Concretes And Mortars In Ancient Aqueducts

by Roman Malinowski

During ACI's 75th year, each issue of *Concrete International: Design & Construction* will present an article devoted to some aspect of concrete history.

Some of these original articles will be about concrete history — bringing to light past developments in the concrete industry — or details about historical structures. Other articles will be reprints of some of the early papers from ACI *Proceedings,* illustrating the technology and methods of yesteryear and comparison with modern practice.

Concrete construction is much more than 75 years old. This first article in the series attempts to explain the mystery of successful concrete construction dating back to 2000 B.C.

Some ancient types of water conduits — tunnels, arch constructions, and pressure conduits are dealt with. Building materials for lining, concrete, mortar, plaster based chiefly on lime as binding material as well as a paste for sealing joints in pressure ducts were examined. Experiments were carried out to imitate this expanding sealant described by Vitruvius. The causes for the great tightness, strength, and resistance of the ancient carbonate concretes were analyzed.

Keywords: aqueducts; calcium carbonates; carbonation; cracking (fracturing); crushed brick; durability; joint sealers; lime cements; mortars (material); plaster; shrinkage; strength.

1 — ANCIENT AQUEDUCTS — VITRUVIAN SCIENCE OF BUILDING MATERIALS

1.1 — *The three ways of building aqueducts*

Roman engineering works have been admired for centuries as one of the golden ages of "man the builder." Many of the most impressive Roman civil engineering works remain as testimonies to their engineering skills. Nevertheless, much remains to be investigated regarding the details of the building techniques actually used. Vitruvious' classic ten books on architecture remain as the most important written source for Roman engineering. By combining archaeological evidence with a careful study of appropriate passages in Vitruvius, new insights are possible regarding the extensive water works systems built by the Romans.

In book VIII, chap. VI Vitruvius[6] describes the three main types of aqueducts:

- —underground tunnels carved through tufaceous or solid rock
- —elevated masonry canals (arched ducts)
- —pressure-conduits (i.e., inverted syphons) made of lead or clay pipes

Remnants of these conduits are found in many places within the boundaries of the ancient Roman Empire. Some are still in use today.

The underground aqueducts carved through tufaceous or solid rock are mentioned in the Bible.[4] Similar mile-long water conduits were built by the Greeks and Etruscans.[5]

The bottom and the walls of the tunnels were lined with water-tight mortar and plaster. The Romans, who admired the Greek tunnel constructions, further developed this way of building.[6] The floors were usually lined with concrete and the walls with bricks covered with watertight mortars.

The best known aqueducts are the masonry arch conduits such as those of the city of Rome, those of Pont du Garde, Segovia, Constantinople, and the Eifel. Open or closed canals of these conduits normally had a jointless watertight lining.

Ancient pressure lines are most admirable from the technical viewpoint. The main part of the book VIII, chap. VI "On aqueducts . . ." deals with pressure conduits. After criticizing the expensive and unhealthy lead pipelines, Vitruvius describes the pressure conduits of clay. This way of building came to Greece from Mesopotamia and Minor Asia as early as the Mycenaean and Minoan era, i.e., 2000 B.C. One of the oldest known is the pressure conduit (i.e., inverted syphon)

Many of the Greek acropoles and temples on the mainland, the Aegean islands, and in the Greek colonies were situated in lofty positions, resulting in difficult problems with regard to water supply. Remnants of pressure conduits using clay, stone or lead have been found at a number of sites. The conduits were loaded, anchored, and a special sealant was used for the pipe joints,[6] so that the conduits could withstand the high pressure.

In choosing an adequate construction method for aqueducts the following recommendations are given by Vitruvius:

- Adaptation to the topography
- Assuring supply of healthy water.
- Protection against evaporation
- Tightness and impermeability of the conduit, avoidance of shrinkage cracking assuring durability
- Easy repair

Often all three of these types of aqueducts were used in the same water conduit system.[6-Table LX]

1.2 — *Building materials and construction*

1.2.1 — Lining materials used for underground and elevated conduits

As mentioned above the canals of the underground and elevated aqueducts generally lacked joints, a fact which astonishes modern concrete technologists. With simple building materials and handicraft methods, the ancient builders developed techniques which insured that the conduits would be impermeable to water, without shrinkage and cracks, and very durable. For solving the problem of choosing the right materials, the decisive factor was the understanding of the influence of climatic conditions.

The bottom of the canals were made of a well-stamped crushed-brick concrete layer at least 15 cm (6 in.) thick.[6] The normal proportion of aggregate to lime was between 3 to 1 and 4 to 1 (book VII, chap. I).[6] The walls of the canals were made of stone blocks of bricks or of concrete. For lining the canals, it was most important to create a watertight and durable mortar layer free from shrinkage. This was achieved by means of polishing a multi-layer stucco plaster. Vitruvius, in book VII, chap. IV, 1[6] recommended: "render and face the exterior wall with mortar made of brick powder and apply upon that stucco plaster," viz. with marble powder. The lime-crushed brick mortar probably provided the hydraulic binding and the water tightness, while the lime-crushed marble mortar was used to prevent shrinkage. The surface of the layers should be carefully rubbed in and polished to mirror brightness (book VII, chap. III, 9).[6] A lining of the columns and walls carried out in such a manner has often been mistaken for slabs of marble. A six-layer, crack-free stucco mortar plaster is described in the same book VII, chap. III, 6.

For closed canals and tunnels where there is continuous moisture and no danger of cracks caused by shrinkage, the problems were solved in an easier way without such careful polishing.

1.2.2 — Sealant for the pressure conduits and floors

Many details on the building materials for pressure conduits made of clay have been described by Vitruvius. The pipe walls shall be two inches thick. On the lowest parts of inverted siphons, heavy stone pipes shall be used. They were often also loaded with sand and anchored with metal. One of the most important details of the pressure conduit was the sealing of the joints. A sealant made of lime and oil is recommended by Vitruvius (book VIII, chap. VI, 8). A similar sealant for the protection layer of frost weathering resistant concrete floors is described in book VII.

1.2.3. — Components of the concretes, mortars and of the sealant

The components of the watertight, durable "shrinkage compensated" mortars and of the sealant for high pressure conduits are dealt with in various parts of Vitruvius' book.

- Various kinds of lime (book II, chap. V, and book VII, chap. II)
- Hydraulic binding materials (lime and pozzolan — book II, chap. VI, brick powder — book VII, chap. II, 1)
- Binding materials (lime and marble powder — book VII, chap. III.).
- Different sand types for concrete or plaster (book II, chap. IV).
- Pebbles, crushed stones and bricks, for concrete are mentioned in many passages.

1.3 — *The empirical rules of the ancient concrete technology for hydraulic structures*

The successful solutions of the ancient engineers as to material technology, demanded a good understanding of the statics of the construction, as well as a good knowledge of the influence of the environmental conditions and climate upon the building.

The general solution for the tunnels was a watertight and smooth lining. In the moist atmosphere of the tunnels there was no risk for excessive shrinkage nor cracks due to shrinkage. A simple surface treatment was thus a sufficient protection.[1] A similar solution, i.e., polishing of the mortar only, was also found in uncovered canals of masonry aqueducts.

The long elevated aqueducts and their canals were built as continuous structures without expansion joints. If the problem were to be solved successfully the material for the arch construction, especially in the open canals, should eliminate detrimental thermal stresses and changes in moisture which often resulted in shrinkage cracking. A multilayer, fine-polished plaster was recommended by Vitruvius for such climatical conditions. Details of this type construction are discussed in a later section.

The stability of the pressure conduits was achieved by loading and anchorage of the pipes (book VIII, chap. VI).[6] For tightening a mixture of quicklime and oil, an old expanding Greek sealant was used.

The solutions described by Vitruvius were of empirical nature and thus based on centuries-old experience of ancient stucco workers. However, the technical explanation of these successful solutions and the mechanisms involved are not discussed. There are no contemporary explanations as to how and in which way the polishing procedure, the thin multilayer mortar, and the addition of marble powder influence the strength and prevent shrinkage, nor which influences are involved in the tightening of the pressure pipes by the oil-lime mixture.

