme le liant, résistant à de nombreux agents agressifs, notamment les sulfates. Les propriétés du ciment sur-sulfaté ont conduit à l'utiliser dans les bétons destinés aux fondations et aux structures massives.

Hydraulisches Bindemittel, dessen Hydratationsprozess aufgrund der besonderen Reaktivität seiner Bestandteile verlangsamt ist; besteht hauptsächlich aus granuliertem Hochofen- und Calciumsulfat. Damit hergestellter Beton ist widerstandsfähig gegen viele aggressive Stoffe, insbesondere Sulfate. Beton mit supersulfatiertem Zement wird vor allem für Fundamente und massive Bauwerke verwendet.

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Trass
Trass
Trass

Porous volcanic tuff used, especially in Germany, in mortars for its pozzolanic properties. Used by the Romans in their northern provinces and known historically also as Tarras or Terrace.
Tuf volcanique poreux utilisé, notamment en Allemagne, dans des mortiers pour ses propriétés pouzzolaniques. Déjà utilisé par les romains dans leurs provinces du Nord et connu historiquement sous le nom de Tarras ou Terrace.
Poröser vulkanischer Tuff, der vor allem in Deutschland wegen seiner puzzolanischen Eigenschaften in Mörteln verwendet wird.

Tuileau
Tuileau
Tuileau

Fragments of crushed terracotta, bricks, tiles, *etc.,* improving the strength of a lime mortar by its pozzolanic properties (see *Roman concrete*).
Fragments de terres cuites pilées, briques, tuiles, etc., améliorant la résistance d'un mortier de chaux de par ses propriétés pouzzolaniques (voir Béton romain*).*
Mörtel, der neben Kalk auch Bruchstücke von bzw. fein zermahlene Terrakotten, Ziegel, Fliesen usw. enthält. Durch die puzzolanischen Eigenschaften dieses Zusatzes wird die Festigkeit von Kalkmörtel verbessert (siehe *Römischer Beton*).

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