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Thomas Nelson Winter
University of Nebraska-Lincoln, twinter1@unl.edu

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ROMAN CONCRETE:

THE ASCENT, SUMMIT, AND DECLINE OF AN ART

THOMAS N. WINTER
Classics Department
University of Nebraska–Lincoln

The evidence of the surviving literature and structure provides this chronology for the development of concrete: Fronto dates for us, by naming consuls, two aqueducts utterly devoid of concrete at 312 and 272 B.C. From Cato, who died in 149 B.C., we can discern that (a) concrete has now become the normal foundation for building, (b) limeburning is now an established trade, and (c) his recipe for cement is primitive—even medieval—and non-hydraulic. The year 140 saw the opening of the Marcian Aqueduct, its water-channel lined in non-hydraulic cement. Vitruvius, ca. 25 B.C., describes different cement formulations for different purposes, even giving, knowingly, a recipe for hydraulic cement. The years 38–52, nonetheless, included the building of two aqueducts in the non-hydraulic variety. The harbor at Ostia, built with hydraulic concrete, is finished by 62 A.D. In this same period a surviving concrete dome is cast over a wooden form to make a room of a palace. The Pantheon, a 144-foot diameter cast-in-place concrete dome, marks the acme of the Roman Art in the reign of Hadrian, 117–138 A.D. The high-quality Roman cement persists until 300 A.D., after which time the mix reverts to the original type of Cato. Finally, the cement of Joseph Aspdin's 1824 patent seems somewhat familiar.

† † †

Cement could have been discovered any time after the kiln. Hodges (1970) dates the first kilns at 4000 **B.C.** in Mesopotamia. Yet it is surprising how very recent cement is—more recent than is widely known. Double and Hellawell (1977) state that the origins of cement "may be traced back to early Egyptian and Greek times." Actually, the origins of this statement can be traced back to Wallace (1865), who did the first chemical analysis of some ancient cements. All were mortars, but the Egyptian mortar samples were plaster, averaging 82 percent gypsum ("sulphate of lime, hydrated"). Subsequent analyses have shown that cement never replaced plaster in Egypt until the Romans took it over (Lea, 1970).

What of the ancient Greek cement? An ancient Greek origin for cement seems to me to stem from a confusion of geography with chronology. Of Wallace's Cypriot or mainland Greek samples, only one has a source which is not indeterminate. This is from the Pnyx, "the platform from which Demosthenes and Pericles delivered many of their orations" (Wallace, 1865). The Pnyx with cement mortar would put cement as far back as the sixth century B.C. in Greece. But the Pnyx is not "the Pnyx"; the Roman Emperor Hadrian rebuilt it around 123 A.D. (Kourouniotes and Thompson, 1932).

Another principal route through which the Greek origin of cement may be traced is Blake (1959, but grounded upon pre-1925 notes of Van Deman, as Blake acknowledges in the preface). Saying that Greece "doubtless" passed on the knowledge of lime cement to Italy, Blake adds, "she seems to have achieved a certain mixture with hydraulic properties for water conduits" (1959). This, as will be seen in text that follows, is an anachronism. Further, the evidence for classical Greek concrete was already shrinking: Blake's note ad loc. remarks, "It has seemed best to pass over the shipsheds of Piraeus [the port of Athens, and thought, in 1874, to be ancient Greek concrete] because of insufficient evidence for dating it precisely."

The standard mode of classical Greek construction was sun-dried brick on a foundation of stone: when the roof fails from stoppage of maintenance, the walls wash away, leaving the archaeologist to find dressed stone foundations surrounded by a layer of reddish clay-earth. Stone walls, laid dry, the Greeks retained with iron H clamps. Halieis, illustrated and discussed by Jameson (1974), nicely encapsulates the Greek experience in construction, for it flourished from about 470 B.C. and was abandoned sometime after 323. It is now about half underwater, and there is no later repair by later inhabitants to muddy things up. And the construction is sun-dried brick on a foundation of stone. No cement, no concrete.

It appears that the idea of a classical Greek origin for concrete, persistent though it be, stems from the last century's naively ignoring the repair and even complete rebuilding implicit in continuous habitation and use.