TABLE 2.1 — CALCULATED COMPOSITION, POINT-COUNTING, AND SOME PROPERTIES OF THE BUILDING MATERIALS IN THE ACQUAROSSA TUNNEL

Composition property		Material			
		Concrete	Mortar	Plaster	Tufaceous rock
Binding Agent ($CaCO_3$) kg/m³ (lb/ft³)	Surface center	250 (16) 300 (19)	350 (22) 300 (19)	400 (25) 300 (19)	
Binding agent aggregates (weight)	Surface center	1:5.5 1:4.5	1:4 1:5	1:3.5 1:4.5	
Density g/cm³ (lb/ft³)		1.85 (115)	2.05 (128)	1.150 (72)	1.30 (81)
Water absorption in percent by weight		28	21	60	53
Water absorption on the surface (polished)		High	Medium	Low	High
Compressive strength MPa (psi)		9.0* (1305)	12.0* (1740)	7.0** (1015)	5-8* (725-1160)

*Cubes measuring 4 x 4 x 4 CM (1.6 x 1.6 x 1.6 in.)
**Cubes measuring 1 x 1 x 1 CM (.4 x .4 x .4 in.)

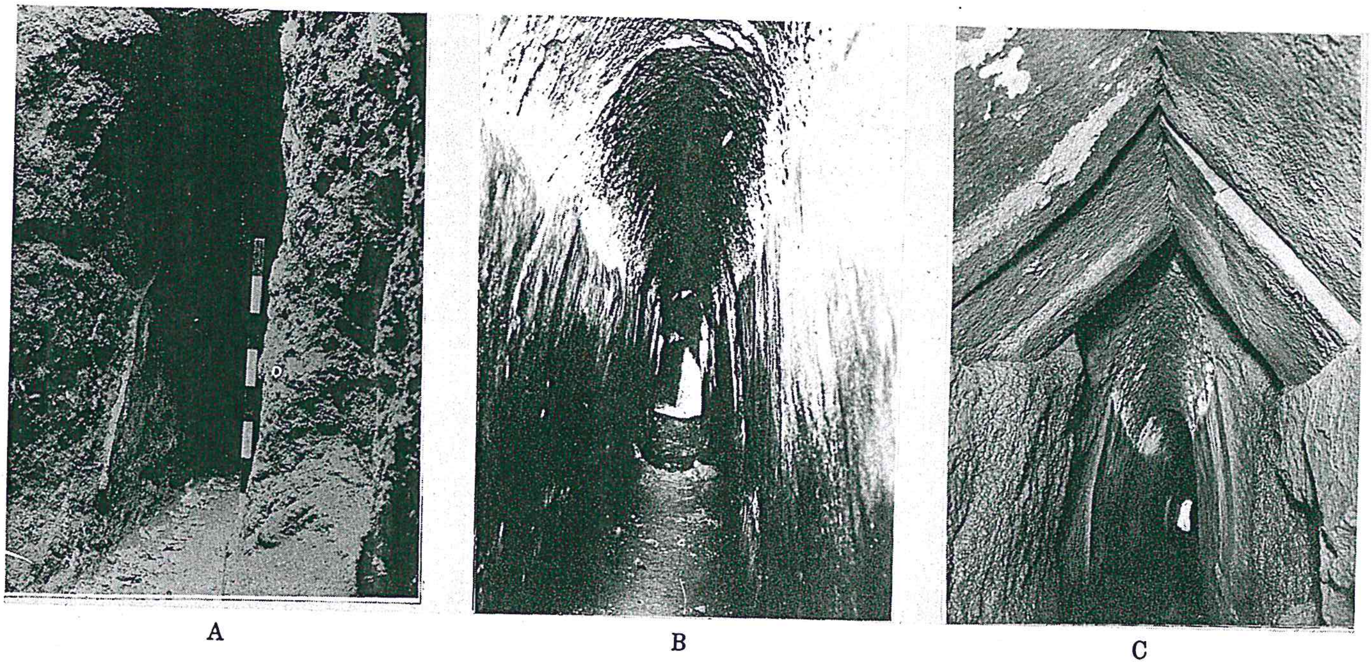

A B C

Fig. 2.1.1. — Tunnel — Cunniculus — of the Etruscan-Roman water conduit in Acquarossa 1.70m (5.6 ft) high (Viterbo, Italy). A. entrance; B. tunnel; C. roof-shaped ceiling lined with large tiles. (photo: D. Kuylenstierna)

2 — INVESTIGATION OF THE MATERIALS

2.1 — *The underground Etruscan-Roman water conduit in Acquarossa, Italy (Table 2.1, Fig. 2.1.1 and 2.1.2)*[1]

About ten years ago the Swedish Institute in Rome, while conducting excavations in an Etruscan settlement (600-700 B.C.) discovered a tunnel. The tunnel, carved through tufaceous rock, was 0.7 m wide and 1.70 m high (2.3 ft x 5.6 ft); floor was made of crushed-brick concrete with a thickness of 15 cm (6 in.). In the lower part the walls were lined with a 7 cm (3 in.) thick small-grain crushed-brick concrete and in the upper part with a 3 cm (1 in.) thick light-colored plaster. The surface of the floor concrete was rough, that of the wall mortar smoothed, and that of the plaster carefully polished. In one part of the tunnel the ceiling was lined with baked clay tiles measuring 70 x 70 x 7 cm (28 in. x 28 in. x 3 in.) (Fig. 2.1.1). Though these tiles were similar to the Etruscan tiles the lining seems to be of Roman origin. The lining has a very good adherence to the tufaceous rock. No limestone sinter was observed on the surfaces, probably because of low lime content in the local water. The composition, properties, and structure of the concrete, mortar and plaster were investigated. In the chemical examination chiefly calcium carbonate was identified as the binding material and only traces of calcium silicates were found. The calcium silicates are probably the result of reaction products of the calcium hydroxide with the tufaceous sand and perhaps also with the brick powder. The mix proportions were found on ground surfaces of the specimens (Fig. 2.1.2), by means of the "point-counting" method. The results of the examination are compiled in Table 2.1.

In spite of low density and strength the material has shown excellent durability. The insignificant water absorbtion of the polished surface of the lightweight limeplaster is noteworthy. In the scanning electron microscopy (S.E.M.) pictures (Fig. 2.1.4.1 and 2.1.4.2) the closely connected carbonation products confirm the beneficial influence of the surface polishing on the properties of plaster — a treatment recommended by Vitruvius.

2.2 — *Roman elevated aqueduct in Caesarea, Israel, (Table 2.2, Fig. 2.2)*[2]

The most important section of the 30 km (19 miles) long aqueduct in Caesarea on the southern rim of the Carmel mountain is a stone arch conduit. The construction consists of stone arches with 5 m (16 ft) clear width and 2.5 m (8 ft) clear height. The sandstone blocks are filled with a lean concrete composed of grey mortar and coarse crushed sandstone, Opus Incertum (Fig. 2.2.1). The open canal is made of similar concrete having an unusually hard lining of multi-layer plaster upon the floor (bottom) and covering the walls, both inside and outside. No expansion joints were used and no cracks caused by shrinkage were observed on the undamaged parts of this very long canal. This unusual property of Roman arch aqueducts which cannot be explained by the materials used, is discussed in part 3.

The six-layer plaster consists of the following mortar layers (beginning from the internal to external part):

- grey (with charcoal) 6-10 mm (.24-.39 in.) (on the concrete)
- white (with finely crushed marble) 5-6 mm (.20-.24 in.)
- red (with finely crushed brick) 5-6 mm (.20-.24 in.)
- grey (with charcoal) 3 mm (.12 in.)
- white (with finely crushed marble) 3 mm (.12 in.)
- red (with finely crushed brick) 4 mm (.16 in.)

