Mortars and concretes of unusual durability have been discovered in the remains of many remarkable ancient buildings and engineering structures /1/. Despite centuries of use and exposure to adverse environmental conditions, these mortars and concretes have often survived better than the natural stone or burnt brick found in the same structures and sometimes even better than modern concretes exposed to similar conditions /2/, Figs 1-6.

This paper combines the author's previously /2, 3, 4, 5, 6/ presented investigations with some new examples, results of new tests and some consideration of the procedures discussed in the literature. Examples are presented of structures and material which display excellent durability. Studies in situ have been complemented with laboratory tests in which physical and mechanical properties, the microstructure and the chemical composition of the material were analysed. From these enquiries it has been possible to attempt an explanation of why these ancient materials are so durable and to comment on the methods used in their ori-
original application. Finally attention is drawn to problems which remain and whose clarification would be useful.

DURABLE LIME MORTARS FOR SURFACE PROTECTION (PLASTERS)

The protection of a weaker substratum of walls, columns and floors by careful polishing of fresh lime mortar has also its origins in the early antiquity. The first until now known use of this procedure, being of religious meaning, is the Mask of Jericho of 7000 B.C. /5/, Fig. 7. Later on many examples of high quality polished mortar have been confirmed in, for example, Mycenaean and Minoan settlements (1500 B.C.), in the famous cistern of Mycenae, and in many buildings of Phaestos (Fig. 8) and Malia in Crete. The Greeks took over this ancient technique and subsequently the Romans applied it to hydraulic structures. Floors, walls and columns in cisterns and the interior of aqueducts were covered with a single or multiple layer of finely polished mortar. Examples of the use of a single layer are the Greek cistern at Megara (500 B.C.) and the Roman aqueduct bridge of Pont du Garde (8 B.C.), Figs 9 and 10. The thickness of a single layer mortar was 1 to about 3 cm, sometimes up to 6 cm. In this thickness the mortar can be considered as fine aggregate concrete. Lime of different types, lime and pozzolan, ground in a mortar (mortarium), as binder, marble powder as filler, natural sand of different size and origin, crushed ceramic tiles and brick or lightweight volcanic stone have been used. High density, impermeability, very high strength and durability are characterizing many of the mortars. Multiple layers were used at Caesarea in the cisterns of King Solomon and the Herodian concrete aqueduct (early 1st century) /2, 3, 6/, Figs. 11, 12 and 13.

Vitruvius* describes the polishing of mortars as an old Greek technique (Bk. II, Ch. 8a, Bk. VII, Ch. 3). He states that careful polishing helps to restrain shrinkage and cracking and gives durability. Vitruvius also discusses the roles of the various components of mortars giving recommendations for their use and proportions.

A modern explanation of the mechanism and function of the polishing technique of mortar as well as the function of the multiple thin layers is a result of recent studies /2, 3, 4/.

The polishing being essentially a process which grinds the lime, carbonate or pozzolan of the mortar creates a dense capillary structure at the surface which increases the impermeability of the material. The carbonation and hydration, i.e. the hardening are also accelerated, especially in mortars placed in thin layers, the strength and durability improved. It restrains shrinkage and cracking but also inhibits the formation of lime sediments on the walls of cisterns and aqueducts due to a better flow of water. The removal of such sediments during maintenance work is also easier /8/.

The author studies also the composition and the function of the multiple six layer mortar on the example of the Caesarean aqueduct /2, 5, 6/. These thin layers of the mortar, each placed separately and finished (after short pauses which are needed for some hardening) cause after hardening a predominantly uniaxial normal directed shrinkage, thus restraining the horizontally oriented cracking. The lightweight porous grayish layer containing cool ashes from burning lime is assuring good bond of the next, white layer and favouring the carbonation hardening; the white layer consisting marble powder improves the carbonation and prevents shrinkage; the third, redish pozzolanic layer (of ground ceramic) is fine polished and assures hardening in water, impermeability and strength (Figs. 12 and 15).