What is the chronology of cement? It occurred to me that the best way to run it down was to consider the structure of items which by their nature should have been in hydraulic cement, and which are indisputably datable. I therefore specialize in aqueducts, for we have a surviving book written by a Roman water commissioner who describes and dates each aqueduct of ancient Rome, Frontinus (97 A.D.). Cato, who died in 149 B.C., and Vitruvius, whose work is usually dated ca. 25 B.C., also add useful evidence. The resulting chronology, based on this mix of the literary and of the more concrete evidence, shows that the Roman art must begin somewhere in the 200's, grows slowly until the age of Augustus, flourishes for about two centuries, reaching an acme in the reign of Hadrian (117–138), and then falls back to the primitive level, where it remains for something over one and a half thousand years.

The *Aqua Appia,* "Appian Water," "was brought into the city by Appius Claudius Crassus the Censor in the thirtieth year after the Samnite War, with Marcus Valerius Maximus, Publius Decius Mus Consuls" (Frontinus, 97; translation mine). We have a complete list of the consuls; the date is 312. This, the oldest of the Roman aqueducts, was principally an underground channel. The channel is either cut of the living rock or walled in friable *capellaccio* rock laid without mortar (Van Deman, 1934). The next, completed in 272, was, like the earlier one, almost entirely underground, only 221 of its 43,000 paces being above ground (Frontinus, 97). This aqueduct, drawing its water directly from the Anio River, is named the Anio Vetus, "Old Anio." For much of its way, this was a tunnel cut in the rock cliff of the Anio valley (Parker, 1876). Where Anio Vetus went through soil, not rock, the channel had a rock floor, dressed stone walls which were wedge-shaped where the stone tails into the surrounding earth, and two long blocks leaning into each other, fitted to form a gable roof. The courses are laid dry—there are no signs of a lime mortar (Van Deman, 1934).

There is no additional aqueduct added to the Roman water supply for 128 years, but Kourouniotes and Thompson (1932) have published a small Greek one just outside of Athens that fits into the interval. It will be of interest to consider it. The channel rests on a low stonework substructure and is simply a trough cut in a line of dressed *poros* limestone blocks. The trough is 0.20 m wide and 0.15 m deep. "The joints," the excavators observe, "were secured by iron clamps, H shaped, ca. 0.18 m in length, heavily bedded in lead, and were rendered watertight by plaster at the bottom and side of the channel at these points" (1932). Kourouniotes and Thompson (1932) place this in the "Third Period" of the site, which they date from ca. 220 B.C. to early Roman.

The one simplest way to account for the absence of cement mortar or formed concrete in these structures of 312, 272, and ca. perhaps 200 B.C. is that cement doesn't exist yet.

The pen is mightier than the trowel, for our next source, and the first which is positive rather than negative, is literary. The *De Agri Cultura,* "On the tending of the Field," cannot be precisely dated, but Cato, the author, lived from 234 to 149 B.C.

It is clear in this work that concrete has become a normal part of any new farm construction: "If you contract for a villa to be built new from the ground, have the builder do as follows: all walls, as ordered, from lime and rubble [*calce et caementis*] . . . the owner will provide: saw, 1; plumbline, 1; materials—so far as he falls short, he'll be sorry; the builder will cut and make do—stone, lime, sand, water, straw, earth from which to make mud" (Cato; translation mine). There shortly follows—with an interesting tacit assumption—the first surviving written recipe, so to speak, for cement; "As for the material from lime, rubble, sand [materials ex calce caementis silice—we notice he does not have a name for it yet] . . . the builder should make foot-and-a-half wall foundations and the owner should provide per foot length one *modius* of lime to two *modii* of sand" (Cato). The underlying assumption here is that the foundation of any new construction at the time of writing was going to be in concrete, "material from lime, rubble, sand" in Cato's phrase. Further, we see that the cement binder is simply two-to-one sand to lime. We also learn from Cato that being a lime-burner (*calcarius*) was a settled means of livelihood. But Cato, as economical of cash as of words, would have the owner provide the calcarius with both the limestone for his furnace and the wood with which to fire it.

The next aqueduct shows the level of attainment in cement construction nine years after the death of Cato, for the *Aqua Marcia* was brought into the city in 140. Its water channel shows an interesting structural experiment: cement is used, not exactly as a mortar, but as a poured-in-place substitute for the iron clamp, leaded into place, which held together the old Greek dressed stones. The stones of the channel had a hemi-cylindrical cut-out at each end. At these cut-outs formed a hollow cylinder mold 5–6 cm in diameter. Cement was poured into the molds to keep the structure in line (Blake, 1959).

