35 YEARS OF PAVEMENT DESIGN AND PERFORMANCE

Gordon K. Ray, Portland Cement Association

Recollections of field performance studies, design studies, laboratory research experimental pavements, test roads, airport pavement load studies, road tests, design committee deliberations, pavement design, highway shoulders and airplane windows, and many, many conversations in bars, lounges, and hospitality suites.

In the late 1940's the author participated in field studies of pumping that were made on pavements built in the 1920's and 1930's with a wide variety of jointing arrangements, soils, and subbase types. Surveys were made of airfield pavements subjected to jet-engine blasts and traffic of the first superbombers--B-36's and B-47's. The performance of concrete airfield overlays was evaluated under a wide variety of aircraft loadings. At Road Test One, Maryland, and the AASHO Road Test, the effects of various axle loads were observed under controlled conditions. Pavements have been observed in the United States, Canada, United Kingdom, and other countries in Europe, South America, and Australia.

Together with Dr. Gerald Pickett, influence charts were developed to permit a ready solution to the problems of determining stresses and deflections under multiple-wheel landing gear. Procedures were prepared to permit designers to arrive at pavement thicknesses that could be expected to give satisfactory performance if future traffic volumes and wheel loads could be estimated with reasonable accuracy.

Subbases evolved from clay-gravel and sand through well-graded gravel, crushed stone, and cement-treated and lean concrete. Jointing arrangements have varied from unjointed to 90-ft expansion and 30-ft contraction joint spacing; to 100-ft contraction joint spacing; to plain pavement with skewed, randomized spacing. Plain, mesh-reinforced, and continuously reinforced pavements have been tried and observed. The performance of prestressed pavements has been studied in Europe and the United States. All have been found wanting if all elements of design--subgrade, subbase, drainage, thickness, jointing, traffic, construction, maintenance, environment, and concrete durability--are not properly integrated in the pavement management process. Pavements on streets, highways, and airfields where all elements have been properly integrated have been observed giving excellent performance for 40 to 50 years.

The paper traces many of the design changes that have been made since World War II as engineers have reacted to increases in loads and as more research has provided information on specific problems related to pavement design details. A plea is made for openminded design, taking into account performance information from other projects in other states and other countries, as well as from research in field studies and laboratories. The perfect maintenance-free pavement may never be developed, but we can "farm a lot better" than we are now in many cases.

Developments in concrete pavement design for highways and airports over the past 35 years, 1945 to 1980, will be traced here. The effects of pavement performance (in test roads, road tests, and actual pavements in service), laboratory research and theoretical analyses on pavement design will be included, as well as information gained from papers, lectures, and discussions with engineers who have been the leaders in concrete pavement design in the United States and in many other countries around the world.

Distress caused by loads: cracking, corner breaks, pumping, punchouts, faulting, and their effects on design will be probed. The effects of the environment as related to design will be covered, including spalls, blowups (buckling), contraction cracking, subgrade swell and shrinkage, and resultant pavement warping. References will be made to pavement distress due to material problems and environment such as D-cracking, scaling, map cracking (caused by alkali-aggregate reaction), popouts, and expansive aggregates and their effects on design.

The author has been fortunate to participate in detailed pavement surveys of pumping and pavement performance in Illinois and Ohio in 1946 and 1947; in surveys of field performance on civil airports (1953 and 1970), military airfields (1954, 1955, and 1956); as an observer during construction of a test road in Kansas in 1949, and subsequent semi-annual surveys on the effects of materials and environment that were evaluated; as an observer on the Maryland Road Test (1950) and as a frequent visitor to the AASHO (now AASHTO) Road Test (from

1958 to 1962). The effects of heavy accelerated loadings on several different concrete pavement designs were observed in accelerated load tests at Lockbourne Air Force Base, Sharonville, Ohio, Patuxent Naval Air Station in Maryland; and the Waterways Experiment Station at Vicksburg, Mississippi.

These personal experiences and indirect involvement with other performance studies of pavements by Portland Cement Association (PCA) engineers, participation in technical committees at Transportation Research Board, American Concrete Institute, American Society of Civil Engineers, American Road & Transportation Builders Association, American Concrete Pavement Association, Roads and Transportation Association of Canada, and Permanent International Association of Road Congresses, as well as discussions with pavement engineers and less formal inspections of concrete pavements in over 48 states, 6 provinces, and 12 foreign countries have helped the author to form a number of opinions regarding pavement design and performance. This information, it is hoped, will be useful to young engineers who may not be aware of how current designs have evolved through the years and to engineers whose experience has been limited to one state or country and to one or two pavement designs.