Lightweight lava aggregate was often used in mortars. Specimens have been found in the buildings of the Forum Romanum, in Ostia, in Pompeii and Herculaneum. The great permanence of such mortars is explained by the water absorption and desorption of the aggregate which, acting in a similar fashion to entruded air, affects the swelling and shrinkage of the mortar.

The use of the polishing technique to improve durability was not limited to ancient Mediterranean. The Chinese in the Far East and the ancient Mexicans applied the same technique of surface protection, Figs. 16, 21 and 22.

STRUCTURAL MORTARS

The use of lime mortar as binder in stone and brick structures has its origin in the early antiquity and is to relate to the invention of the binding properties of lime. The story of the Bible on the Tower of Babylon is mentioning that burnt bricks and clay binder instead of stone and lime were used (1. Mos. 11:3). The use of the same materials is to confirm in the Zigguraths of Mesopotamia, in the Minoan and later on in the Greek buildings (Fig. 17), /10/. This "Greek" method, according to Vitruvius (Bk. II, Ch. 3 and Ch. 18), of laying unburnt or burnt bricks jointed with lime mortar, well known in Greece, was adapted by the Romans and then spread all over the ancient world, and is continuing without essential changes until our modern times.

The thickness of the structural mortar was between 1-4 cm. Different binders, lime, lime with pozzolana, different fillers and fine aggregates of natural sand, crushed brick, marble and lightweight vulcanic ashes as medium size aggregate have been common in the ancient mortars. Asphaltic binders described by Vitruvius (Bk. VII, Ch. 2) and used in watertight mortars in harbours, embankments and many buildings of Babylon /1/ were not analysed here.

Famous examples of brick structures showing in their remains excellent durability of the mortars are Collosseum, the "City" of Ostia (the Trajan Market) in Rome, the Basilica of Constantin in Trier, the great Cistern of Constantinople, Figs. 18, 19, 20, 21, and 22.
A similar development of the bricklaying used in the Mediterranean and fine examples of durable brick structures are to notice in the Far East - India, Indochina and China (Great Chinese Wall, Pagoda of Lampoon, Northern Thailand), Figs. 4, 23-24.

**DURABLE STRUCTURAL CONCRETE**

Concrete, opus caementitium, is generally supposed to be a material of Roman origin. However, the use of mortar and plaster in Greek buildings - which is described in detail by Vitruvius in Book VII - suggests that concrete was in all probability used in the pre-Roman period. This view is born out by studies of the cistern at Kameiros in Rhodes (500 B.C.) /12/ whose walls are covered by pozzolanic concrete (Figs. 25 and 26). According to more recent archaeological discoveries lime concrete was used in pavements more than 7000 years ago /11/. In pavements and floors in many sites in the Middle East, as Hazor, concrete with good polished surfaces have been found. Similar technology was applied also in other parts of the world, in the Far East and by the Mayas and Aztecs in Mexico, in floors and altars of temples and on ceremonial roads.

For marine and hydraulic structures in which concrete of great strength and durability was necessary - for example in protecting walls, harbours, aqueducts and buildings in very cold climates - a lime-pozzolana binder was often used. The use of this type of concrete has been confirmed in the harbours of Ostia, Puteoli and Villa Polia (near Sorrento) and in many buildings of the Capitolium. Especially interesting is the town wall of Ampurias in Spain (A.D. 50). It is made of lime-pozzolana concrete and was built without any dilatation. Not a single crack is visible in the hundreds of meters of the wall which survive (Figs. 27, 28, and 29).

It should not be concluded that a lime-pozzolana binder was always resorted to for the more important Roman constructions /2, 6, 9/. There were exceptions. Sometimes, even in hydraulic and marine structures, and in bath for mineral springs, lime-based concrete was used and expected to meet the needs of long-term durability being often exposed to more severe environmental conditions. Examples are the harbour in Caesarea /1/, the Cloaca Maxima in Rome, the North German aqueducts at Eifel /13, 14/ and many other places (Fig. 30). In spite of discovered ancient quarries of trass (pumice) in the Eifel the use of this material in the hundred kilometers long concrete aqueduct in the Eifel was not confirmed.