There were other variations in the making of the underground channel walls, apparently just over the five-year span of its construction time. Some of the channel cut through native rock was not walled at all. Instead, the rock-cut sides were lined in a simple cement of lime and clean sand. Elsewhere such rockwalls are lined in rough-dressed stones "with poor earth mortar showing but few traces of lime." (Why it still there? I do not know.) Elsewhere there is a sort of concrete: walls of large, unshaped rock in a mortar or matrix of the Catonic lime and sand cement (Van Deman, 1934).

The *Marcia* takes its name from the man the Roman Senate contracted the work to in 144 B.C., Quintus Marcius Rex. Frontinus (97) tells us he was engaged at the same time to repair the *Anio Vetus.* Some few remains of the Marcian repairs survive, are recognizable as his work, and so are as-

signed (Van Deman, 1934). This leads to the principal advantage of attempting to develop a chronology for cement and concrete from the aqueducts supplying Rome: an inherent problem is gotten around. The problem is expressed sagely and succinctly by Burns (1974), writing of the waterworks of Acragas and Syracuse, in Sicily: "Since many of the installations described here were repaired, enlarged, and rebuilt repeatedly, it is generally difficult, if not impossible, to determine the exact age of many of their features." But for the waterworks of Rome, we have Frontinus, who tells when they were rebuilt as well as recording the time of the original construction. There are at least two further sources of assistance: during a long period of neglect, a distinct new style of setting rock into mortar comes into general use. This is called *opus reticulatum,* "reticulate masonry." "There are two kinds wall (*structura*), reticulate, which everyone uses now, and random (*incertum*)," records Vitruvius (25 B.C.). Rodolfo Lanciani (1897) places the introduction of *reticulatum* in the Sullan period, ca. 80 B.C. But best of all, the Augustan repairs were labeled as such every 240 feet. Eleven such labels, for example, survive from the channel of the *Marcia.* They are numbered and bear the inscription MAR IMP CAESAR DIVI F AUGUSTUS EX S C = *Marcia Imperator Caesar Divi Filius Augustus ex Senatus Consulto* = Marcia. Emperor Caesar, son of the deified [Julius Caesar], Augustus, after a decree of the Senate (Ashby, 1931). Aided by the labels and, of course, the structure of the other Augustan monuments, one can recognize and assign cement from this period. And the three oldest aqueducts apparently went unrepaired from 149 to 33 B.C.: "In the same year [33 B.C.], Agrippa [Augustus's principal lieutenant, and Rome's first water commissioner] restored the nearly ruined ducts of the *Appia,* the *Anio,* and the *Marcia*" (Frontinus, 97). The problem illustrated above by the Pnyx of the ancient Greeks and the Pnyx of the emperor Hadrian is obviated.

No remains have been found of the original *Aqua Tepula,* which was brought into Rome next after the *Marcia,* in 127. There is, however, an interesting structure from its period: "The Temple of Concord erected by Opimius in 121 B.C. still furnishes the earliest concrete of which the date is sure" (Blake, 1959). And this recorded by the same author who, as noted above, assumes the Greeks of classical times had cement and "doubtless" passed it on to the Romans. It is not consistent. Opimius's temple of 121 B.C. has a cement matrix described by Blake as "exceedingly friable." I expect this means is it is still basically Cato's simple recipe.

For the next developments, we must return to the literature. Why, we might ask, should the cement set in the first place, solidifying into an artificial stone? Cato, always matter-of-fact, never thought to ask. Romans were asking in the first century B.C. and produced a theoretical answer which we will compare to the modern one:

> Stones, like all bodies, are compounded of elements [earth, air, fire, and water being the "elements" of the period]. What has more of air is soft; of water, smooth; of earth, hard; of fire, fragile. Therefore, stones of these elements, uncooked, if they are crushed and thrown into the work, do not set and hold it together. But once thrown into the furnace, seized by the power of the flame, they lose their former strength of solidness. They are left with forces spent, with their pores gaping and empty.
>
> So when the air and moisture which are in the body of the stone have been burned out and removed, the stone has residual latent heat in it. It seethes before it recovers the force of the fire from the water which, on immersion, penetrates into the gaps of its openings, and on cooling gives back the heat from the body of the stone. Even though the size stays the same, the stones, when they are weighed out, cannot respond to the weight they had when they were thrown into the furnace, but are found diminished by about a third part. Thus with their pores and gapings overt they grip the mingling of sand and so cohere, and commingle with the aggregate *[caementis]* in the drying out process and make up a solid structure (Vitruvius, ca. 25 B.C.).

