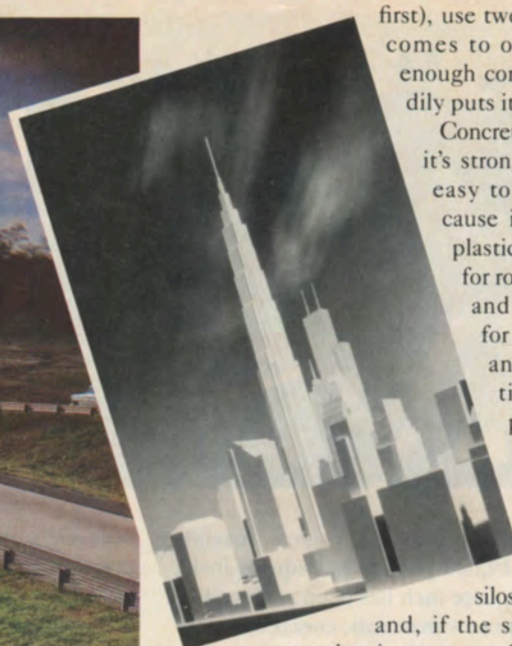
Despite its seeming indestructibility, concrete is susceptible to the elements and to a variety of peculiarly modern punishments. This, along with scarce funding for maintenance, has resulted in a literally crumbling infrastructure that will take $1 trillion to repair

STRONG BUT SENSITIVE

BY JOHN SEDGWICK

EVER SINCE THE VICTORIANS COMPLAINED, more than a century ago, about concrete's artificiality—or, to use John Ruskin's phrase, its "surface deceits"—most right-thinking people have disdained the stuff for one reason or another. But concrete has always maintained an impressive aura of indestructibility. This stems partly from its rock-hard solidity; partly from the survival of the Pantheon and the Coliseum, both built of concrete by the Romans; and partly from the promotions of concrete producers, who have long used "Concrete for Permanence" as an industry slogan. Now, however, as the nation surveys the wreckage of its infrastructure—its pitted highways, collapsing bridges, and leaky water mains—it is learning that concrete does not last forever, at least not the concrete that is currently in place in the United States.

The story of our crumbling infrastructure is in many ways the story of our crumbling concrete, for the infrastructure, along with practically everything else in the civilized world, is made up largely of the "artificial stone," as it was known in Ruskin's day. Concrete is second only to water as the world's most heavily consumed substance. Slightly more than a ton of concrete is produced every year for each human being on the planet, some six billion tons a year altogether. Americans, who rank tenth in the world in concrete consumption (the Swiss are



first), use two tons per person, which comes to one cubic yard each—enough concrete, as one analyst tidily puts it, to "bury everyone in."

Concrete is everywhere because it's strong, cheap, plentiful, and easy to make, but mostly because it's so versatile. It's like plastic. It can replace asphalt for roads and sidewalks, wood and brick for houses, steel for bridges and high-rises, and PVC (hardened plastic) for water and sewer pipes; and it does certain things that no other material can do nearly as well, such as dam waterways, line canals, shield missile silos, entomb nuclear wastes, and, if the space program ever gets around to it, construct lunar bases. Unlike plastic, concrete is virtually an all-natural product—an amalgam of sand, gravel, crushed stone, and other aggregates, held together by water and cement, which is itself a fine powder of limestone and clay. Cement, then, is the bonding agent in concrete; it is not, as is popularly thought, the same as concrete. (Thus there are no "cement sidewalks" or "cement buildings," only concrete ones.) Concrete hardens on its own not by "drying," as many people imagine, but by a chemical process called hydration, in which the cement and water combine into calcium and silicate hydrates; the hydrates act like a combination of Velcro and Super Glue. The long, bladelike petals of the hydrates, which under an electron microscope look like sea anemones, reach out to bind the concrete package with what amounts to electrostatic cling. The hydrates continue to grow, increasing the concrete's strength virtually forever.

The finished product is waterproof and soundproof (no small thing for apartment-dwellers), it neither rots nor rusts, and it can be molded into any shape. Because of the nature of the chemical bond, concrete combines high compressive strength with low tensile strength, which is to say that it is hard to crush but easy to pull apart. Builders compensate for concrete's tensile deficiency by embedding in it steel reinforcing bars, which have precisely the opposite characteristics.