Until now is the riddle of the carbonation hardening of thick concrete walls made of lime concrete not sufficiently clarified. More easy to explain is the hardening of 40 cm thick concrete floors in many of the Roman hot baths, where the floors in the hypocaust (Tepidarium and Caldarium) and the walls were heated by the burning gases, Figs. 31 and 32.
In both lime and pozzolana-lime concretes differing types of coarse aggregates were utilised. Various natural gravels, crushed aggregates of heavy basalt or porphyry, granite or limestone, and crushed clay bricks, tiles and light lava of different size were all used. In one case gap grade aggregate concrete has been discovered (Figs. 33, 34, 35 and 36). Vitruvius (Bk. II, Ch. 4) describes in detail sands of different qualities and recommends their various applications. The lime/sand ratio was adjusted to the quality of the sand. To improve primarily the durability of concrete, but also its workability, air entrainment was applied to concrete exposed to frost action (Fig. 37). This has been revealed by the very interesting microscopical investigations of Idorn /15/. The use of blood and other additives resulting in entrained air and proteins to increase durability were mentioned in the ancient literature and recently studied /16, 17/. Lightweight aggregate concrete similar to the previously mentioned lightweight mortar made of lava aggregate was often used in Roman buildings, either as a local material or to provide better insulation and to reduce weight. A famous example is the top part of the dome of the Pantheon (Fig. 2). Another example is the vaulting in the remain of the theatre of Taormina, Fig. 35.

As in the case of plasters and structural mortars the use of concrete was not limited to the western ancient world only, and the use of this material and its excellent durability is to confirm in India, in the ancient Far East, and America (Figs. 39, 40, 41).

SPECIAL ENGINEERING AND MATERIAL SOLUTIONS

Occasionally ancient builders adopted particularly unusual material solutions in solving their difficult engineering problems. Especially interesting is the technique of using the expanding paste for fitting the joints of pipes in pressurised conduits. The paste, which was first found in Knossos, Fig. 42 and 43 /18/, has subsequently been identified in many Greek and Roman ducts made of clay, stone and lead, Figs. 44-48 /3, 5, 6, 8/*. The joints sealed in this way ensured that internal pressure equivalent to many atmospheres could be safely sustained. In the famous Pergamon aqueduct (Fig. 49) the lead pipes were subjected to a pressure of nearly 20 atmospheres. The sealing material used was the one described by Vitruvius (Bk. VIII, Ch. 6), a mixture of quicklime and oil to which was probably added finely ground lime-stone, as in stucco mortar. This formula was confirmed in studies in situ and tests carried out by the author (Figs. 50-53). The mechanism of sealing by expansion was also given /3, 5, 6/. Due to the oil in the mix the hydration of the quicklime is delayed. The expansion caused by hydration of the CaO and the mortar is restrained and limited to the space of the joint. As result a tightening takes place and high density strength and hydrophobe properties of the sealing paste are achieved. Part of the oil is pressed out from the joint or in case of ceramic pipes pressed into the capillaries of the material, Fig. 51. The part which remains makes

* Regarding the lead pipes it is of interest to mention the opinion of Vitruvius regarding the harmfullness of the lead pipe aqueducts and the recommendation to use ceramic pipes.
the joint water-repellent. This interesting sealing method was confirmed in German pressure ducts of the 19th century /20/. The principle of the restrained hydration is used in modern concrete technology in production of expansive cements, mortars and concretes and many patents are applying the ancient idea /21/.

Another material for sealing water-pipe joints by expansion, montmorillonite, was found in one of the Pergamon aqueducts /8/. In aqueducts exposed to lower hydraulic pressure ceramic pipes were often embedded in concrete, Fig. 54.