Subgrades

Until the late thirties or early forties, subgrades apparently had little or no major effect on pavement design or performance. Concrete was placed on the existing subgrade or soils with no special attention to soil design. Soils technology or engineering was practically unknown. Traffic was relatively light and concrete pavement failures were not frequent enough to be a major problem.

In the late thirties, however, several states began to report pavement warping (high or low joints) caused by expansion or shrinkage of highly expansive soils when the subgrade was saturated or dried out during prolonged drought. Recommendations resulting from these studies(1) led to the use of subbases in an attempt to maintain subgrades at a more uniform moisture content after construction. Today special treatment of expansive soils with lime or cement or both is generally recommended. Soils are compacted above optimum moisture and extremely expansive soils are presaturated.

In certain northern states, severe and unusual diagonal cracking of pavement in limited locations led to investigations(2) that disclosed the effect of frost heave. It was found that differential heaving caused by pockets of highly frost susceptible subgrade soils, particularly in cut and fill transitions, resulted in nonuniform slab support and the resulting cracks. A layer of frost-free granular subbase under concrete to minimize the effects of frost-susceptible subgrades was tried by some engineers. Others advocated special drainage to minimize frost heave at subgrades. Today frost heave is not considered a major factor in concrete pavement performance. Many northern states in the United States, some Canadian provinces, and several European countries are successfully controlling frost heave through careful subgrade construction and the use of relatively thin granular subbases.

The major pavement performance problem related to subgrades was the pumping that developed on concrete pavements in many locations during the late thirties and World War II as truck traffic increased in weight and frequency. Pumping is the forceful ejection of waterborne subgrade soil at joints and cracks, which may cause faulting at joints and cracks, cavities under the pavement, and eventual slab cracking. Detailed pavement performance studies(3) in five states and several years of study and discussion by a special committee of the Transportation Research Board (then the Highway Research Board) identified the three factors (free water, fine-grained soil, and frequent heavy wheel loads) that must be present for faulting to develop, and resulted in recommendations for granular subbases to effectively control pumping under the traffic existing at that time. The committee also concluded, and many subsequent studies proved, that many highways, streets, and airport pavements with low volumes of heavy traffic will not develop pumping and will not require granular subbases. It was also found that free-draining granular subgrades will not pump and do not require special subbases. This was dramatically proved on Road Test One, Maryland.(4)

Other special subgrade problems and their effects on concrete pavement performance have been documented. Large settlements over peat and other unstable soil materials have caused serious cracking in large slabs, particularly at transitions to more stable soils. In Switzerland it has been demonstrated that substantial settlements, up to 2 ft., (61 cm), will not cause cracking or even seriously affect pavement riding quality if small slabs (a maximum of 15 ft. (4.6 m)) are used and if they are joined by dowels to provide some pavement continuity. A paper on the Swiss experience is included in this conference.

In certain limited areas in rock cuts, severe diagonal cracking of slabs has been found to be caused by large boulders or rock outcroppings located too close to the bottom of the slab so that they form pedestals of point support. Most engineers call for a layer of normal subbase material directly under the pavement to provide more uniform support.

Some of the early attempts to correct settlement by slabjacking resulted in similar pavement performance. Pedestals of support at and immediately surrounding the grout holes in the slab cause diagonal cracking. The grout material must flow uniformly under the slab to provide a uniform support.

Subbases

In the studies mentioned it was learned that granular subbases would be beneficial to pavement performance under certain conditions. Later performance studies by PCA in five states and several special study sections, research in the laboratories, and accelerated traffic tests on test roads including the AASHO Road Test in Illinois helped pavement engineers to improve their designs for granular subbases.

It was found that on heavy traffic routes even higher quality granular subbase was desirable (less fines), thin subbases performed as well as thick ones, inadequate drainage led to distress in open-graded subbases. Nonuniform compaction of granular subbases during construction caused problems(5) leading to more careful control of in-place density. Uniformsize sands proved to be susceptible to movement under traffic, therefore well-graded materials are usually specified.

California developed cement-treated granular subbases that stop pumping and give excellent pavement support. This led to the design of hardened cement-treated subbases (CTSB)under thousands of miles of highway and many airfield pavements.