This is, one sees, one of the nicest bits of experiential *practical* chemistry. Vitruvius is aware that the setting of cement could not occur at all on the purely mechanical level. He is aware that the kiln produces a change which goes beyond mechanics and is exactly right when he says that water is driven out of composition with the stone. This direct hit, so to speak, is partly for the wrong reason; obviously, the other three "elements"—earth, air, and fire—could be eliminated, but Vitruvius's insight comes mostly for the observation that water was required for recomposition.

It appears, though, that he has missed his guess about any bonding, ultra-mechanical in nature, between the sand and the cement. We must now commit the anachronism of considering that embarrassingly recent phenomenon, chemistry. With Cato's recipe, which Vitruvius was attempting to explain, the limestone is now known as calcium carbonate and varying hydrates thereof: $Ca(CO_3)$ x H_2O, where "x" is one to four. When kilned, this substance loses water and carbon dioxide. The two-thirds that remain are CaO, calcium oxide. This compound, synonymously named burnt lime, caustic lime, quicklime, and in Latin, *calx,* slakes violently in water—as Vitruvius knew—and produces slaked lime, $Ca(OH)_2$, or calcium hydroxide. Now add two parts of sand to this and you have Cato's mix. But the sand stays out of the chemistry. The calcium hydroxide, a colloid in the mixing trough, is slowly converted to calcium carbonate and its hydrates by the gradual absorption of CO_2 and water vapor from the atmosphere (Blount, 1911; Lea, 1970; Double and Hellawell, 1977), i.e., the mix "cures." It is a beautiful circle, and the ancients could have waxed poetic about it if they had only known: you tear the stone apart, put it in any shape you like, and let the *residuus calor latens,* "chemical potency," or some other magic words put it back together again. But the silica in the sand is mere filler.

Suppose, though, that the silica is not crystalline, but

amorphous, i.e., has been heated into a slag. Slag, crushed and powdered, contains potential for chemical bonding (Lea, 1970). Slag is found in nature as the result of vulcanism. Tufa, santorin earth, trass, and possolan—named after the ancient city Puteoli—are names for the more important naturally occurring slags. Pozzolan, for instance, contains 27.8 to 32.6 percent soluble (chemically potent) silica (Blount, 1911). The vulcanism which produced it is replaced by the iron blast furnace in modern production, slag from which is quenched for fast cooling; when cooled slowly, it doesn't work (Lea, 1970).

When the volcanically produced slag was used in granulated form, it was ground together with slaked lime about three to one. This makes a "Roman cement." It is not a Portland, but it is hydraulic, with a significant portion of silicate of lime (Blount, 1911). By Vitruvius's time (ca. 25 B.C.), furnace ashes or burnt clay were recognized as useful ingredients. Interestingly enough, clay is the vital ingredient in Portland cement, containing the aluminosilicates that make it work (Double and Hellawell, 1977).

But the Romans of the Augustan Age didn't exactly know what they had with their kilned clay cement, except that it was better. Here is a recipe from Vitruvius (ca. 25 B.C.) with his comment:

> When slaked, the cement [*materia*] should be mixed viz: if it is pit sand, three parts sand to one of lime should be poured in. Sea or river sand, match two of sand to one of lime. . . . Then again with river or sea sand, if you put in a third part of *broken and sifted potsherds,* you get a blend better for use."

We may make a number of observations from this useful passage. First, the Romans still have no special name for cement: it is still *materia, no* more specific that our "stuff," or the German *Staff,* as in *Wasserstoff,* hydrogen—our author is simply shortening Cato's second century phrase *materia ex calce caementis silice.* There is here no observation that it had structural strength or that it would last forever. So far as being concerned about what it is good for, he only has it as a sealant for the wood superstructure of Roman baths. This is to say, Vitruvius apparently is aware that it is essentially waterproof. Where he speaks of the pozzolanic cement, he makes clear he knows that it is hydraulic, recommending its use in breakwaters. What he didn't know of the pozzolanic cement was just how good it was—that it would last forever, or at least be around in a harbor wall long after the sea had worn away rock, leaving a honeycomb in mortar. Such evidence, of course, takes time to come by. Legal practice of his day, for instance, had not caught up with it:

> When they assay the value of common walls, they don't evaluate them as when they were made, but they find the contract from the records and deduct an eightieth for each year past, pronouncing the judgement that they cannot endure more than eighty years (Vitruvius, ca. 25 B.C.)