To ensure the durability of floors exposed to frost action Vitruvius (Bk. VII, Ch. 1) suggests impregnating the mortar jointing between the stone flags with oil. A similar technique is used today for pavements in the United States. Very interesting is the development of mosaics. One of the first is the mosaic column of Uruk (Mesopotamia, 3000 B.C.) where the coloured ceramic cones are protecting the weaker substratum and simultaneously being of estetical value /1/. Much later were used stone pebbles of different sizes embedded in lime mortar for abrasion protection of floors and pavements in Greece (Rhodes 600-500 B.C.); at the beginning whole pebbles, later on cut. Similar pebble mosaic used for decoration was found much later (Pella 400 B.C.). The alternate development of the mosaics is with cut stones, Figs. 55-59. Of interest is to mention that in the mosaic floors of Roman baths, in which the functions of sealing, water repellency and strength were alike, a similar expansive paste as in pressure aqueducts has been found, Figs. 58 and 59 /3/.

An ingenious engineering method of producing breakwaters in the sea, being in principle similar to the modern offshore technique is described by Vitruvius (Bk. V, Ch. 12). Heavy prefabricated concrete cofferdams cast at the seashore, inside prepared sand walls, are after finishing transported as pontoon to the proper place, sunked creating breakwaters.

It is well known that the Greeks used iron bars to reinforce long span beams in temples as Propylaiae in Athens. Based on archaeological studies this solution was described in literature /10, 22/. Also in other places where long span heavy beams were used (Nimes, some temples in Sicily) a similar reinforcement was to expect. How such reinforcing bars were protected against corrosion is still a question to be solved, Figs. 60 and 61.

The examples of crackless structure in many Roman buildings indicate a proper choice and adjustment of the material and a sound understanding of the material's behaviour when applied to different structural forms in varying environmental conditions. This is exemplified by, for example, thick concrete sloping walls and domes and arches cast in massive concrete such as the Pantheon and the Basilicae of Constantine and Maxentius. The curvature of these structures results in uniaxial vertical creep deformation of the concrete and restrained creep in the horizontal direction which compensates for the shrinkage deformation and avoids cracking (Fig. 62) /3/. In the before mentioned protection walls of Ampurias the tunnel segments inside the wall are double vaulted and probably resulting in similar condition of restrained shrink-
and probably resulting in similar condition of restrained shrinkage and creep (Fig. 28).

In De Architectura Vitruvius recommends various rules for the selection, proportioning, mixing and compaction of the different types of the opus caementitium. It is interesting therefore to observe that the concretes used in many structures from different parts of the Roman Empire do indeed display evidence that these rules were observed. As example can be mentioned the base for mosaic in the floors on the Basilica of Ampurias, Spain, and the floors of the temple of Nessebre (now Bulgaria), probably built in the same time, Fig. 59.

Another interesting case of the ancient concrete technology is the use of gypsum as structural material, often in severe environmental conditions. The use of gypsum concrete in the pyramids can be explained. By covering the pyramid with large granite tiles in the antiquity (later removed) and by the dry climatic conditions the permanence could be assured. The same explanation can be applied considering the stability of gypsum in the walls of the Palace in Mycenae. But the use of gypsum concrete as "opus caementitium" between giant blocks in the ancient harbour of Kition is a rare example of durability of the material in marine environment and would repay further study.

SUMMARY

This paper has described briefly a number of impressive and successful building techniques improving durability used by ancient engineers: single and multiple layered mortars; surface polishing techniques to protect weaker internal layers; various concretes based on different binders and aggregates; air entrainment; the impregnation of jointing materials with oil; expanding sealants for pressure conduits and others.

In the ancient world a lack of scientific method and specialised knowledge were compensated by experience based on traditional practices and know-how of a more general character. Studies of these techniques reveal that ancient engineers had a sound understanding of numerous aspects of the construction, protection and maintenance of engineering structures and components. In modern times invention and engineering solutions frequently precede a full scientific explanation. Ancient engineering techniques were used for centuries in the absence of a clear scientific understanding of what was involved. Nevertheless, what was done was eminently successful; what was achieved could be very impressive indeed. Many of the techniques and processes evolved, especially those assuring the unusual durability, are of interest - and sometimes importance - to modern concrete engineers, historians of science and technology and archaeologists /16, 17, 21, 23/.