Since the first use of CTSB in California in the late forties, performance studies of concrete pavement on CTSB have led to refinements and improvements. Test pavements in Ohio and Indiana showed that soil-cement made with fine-grained soils does not prevent pumping. Water action caused by slab deflection eroded the soil-cement and caused slab cracking and faulting.

Later performance studies in France, California, and Georgia indicated that cement-treated subbases with low cement contents were also susceptible to erosion, pumping and pavement faulting under large volumes of heavy traffic. Pavements in service indicate that use of CTSB under concrete for airfields and highways should be limited to granular materials (A-1, A-2, or A-3), and a high enough cement content to ensure that the CTSB will meet the requirements of the American Society for Testing and Materials wet-dry, freeze-thaw, and weight-loss criteria.

During recent years, England, France, Florida, California, Utah, Georgia, and several other states have adopted a lean concrete base (econocrete) under concrete pavement as further insurance against subbase erosion. Econocrete utilizes locally available aggregates and a lower cement content than concrete. It is mixed in a normal concrete mixer and placed with a slipform paver.

Pavement Thickness

Concrete pavement thicknesses for various traffic applications range from 4 in. (120 mm) on automobile parking areas and 5 in. (130 mm) on residential streets to 6 to 14 in. (150-360 mm) on highways and 6 to 20 in. (150-500 mm) or more on airfields. Pavements used in road tests and in heavy-load, accelerated-traffic airfield tests have varied from 2½ to 32 in. (63-810 mm). Since the Bates Road Test in Illinois in the early twenties, a series of thickness design procedures have been proposed by Older, Goldbeck, Westergaard, Spangler, Kelly, Pickett, and many others. Their theoretical analyses, empirical methods, performance equations, and simple rules of thumb have permitted engineers to arrive at thicknesses that will give satisfactory performance over the pavement's design life if the jointing and subbases are properly designed for the traffic and environment and if future traffic can be estimated with reasonable accuracy.

The AASHO Road Tests(6) and many other performance studies have demonstrated that overdesign in pavement thickness is wasteful. If 6-in. (150 mm) concrete is enough, 7 in. (180 mm) is too much. Some 6-in. (150 mm) airfield pavements are still giving satisfactory service, after 30 years or more because aircraft wheel loads have not exceeded the load range for which the pavement was designed. The 1951 Greene County, Iowa, project demonstrated the ability of 4½-in. (110 mm) concrete pavement to carry typical farm-to-market traffic for almost 30 years, and Iowa counties now have almost 4,000 miles (6400 km) of 6-in. (150 mm) slipformed pavement up to 20 years old.

The AASHO Road Test, the heavy-load wheel tests at Vicksburg Waterways Experiment Station, and the performance studies of pavements in service in recent years have shown that, with heavy multiple-wheel loads, deflection of the pavements may have a critical effect on pavement performance, in spite of slab stresses not exceeding theoretically critical values. Excessive deflections, particularly when slabs are curled up, can aggravate water action and erosion and may cause permanent subgrade distress in some pavement systems. Pavement deflections should be given some consideration for such heavy multi-wheel arrangements subjected to frequent repetition, or with thinner slabs made possible by prestressing on the use of fiber reinforced concrete.

PCA has published pavement design procedures for streets, highways, and airfield pavements for approximately 50 years. These have undergone many changes over the years as theoretical analyses have become more sophisticated, as new research and road test data become available, and as more performance data have been gathered from studies of actual pavements under heavy traffic in a wide range of environmental conditions.

Equations for corner loading, edge loading, interior loading, influence charts, and computer programs have all been considered in PCA design procedures. The procedures have generally been based on some method for determining fatigue and considering the strength of the concrete and the bearing strength of the subgrade. PCA has always recognized and tried to evaluate the effect of load transfer across joints in calculating pavement thickness.

At the present time Bob Packard, our Principal Paving Engineer is working with PCA's Transportation Development Department on a new improved procedure for designing concrete streets and highways. This is being done to recognize the effects of tied concrete shoulders, mechanical load transfer, and stronger subbases such as those of lean-mix concrete.

