CONCRETE MATERIALS AND MIX DESIGN FOR ASSURING DURABLE PAVEMENTS

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INTRODUCTION

Concern with the durability of concrete pavements is not a new phenomenon. Consider the following quotes from Agg (1) made in 1940.

First, while discussing concrete slabs, he states: "The concrete road slab whether it is to be used as a foundation course or as a wearing course, has the property of an imperfectly elastic solid, and hence on any subgrade its stability under load is related to its structural strength. The use of slabs of this type introduces illusive problems of structural design, since consideration must be given not only to the traffic load to which the slab is subjected but also to temperature and moisture effects on the concrete and the influence of the subgrade support upon the stability of the overlying slab."

On the subject of concrete mixes he says: "Concrete road slabs are designed on the basis of an assumed strength of concrete, and the first consideration in the design of the concrete mixture itself is to make sure that a concrete is produced that will have strength at least equal to that assumed in the design. Although standard specifications frequently mention the proportions of coarse and fine aggregate to be used with a cubic foot of cement, this is generally to be considered only as a guide, and the exact proportions are developed by laboratory tests to establish the most economical combination of the available fine and coarse aggregate that will produce concrete of the required strength. It is recognized that the critical element in a mixture is the water and that the best concrete will be that which is produced with the lowest water-cement ratio consistent with a workable mixture."

Finally, on aggregates: "The aggregate should be sound, by which is meant that the effect of repeated freezing and thawing, together with absorption of water, does not cause the aggregate to soften sufficiently so that it will be unable to resist the wear to traffic. The maximum size should not be greater than about 2 ½ in., ... the minimum size is that which will pass a 50-mesh sieve; of this there should not be more than 5 or 6 percent. Between these two sizes the proportion of the several sizes should be such as to insure that when the particle-size distribution is plotted it will be definitely concave upward, and the more nearly it approaches the curve of maximum density, the better. The ratio of water to cement has so powerful an influence on the strength of the concrete, however, that more attention is paid to water-cement ratio than to the grading of the mineral aggregate. The engineer should, however, take both factors into account and, by laboratory studies on the available materials, determine the proportion of coarse and fine aggregates of the kinds commercially available that will produce concrete of the desired strength at the lowest cost"

These few paragraphs serve to illustrate the thoroughness of understanding of concrete in pavements in the 1940's (and earlier - the first edition of this book was published in 1916). We may quibble with some of the details of these statements, but the basic reasoning still sounds pretty good today. But, perhaps we have learned some things in the intervening 50 plus years, and in this paper I will explore some of the materials-related factors which influence the durability of concrete pavements. [In the context of this paper, durability is considered the resistance of the concrete and pavement to their surroundings, including the environment and traffic.] These factors include: materials and mix design; concrete's role in pavement structural design and performance; the environment; and the construction process.

INFLUENCE OF MATERIALS AND MIX DESIGN

Let's examine some of the aspects of the concrete and its constitutive materials which influence various aspects of pavement performance.

Aggregates

Aggregates influence the performance of concrete, and the pavement in which it is used, in many ways. The influencing characteristics of aggregates, which are listed in Table 1, are discussed below.

As maximum aggregate size increases, the volume percentage of the aggregate in the concrete can also increase (for the same gradation) and the surface area of the aggregate will decrease. This means a more economical mix, since less cement paste is present and therefore less cement will be required for a given volume of concrete. At the same time, when larger aggregate sizes are used, attention must be paid to possible effects on concrete workability, ease of consolidation and susceptibility to segregation. Due the greater volume of aggregate, the hardened concrete will have less shrinkage.

It is often assumed that good concrete can be made with almost any aggregate gradation. Although sometimes not easy, this is usually true, as long as the gradation is consistent from mix design through production. Often, however, the concrete may not be optimal, in terms of either economy or performance. It has been found that a dense (continuous) graded aggregate will often provide the best workability, as well as minimizing the volume percent of cement paste. While maximum density gradation is usually not available for a particular aggregate source, (and may not be practical from a workability standpoint) economical gradations of low void content and high density should be sought.

Another aggregate property important to producing durable concrete is soundness. Often thought of as resistance to freezing and thawing, soundness is more properly the aggregate's resistance to all aspects of weathering. This includes heating and cooling, wetting and drying, and freezing and thawing. Thus in all types of climate, including non-freeze zones, aggregate soundness is important.

The particle shape and angularity of the aggregate, particularly the fine aggregate, will affect the workability of the mixture. This should be assessed during the laboratory design phase, and any necessary adjustments made at that time so that potential problems of placement, consolidation and finishing during construction are avoided.

Good concrete can be made with a smooth gravel or a rough crushed stone. The paste-aggregate bond for these two aggregates will be different, and therefore the flexural and tensile strength of the concrete will also be different. This may require somewhat different mix designs according to aggregate type in order to meet specifications.

The hardness of the fine aggregate (since it is exposed at the surface), in particular, should be considered where pavement surface friction is of concern, as in higher-speed pavements. This is because the fine aggregate, along with any surface texturing applied at the time of placement, is responsible for the friction developed at the pavement/tire interface.

The thermal coefficient of expansion of the aggregate plays a large role in determining the thermal coefficient of expansion of the concrete as a whole. If this influence is not considered during pavement design, it could lead to uncontrolled transverse cracking (in jointed plain concrete pavement(JPCP), or undesirable crack spacing (in jointed reinforced concrete pavement(JRCP) and continuous reinforced concrete pavement (CRCP)). Since the thermal coefficient of expansion of the cement paste is usually 1 ½ to 2 times that of the aggregate (2), the volume percent of each component in the concrete will also have an effect.

