Roman concrete and mortar

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There must be few engineers who do not know that the Romans used concrete but almost as few who have a clear idea of its nature or what happened to concrete between Roman times and today.

As a first step towards filling this gap, the Institution's **Study Group on the History of Structural Engineering** *asked Dr. Norman Davey to write this article on Roman concrete and mortar. It is hoped that it may be followed by a further note taking up the story again at the virtual rebirth of concrete in the late 18th Century. The second note might follow the evolution of concrete and mortar from the patent medicine era of the rival cements in Britain in the 1790's and early 1900's, through the consolidating developments in Germany in the second half of the 19th Century to the relatively controlled products which we take for granted today.*

The Romans used two types of cementing material—lime mortar, and lime mortar with an addition of pozzolana, which was of natural origin or artificial. The lime was made by burning limestone (calcium carbonate) at about 900°C to convert it into quicklime. For building purposes this quicklime was slaked with water to produce hydrated lime, and sand was added to this. The resulting product acquired very little strength. There was, therefore, a need for a cementing material that would attain much more strength, and this led to the use of pozzolanic materials. The concrete, or *opus caementicium*, used by the Romans for their mass work consisted mainly of large pieces of rock or stone which they called *cementa* embedded in a lime mortar matrix. The pieces were either thrown in at random, or in the better class work were placed in layers in sandwich fashion. Possibly the earliest use to which concrete was put by the Romans was in foundations, as in the *podia* of the temples of Concord and of Castor, 121 and 127 BC, but it seems likely that it was already in use by the Romans by the end of the third century BC. However, they were not the first to use it as it had been used for the foundations of prehistoric houses at Tiryns and Mycenae a thousand years earlier.*

The Romans also used this lime concrete as a filling or hearting to walls faced with stone blocks. It comprised layers of broken stone and broken tiles, each layer being grouted with lime mortar so as to fill the interstices. In the first and second centuries BC the stone block facing was often replaced by a facing of small stones, and the work was called *opus incertum*. The construction necessitated the use of timber formwork and this consisted of upright posts 3 m (10 ft) or more in height set in the ground along the line of both faces of the wall at intervals of several feet. Nailed to these posts were wooden boards placed horizontally and often overlapping each other. To resist the lateral pressure imposed by the wet concrete, cross timbers were nailed to the upright posts. The holes which passed through the wall that were left after the withdrawal of the cross timbers can sometimes be seen in remains of Roman walls as can also the impressions left by the wooden boards.

Another type of construction was called *opus reticulatum* and consisted of squared pieces of stone, set with their sides at 45° to the horizontal to form a netlike, or reticulate, pattern. It was in use for about 150 years from the first century BC to the second century AD. An example of the work can be seen in the breakwater near Naples, see Fig 1. Concrete walls faced with brick called *opus testaceum* were more popular and were commonly used from the first century BC until the end of the

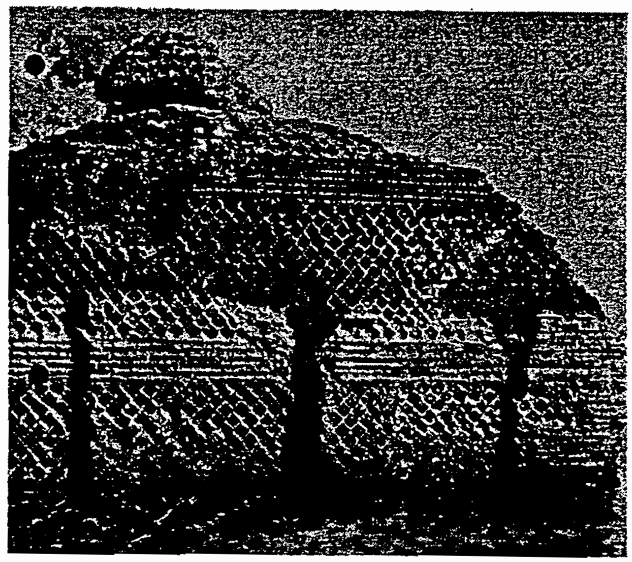

Fig 1. Roman breakwater near Naples built with pozzolanic cement

Western Empire. Sometimes, from the third century AD onwards, stone and bricks were mixed to produce work which the Romans called *opus mixtum*.

These methods of construction were used throughout the Roman Empire and there are many examples to be seen in Britain. In some places—as at Verulamium near St. Albans where natural stone was not readily available—flints were used instead. These were placed in layers in timber formwork and mortar was spread on each layer before the next was placed. The mortar in this case was of stiff consistence which did not penetrate far into the interstices between the stones. By building in this way, rather than by grouting with a more fluid mix of mortar, the pressures on the timber formwork during the building of the wall were greatly reduced, and work could proceed at a greater pace with less fear of collapse. It was usual, however, to carry up the concrete in 'lifts' about 1 m (3 ft) in height and then to lay on a bonding course of two or three thicknesses of tile. Apart from the fact that these string courses, or bonding courses, strengthened the work and helped to ensure its stability, they also provided a level base on which to place the next lift of concrete.