In recent years there has been considerable interest in the use of thicker concrete pavement as an alternate design to the use of stabilized subbases and dowel load-transfer devices. Some designers have also justified thicker slabs as zero-maintenance pavements, sacrificial pavements to permit future grinding, or simply pavements to provide for anticipated increases in legal axle loads or heavier aircraft. The use of thicker slabs and their justifications will no doubt be explored thoroughly in the next few years. This concept will also be discussed in several other papers at this conference.

Jointing and Reinforcement

Jointing arrangements and the decision to use plain or reinforced pavement have been through even more changes and cycles than thickness and subbase design. Preference on the use of plain or reinforced, continuously reinforced or even prestressed pavement is a subject of great controversy, prejudice, and in some cases almost fanaticism.

The large mileages of concrete pavements built to "get us out of the mud" in the twenties were almost all plain. In fact, the first road test to compare plain and reinforced pavement--the Pittsburg, California, test in the twenties--showed no particular advantages for reinforcing. Unfortunately, most of these early plain pavements were built without joints, either longitudinal or transverse. The performance of these early pavements was quite varied. There are still a few in service where traffic volume or loads have been light, where good subgrades existed, or where the environment has been mild. There are many examples of these 50 or 60 year old 5- to 8-in. (130 to 200 mm) pavements still in service.

In many cases, however, the irregular wandering longitudinal cracks developed serious spalling, faulting, and separation. This experience and the results of the Bates Road Test led to the adoption of longitudinal center joints with the two lanes

tied together with deformed tiebars or tiebolts. Today there is little disagreement on the need for longitudinal joints in highway pavements. Highway pavements are designed with these joints at approximately 12-ft (3.8 m) spacings. This dimension happily coincides with that generally used for traffic lane width, a fortunate coincidence.

In light-traffic streets and parking areas and on general aviation airports where 4- to 7-in. (120 to 180 mm)-thick pavements are used, the longitudinal joint spacing should be reduced. Spacings of 8 to 10 ft (2.5-3 m) are recommended in many cases.

In thick pavements for airfields or heavy container ports a wider lane width may be used. In pavements over about 16 in. (400 mm) thick, a longitudinal joint spacing of about 25 ft (7.6 m) has been extensively used with good performance. In the range of 12 to 16 in., (150-410 m) 25-ft (7.6 m) widths without intermediate longitudinal joints have given good crack-free performance on some projects, but have developed longitudinal cracking on others, particularly when channelized longitudinal traffic is heavy such as on airfield taxiways. Perhaps an intermediate spacing such as 18 ft (5.5 m) would be satisfactory. The Seattle-Tacoma Airport used 18-3/4 ft (5.8 m) in 37-1/2-ft (11.6 m)-wide construction lanes. However, if 25-ft-wide construction lanes are used, 12-1/2 ft (3.8 m) is still the recommended spacing of longitudinal joints in channelized traffic areas.

In the old, unjointed plain pavements, transverse cracks formed at very irregular spacing during the early life of the pavement. Depending on subgrade, traffic, aggregate, concrete strength, and climate, the cracks that opened due to pavement contraction were impossible or difficult to seal and spalling and infiltration of incompressible material took place. In time many of these early pavements developed buckling and blowups. These blowups led to expansion joints, a new phenomenon that became the source of many pavement problems and controversies among designers. In the thirties, most concrete pavements were designed with mesh reinforcement and some combination of expansion and contraction joints. The then Bureau of Public Roads apparently favored mesh and dowel designs with expansion joints at 90-ft (28 m) spacing and contraction joints at 30 ft (9 m). Many states used this design and many manufacturers were selling proprietary joint devices. Most of these devices used some type of metal (usually copper) plate or air cushion to serve as the expansion joint filler and various types of plates for inserts to help form the contraction joint. Other states used 100-ft (30.5 m) expansion joint spacing and 50-ft (15.2 m) contraction joints.

In service these pavements performed poorly. The expansion joints gradually closed and contraction joints opened. By the late forties the metal joints had corroded, poorly sealed joints had permitted infiltration of incompressible materials, and carelessly constructed expansion joints had spalled. The results were serious spalls and some blowups. Many dowels corroded and froze in the pavement and others broke off in the joints.