Concrete is getting better. In the past ten years chemical and mineral additives have been developed to in-

A century's progress: the 1903 Ingall's Building, in Cincinnati, the first reinforced-concrete skyscraper (far left), and the proposed 125-story Miglin-Beitler Tower, in Chicago (above), to be the world's tallest; left, cruising by the new interstate, in the late fifties.

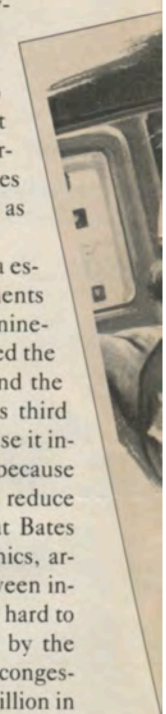
The country's romance with highways, shown by a 1959 ribbon-cutting ceremony in Eau Claire (left) and a 1955 advertisement (right); the site of the first concrete street in America (above) is about to celebrate its hundredth anniversary.

crease concrete's already formidable compressive strength from 5,000 to 19,000 pounds per square inch, and 40,000 pounds per square inch has been achieved in the laboratory. With these new materials, concrete is now making its way into new territory, such as automobile brake linings, the backing for computer chips, and even, with lightweight aggregates, indoor furniture. Reinforced concrete has finally been able to obviate steel I-beams in skyscrapers, in part because its stiffness reduces nausea-inducing sway. The world's fifth tallest building, at 311 South Wacker Drive in Chicago, is built entirely of reinforced concrete, without the conventional skeleton of I-beams, and plans call for the world's tallest building, the slender 125-story Miglin-Beitler Tower, in Chicago, to use nothing but reinforced concrete for its vertical support.

Francis Young, a professor of civil engineering at the University of Illinois, believes that such dramatic improvements show that concrete is finally coming into its own. "Concrete is where metals were in 1960, when their strength shot up five or ten fold, and where ceramics were in 1970, when they did the same thing," he says. "Concrete will go through an explosion of understanding in the 1990s. It's a material for the twenty-first century."

The Literally Crumbling Infrastructure

BUT PERHAPS NOT FOR THE TWENTIETH, IF ITS performance in the nation's public works is any indication. By weight, concrete constitutes one half to two thirds of the roads, bridges, buildings, airports, sewers, canals, dams, subways, and other essential structures that collectively make up the nation's now shaky infrastructure. The statistics of disrepair are disheartening. Sixty percent of the nation's highways need work, ranging from repaving to major structural rehabilitation. More than 40 percent of all highway bridges—some 238,000 of them—are either structurally deficient or functionally obsolete. In New York City (everyone's Exhibit A when it comes to infrastructural decay) engineers recently listed 355 hazardous conditions on four East River bridges alone. In Massachusetts, after a motorist's car on a road under the heavily traveled Route 1 was struck by a falling chunk of concrete, the Department of Public Works took to stringing nets under decayed overpasses to catch the concrete as it shears off. In one recent two-year period thirty-four cities suffered an average of 229 water-main breaks for every 1,000 miles of pipe. Leaks now cause some large cities to lose as much as 30 percent of their daily water supply.



The Associated General Contractors of America estimates that the necessary repairs and improvements to the infrastructure will cost $3.3 trillion over a nineteen-year period—a debt that has come to be called the "third deficit," after the federal budget deficit and the international trade deficit. In some respects this third deficit is more alarming than the other two, because it increases exponentially the longer it is ignored and because its very existence cripples the nation's ability to reduce any of the three. David Aschauer, a professor at Bates College who specializes in infrastructural economics, argues that there is "a strong and robust link" between infrastructure investment and productivity. It is not hard to see why this might be so: according to a study by the Highway Users Federation, Los Angeles traffic congestion alone cost businesses and commuters $500 million in lost time in 1988. In a recent twenty-year period, Aschauer notes, the United States invested a scant 0.3 percent of its national output in infrastructure, and its annual growth in productivity was a dismal 0.6 percent. In contrast, the British invested 1.8 percent and saw their productivity increase by 1.8 percent. The French spent 2.0 percent and saw a productivity return of 2.3 percent. And the Japanese put 5.1 percent into their infrastructure and became 3.0 percent more productive.

While all building materials are implicated in the general infrastructural decay, concrete is implicated most heavily, simply because it has been most heavily used. Surendra Shah, a professor of civil engineering at Northwestern University and the director of the National Science Foundation's Center for Advanced Cement-Based Materials, which has its headquarters at Northwestern, believes that more than $1 trillion of the $3.3 trillion infrastructural deficit is needed for repairing the nation's concrete.