Variations in technique in the use of concrete can be seen and studied in other Roman towns and forts, for example, in London, Colchester, Wroxeter, Richborough, etc. The more

* Middleton, J. H. 'On the chief methods of construction used in ancient Rome', *Archaeologia* LI, Part 1, 1888, p 41–60.

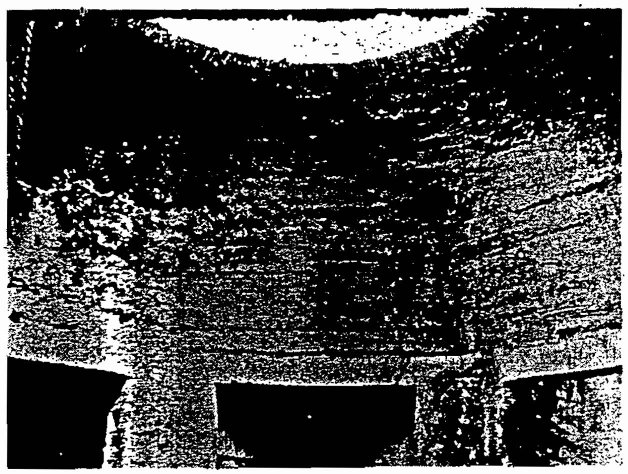

Fig 2. Octagonal domical vault of the Golden House of Nero, Rome, showing impressions of the timber formwork and brick ring at the central 'eye'

daring use of concrete, or mortared rubble by the Romans was in the construction of vaults and domes. When the concrete hardened, rigid structures resulted, but these did not behave in the same way as those built as true arches, as in the much later Gothic period. The Roman vaults and domes were cast on timber formwork, the impressions of which can still be seen on many of the surviving buildings in Rome and elsewhere. Sometimes, as in the construction of vaults at the Golden House of Nero (see Fig 2), a layer of mortar was spread on the formwork and a ring of bricks was built at the exposed ends of the vault to give a fair finish to it and also to contain the rubble concrete which was next-poured behind to complete the construction. In other cases a layer of tiles was first laid flat on the timber formwork with occasional tiles laid on edge to provide a good key into the concrete when it was later poured into position. When the timber forms were struck a tiled soffit to the vault was exposed and this could be rendered and decorated if desired. Examples of this type of construction occur in the Colosseum in Rome, at Hadrian's Villa near Tivoli and in the Baths of Caracalla.

During construction and until the concrete had dried out, the weight on the timber formwork could be enormous. To relieve the formwork of some of this load, brick ribs were often first built at intervals along the transverse lines of vaults, as at Hadrian's Villa; along the diagonal lines of intersection of cross vaults, as in the Baths of Diocletian; or along the meridians in cupolas and apses, as in the Sibylline Temple at Tivoli; in the Temple of Minerva Medica (see Fig 3); and in the Baths of Aggrippa in Rome. The ribs were sometimes interlaced as in the apses of the Temple of Venus and Roma.† These brick ribs, built in pozzolanic mortar, formed arches capable of supporting

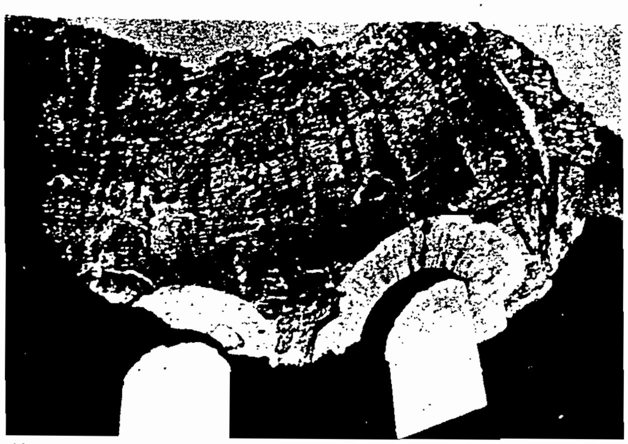

Fig 3. Detail of the dome of the Temple of Minerva Medica, Rome, showing embedded brick ribs

a large proportion of the load of the concrete which was subsequently poured in the intervening spaces. When the concrete had appreciably hardened and become a monolithic structure capable of supporting its own weight, the functioning of the brick ribs became of quite secondary importance.