During World War II the Bureau of Public Roads encouraged steel-free pavements to make steel available for the war effort. A plain pavement design was advocated. This design, with expansion joints at 105 ft (32 m) or perhaps 120 ft (38 m) and contraction joints at 15 or 20 ft (4.6 or 6.1 m) had no dowels and the results were bad. Expansion joints closed and contraction joints opened. The undoweled expansion joints faulted and so did the contraction joints where aggregate interlock became ineffective after the joints opened. These pavements were relatively free of cracking, spalling, and blowups, but the faulting was serious and the design was abandoned by most states after World War II and performance evaluations of the projects in service.

In the postwar years, states adopted several designs--plain undoweled pavements with short joint spacing and no expansion joints or long mesh-reinforced slabs with either contraction joints or expansion joint spacings at from 50 to 100 ft (15-30 m).

In a paper published by the American Society of Civil Engineers in 1948,(7) A. A. Anderson recommended that all regularly spaced expansion joints be omitted if contraction joints were placed at intervals of 40 ft (12 m) or less. He warned about problems of infiltration in pavements with long contraction joint spacing. Unfortunately, many states that adopted this mesh-dowel design (long slabs, narrow contraction joints) have experienced serious spalling, blowups, and broken reinforcing at intermediate cracks that have resulted in crack spalling and faulting. The one state, New Jersey, that retained the long reinforced slabs with all expansion joints at 89 ft (27 m) with stainless-steel-clad dowels has had excellent performance.

Other states, including California, Washington, Florida, and Georgia, adopted a plain undoweled pavement design with joints at 15 to 30 ft (4.6-9.2 m). These slabs were generally crack-free and the pavements had few if any spalls or blowups. The advent of sawed joints in the early fifties and slipform paving in the early sixties made this design by far the simplest to build and the most economical. The AASHO Road Test in Illinois included both plain and reinforced concrete pavement test sections. The plain pavements contained contraction joints at 15 ft (4.6 m) with dowels and mesh-reinforced slabs with dowels and contraction joints at 40 ft (12.2 m). Two years of traffic resulted in slightly better performance of the plain pavement. After another 15 years under heavy interstate traffic, the plain pavement of the same thickness was performing even better than the 40-ft (12.2 m) reinforced slabs with less faulting and spalling.

Faulting of plain undoweled pavements and problems with long-panel mesh-dowel designs have led several European countries, including England, Austria, Germany, and Switzerland, to adopt a plain pavement with short panels of 15 to 20 ft (4.6-6.1 m) and doweled joints. In the United States, Indiana, Iowa, Arkansas, Florida, Georgia, New York, and Pennsylvania are among those who have now adopted this design.

A few states are still using reinforced mesh dowel designs with contraction joint spacings at 40 to 50 ft (12-15 m). Most have adopted coated dowels to minimize corrosion and most have adopted improved shape factors and improved joint sealants (compression premolded sealants) to minimize infiltration and spalling. Dowel diameters are normally 1/8 in. (3 mm) for each 1-in. (25 mm) pavement thickness based on research by the Federal Highway Administration (FHWH).(8) Mesh is designed with large enough longitudinal wires to hold cracks tightly closed under heavy traffic.

There are still several foreign countries--France, Italy, Spain, and South Africa--as well as numerous western states, including Washington, Idaho, Utah, California, Oklahoma, Colorado, New Mexico, and Nevada that use plain undoweled pavements, mostly on cement-treated subbases. Joints are generally skewed to reduce impact by preventing all wheels from crossing the joint simultaneously and to minimize any roughness if faulting develops.

Most states using skewed joints have now also adopted randomized jointing to minimize or prevent serious harmonic resonant thumps or beats from developing in certain cars driven at certain uniform speeds.

M. P. Brokaw developed a new design procedure for plain undoweled pavement that is intended to keep the faulting within tolerable limits during its design life.(9) R. G. Packard presented a paper at the First International Conference on Concrete Pavement Design in 1977 with a model equation to forecast faulting in undoweled pavement.(10) The question "to dowel or not to dowel" was thoroughly explored by Michel Ray of the French Department of Roads and Bridges and a subcommittee of the Permanent International Association of Road Congresses Technical Committee on Concrete Roads for the XVIst World Road Congress in Vienna, Austria, September 1979.(11)

Michael Ray's paper which follows in this session discusses the relationship of jointing, drainage, thickness and subbase for plain pavements.

Both plain pavement designs, doweled and undoweled, can give satisfactory performance if subbases and shoulders are properly designed and built.