How could so much concrete have deteriorated so badly? In appraising concrete's performance, one cannot look just at the concrete. "Durability is not a property of a material itself but a result of the material's interaction with its environment," says Geoffrey Frohnsdorff, the chief of the building-materials division of the Building and Fire Research Laboratory at the National Institute of Standards and Technology. "Concrete may survive millions of years in a benign environment, but less than a year in a very severe one." Frohnsdorff means the environment in the strict sense of physical surroundings, but the statement is no less true in the larger sense, as a host of political, industrial, economic, and even aesthetic factors have conspired to make the country's concrete environment anything but benign.

Still, concrete itself cannot entirely escape blame. Despite its monolithic appearance, it is by nature far from impervious. Practically as soon as it hardens, concrete shrinks and starts to crack as excess water evaporates. Ordinarily the best that contractors can do to control the cracking is to groove or cut the concrete at regular intervals so as to channel the cracks into an acceptable pattern. Further, concrete's interior space is riddled with tiny pores left behind after the water bonds with the cement.

On the highway the cracks are worsened by the punishing loads, chiefly in the form of monstrous eighteen-wheel trucks, that now far exceed the capacity planned for the interstate highway system during the Eisenhower years. Freeze-thaw cycles in the nation's frost belt make matters worse. Water drains down into the cracks to reach the concrete's internal pores, where, like milk freezing in a bottle, it can burst the concrete apart as it solidifies. Sulfates from the soil can also penetrate the pore structure and cause damage. And the current reliance on de-icing salts (the general solution to road ice was once to slow down) has had such a brutal effect that one might think they were designed specifically to destroy our roadways. Once the concrete has suffered the effects of a few freezes, the salts bleed down to the steel reinforcing bars, where the combination of salt and steel creates an electrochemical reaction akin to that in an electric battery, causing severe rusting at one electrical pole. As the rust expands, it pops out chunks of the surrounding concrete, further exposing the steel bars to salt corrosion. This has been devastating for bridges and parking garages across the north, where they are bathed in salt and exposed to freezing temperatures from all sides.

Underground concrete has been subjected to surprise chemical attacks as well. One of the many problems facing the country's concrete sew-

ers, for example, stems unexpectedly from federal water-pollution legislation of the early 1970s, which sensibly forbade the continued flushing of heavy metals like chrome, iron, and zinc into the sewer system. But those metals had had the beneficial side effect of poisoning certain sewage bacteria that convert waste sulfides into sulfuric acid, which is extremely corrosive. Without the metals to hold the bacteria in check, the acid has come out in force and begun dissolving the concrete sewer pipes—"just like Alka-Seltzer in water," according to Dan Glasgow, a sewer engineer with the Los Angeles County Sanitation District, where the problem was first addressed. After evaluating the damage with remote-controlled TV cameras and by dispatching sewer workers in scuba gear into the sewers during periods of "low flow," the county has "slip-lined" thousands of miles of corroded sewer pipes with acid-proof plastic pipes to protect the sewers from further assault. Glasgow estimates that 800,000 miles of sewer pipe are affected nationally, at a potential repair cost of many billions of dollars.

In evaluating the nation's concrete, one also has to take into account the way it was laid down, which often was not very well. Whereas most other building materials are fabricated under controlled conditions in a factory, wet concrete is shaped at the construction site by common laborers. Among the lowest-paid of all construction personnel, they have little if any training in concrete placement, and they are under substantial pressure to work quickly. The supervising contractors, who have not had much more formal training in concrete manufacture than their workmen, are sometimes all too willing to trade quality for speed.

Although concrete mixing is a relatively simple process, a few critical variables can make all the difference. One is temperature. On cold days the mixture requires the addition of enhancers to speed up the hardening process; on hot days it requires retardants to keep it from setting too quickly. Water is essential for hardening, but too much water can drastically sap the concrete's strength, leaving behind an abundance of the cracks and pores that expose the material to chemical penetration. Yet extra water makes the concrete more fluid and workable, and is thus a constant temptation at the work site. Also, concrete has to be carefully tamped down to make sure that it fills the forms that shape it and fully covers the steel reinforcement bars inside. Little wonder that when Robert Byrne, the author of the disaster novel *Skyscraper,* needed a likely reason for his New York City skyscraper to collapse, his engineering consultant, Charlie Thornton, advised him to choose weak concrete.