Various other devices were adopted to lighten the structures. One was to introduce a system of coffering seen so well illustrated in Rome in the recessed squares in the soffit of the dome of the Pantheon, or in the octagonal recesses in the vaults of the Basilica of Constantine, and in the lozenge-shaped recesses in the roof of the apses of the Temple of Venus and Roma. The last, with its stucco ornament, is a particularly fine example of coffered work. Another device was to embed hollow terracotta pots in the concrete to reduce weight. Sometimes storage jars and amphorae were used, but more often terracotta tubes made for the purpose. The dimensions of the tubes varied, but they were usually about 200 mm to 250 mm long (8 in to 10 in), and 60 mm to 90 mm in diameter (2·5 in to 3·5 in). Sometimes they tapered along their length but often they had parallel sides. One end of the tube was open and the other sealed and provided with a protruding conical stem that fitted into the open end of the next tube, so forming a continuous line of tubes. Examples occur in Rome in the tomb of Scipios on the Via Appia and in the Golden House of Nero.

The ancients had discovered that they could convert non-hydraulic lime into a hydraulic or partially hydraulic one by adding suitable materials. Such additions, called pozzolanas after Pozzuoli, the locality in Italy where a natural source of such material—volcanic earth—exists, are those which, though not necessarily cementitious by themselves, possess the requisite compounds of silica and alumina which will combine with non-hydraulic or semi-hydraulic limes at ordinary temperatures in the presence of moisture to form stable insoluble compounds of cementitious value, such as calcium silicates and aluminates. When mixed with lime mortar in addition to, or in partial substitution for, sand, they will impart hydraulic properties and greater strength. The Romans found materials in other parts of their empire which served the same purpose as the material from Pozzuoli. For example, the trasses of the Eifel, the Moselle, Nette and Brohl valleys played an important part in the construction of the magnificent water-works of Gaul which were erected in the reigns of Emperor Trajan (98-117 AD) and Emperor Hadrian (117-138 AD) and supplied water to the various Roman fortifications near Cologne (Colonia Agrippinensis).

It had been known for many years that crushed brick and tile, and burnt clay when added to lime mortar, produced a mortar with very much the same characteristics as that prepared with the natural pozzolana. Crushed pottery has been observed in mortar of the middle Minoan period (Circa 1500 BC) but whether it was a deliberate addition or purely fortuitous is not known. It is clear that the knowledge of the use of lime mortar, and the benefits to be derived by adding pozzolanic material spread from Greece to Rome. The Romans used lime mortar embodying crushed tile for specific purposes throughout the empire. It was, in fact, in some parts as in Britain, the only hydraulic cement available to them.

The Romans used these pozzolana mortars in positions where it was important to prevent the penetration of damp—for example, for lining the inner surfaces of channels, drains, tanks and aqueducts, for rendering walls in damp or exposed positions, for bonding masonry in waterlogged ground, for pavements, and for torching (sealing the spaces between) roofing tiles to prevent the penetration of driving rain. An early example of the use of lime mortar with crushed tile admixture is the lining of the *specus* of the aqueduct called Aqua Marcia, near Rome (144 BC). With the stronger mortar it was possible for the Romans to erect more slender walls and to construct

† Davey, N. *A history of building materials*, London, Phoenix House, 1961, p. 146.

arches and vaults with greater ease. The cement also offered good resistance to seawater and in consequence it was extensively used for marine structures. An example is shown in Fig 1 of a Roman breakwater near Naples, which has been exposed to the sea, and in spite of the fact that the tufa blocks have been appreciably eroded, the pozzolanic mortar between them has successfully endured.

Considerable care was taken in the choice of aggregate used. An examination made of some hundreds of samples of concrete and mortars from many Roman buildings in England has indicated that the sand and coarse material was selected for size and may have been specially screened for the work. For example, of 58 samples of wall renderings, 55 had sand that passed through a screen with slots 12 mm (0·48 in) *(semuncia)* wide; of 209 samples of masonry mortars 200 had sand and coarse material passing through 19 mm (0·76 in) *(digitus)* slots; and of 95 samples of concrete for floors and foundations, the material of 90 of them passed through 25 mm (0·97 in) *(uncia)* slots. This points very strongly to some means of grading the aggregates for particular work. What precise form the screens, if any, took remains to be discovered. It is apparent from the comments made by Vitruvius‡ that much was known in Roman times about the importance of proper selection of the sand for building mortars and some of his statements are worth repeating:

> 'Now where there is no quarry sand we must use washed river or sea sand . . .'

which draws attention to the importance of washing sand to remove impurities. The crushed stone of the quarry sand would be clean and generally need no washing.

> 'Now in rubble structures we must first inquire about the sand, that it is suitable for mixing into mortar, and without the admixture of earth'

suggesting that the sand should not be deficient in fine material.

> '. . . that (sand) which makes a noise when rubbed in the hand will be best; but that which is earthy will not have a like roughness.'

In other words the sand should be what in modern terminology is called 'sharp'.