There is one other design that should certainly be mentioned--continuously reinforced concrete pavement (CRP). After an experimental section in Maryland in the twenties and a test road in Indiana in the late thirties, it was not until the late forties that the steel industry, the Bureau of Public Roads, and four states--Illinois, New Jersey, Texas, and California--teamed up to build four major demonstration sections. They all performed quite well (most are still in service today), and enough information on design (thickness, steel percentage, and so on) was developed to encourage several states to engage in a major program of CRCP construction. By 1970, 16 states and Belgium were making extensive use of CRCP.

Unfortunately, the demand for economy and overconfidence in the maintenance-free, "jointless" pavement led to some underdesigned projects on some questionable subbases, constructed to less than satisfactory standards. Longitudinal cracking, spalling, and punchouts have developed in many CRC pavements. At least eight states--Ohio, Indiana, North Dakota, Michigan, Minnesota, Pennsylvania, Arkansas, and Louisiana--all of whom have built substantial mileages of CRCP, have changed their design standards to plain or mesh-dowel pavements. Other states, the Federal Highway Administration and AASHTO have reevaluated CRCP designs and are now recommending the same thickness as conventional designs. Belgium, Holland, Oregon, Texas, Wisconsin, Illinois, Mississippi, and Virginia are still building substantial mileages of CRCP. A paper on CRCP designs in Australia will be presented later in this conference.

The long-term economy of this design depends on relatively long service lives with relatively low maintenance. The riding quality of CRCP is generally good.

In the late fifties or early sixties, several European countries and United States military airfield agencies became interested in the possibilities of prestressed pavements for both roads and airfields. Much research was done and many experimental pavements were built in the United Kingdom, France, Belgium, Switzerland, Germany, and Holland. In this country the Navy and the Corps of Engineers built test sections that were subjected to accelerated traffic, and later these two agencies constructed full-scale projects on taxiways at Biggs Air Force Base in Texas and LeMoore Naval Air Station in California, which are still in service.

The European countries have apparently lost their interest in prestressed highway pavements. None have been built since about 1962. However, interest in prestressed airfield pavements has remained high, particularly in Germany, and we will hear a paper on the performance of these projects later in this conference. At the First International Conference on Concrete Pavement in 1977 a paper was presented on the design of a prestressed runway that has since been completed in Brazil. In the United States there have been four highway projects built recently in Washington, D.C., Pennsylvania, Mississippi, and Arizona, and performance reports will also be presented on these at this conference.

A new, prestressed-concrete overlay was built last year at O'Hare International Airport, Chicago.

At this point it appears that prestressed pavements may have a place in our family of designs. Whether they are economically competitive with plain pavements and reinforced pavements in terms of construction costs and, more importantly, life cycle costs, has yet to be determined.

Shoulders

Concrete shoulders were first used in an experimental project in Illinois in 1964.(12) In 1974 the FHWA followed up a NEEP project and several other experimental projects around the country with a notice that concrete shoulders were no longer in the experimental category and could be used whenever they could be economically justified. As of December 31, 1979, there were over 20 million sq yd (17.3 million sq. m) of concrete shoulders in service in the United States. Performance of the early projects and research in the laboratory and on projects in the field have demonstrated the advantages of concrete shoulders. Reduced deflections and stresses in mainline pavement are an important result of tied concrete shoulders. Improved safety, better surface drainage, and reduced shoulder maintenance are other advantages. Performance of concrete shoulders to date will also be discussed later in this conference.

Resurfacing

This discussion would not be complete without some reference to concrete pavement resurfacing. The author has spent considerable time studying the performance of concrete overlays on both highways and airports. Research in the laboratory, test roads, and demonstration projects have provided valuable information on the design and construction of concrete resurfacing. Surveys of many projects in service for up to 35 years have proved the good performance of properly designed and executed projects on both highways and airports.(13,14) Bonded resurfacing, separated and direct overlays, and overlays over asphalt pavement can be designed to provide many years of service if the conditions of the existing pavement are properly evaluated and considered. Overlays of plain concrete, conventionally reinforced concrete, fiber-reinforced and prestressed concrete can all be used satisfactorily to overlay existing pavement. A number of papers will be presented here on the design and performance of concrete resurfacing for highway and airport pavements.