Real-life calamities have happened for a variety of reasons, some of them amazingly stupid. In Boston a concrete building collapsed during construction one winter because workmen thought that the concrete had hardened when it had actually frozen. In Chicago a floor gave way after a contractor decided to economize by using thicker reinforcing bars and fewer of them than the ones specified in the contract, not realizing that this markedly reduced the surface area, and with it the bonding power, of the steel. Francis Young, of the University of Illinois, says that notable accidents occur "every five years," generally in the spring or fall, when temperatures are fluctuating widely. Usually the collapses occur during construction and without loss of life. But other specialists believe that they are simply the most visible portion of widespread sloppiness that reduces durability.

The political environment has not helped to extend concrete's life either. As one engineer puts it, "The politicians are always there for the ribbon-cutting, but just try asking them for money for maintenance." As an example of misplaced priorities, many cite the fact that until 1976 the Federal Highway Trust Fund was allowed to spend money only for new interstate-highway construction, not for repairs. Annual increases in infrastructure

The ravages of time: in 1951, an inspector in Naperville, Illinois, noted the durability of different cements (below). Steel beams reinforce a bridge in Brooklyn (left), where repair funds have been cut.

spending dropped from 4.5 percent in the sixties to less than one percent in the eighties. Currently about $30 billion is sitting idly in various infrastructure-related trust funds for a political reason: it makes the federal deficit appear lower. Such federal policies have left maintenance to state and local governments, whose budgets are already severely strained. New York City, for instance, recently announced that it would reduce spending on bridge repair from $1.2 billion to $930 million, thus postponing work on some bridges until after 1995, even if they have to be closed down in the meantime. The Bush Administration recently proposed a $105 billion federal and state highway-building initiative that would include an increase in spending for bridge repair from $1.8 billion in 1992 to $2.8 billion in 1996. But for the moment the deterioration continues unchecked. "The infrastructure is like a house," Surendra Shah explains. "If you don't do anything to it for thirty or forty years, you have a problem."

But the concrete industry has not been an innocent bystander as America's concrete crumbles. "During the Eisenhower Administration," Shah says, "we discovered highways and television. After forty years the cost of TV has fallen and the quality improved. Can we say the same of highways? Okay, why not?" One reason has to be the general complacency of the industry, which tends to view concrete as a commodity item that is just fine as it is. In the 1970s a system of coating reinforcing steel with epoxy was developed to make it impervious to corrosive salts. Although epoxy coating has been shown to be beneficial, it has only recently been widely employed in the nation's roadways. In the past few years researchers have devised a technique called cathodic protection, in which the steel reinforcement is connected to a low-voltage DC current, to counter the destructive electrical current flowing through the bars. This technique has shown significant promise but has yet to be widely implemented. Finally, the new high-strength concretes that have been a boon to skyscraper construction offer significant promise in extending concrete's durability as well. They employ synthetic fluids called "superplasticizers" to cut down on the concrete's water content without reducing workability. They use silica fumes—minute particles that are a waste product of computer-chip manufacture—to fill in concrete's pores. Such additives have not yet been widely employed in public-works projects. "The problem with our infrastructure is not really the knowledge," Surendra Shah says. "The problem is getting the knowledge out of the laboratory and into practice."

The Glamour Problem

ANOTHER REASON THAT CONCRETE HASN'T KEPT up with television is so obvious that it is rarely mentioned: concrete's deplorable image. Modern concrete developed in the late eighteenth century as a waterproof version of the rammed earth—mud, really—that had been used for construction before that. Concrete technology had been abandoned—forgotten, most likely—since the time of the Romans. A less lovable building material is hard to imagine. It lacks all human scale, it looks dirty, and it is so rough that a chance encounter can draw blood. Concrete has not benefited from its service as the ultimate holding tank for much that is undesirable, be it criminals, hazardous-waste products, or the compacted remains of Jimmy Hoffa. It says something that nearly all the really good stories about concrete are untrue. A Chicago concrete supplier told me a wonderful tale about a concrete-truck driver who was so outraged to discover the car of his wife's lover in his driveway one afternoon that he emptied a full load in the man's car window. Unfortunately, the same story turns up in *The Vanishing Hitchhiker*, a volume on urban folktales. And no Mafia experts could confirm for me the mob's supposed fondness for "cement overshoes."