> '. . . Also, if it is covered up in a white cloth, and afterwards shaken up or beaten, and does not foul it, and the earth does not settle therein, it will be suitable . . .'

meaning that the sand must be clean and not contaminated with earth.

> '. . . But if there are no sandpits whence it may be dug, then it must be sifted out from the river bed, or from gravel, not less also from the sea shore . . .'

which suggests that sifting, or sieving, was resorted to on occasion to prepare a suitable sand. Vitruvius goes on to point out the disadvantages of sea sand in that it causes efflorescence on walls. He says:

> '. . . But sea sand has these faults in building; it dries with difficulty, nor does the wall allow itself to be loaded continuously without interruptions for rest, nor does it allow for vaulting . . .'

thus pointing out quite correctly that the salt, being hygroscopic, the mortar remains damp, and as would be the case with lime mortar its hardening may be delayed, and slow up the rate of building. The disdavantage of sand derived from stone quarries is that if it is left exposed to weather before use, it may disintegrate and become dusty. Vitruvius said:

> '. . . For if after being taken out (from the quarry) it lies too long it is weathered by the sun and the moon and the hoar frost, and is dissolved and becomes earthy.'

It is remarkable that these observations made by Vitruvius about 16 BC, almost 2000 years ago, compare so well with those in a modern specification or code of practice.

‡ Vitruvius, *De Architechira*, books I to IV.

institution notes

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JLO conference

The 1974 conference of the Junior Liaison Organization is to be held at St Anne's College, Oxford over the weekend 27/29 September. The theme is 'Have you got the energy?' and younger members of the Institution are invited to join their colleagues from the other building industry professions in considering whether the planning and building team is responding to the need for a changed attitude to energy use. And if not, why not?

Full details of the arrangements and registration forms are available from Mrs. Jacobs, JLO Secretariat, c/o IEE, Savoy Place, London WC2R 0BL.

Joint Building Group 1974/75

As has been previously announced, discussions are proceeding which, it is hoped, will result in the Joint Building Group, the Junior Liaison Organization and the Building Services' Engineering Society coming together to form a single society covering all aspects of the built environment. In the expectation that this reorganization will be completed in the coming year, the Institution, at the request of the other sponsoring institutions, has agreed to retain until the end of 1974 the Secretariat of the Joint Building Group, the Organizing Committee of which will continue under the Chairmanship of Mr. Peter Dunican (Vice-President).

The Institution will therefore be arranging a further series of JBG meetings some of which will be held in the latter half of 1974. If the reorganization is not completed by the end of the year then the Committee will complete a 1974/75 programme of JBG meetings at the Institution but the other sponsoring societies, will share the costs from the beginning of 1975 onwards.

New Royal Society award

It has been announced that the Royal Society in agreement with the Esso Petroleum Company has established an award for outstanding contributions to the advance of science or engineering technology leading to the more efficient conversion or use of any form of energy. It will be known as the Royal Society Esso Award for the Conservation of Energy and will consist of a Gold Medal and a prize of £1000. The award will normally be made annually by the Council of the Royal Society which will receive advice from a specially appointed committee.

Details of this new award and a copy of its regulations may be obtained from Dr. D. C. Martin, Executive Secretary, The Royal Society, 6 Carlton House Terrace, London S1Y 5AG.

BSI

Draft code of practice for stairs

BSI has published a draft code of practice for stairs based on a draft prepared by the National Building Agency on behalf of the Code of Practice Committee. Copies are available from BSI, General Office, 101 Pentonville Road, London N1 9ND. Requests must be accompanied by an addressed label with 13p postage (plus 50p for non-members of BSI), and quote Ref. 74/10642 DC. The final date for the receipt of comments is 30 June 1974.

Draft British Standard Specification for external rendered finishes (CP 221)

This draft is available for public comment; first published in 1960 the draft revision brings the recommendations of the earlier code into line with current techniques. The recommendations are given in logical sequence; for example, the influence of the background on the choice of render mixes, guidance on preparation of surfaces to be rendered; choice of suitable mixes and methods of application. Data on the choice of mixes for different backgrounds and finishes are given in tabular form. Copies of the draft are available from BSI, General Office, at the address given above. Requests must be accompanied by an addressed label with 13p postage (plus 50p for non-members of BSI), and quote Ref. 74/10912 DC. The final date for the receipt of comments is 31 July 1974.

New BS 4248

A revised British Standard 4248: 1974: *Specification for supersulphated cement* has been published and replaces the 1968 edition. It gives values in terms of SI units and specifies requirements for the composition, manufacture, sampling and testing of supersulphated cement. It is available from the BSI Sales Office at the address given above.

C&CA publications

A number of new reports are available from C&CA, Wexham Springs, Slough SL3 6PL. The appropriate reference should be quoted when ordering.

Strength and deformation of concrete under short-term loading (Ref. No. 42.484)

A review of the publications on this subject. Price £1.

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