Conclusion

After 35 years of talking, walking, looking, and dreaming about concrete pavements, I have come to a number of conclusions:

1. Concrete pavements must be made with good materials and proper mix designs to withstand the environment to which they will be exposed in whatever climate they are located. Special care must be taken to avoid alkali-aggregate reaction and D-cracking in areas with susceptible aggregates. Adequate air entrainment is necessary in those areas where deicing salts are used.
2. Any of the major designs--plain, reinforced, continuously reinforced, or prestressed--will give good performance if the subgrade, subbase, jointing, and use of steel, if any, are properly considered and provided for in the design, and if traffic is reasonably well forecast.
3. Plain concrete pavements with short joint spacings (15 ft) will give the most economical life cycle costs for most pavement installations. Dowels may be required under certain conditions of heavy traffic, but many light traffic roads and streets can be built without dowels.
4. Properly designed concrete shoulders tied to the mainline slab and provided with keyed construction joints or aggregate interlock below a dummy-groove longitudinal joint will greatly improve the performance of both the mainline pavement and the shoulders.
5. Concrete resurfacing--bonded, direct, or separated--can be designed for overlaying existing concrete or asphalt. Good engineering judgment in the evaluation of the old pavement and in selecting the best design details for the resurfacing will result in excellent overlay performance.
6. Adequate specifications and quality construction are important to good pavement performance. No design will result in good performance if construction of any element in the pavement is inadequate or improper. Well-designed pavements will develop failures if construction is not properly executed.
7. Pavement designers must be familiar with economics, performance, and research as well as design procedures. They should understand pavement design fundamentals and must use the best means available to estimate subgrade strength, future traffic, and contractor capabilities. Pavement design requires a thorough application of good engineering judgment.
8. Concrete pavements are here to stay, but they can be made even better when they are properly designed. This conference which brings together engineers from many parts of the U.S. and many other countries of the world should help to improve concrete pavement design. We can learn much from each other and from the performance and evaluation of many pavement designs under a wide variety of traffic and environmental conditions. Let us all keep an open mind during these three days to the ideas and experience of others. Let's do a better job of designing, evaluating performance and rehabilitating concrete pavement.

References

1. Report of Committee on Warping of Concrete Pavements, Proceedings of the 25th Annual Meeting, Highway Research Board, 1955, p. 199.
2. Frost Action in Roads and Airfields, Highway Research Board Special Report No. 1, A Review of the Literature, pp. 1765-1951.
3. Report of the Committee on Maintenance of Joints in Concrete Pavements as Related to the Pumping Action of Slabs, Proceedings of the Twenty-Eighth Annual Meeting, Highway Research Board, 1948, p. 281.
4. Road Test One-Md, Highway Research Board Special Report 4, 1952.
5. P. Fordyce, and J. D. Geesaman, Performances of Concrete Pavements as Related to Subbase Construction Methods, Highway Research Board Bulletin 229, 1959, pp. 1-10.
6. The AASHO Road Test, Report 5, Pavement Research, Highway Research Board Special Report 61 E, 1962.
7. A. A. Anderson, Expansion Joint Practice in Highway Construction, American Society of Civil Engineers Transactions, 1948, pp. 1159-1177.
8. L. W. Teller, and H. D. Cashell, Performance of Dowels Under Repetitive Loading, Public Roads, Vol. 30, No. 1, April 1958.
9. M. P. Brokaw, Effect of Serviceability and Roughness at Transverse Joints on Performance and Design of Plain Concrete Pavement, Highway Research Record 471, Highway Research Board, 1973, pp. 91-98.
10. R. G. Packard, Design Considerations for Control of Joint Faulting of Undoweled Pavement, Proceedings, International Conference on the Design of Concrete Pavement, Purdue University, 1977, pp. 121-136.
11. Concrete Pavements--Load Transfer at Transverse Contraction Joints and Design of Concrete Pavements, Report and Appendices of Subcommittee No. 1, Permanent International Association of Road Congresses Technical Committee on Concrete Roads, September 1979.
12. E. C. Lokken, What We Have Learned to Date from Experimental Concrete Shoulder Projects, Highway Research Board Record 434, 1973, pp. 43-54.
13. Continuously Reinforced Concrete Overlays--1975 Condition Survey, Ad Hoc Committee for Concrete Overlays, Portland Cement Association, American Concrete Pavement Association, Associated Reinforcing Bar Producers, and Wire Reinforcement Institute.
14. 1977 Condition Survey, Concrete Resurfacing--Plain and Reinforced Concrete, Portland Cement Association and American Concrete Pavement Association.