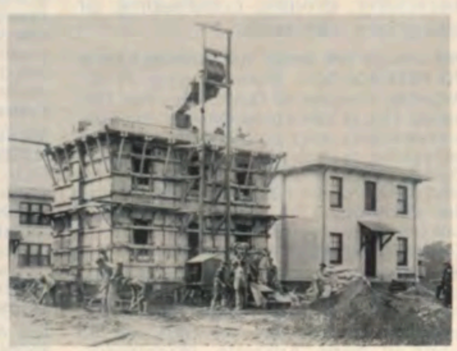
Concrete has always had its architectural partisans, most notably Le Corbusier, who took its harshness for authenticity, and Eero Saarinen, who exploited its sculptural qualities so fluidly that his TWA terminal at Kennedy Airport suggests a bird in flight. The public has not always been so enthusiastic. Concrete's last heyday came in the 1960s, with an architectural trend known as Brutalism, which made use of its possibilities for monumental forms. That movement started to peter out in 1969, when one Yale student felt so oppressed by the massive Brutalist scheme of Yale's Art and Architecture building (designed by the chairman of the school's architecture department, Paul Rudolph) that he set fire to it. Moshe Safdie, the designer of the all-concrete Habitat at Expo '67, now admits that "people like concrete only when it doesn't look like concrete." I. M. Pei is probably the foremost architect using concrete today. His concrete work in the East Building of the National Gallery and in the Louvre looks like limestone. To get such a smooth finish, he uses forms built by cabinetmakers of hardwoods instead of the more conventional plywood forms built by workmen. Since concrete bears the imprint of the forms that shaped it, it often resembles petrified plywood, right down to the rough grains and football-shaped knothole plugs.

Concrete's inherent drabness has dampened the spirits of the little community of concrete specialists as much as of those obliged to live in concrete housing projects. One career researcher greeted me over the phone by asking, "Why do you want to talk about something as boring as concrete?" And the Portland Cement Association, the trade association for cement manufacturers, in Skokie, Illinois, was so tickled that I would come for a visit all the way from my home in Massachusetts that its Construction Technology Laboratory posted a large sign by the front door, welcoming me in capital letters. I got the feeling that no one else had come around in years.

When specialists talk about the image problem, they usually do so in terms of concrete's being taken for granted, by which they mean that concrete is not scorned but merely overlooked, because of its apparent simplicity. Either way, society has tried to ignore the substance, and it is paying the price, for there is still much to be learned. "Our knowledge of concrete gets shakier and shakier the deeper we delve into it," Francis Young says. At the visible level matters seem clear enough. At the microscopic level researchers are only just beginning to get an idea of what is happening. At the molecular level they are still in a total fog. Yet researchers are in short supply. Concrete has never been viewed as an area worthy of intensive academic study, and there is no equivalent of, say, metallurgy for concrete. The country's relatively few concrete specialists have had to train themselves, designing their own programs of chemistry, physics, materials science, and civil engineering. The organization that comes closest to treating concrete in an academic fashion is the American Society of Civil Engineers, which every year sponsors a concrete-canoe race to demonstrate its interest in the material. (It was won last year by Michigan State University's "Rowing Stone," a 17.5-foot U-shaped canoe employing special lightweight aggregates of ceramic particles.)

Improvements to concrete are increasingly being made overseas, where the material receives greater respect. The usefulness of silica fumes was discovered in Norway, and superplasticizers in Germany and Japan. The Portland Cement Association, which was through the 1960s

Images of concrete from around 1918: promotional advertisements (page 76; facing page); early methods of paving (left); and some of the concrete houses Thomas Edison built in Union, New Jersey (below).



responsible for nearly all the American advances in the understanding of concrete, has substantially cut back its basic research and in the past thirty years has reduced its work force from 1,100 to seventy-five. At the PCA's testing laboratory the equipment has difficulty crushing samples of the new high-strength concretes to determine their compressive strengths. The machine is essentially an enormous hydraulic-powered nutcracker; the strain of generating the necessary pressure causes a small earthquake each time it succeeds in bursting a sample, jiggling microscopes all through the building.