The mortar layers become thinner towards the surface. In the grey concrete mortar consisting of lime, seasand and tufaceous sand, there are major quantities of charcoal particles of a size up to 3 mm (.12 in.). Probably residue lime of smaller grains of lower quality, and coal from the kiln were used for the concrete and the grey lean mortar.

In the multilayer material the grey mortar forms a slightly absorbing base resulting in good adherence of the fresh white and the following red mortar. This adherence is of special importance for the construction of the vertical surfaces.[2]

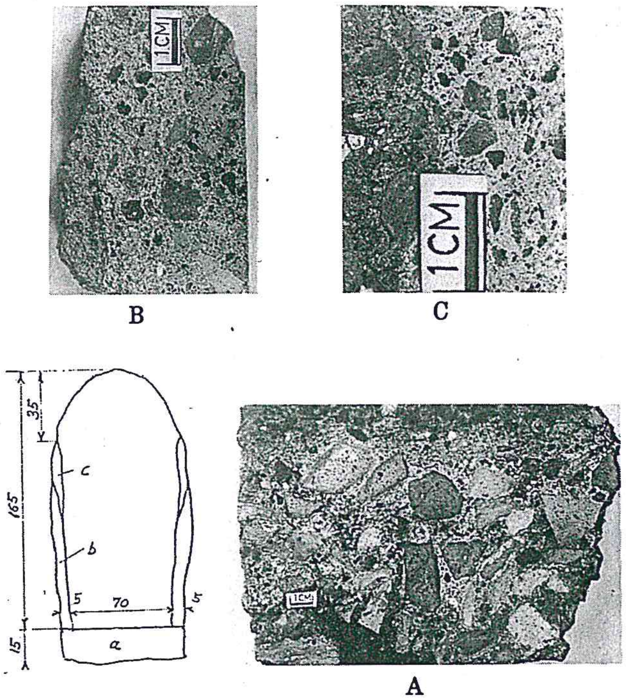


Fig. 2.1.2. — Section through the tunnel and lining. A. floor crushed lime-clay concrete. B. lime mortar C. lime plaster

The grey mortar has poor tightness and strength, the white one shows unusual hardness and great tightness, the red one is tight and very strong, too (Table 2.2). The S.E.M pictures corroborate the great structural tightness of the white and red mortar. They show in the white mortar chiefly calcium carbonate, frequently crystalline, packed closely together; in the red mortar mixed calcium silicate and calcium carbonate structures; and in the grey mortar a porous structure with characteristic spherical particles of calcium carbonate. It appears that the composition as well as the polishing cause favorable conditions for carbonation, which guarantees the extraordinary properties of the white and red mortar.

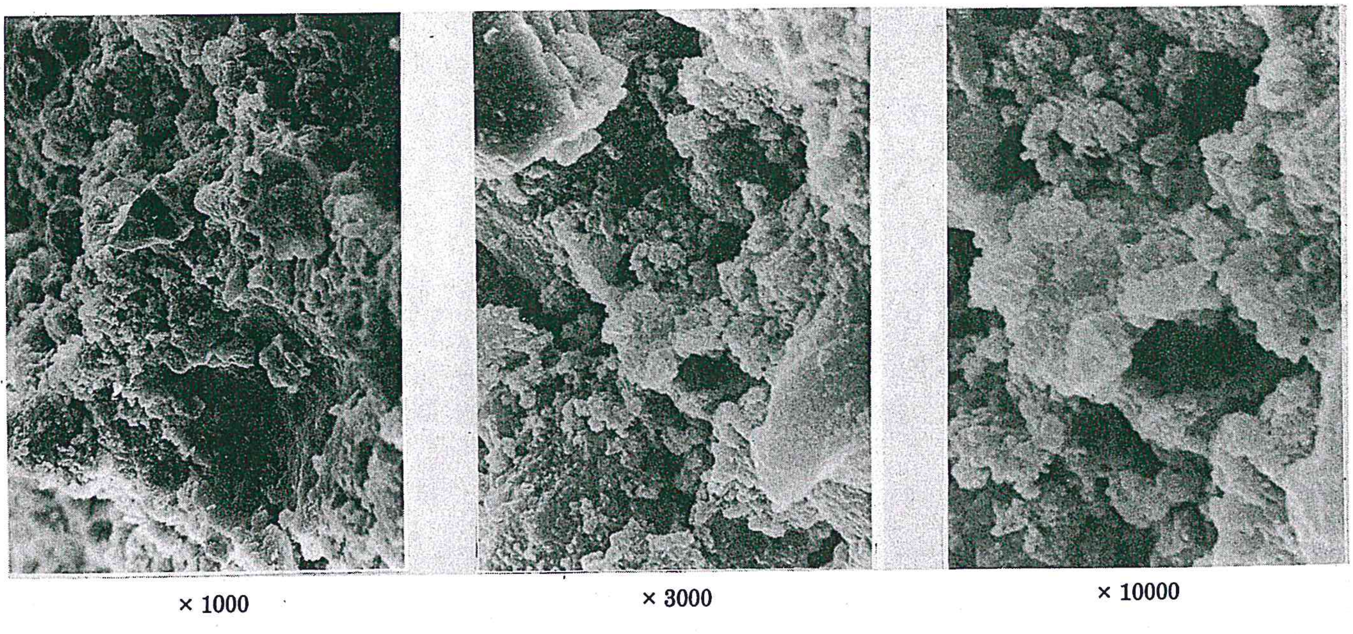

× 1000 × 3000 × 10000

Fig. 2.1.4.1. — Rupture surface of the lime mortar. S.E.M.-picture of the surface. Spherical products of carbonation lying closely together, frequent major pores. (photo: B. Hedberg)

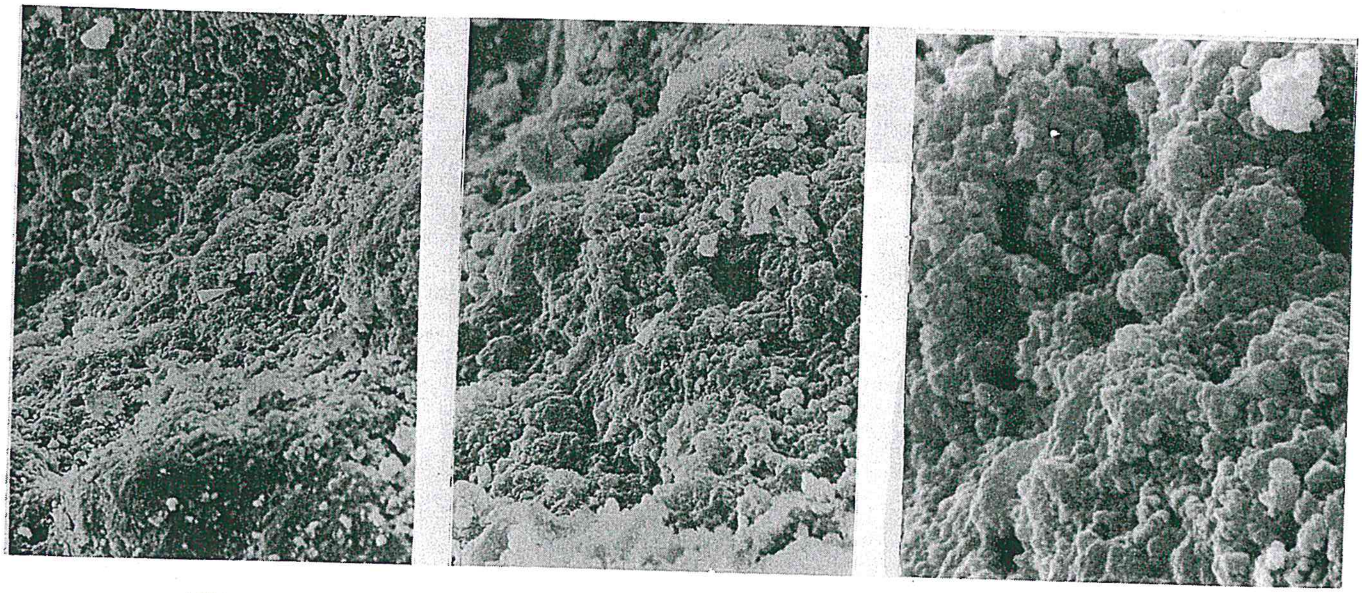


Fig. 2.1.4.2. — Rupture surface of the plaster. S.E.M.-picture of the suface. Spherical products of carbonation lying closely together. Small pores. (photo: B. Hedberg)

TABLE 2.2 — CALCULATED PROPORTIONS OF THE MIXTURE BY WEIGHT AND SOME PROPERTIES OF THE SIX-LAYER MORTAR IN CAESAREA (100 A.D.)