Not all problems of the ancient technology are clarified. A collaboration between concrete technologists, historians and archaeologists for solving their riddles is of importance.
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NOTES


21 Sw. Patent of Master Builders (USA), No. 422.784/82.


ANCIENT STRUCTURES OF EXCELLENT PRESERVATION, MADE OF MORTARS AND CONCRETES OF UNUSUAL DURABILITY

Fig 1. Aqueduct of Segovia, 200 A.C., in use for 1800 years. Concrete conduit.

Fig 2. The concrete dome of Pantheon, 200 A.C. Lightweight concrete at the top.

Fig 3. The aqueduct of Pont du Garde, 8 B.C. Conduit covered with 10 cm thick mortar.

Fig 4. The Great Chinese Wall, 200 B.C.-1400 A.C. External wall and pavement of brick and mortar joint. Concrete core.

Fig 5. Ostia Theatre, weathered reticulae, good preserved mortar joint. 50 A.C.

Fig 6. Harbour of Caesarea, Israel. Modern concrete damaged, while Crusaders' mortar well preserved (1150 A.C.)
ORIGIN AND APPLICATIONS OF THE POLISHING TECHNOLOGY FOR SURFACE PROTECTION

Fig 7. Mask of Jericho, 7000 B.C. Polished lime mortar on skull /7/.

Fig 8. Phaestos, Crete. Minoan palace, polished plaster on alabaster block - painted. 1500 B.C.

Figs 9-10. Pont du Garde. The lining of the aqueduct on fine polished mortar (right), thick deposit of travertine. 8 B.C.

Figs 13, 14, 15. The Aqueduct of Caesarea: weathered arch of calcareous sandstone and well preserved polished mortar (13). Six-layer mortar (14). SEM micrograph x400 of the polished red layer (15). 30 B.C.-30 A.C.

SURFACE PROTECTION BY MEANS OF POLISHING TECHNOLOGY

Fig 16. Uxmal, Mexico, before 900 A.C.
Polished mortar on columns and pavement.
Fig 17. The Ziggurath of Aqar Quf, 1300 B.C. Heavy burnt brick and clay lime mortar.

Fig 18. Colosseum, Rome, 80 A.C. Main internal structure of brick and jointing mortar.

Fig 19. Brick vaultings in the Cistern of Constantinople, 30,000 m$^3$ water, 400 A.C.

Fig 20. Trier (Augusta Treveorum), Germany, the Basilica of Constantine, 305 A.C. Brick structure.
Figs 21-22. Trier - Barbaris Therme, 150 D.C. (cross section of the brick wall. Dense mortar of high strength (35.0 MPa in compression).

Figs 23-24. Rampart in Great Wall (Fig 4). Structure of grayish brick and white pozzolanic (rice husk) mortar, fine polished in the joints.
ORIGIN AND EXAMPLES OF LIME-POZZOLANA CONCRETE


Fig 27. The Roman harbour of Caesarea, 200 A.C. To the left a thick concrete wall and to the right the pool of Cleopatra.


Fig 29. Tiberias - Concrete in a Roman bath. Example of pozzolanic reaction. A crystalline silica particle (olivin) reacted with lime. Transmission microscope x100 /2/.
CARBONATED LIME CONCRETE - NO POZZOLANIC REACTION IN THE MATRIX

Fig 30. Köln, Eifel Aqueduct. Section of concrete conduit, different aggregates, large basalt stone (top) concrete of $d_{max} = 50$ mm, bottom covered with a layer of red mortar. 100 A.C.

Fig 31. Theatre Perentium Etruria, 100 A.C. - Italy. "Opus mixtum"-concrete of large brick aggregate placed between bricks.