Surendra Shah blames a too-diversified construction industry for the lack of research. He notes that in Japan construction companies control virtually every stage of the construction process, including the fabrication of materials, thereby giving them the scale and incentive to create the best possible concrete. Recently the National Science Foundation tried to rectify the problem by integrating five of the country's concrete-research laboratories into the coordinated center that Shah heads. There I found it startling to see chunks of concrete being analyzed by earnest graduate students wielding enormous electron-scanning microscopes, rainbow-colored laser holograms, and acoustical sensing devices for charting "microseismic" activity. I nearly thought there had been some mistake. Didn't they know this was just *concrete*?

Early Enthusiasm

THE MODERN CONCRETE INDUSTRY BEgan humbly, in 1824, in Leeds, England, when an obscure bricklayer named Joseph Aspdin patented a recipe for Portland cement, the bonding agent in today's concrete. To make his cement, Aspdin scraped up quantities of limestone that had spilled onto the road near a local lime works, combined it with some clay, and heated up the mixture in his beehive kiln to far higher temperatures than had been previously attempted. For fifty years before that, builders had tinkered with various "natural cements" (naturally occurring mixtures of limestone and clay) that they essentially scooped out of the earth, just as the Romans had done almost 2,000 years before, heating and mixing the cement with aggregates. Aspdin was the first to make the manufacture of cement into anything close to an industrial process.

In his patent application Aspdin cloaked the details of his formula in mystery. In retrospect it appears that he may not have known exactly what was in it. After much sleuthing, a competitor named Isaac C. Johnson concluded that Aspdin simply scattered handfuls of various powders willy-nilly into the kiln like an improvising chef. But Aspdin displayed a keen marketing talent, naming his cement after Portland stone, the most impressive stone of its day, quarried at the Isle of Portland. Sir Christopher Wren had specified Portland stone for the rebuilding of St. Paul's Cathedral after the fire of 1666.

Although Portland cement was quickly shown to be stronger than the natural variety, Americans did not produce any until 1871. Natural cement had been discovered in 1818 by an engineer named Canvass White near Fayetteville, New York, and was quickly put to use in building concrete locks for the Erie Canal. The American cement business expanded with the canals, following the westward path of the Erie, the Richmond and Allegheny, the Chesapeake and Ohio, and the Lehigh. Each enterprise profited from the other: the cement built the canals, and canal barges distributed the cement.

Europeans had been erecting concrete buildings since the end of the previous century, but Americans didn't think to try that until 1835, when a concrete promoter in New York City named Obadiah Parker built his office—in surviving sketches a rather elegant little place, with Doric columns out front—entirely of concrete. Horace Greeley, the editor of the New York *Tribune*, was one of the more notable Americans to further the cause. He built a concrete barn in Chappaqua, New York, in 1852. But concrete's versatility was seriously limited by its low tensile strength. Walls had to be thick as a bank vault's to hold a roof up. In 1867 a French gardener named Joseph Monier devised a system of reinforcing concrete flower pots with wire mesh. The construction industry seized on this idea, adapting it to solve many problems. An array of iron reinforcing bars—square, spiral, nubbed—were introduced before the industry finally settled on the current ribbed pattern.

William E. Ward, an American mechanical engineer, independently came upon the idea of iron reinforcement the same year Monier did, when he saw how much trouble workmen had removing hardened concrete from their shovels and concluded that cement and iron had a natural affinity. Ward was terribly afraid of fire, and he was determined to build a house that couldn't burn down. And so he built in Port Chester, New York, a grand château of reinforced concrete with a crenelated tower, which was called "Ward's Castle" or "Ward's Folly." (It is now the Museum of Cartoon Art.) The only wood in the house was used for the window frames, doors, and stair rails.

The first reinforced-concrete bridge in the United States came in 1889; it was a twenty-foot span with an imitation rough-stone finish in San Francisco's Golden Gate Park. The first concrete street followed in 1891, at Bellefontaine, Ohio; it was installed by a concrete dealer eager to create a new market for his product, which he did. (The street is celebrating its hundredth anniversary this year.) The first major concrete dam was the Hoover Dam, on the Colorado River, finished in 1936. So much concrete was required for the job—some 4.5 million cubic yards altogether—that the construction team built a concrete supply company at the site. That much concrete generates a tremendous amount of heat during the hydration, or hardening, process; engineers calculated at the time that if the concrete were laid down in one continuous pour, rather than in thousands of small, carefully vented blocks, it would take 125 years to cool.