Composition properties		Type of mortar		
		Grey	Red	White
Components (weight)	Binding agent $CaCO_3$	1	2.0	1.5
	Sand 0-0.5	1.5	1	1
	Marble Sand <1 mm ($CaCO_3$)	0-1	1	3
	Fine crushed clay 0.5-3 mm (.02-.12 in.)	0	3	—
	Pebble 2-5 mm (.08-.20 in.)	3	1	1
	Charcoal	0.5	—	—
Density g/cm^3 (lb/ft^3)		1.5 (94)	1.85 (115)	2.05 (128)
Water absorption %		35-40	10-15	5-8
Strength MPa (psi) Vickers (hardness)		4-6 (580-870)	20-40 (2900-5801)	30-50 (4351-7252)

It is of interest to emphasize the similarity of the solution of the six-layer lime mortar of the aqueduct in Caesarea with the mortar described by Vitruvius (book VIII, Chap. III, 6 and 7).[6]

2.3 — *The pressure conduits of clay and stone pipes*

2.3.1 — Pressure conduits of clay pipes

Remnants of some pressure conduits and details of their watertight joints are shown in Fig. 2.3.1. Pipes with an external diameter of up to 30 cm (12 in.), and a wall thickness of 5 cm (2 in.) were often covered with concrete (picture A). For low pressures even thin-wall clay pipes were used, e.g. in the Herodian aqueduct in Jerusalem. Demounted pipes of a pressure conduit from Rhodos and their "packing-rings" are shown in picture B and D of Fig. 2.3.1.

2.3.2 — The pressure conduit of stone in Bethlehem and tests of the jointing pastes

Details of the stone pressure conduit of the ancient water supply system of Jerusalem are shown in Fig. 2.3.2 and 2.3.3. The water was led from the so-called King Solomon's water reservoirs (picture A) chiefly in stone pipes with external dimensions of 90 x 90 x 50 cm (35 x 35 x 20 in.), (pictures B and C) and with an interior diameter of 38 cm (15 in.). In the vicinity of Bethlehem the pressure was 5 atm (approx. 70 psi).[8] The 2 cm (.8 in.) wide joints of the conduit are filled with a white, hard sealant (picture D). The exterior part of the joint is covered with two types of mortar viz. a soft grey one, and thereupon a red one of greater hardness, with crushed-brick aggregate. The test results given in Tables 2.3.1 and 2.3.2 include data from the Bethlehem and Rhodes pressure conduits as well as data of a Roman floor mosaic in which a similar white

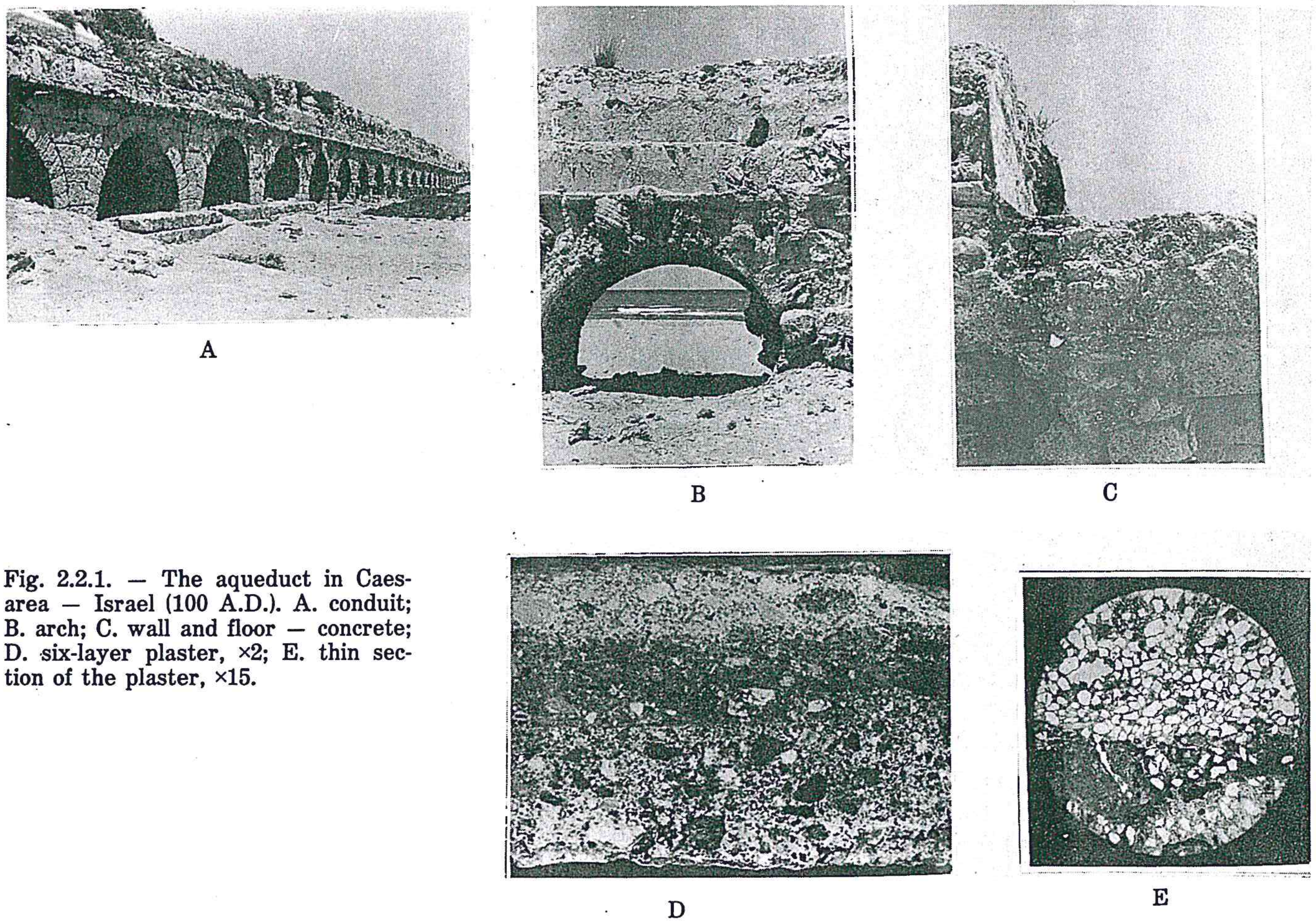


Fig. 2.2.1. — The aqueduct in Caesarea — Israel (100 A.D.). A. conduit; B. arch; C. wall and floor — concrete; D. six-layer plaster, ×2; E. thin section of the plaster, ×15.