Vitruvius is enthusiastic when he introduces the pozzolanic cement, and his departure from the matter-of-fact leads me to suspect we have here some of the thrill of novelty. His contemporary, Horace, a poet, records some indignation at what they were doing with it:

> *Contracts, pisces aequora sentiunt iactis*
> *in altum molibus.*
>
> And the fish feel the seas contracted,
> with breakwaters dumped in the deep.
>
> (*Odes* 3.1.33)

It appears safe to assume, then, that the pozzolanic concrete is purely a development of the first century B.C. The proto-Portland cement, with crushed and sifted kilned clay, must come into use somewhere between Cato and Vitruvius. It can only be said that Cato didn't have it yet, for his closest approach is the instruction to strew potsherds over lime for the floor of a wine-press. This, of course, would improve the lime cement only at the interface of sherd and mortar, leaving the cement interstices unaffected; it is apparently simply a cheap grouted tile floor, though Vitruvius's later proto-Portland must be a development from it.

A Roman construction holiday, or rather, hey day, occurs under the reign of Augustus, 27 B.C. to 14 A.D.. His political success and foundation of empire ended nearly a century of intermittent civil anarchy and civil war, and a great number of things got done, permitting us to switch back from the literary to the substantial evidence.

The next aqueducts to be built, stemming from the years 33 B.C. and 52 A.D. (in the latter year two were dedicated) show a spotty and uneven advance. They were not built in the best concrete that the age knew how to produce. Progress was even retrograde. The last two, produced by the contractors of the Emperor Claudius, used plenty of cement both for mortar and lining, but it was bad stuff: "Both the sidewalls and the found roof are of the typical coarse concrete of the Claudian period, with large aggregate of local limestone laid at random in the mass with poor, friable mortar" (Van Deman, 1934). These were obviously contracts undertaken not with a view to eternity, but for future work.

We might ask why the better grades were not used. I believe Vitruvius (ca. 25 B.C.) provides the answer in his paragraphs on breakwaters: "The concrete which is going to be underwater, see to it you make it this way, that powder, which is in the region from Cumae extending to Sorrento, be imported and mixed two to one [with lime] in the mixing trough," even though pozzolanic tufa underlies all of Rome

(Porter, 1907). I think we can see from this two very clear conclusions: for a Roman of the first century knowingly to produce the good stuff, he thought he had to bring up raw material from around the Bay of Naples. Second, the Romans apparently never came up with the idea of testing batches of mix, but simply went by construction experience. The Emperor Claudius also had a harbor built in Ostia to replace Rome's more distant seaport at Puteoli. It is in some of the best concrete ever mixed, and Pliny (77) confirms that the harbor was built with the Neapolitan powder.

The next advances in the art are not in making better cement but are advances in learning some of the things which could be accomplished with this marvelous and Protean material. After Claudius came, Nero took advantage of all the cleared land to build a huge palace, after that famous fire of 64 A.D. It was never finished, but a very conspicuous portion of it that still stands shows that the Roman engineers by 64 had begun to realize something of what concrete was capable of. One room has octagonal sides blending into a poured-in-place concrete dome (Boethius, 1960). A wooden dome form was made first, and its boards are still visible by their imprint in the dome's interior.

As the Romans went by construction experience, this modest dome served, in effect, as a practice-piece for the high point of the Roman art of mixing and pouring cement, a fantastic building which is concrete from top to bottom—and from bottom to top it still stands. It is the Pantheon. This was thought to be a product of the Augustan age until Louis Chedanne, during some repair of interior cracks in 1892, obtained permission to examine the interior construction. He found brick-stamps. Augustan bricks were not stamped. Chedanne, to determine whether he had simply found a local later repair or if the established date of the building was about 150 years off, took bored samplings from the bonding courses—which are spaced every 1.2 m up the wall—from the foundation, the dome, from the arches and vaults. Each one of the fifty samplings yielded a dated brick-stamp. These were from 115 to 125 A.D. The fruits of Chedanne's efforts were published in Lanciani (1897). Chedanne himself, regrettably, never published anything on the building.