The first reinforced-concrete high-rise came in 1903, the fifteen-story Ingall's Building, in Cincinnati. In 1908 Thomas Edison tried concrete for cheap housing—or, as the *New York Press* termed it, "cosy houses for working men." Apparently he found concrete nearly as intriguing as electricity. He made significant improvements in the rotary kiln for cement manufacture, and he owned a cement plant in New Jersey. Edison perfected his concrete-building technique by molding a chicken coop in his back yard. "Members of my family laughed at

Concrete houses never caught on, despite the efforts of ads (left, 1939), developers (1880 row houses, above), or William Ward, whose 1876 "Folly" (right) arose from his terrible fear of fire.

me when I told them I was going to make a chicken coop out of concrete," he declared when the job was done, "but they are not laughing at me now." He built eleven concrete houses in Union, New Jersey, each of them cast in one continuous pour using exceptionally elaborate iron molds developed by Edison himself. A number of the houses survive, and they look surprisingly posh. Everything was made of concrete, including plumbing, chimneys, mantels, stairway balusters, and bathtubs. The houses cost $1,200 each, a quarter of the price of conventional houses. They didn't catch on.

Natural cement pretty much died out at the turn of the century. Today portland cement (the capital was dropped after the patent expired) is produced by fifty-six companies operating 123 plants in thirty-eight states. The industry is a regional one primarily because of high transportation costs, which are due to the sheer weight of the product; most plants are located within 200 miles of their markets. Because of the generally low rate of return on investment, American owners have recently been opting out of the business, leaving 65 percent of it to foreigners, mostly Europeans, who are unable to expand in their native countries in part because of far higher real-estate costs.

Cement manufacturing today follows the essential principles formulated by Aspdin. Limestone and clay are quarried, crushed, and sorted, and then heated in tremendous rotary kilns to 2700° Fahrenheit. (To reduce the fuel bill, some companies have turned to burning discarded automobile tires and other combustible garbage drawn from local landfills.) The resulting glassy pellets, or clinker, are pulverized to a powder so fine that it will pass through a sieve that holds water. The fineness is critical, since the smaller the particles, the greater the total surface area, and the bonding power of cement is primarily a matter of surface attractions.

The cement is shipped by tanker truck to the country's 4,000 concrete producers, called ready-mix companies after the state of their product. The ready-mix companies are even more widely dispersed than the cement makers, since as a rule the trucks have only ninety minutes to reach their destination before the concrete "locks up" in the mixer. "If that happens you've really got problems," says Wayne Tarr, of J. H. McNamara, a prominent Massachusetts ready-mix firm. "All you can do is open up the hold and start jackhammering."

Ready-mix companies hold reserves of aggregates, cement, water, and additives, mix them to order, and then ship the wet concrete to the construction site in concrete-mixer trucks, their drums spinning to retard setting. On big jobs the trucks line up dozens deep to be emptied by a boom crane that pumps the concrete out through a long hose to the job site. (For high-rises the concrete is pumped up the side of the building through a pipe.) There gangs of workmen take over to smooth into place with trowels the concrete for flooring, or tamp it with long vibrators into the upright forms for walls. They work fast to keep up with the concrete flow; if the hose ever had to stop, the concrete inside could lock up in minutes.

Since the ready-mix plants all buy their own aggregates locally, concrete from one part of the country is never exactly like concrete from another. "You can't assume it's all the same box of Wheaties," says Harold Roth, an architect and faculty member at the Yale School of Architecture. The sand is saltier at the coasts, and the hardness of local rocks varies markedly. All concrete is tested regularly at the site for strength and wateriness, to make sure it conforms to industry standards.

Popularity Contest

AS THE TWENTIETH CENTURY HAS PROGRESSED, the concrete industry has succeeded in turning the United States noticeably grayer (and pinker, yellower, and tanner too, now that concrete companies have started offering such designer tints as "dusty mauve," "coachella sand," and "mesa beige").

Concrete has by no means spread uniformly from coast to coast, however, although it has made a clean sweep of certain market niches, such as large dams and airport runways, which turned away from asphalt in the 1960s, when the planes got so heavy that they required concrete's rigidity to support them. But in broader markets, such as building construction and highway paving, which account for 65 percent and 22 percent, respectively, of all concrete sales, the pattern is harder to discern.