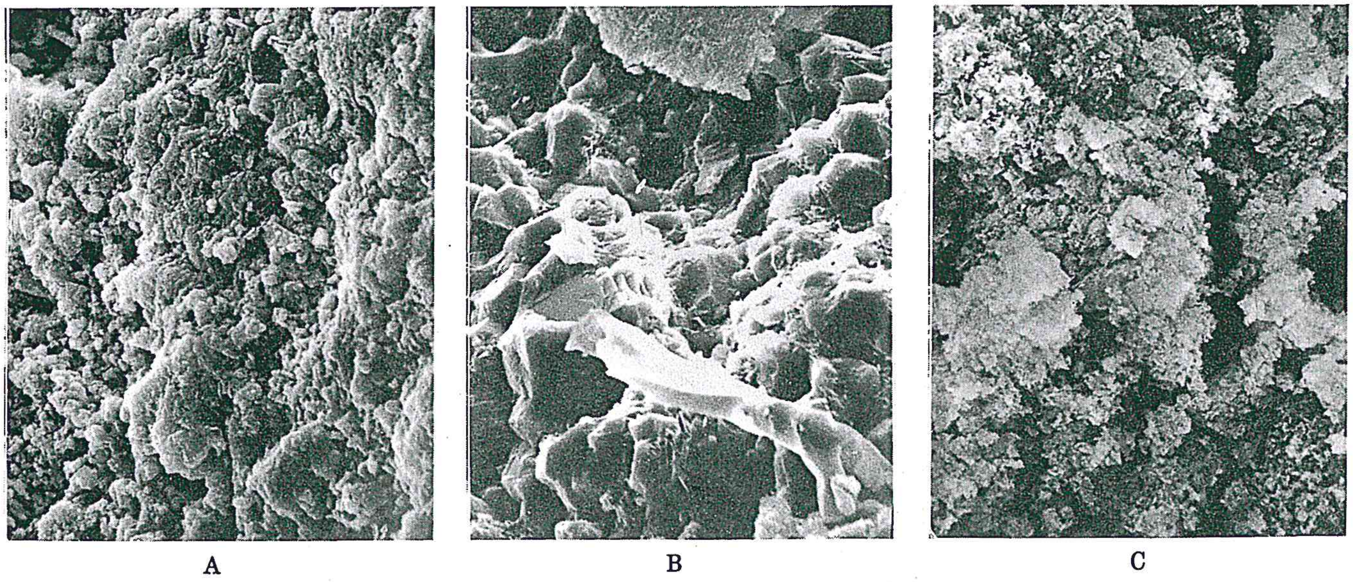


Fig. 2.2.2. — S.E.M.-picture of the rupture surface of the six-layer plaster from Caesarea, × 3000, 1 cm = 3.3 m (.39 in. = 10.8 ft). A. red lime mortar; B. white lime mortar; C. grey lime mortar. (photo: B. Hedberg)

paste was applied (also described by Vitruvius). The tests comprised the chemical composition and important properties of the materials. The experimental results are compiled in Table 2.3.1 and 2.3.2. The sealant consists chiefly of calcite and aragonite. The larger quantity of aragonite as well as the high density and hardness of the mass indicate that high percentages of ground marble and quicklime as a binding material were used in the sealants. Some type of oil was added — as recommended by Vitruvius — to assure a proper and dense filling of the joints. The necessity to use quicklime in the mixture and the mechanism of tightening and hydration of the paste will be analyzed later on. In the laboratory tests of the sealants no traces of oil could be found.

2.3.3 — Experiments of Simulated Sealants

Two series of experiments to imitate various lime-sand-oil mixtures were carried out. In the first preliminary series of experiments[3] the expansion of the fresh lime-oil mixtures and their subsequent volume stability, was determined by measuring the drying-shrinkage, and some other properties.

TABLE 2.3.1 — CHEMICAL COMPOSITION IN % BY WEIGHT AND PROPERTIES OF THE ANCIENT AND NEW SEALANT

Particulars		Sealant			
		Rhodos	Bethehem	Mosaic	New
Mixture CaO to $CaCO_3$ to oil		1 to 2 to (?)	1 to 2 to (?)	1 to 2 to (?)	1 to 1 to 0.35
Chemical composition	CaO	50.40	Chiefly $CaCO_3$, calcite and aragonite		34.44 } dolomite
	MgO	0.42			7.83 } dolomite
	SiO_2	1.31			1.17
	Al_2O_3	0.37			0.56
	MnO	0.01			0.03
	Fe_2O_3	—			0.30
Density g/cm³ (lb/ft³)		2.20 (137)	1.6-2.0 (100-125)	Tight/dense and very tight/dense	2.02 (126)
Porosity % by volume		25	40-30	25	30
Water absorption % by volume		Surface 5 middle 2	6	Very low	After 7 months 2 (±0.1)
Compressive strength MPa (psi)		24 [±5] (3481)	Up to 20.0 (2901)	5-100 (725-14,503)	7 months 22 [±2] (3191) after 1 year >26 (3771)

TABLE 2.3.2. — PROPERTIES OF THE ANCIENT BUILDING MATERIALS TESTED

Building part	Material		Density g/cm³ (lb/ft³)	Water Absorption %	Compressive* strength MPa (psi)
Pipe-line Betlehem ~100 B.C.	Sealant	exterior	1.6 (100)		1-7 (145-1015)
		center	2.0 (125)	6	5-20 (725-2901)
	Mortar	red	2.0 (125)	8	15-30 (2175-4351)
		grey	1.8 (112)	20	5 (725)
	Dolomite stone pipe		2.85 (178)	<1	150 (21,775)
Mosaic Roman (?)	Sealant white	soft	Tight/dense 2.0 (125)	—	5 (725)
		hard	Very tight/dense 2.4 (150)	—	100 (14,503)
	Red mortar	fine	2.0 (125)	—	35 (5076)
		coarse	2.2 (137)	8	40-60 (5801-8702)
	Basalt cube		3.0 (187)	<1	150-300 (21,755-43,510)

*Evaluation based upon the micro hardness test.

TABLE 2.3.3. — EXPERIMENTS OF IMITATION, INFLUENCE OF THE DIFFERENT EXPANSION AND HARDENING CONDITIONS UPON THE PROPERTIES OF THE SEALANT. QUICKLIME, CaO, TO MARBLE SAND, $CaCO_3$, TO OIL = 1 TO 1 TO 0.30. WATER PRESSURE 6 ATM — 24 HOURS

Property			Expansion %		
			Free 33%	Limited 10%	None (restrained)
Density after g/cm³ (lb/ft³)	P		1.82 (114)	1.82 (114)	1.82 (114)
	W_L		1.68 (105)	1.82 (114)	2.02 (126)
	W_W		1.72 (107)	1.90 (119)	2.04 (127)
Water absorption as % by weight			<2%	<1%	<1%
Compressive strength, MPa cube measuring 1 x 1 x 1 cm (.4 x .4 x .4 in.)	W_L	7 T	0.6 (87)	1.5 (218)	6 (870)
		7 M	6 (870)	12 (1740)	22 (3191)
	W_W	7 T	0.6 (87)	2 (290)	5 (725)
		7 M	6 (870)	10 (1450)	22 (3191)

Designation P — After compaction
W_L — After 24 hr water pressure, subsequent storing in air
W_W — After 24 hr water pressure, subsequent storing in water
7 T — After 7 days
7 M — After 7 months

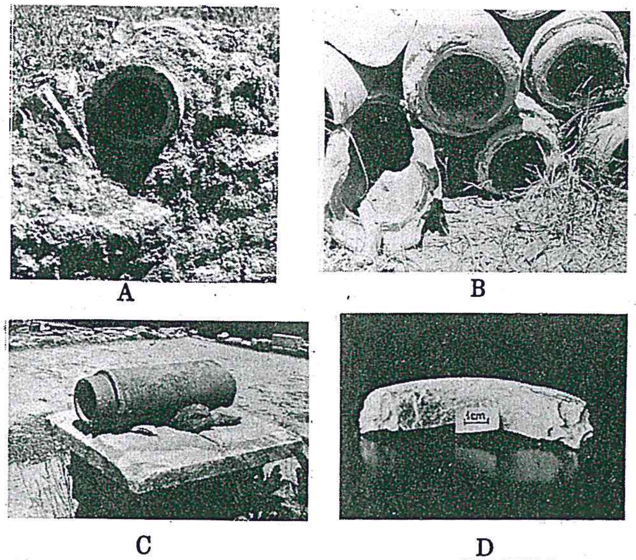
As binding agents quicklime, CaO, or calcium hydrate, Ca $(OH)_2$ were used. Also an addition of brick powder was tried out. The proportions of binding agent to brick powder to linseed oil in this series were 1 to 0.3 to 0.25, or 0.3. Prisms measuring 2.5 x 2.5 x 20 cm (1 x 1 x 8 in.) were used as specimens. Only the quicklime-oil mixture expanded in the water bath. After prolonged storage in water in the closed mould the subsequent expansion of the demoulded prisms was considerably smaller. An insignificant shrinkage was observed after further storage in air. A compressive strength of 0.1 MPa (15 psi) was achieved after one week.