Figs 32-33. Trier, Barbara Therme Hypocaust, 300 A.C. Thick (40 cm) lime + brick concrete (32). Well compacted aggregate (gap grade - 33). White limestone as sand. Calcium carbonate in the matrix, traces of silica reaction on and near the surface of the aggregate.
CONCRETE MADE OF DIFFERENT AGGREGATES AND AIR ENTRAINMENT CONCRETE

Fig 34. Capitolium, Rome. Lightweight aggregate (lava) concrete. Density 1.5 g/cm³. Strength 8.0 MPa.

Fig 35. Taormina theatre (100 A.C.), Sicily. Coarse aggregate, lava concrete, D_max 120 mm. Density 1.8 g/cm³. 15.0 MPa.

Fig 36. Italica theatre, Spain. Gravel concrete of D_max 48 mm. Density 2.3 g/cm³. 25 MPa in compression. 100 A.C.

Fig 37. The Barbegol Aqueduct to Nimes, 0-100 B.C. Air entrained concrete - Idorn /15/.
ANCIENT CONCRETE OUTSIDE MEDITERRANEAN

Fig 38. Qutb Minar, Delhi (Arabic), 1200 A.C. Brick aggregate concrete structure.

Fig 39. Great Wall, China. Section of the core in repair, stone block embedded in lime pozzolana mortar.

Fig 40. Chicken Itza, 300 A.C., Yucatan, Mexico. Concrete pyramid (rubber and blood added to improve durability).

Fig 41. Uxmal, Mexico. Large stones embedded in lime mortar of high durability. 300 A.C.
SEALING OF JOINTS WITH EXPANDING QUICKLIME-OIL PASTE IN HIGH PRESSURE CONDUITS

Fig 42-43. Knossos. The Minoan ceramic pipes, 1500 B.C. jointed with "expanding rim" - Evans (42). Pipe embedded in mortar (43).

Fig 44. Kameiros, Rhodes. Ancient heavy pipe from pressure duct (400 B.C.).

Fig 45. Scheme of a joint filled with expanding paste (quicklime + oil).

Figs 46-47. Stone pressure duct in Bethlehem (46). Detail of the joint with paste (47). Probably Hellenistic or Roman (as in Methymna.)
Fig 48. Lead cast pipe, in stone muff and expanding sealing paste. Ephesus, 200 B.C.

Fig 49. The high pressure conduit (20 atm) to the Citadel of Pergamon, 200 B.C.

Fig 50. Sealing paste from a joint (Rhodes Museum), 400 B.C.

Fig 51. Perge, Anatolia, 400 B.C. Sealing paste and traces of penetrated fluids (black line) in the pipe.


Fig 54. Alhambra, Spain. Pressure pipe embedded in calcareous sandstone concrete.
THE DEVELOPMENT OF FLOOR MOSAIC

Fig 55. Athens Agora. Sand gravel pebbles embedded in lime mortar, 200 B.C.

Fig 56. Rhodes, Greece. Cut limestone pebbles with larger abrasion surface, embedded in mortar, 400 B.C.

Fig 57. Piazza Armerina, Sicily. A mosaic in the Bath of Maxentius, ~350 A.C.

Fig 58. Substratum of mosaic. The upper from Ampurias (Spain), the bottom from Nessebre (Bulgaria). Both from the same age, 300 B.C. The origin of the German Estrich.

Fig 59. Quicklime-oil sealing of mosaic floor. Basaltic prism embedded. Roman, 100 A.C.
UNUSUAL ANCIENT SOLUTIONS

Fig 60. Propylayae, Athens. Greek stone beam approx. 60 m, previously iron reinforced /10, 20/.

Fig 61. The beam removed for repair. How was the corrosion prevented?

Fig 62. Scheme of the time-depending deformations, creep and shrinkage in an arch, causing compaction and no cracking.

Fig 63. Opus incertum made of gypsum. Concrete between giant dolomite blocks in the harbour of Kition, 600 B.C.?