According to Portland Cement Association statistics, concrete is used most in the Southeast, the Midwest, and the Far West, and least in the Rocky Mountain states and New England. Cities like Chicago, Houston, and Seattle have become known as "good concrete towns," while others, such as New York, Pittsburgh, and Boston, are not so good. Some of the regional differences stem from practical matters. One architect explains New York's resistance to concrete by asking, "Can you imagine trying to get fifty concrete trucks down Broadway?" And local costs of competing products are obviously a consideration. A political factor like the Mafia's alleged infiltration of ready-mix suppliers in New York can tip the balance, as can the quantity and quality of the supply of available concrete. Even light is a factor: concrete simply doesn't look as good under the gray skies of the Northeast as it does under the bright-blue skies typical of the Southwest. But a key ingredient is the inherent bias of major building contractors. They go with the material they like, and what they like is often what they're used to.

Yet a region's attitude toward concrete can turn on the actions of surprisingly few people. Chicago was not known for its concrete until 1961, when a structural engineer named William Schmidt became determined to build out of concrete a forty-story high-rise apartment building called Outer Drive East. The architects were put off by the massive supporting columns required; their size decreased the amount of rentable space, especially on the ground floor, which could be rented to retailers. Schmidt spurred on his concrete supplier, Material Service, to create a stronger concrete that would not need to be so thick. Material Service in turn spurred on its researchers, and the result was the first use of high-strength concrete in an American high-rise. Largely because of its leadership in high-strength concrete, Chicago has most of the country's tallest concrete high-rises and is recognized as the country's concrete capital.

For marketing purposes concrete faces a war on all sides. As one public-relations official at the Portland Cement Association wearily told me, "We compete with everybody." Despite Thomas Edison's efforts, concrete has not done well against wood in the domestic single-family-housing market, although it is common for small houses in many parts of Europe. Here the time required to pour and place the concrete makes concrete houses more expensive than wooden ones, which can be quickly assembled of plywood and two-by-fours, even though concrete is far more long-lasting and completely fireproof besides. Surendra Shah notes that European visitors are often astonished to discover fire departments virtually on every corner in the United States.

Concrete has been more successful battling steel in high-rises, where wood is not an option. Its first victory was in residential high-rises. The low tensile strength of concrete traditionally limited its horizontal reach, but the small rooms in apartments created relatively short spans for it to cover. The wide-open floor plans of office buildings, in contrast, left concrete out of the picture until the development of high-strength concrete, which has greater tensile as well as compressive strength, and so is able to cover the critical horizontal spans.

On the highway concrete faces a bitter contest with asphalt, and the division between them is a large and unresolved controversy in the highway-construction business. "Very smart people argue both sides of the issue," says David Hensing, the deputy executive director of the American Association of State Highway and Transportation Officials. "Which is better depends on local circumstances." Of all the paved roads in the nation (more roads are unpaved than paved), 93 percent are covered with asphalt, but that figure largely reflects the secondary roads and city streets that make up the bulk of American auto routes. Asphalt and concrete currently divide the 42,000 miles of the interstate highway system sixty-forty. A look at the map makes the choice seem completely arbitrary: southern Indiana's highways, for example, are paved mostly with asphalt, while northern Indiana's are paved mostly with concrete. Asphalt is cheaper to lay than concrete, but it is significantly softer and wears out much faster under heavy loads. And if concrete does require work, it costs substantially more to fix. The choice comes down to the preference of the politicians in charge, many of whom find asphalt's lower initial cost appealing. "It's a take-care-of-it-now-and-I'll-be-out-of-office-in-two-years kind of thing," says Rita Knorr, the director of research for the American Public Works Association. "That's pretty much what decides it." And that is precisely the attitude that has brought the national infrastructure to its current state of disrepair.

Concrete will never win over all construction markets, of course, but it is remarkable how well it competes in so many of them. And the current concrete revolution should improve its prospects, which is all to the good. For concrete may be the only material capable of supporting the sheer weight of our overgrown society, with its ever-heavier planes, ever-greater automobile traffic, ever-higher sewage flows, ever-taller buildings, ever-deadlier wastes. All concrete needs now is to be appreciated. □

CREDITS: *Page 74 (left), Nancy Siesel, and (right) AP/Wide World Photos; page 78 (right), Edison National Historic Site, National Park Service, U.S. Department of the Interior; all other photographs and archival advertisements appear courtesy of the Portland Cement Association. Many thanks to Bruce McIntosh for his research assistance.*