The mixture of hydrated lime and oil did not show any expansion, but on the contrary, after 3 months, a considerable shrinkage, of 3 percent, and an increase of the compressive strength, of 5.0 MPa (725 psi) were observed. The conclusions of this series was that only quicklime could be suitable for a sealant.

In the second series of experiments, in 1975, conditions for the water pressure conduit were simulated. An apparatus was built for experiments of expansion with the sealant exposed to a water pressure of 6 atm. (approx. 89 psi) utilizing 4 x 4 cm (1.6 x 1.6 in.) cylindrical specimens. To begin with the conditions for the expansion were chosen, viz. free, limited or restrained. The expansion was measured under pressure and after demoulding. Part of the specimens were subsequently stored in air, part in water. The density, water absorption, and strength of the examined sealants were determined after different storage conditions.

The sealant shows the highest compressive strength at the age of 7 days when the expansion is restrained. A further important increase of strength takes place up to the age of 3 months. The material was completely watertight.

An insignificant expansion in water and an insignificant shrinkage in air were observed. The structure of the ancient and new sealants were compared. S.E.M. pictures show great similarity of the new and ancient reaction products which were determined to be calcium carbonates (Fig. 2.3.6). Even the physical and mechanical properties of the ancient sealants were similar to those of the new ones (Table 2.3.1). The ancient and new sealants also show a



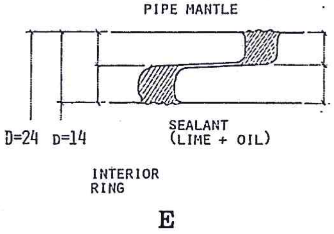


Fig. 2.3.1 — The ancient pressure conduits of clay pipes. A. Alhambra, Spain, (Roman 100 A.D.); B. Pipes of a Greek conduit. (Rhodos 400 A.D. — Dr. Dumas) with part of the packing ring; C. A pressure pipe, Kameiros — Rhodos, (Roman); D. The sealant of the Greek conduit from Rhodos, interior ring — Dr. Dumas, E. Diagram of the joint. D,d — exterior and interior diameter of the pipe.

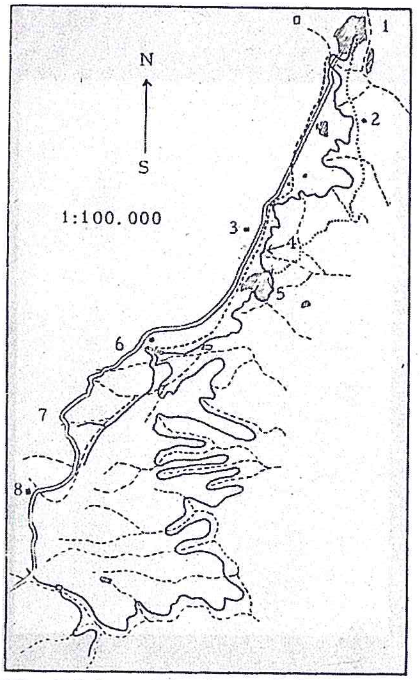


Fig. 2.3.2. — The map of the ancient water conduit system, pressure conduits of Jerusalem. 1) Jerusalem; 3) Rachels grave; 4) The pressure conduit of stone; 5) The three water reservoirs of King Solomon.

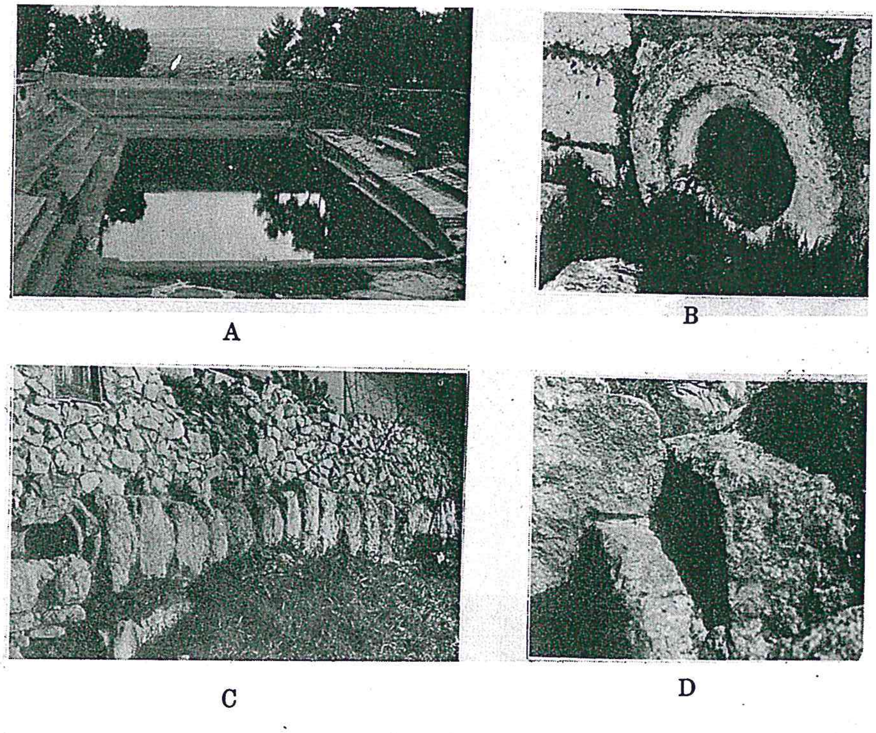


Fig. 2.3.3. — The ancient water conduit system of Jerusalem. A. King Solomon's Reservoir; B. The pressure conduit of stone; C. & D. Details of the pipe and the joint.

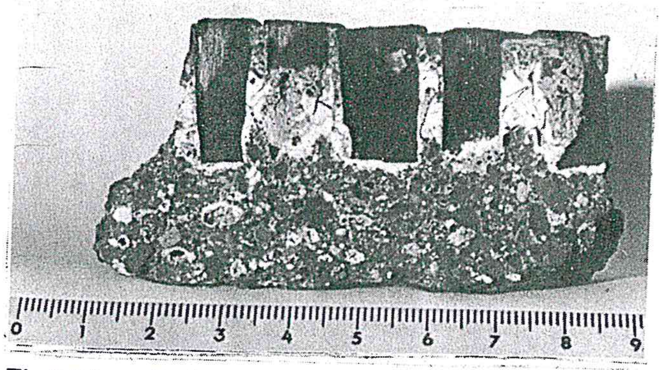


Fig 2.3.4. — Sealant of the mosaic floor Roman 100 A.D.

great structural similarity in S.E.M. tests with artificial modern stones of calcium carbonate as well as with natural lime sinter (travertine).

3 — SOME GENERAL REMARKS

3.1 — *The materials of the three characteristic types of the ancient aqueducts.*

The building materials of the lining of an underground conduit and an elevated water conduit with free flow and sealants from two pressure conduits were investigated. Field examinations were supplemented with tests in the laboratory concerning chemical composition, physical properties, and strucural investigation, i.e. S.E.M. of the building materials.

3.3 — *The influence of polishing on the properties of mortar, the multilayer mortar of Vitruvius (p. 2.2)*

It is known that the strength of modern lime mortar and plaster is rather low. However, we found columns and walls of ancient Greek temples covered with plaster of very high strength, protecting the substrata made often of a soft sand-stone. The properties achieved by polishing of the fresh plaster and especially of the multilayer plaster can be explained as follows:

- Through rubbing and polishing of mortar the components, lime and marble, were horizontally oriented and ground to fine particles. An increase of their specific surface leads to a decrease of the capillarity in the thin layers in the horizontal plane. This decrease of the capillarity in the thin layers of the mortar probably causes a very intense carbonation and accelerated hardening. Shrinkage and cracking are limited and durability increases. The multilayer mortar seems to be an ancestor to the modern lamellar and sandwich structures.
- The addition of crushed marble and marble powder considerably increase the final strength of the mortar (in the later age). Terazzo workers have known this fact for a long time. It depends probably upon a better bond between the new and old natural calcium carbonates (marble) than between the new carbonates and the inactive silica, SiO_2. It is also known that shrinkage of the products of carbonation is considerably decreased.