The Pantheon, from foundation to domed roof, is the work of the Emperor Hadrian, whose modesty is at the bottom of much of the confusion in the chronology of concrete. "He built buildings and gave gladiatorial shows in practically every city of the empire" (Spartianus, ca. 306 A.D.). Spartianus adds:

Though he made infinite public works everywhere, he never wrote his own name, except on the temple of his father Trajan. In Rome, he re-did the Pantheon, the Voting Pens, the Basilica of Neptune, many sacred buildings, the forum of Augustus, the Baths of Agrippa, *and labeled every single one of them with the name of the original builder.*

The result is, in effect, an historical practical joke: the inscription over the entrance to the Pantheon proclaims that Agrippa built it, and Burford, who will forgive my mentioning it, still writes of it that way (1972). Agrippa's Pantheon from 25 B.C. was found by the Department of Antiquities. Spurred by Chedanne's startling discovery, they found remnants of a rectangular foundation with the dimensions 43.75 x 19.82 m beneath the present rotunda (Von Gerkan, 1929). Hadrian must have leveled what remained in his time of the Agrippan work. He then built an entirely different building.

What sort of building is the Pantheon? Its foundation is a poured concrete ring, 4.5 m high, 7.3 m wide. From this ring foundation on up, the composition of the aggregate changes. The foundation aggregate is chunks of travertine. From this to the first cornice, a height of 12.3 m, the wall is a concrete mix with alternating scraps of tufa and travertine, brick-faced inside and out. From first to second cornice, a height of 9.5 m, the wall aggregate mingles tufa with broken brick. From this height, 21.8 m above the floor, the dome was cast on a wooden hemispherical form. The first 11.75 m of the dome's height has broken brick aggregate. For the next 2.25 m, the dome is in alternating layers of tufa and brick. From this point to the brick compression ring of the dome's skylight, the aggregate is tufa and pumice (Terenzio, 1932).

The constantly changing composition, with the resultant change in density, makes it very clear that the entire construction was carefully, even ingeniously thought through. Terenzio (1932) shows that the weight of structure decreases as you approach the top:

foundation	2,200 kg/cm
bricks, travertine, and tufa . . .	1,750
bricks	1,600
tufa and pumice	1,350

This building has about it a multitude of fascinating data. The dome, under its lead sheath, was sealed with lime and potsherd powder cement, the proto-Portland of the Romans, which they called *opus signinum* (Terenzio, 1932). This tends to show that the Romans were satisfied having found one good use for it and never learned to trust it for structure. To them, it was good for such requirements as cistern linings (Davey, 1961). The 144-foot diameter dome has an open, 27-foot diameter skylight. What do they do when it rains? Whatever the Romans did, today's Italians mop the floor.

No other building from Greek or Roman antiquity is so completely preserved. This is a tribute not only to its structural integrity, but also to its unique and powerful design, which has, through the ages, invited upkeep. Basically, the Pantheon is all there, and we ought not leave it without going beyond its banausic mundanities, the mixes, the aggregates, the mops. You can walk into it and, for the moment, be a second-century Roman. The architect Heimsath (1960)

describes something of the effect one receives when seeing the Pantheon:

> Entering the Pantheon is an experience. One feels insignificant between the great columns of the portico; moving into the rotunda one is struck down. The puny spectator is overpowered by the awesome space. It seems indeed to be the home of pagan gods.... In 608 A.D. the Pantheon was dedicated as a Christian church, but to little avail, for the space will not change and the space is pagan . . . the scale of the elements below the dome is monumental; the coffered hemisphere spans awesomely above; the "eye" at the center is a focal point 142 feet above the spectator. It stands as a great brooding mass, a monument that speaks eloquently of the Roman mind.

One of the last great monuments built in Roman cement was the *Aqua Alexandrina.* This comes one hundred years after the Pantheon and was constructed by Alexander Severus to supply water for the new baths which he completed for the people of Rome around 226. The structure is brick-faced concrete, the binder of which is an excellent pozzolanic cement (Van Deman, 1934). The good Roman cement, then, was still around in the third century A.D. What happened to it? Diocletian, around 300, built massive encasements to keep the stones of the *Aqua Marcia* from falling down and supplied his baths from it, grandly renaming it the *Aqua Jovia* as a part of his Jovian reign (Ashby, 1931). The surviving work of the *Aqua Jovia* shows that the good hydraulic Roman cement persists still to 300 (Van Deman, 1934; Ashby, 1931).

The later repairs show a reversion to an aboriginal level, with mortar that is friable, and not even clean (Van Deman, 1934).