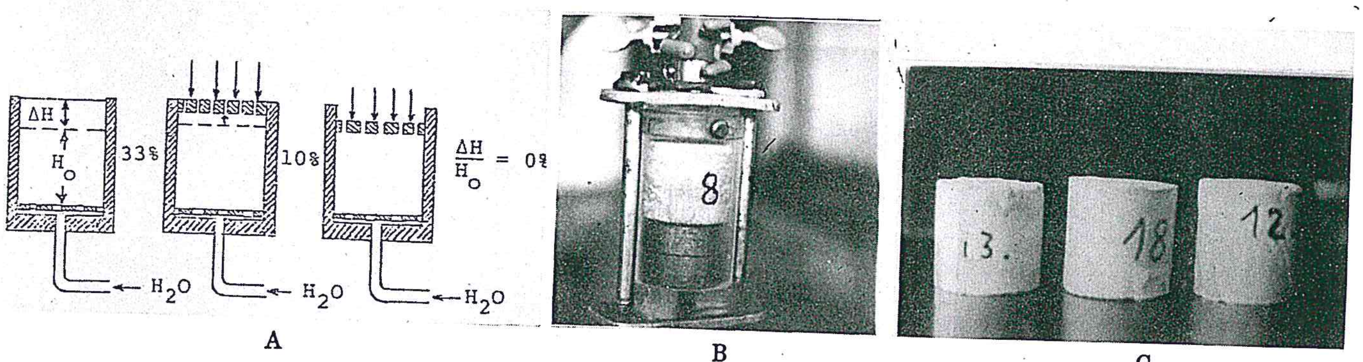


Fig. 2.3.5. — Experiments of imitation with an expanding lime-oil mass. A. Diagram of the apparatus; B. Apparatus for expansion experiments; C. Specimens after free and limited expansion, tightening.

3.2 — *The riddles of the unusual ancient engineering techniques*

In spite of purely empirical knowledge, the ancient building engineers solved, with simple building materials, complicated technical problems and achieved admirable durability of their aqueducts. Some explanation of these techniques is to be found in Vitruvius for example, details describing:

- the mechanism of lime burning, slaking and hardening in air and the changes in energy in the structure (book II, chap. V)
- the unusual properties of the pozzolana as a hydraulic binder (book II, chap. VI) and burnt brick, powder or aggregate.

But many other phenomena and procedures are left without any explanation, namely:

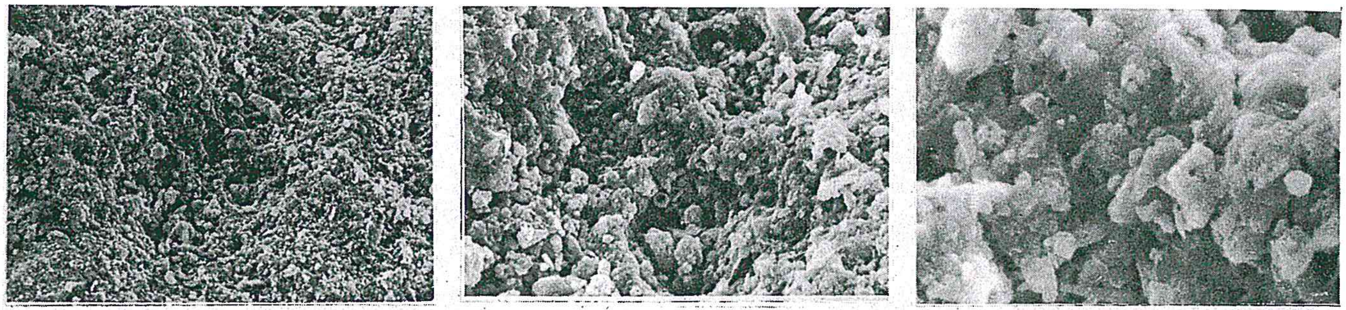
- the mechanism of polishing
- the multilayer mortar
- the high strength of the carbonate mortar
- the tightening mechanism of the lime-oil mortar
- the construction principle of the durable and crackless stone arch aqueducts built without expansion joints.

- With the addition of chemically active brick powder or pozzolan a combined hydraulic and carbonation binding occurs, which increases the strength, volume stability, and the chemical durability.
- The beneficial influence of polishing on strength, shrinkage, and durability and the improved properties of thin and multilayer structures have been well-known for a long time in many fields of material technology.
- The surface treatment by polishing is also used in concrete flooring techniques, improving strength, abrasion resistance, and durability, for example in the vacuum concrete procedure.

3.4 — *The unusual expanding sealant of pressure aqueducts — The mechanism of tightening.*

The tightening mechanism of this lime-oil mixture was not explained by Vitruvius but without doubt known to him. He refers to the pressure aqueducts as an old Greek method well-known to his contemporaries (book VIII, chap. VI.) The clay-pipe pressure aqueduct is the Minoan one in Knossos, Crete, discovered and described by Evans' dated to 1400 B.C. It used an "expanding rim" sealant.

Rhodos



Experiments of imitation

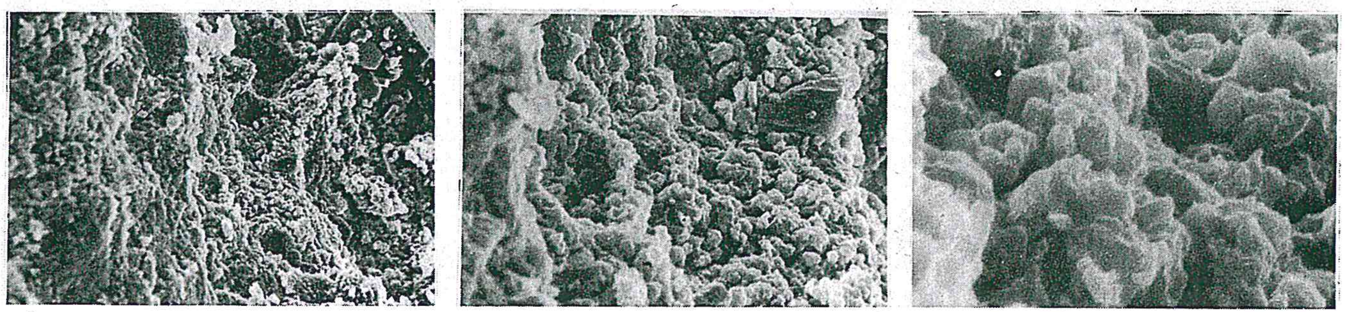


Fig. 2.3.6. — S.E.M.-picture of the ancient sealant, from Rhodos, and the new sealant, experiments of imitation.

An understanding of the tightening mechanism of the ingenious sealing procedure was investigated by means of an analysis of the terminology used by Vitruvius and his translators. The lime-oil mix is described by Vitruvius in two cases: as sealant for pressure aqueducts (book VIII, chap. VI, 4) and as mass of lime and oil for tightening of a weather and frost resistant floor (book VII, chap. VI, 6). In the first case, the Latin expression "Calx viva" was translated by I. Prestel[6a] into German as freshly slaked lime, whereas the same expression was designated by M. H. Morgan[6b] into English and Kumaniecki[6c] into Polish as "quicklime." In the second case in Latin and in all subsequent translations, the type of lime was not specified. No information on a filler — probably marble was used in the mix — is given in either of the two cases.

The question of a lime type giving proper sealing was answered by means of tests. The data are presented in Table 2.3.3. Only ground quicklime was able to secure a tightening of the mass in the joint and later on developed a proper hardening. Neither hydrated lime powder $CA(OH)_2$ nor waterlime resulted in the needed restrained expansion. Additionally both types of lime when mixed with oil in contact with water are rather "soupy" and shrink at a later time. An attempt to explain the process when using quicklime follows.

The tightening mechanism. In a mixture of a tight mass of CaO, and oil in a dry atmosphere the structural changes are slow. After the intrusion of water into the mass under pressure, the oil is partly displaced and simultaneously there occurs an expansion owing to the change of CaO to $Ca(OH)_2$. The volume of the hydrated lime is about 40 percent higher than that of the CaO. In the size joints the expansion limited only at the free surface in the inner part of the pipe (Fig. 2.3.1E) can an expansion occur. Even this one is partly limited through the radii shape of the packing ring.

The hardening mechanism seems to be similar to that described for the polished lime mortar in section 3.3. The carbonation, i.e. hardening of $Ca(OH)_2$ in water is probably slow. It is caused by major quantities of air, acid, and even CO_2 and salt in the water. Perhaps the presence of oil and the marble powder is also important for the carbonation. In the atmosphere of air the process is similar to that of lime-marble plaster. The calcium hydroxide absorbs the carbon dioxide from the air forming calcium carbonate. The density of the plaster and thin sections accelerate the carbonation and hardening processes. Thus, the exterior shrinkage apparently is of lesser importance. Only small cracks due to drying shrinkage were observed only on the interior of both the ancient and the simulated sealants.

3.5 — The crackless concrete canals of the Roman arched aqueducts without dilatation joints

One question has not been entirely answered. How could the Romans build mile-long arch structures from stone and brick with concrete canals without using expansion joints and avoid cracks, even though in situations where thermal deformations and those caused by changes in moisture were of considerable magnitude? Here is an attempt to explain this phenomena:

- In arch construction the material acts under approximately centric pressure.
- This pressure leads to increased deformation due to shrinkage and creep in the mortar and in the stone material of the arch thus decreasing the rise of the arch (Fig. 3.5).
- Through this the pressure increases in the upper part of the arch and subsequently in the canal carried out from concrete or from stone with a mortar lining.

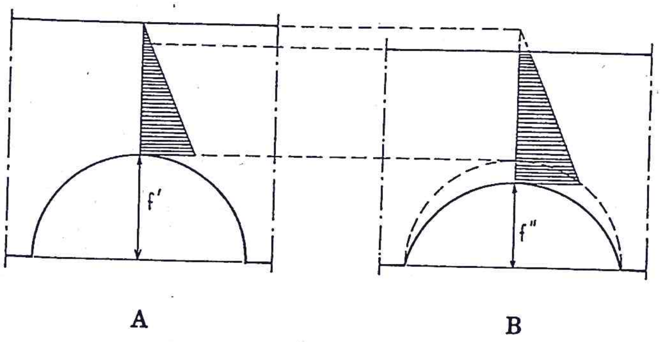


Fig. 3.5. — Scheme of the bending in the arch and the increased pressure in the arch and in the canal due to the time dependent deformations (creep), A) At early age; B) After long time loading.

- A similar transition of the pressure is known in composite prestressed construction with normal concrete placed above pretensioned members.
- If the arch construction and the canal are carried out under conditions with regard to the season and with proper materials the pressure can increase still more.
- The application of good compacted concrete and low shrinking, multilayer well-polished plaster, combined with the above mentioned structural measures seems to be the main reason for the construction being free from cracks despite not having any expansion joints. It also accounts for its superior durability.

3.6 — *Conclusions*

The Roman lime concrete, multilayered plaster, polishing techniques for the protection of the materials, and the ancient expanding sealants are impressive examples of successful solutions to the complex problems of water supply. Studies of these techniques reveal that the ancient engineers had a good understanding of the environmental factors involved in transporting large quantities of water over great distances.

The lack of modern scientific methods and detailed specialization were compensated by an experience based on tradition and knowledge of a more general character. In our own times invention and engineering solutions often proceed a proper scientific explanation. The ancient engineering practices were used for centuries without a clear understanding of the scientific basis of the techniques used. Nevertheless, they were eminently successful. Many of these techniques are of interest and importance to modern concrete technologists.

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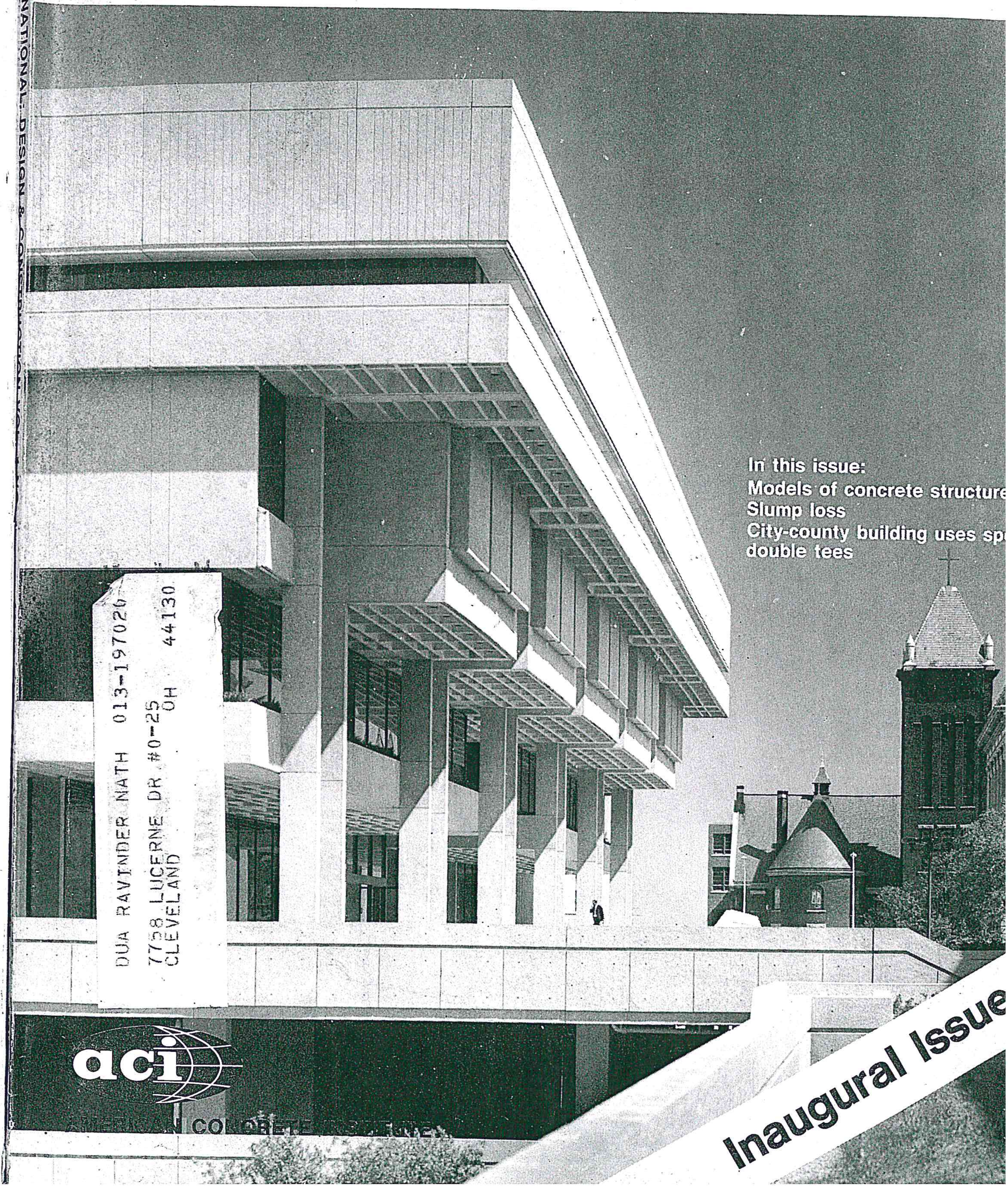

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