Cement was used from the decline of the Empire and through the Middle Ages, but none of it was any good until comparatively recent times (Davey, 1961). Though I have no desire to continue the history of cement up to present times, it will be of interest, for the sake of comparing materials and procedures, to jump ahead to Joseph Aspdin's patent for Portland cement, now in general use. The patent stems from 1824, and the portion of it describing his method is readily available in Davey (1961). First, he calcines limestone. "I then take a specific quantity of argillaceous earth. . . ." That's clay. He mixes it in water to a slip, evaporates it in a slip pan, kilns it, and then powders it. I observe that he does everything to the clay that the potter does, neglecting only to shape the clay into vessels before putting it in the furnace. It is, essentially then, Vitruvius's cement, noted above, with sittings from crushed potsherds. This may fall under the category of what the United States Patent Office denominates "prior art." Aspdin's point of difference is that he kilned the clay in a mix with the already burned lime.

In this case, it was not that a Roman secret was lost, rather that the Romans, who did no testing, never learned what they had. The very idea of testing is comparatively recent, and the engineer John Smeaton, who tested samples for the construction of the Eddystone Light in the years 1756–1759 (Davey, 1961) is, I suspect, the first man on the planet deliberately to test cements of differing compositions.

REFERENCES

Ashby, T. 1931. *The aqueducts of ancient Rome.* London, Oxford University Press: 342 pages.

Blake, M. E. 1959. Ancient Roman construction in Italy from the prehistoric period to Augustus. *Publication of the Carnegie Institution of Washington:* 421 pages.

Blount, B. 1911. Cement. *Encyclopedia Brittanica.* (11th edition), 5:653–659.

Boethius, A. 1960. *The golden house of Nero.* Ann Arbor, University of Michigan Press: 195 pages.

Bums, A. 1974. Ancient Greek water supply and city planning: a study of Syracuse and Acragas. *Technology and Culture,* 15:389–412.

Burford, A. 1972. *Craftsmen in Greek and Roman Society,* Ithaca, Cornell University Press: 265 pages.

Cato, M. P. [Before 149 B.C.] *In* H. Keil (ed.)*, De agri cultura,* edition of 1895. Leipzig, B. G. Teubner: 86 pages.

Davey, N. 1961. *A history of building materials.* London, Phoenix House: 260 pages.

Double, D. D., and A. Hellawell. 1977. The solidification of cement. *Scientific American,* 231(1):82–90.

Frontinus. 97. *In* F. Bücheler (ed.), *De aquis,* edition of 1858. Leipzig, B. G. Teubner: 54 pages.

Heimsath, C. B. 1960. Curvilinear forms in architecture: the

Pantheon and the Olympic Sports Palace. *Concrete in Architecture,* 63:2–5.

Hodges, H. 1970. *Technology in the ancient world.* London, Allen Lane: 260 pages.

Jameson, M. H. 1974. The excavation of a drowned Greek temple. *Scientific American,* 231(4):110–119.

Kourouniotes, K., and H. A. Thompson. 1932. The Pnyx in Athens. *Hesperia,* 1:90–207.

Lanciani, R. 1897. *The ruins and excavations of ancient Rome.* London, Macmillan: 631 pages.

Lea, F.M. 1970. *The chemistry of cement and concrete.* Glasgow, Edward Arnold Publishers, Ltd.: 727 pages.

Parker, J. H. 1876. *The aqueducts of ancient Rome traced from their sources to their mouths.* London, John Murray: 272 pages.

Pliny [Plinius]. 77. *In* J. Ludwig and K. Mayhoff (eds.), *Historia naturalis,* edition of 1906–1909. Leipzig, B. G. Teubner, 6 volumes.

Porter, M. W. 1907. *What Rome was built with.* London, Henry Frowde: 108 pages.

Spartianus, A. *In* E. Hohl (ed.), De vita Hadriani. *Scriptores Historiae Augustae,* edition of 1927. Leipzig, B. G. Teubner, 1:1–27.

Terenzio, A. 1932. La restauration du Panthéon de Rome. *Mouseion,* 6:52–57.

Van Deman, E. B. 1934. The building of the Roman aqueducts. Publication of the Carnegie Institution of Washington: 440 pages.

Vitruvius. ca. 25 B.C. *In* V. Rose (ed.), *De architectura,* edition of 1899. Leipzig, B. G. Teubner: 371 pages.

Von Gerkan, A. 1929. Das Pantheon in Rome. *Gnomon,* 5:273–277.

Wallace, W. 1865. On ancient mortars. *Chemical News,* 11:185–186.