Finally, the reactivity of the aggregate with the cement and other components in the mix, in terms of the potential for deleterious expansion due to alki-aggregate reactivity (AAR), can greatly influence the long term durability of the concrete. If in doubt, screening tests should be carried out to evaluate this potential.

Cementitious Components

For paving concrete, the only cementitious component normally used is portland cement, usually Type I or Type I-II. Other types of cement may sometimes be used in those situations where additional sulfate resistance is desired, or when more rapid strength gain is needed, such as with fast track paving. However, even with a given cement type and source, the user should be aware of the potential for changes in the cement actually supplied. One should also consider the fineness, and therefore the rate of hydration, heat generation and strength gain (see Table 1). What is the chemical composition, for instance the alkali content, of the cement and should it be of concern with the other components to be used, including the aggregate?

Additives/Admixtures

There currently is a multitude of mineral and chemical additives/admixtures to improve the characteristics of concrete in both the plastic and hardened state (see Table 1). These may be used to combat alkali-aggregate reactivity (AAR); increase workability; enable the reduction of the water to cementitious plus pozzolanic materials ratio (W/(C+P)), entrain air, etc. The simple advice when using these materials, either singularly or in combination, is to evaluate them during the mix design process, not only for their effect on the concrete, but just as important, their effect on each other, in terms of both effectiveness for the intended purpose, and compatibility with each other. Fly ash is a commonly used pozzolanic admixture in paving concrete. If AAR is a potential problem, the type and composition of the fly ash should be noted, and tests run as appropriate, since some fly ashes appear to increase AAR potential, and others decrease it.

Various composition and types of fibers have been used in concrete for their effect on the plastic and hardened properties. Depending on several factors, including fiber type and volume percent in the concrete, fibers may reduce bleeding, add toughness, reduce cracking and reduce crack opening.

Water/(Cementitious + Pozzolanic Materials) Ratio

With the complexity of present day concretes, often including supplementary cementitious materials and/or pozzolanic admixtures, it is no longer sufficient to consider simply the water/cement ratio, but rather the ratio of water to the sum of all the cementitious and pozzolanic materials (W/(C+P)). Because some pozzolans have low density, volumetric instead of mass equivalencies are sometimes used for these materials. Even with the more complex W/(C+P), however, the principal of keeping the ratio as low as practical within the confines of having a workable mixture capable of being placed, consolidated and finished, remains the same. This is simply because, as this ratio goes down, the strength of the concrete generally goes up, the permeability of the concrete goes down, and therefore the likelihood of a durable concrete pavement improves. Further, if lower water content per unit of concrete also results, the potential for drying shrinkage is also less, decreasing the likelihood of uncontrolled cracking in the pavement.

CONCRETE'S ROLE IN PAVEMENT STRUCTURAL DESIGN/PERFORMANCE

The three most common rigid pavement types are JPCP, JRCP, and CRCP. Several concrete characteristics may influence the structural performance of these pavement types(see Table 2).

Strength

Concrete strength is directly considered as a part of the pavement structural design. Requirements are typically in the range of 5 MPa (700 psi) flexural modulus of rupture or 28 MPa (4000 psi) compressive strength. In order to provide some additional insight on the influence of strength on performance, one of the factors being investigated in the Long-Term Pavement Performance Program (LTPP)is the effect on pavement performance of two levels (3.8 and 6.2 MPa (550 and 900 psi))of flexural strength (3). The performance of adjacent pavement sections built using concrete of these two strengths should provide some empirical evidence on the influence of strength on performance.

For the two reinforced pavement types, JRCP and CRCP, there is the additional subset of strength concerned with the bond strength of the concrete to the reinforcement, and so-called bond development length. These properties influence the performance of the slab at joints and cracks.

Tensile Stresses and Uncontrolled Cracking

Concrete is much weaker in tension than compression, and therefore transverse cracks which occur in pavements are due to development of excessive tensile stresses in the concrete. Pavement design must consider this property of concrete, and incorporate features to either control crack location or maintain structural performance in spite of the occurrence of random cracks.

Since, by definition, JPCP has no reinforcement, uncontrolled cracking must be prevented. Therefore, for JPCP, contraction joint spacing must be kept small, in order to induce cracking at the weakened plane of the joint, and prevent cracking at mid-slab, between joints. If an uncontrolled (mid-panel) crack does occur, the slab will soon fail due to crack-opening, subsequent loss of load transfer and faulting. Prevention of uncontrolled cracking can be assured in JPCP by using short transverse joint spacing (4 - 5 m,(12 - 15 ft)), and timely sawing of those joints during construction.

Transverse cracking in JRCP is as serious a problem as it is in JPCP. Contraction joints are used in JRCP to control the location of some cracking and all horizontal separation. Because of the size of the joint opening which can occur, the use of load transfer devices is required. The pavement design incorporates the allowance for mid-slab cracking, and hence transverse joint spacing can be greater than for JPCP. The purpose of the reinforcing, then, is not to prevent these cracks, but to keep these cracks tight once they occur, so that load transfer across the crack is accomplished through aggregate interlock and no faulting occurs. The steel percentage must be sufficient to keep the cracks tight, since the steel is not designed to serve as a load transfer device, and will soon fail in that situation.

Transverse joints are not a part of the CRCP design, therefore transverse cracks are expected to form soon after placement. The critical performance parameter is the spacing of those cracks: close enough to keep any one crack from opening too wide, but far enough apart so that good bond is maintained with the reinforcing, and the pavement between cracks is long enough to be stable.

INFLUENCE OF THE ENVIRONMENT

The environment in which a pavement is placed greatly influences the performance of that pavement (4). This influence has two phases or stages: first, when the concrete is placed, and second, over the life of the pavement. Lack of consideration of the environment during either phase can negate otherwise good mix and pavement designs (see Table 2).

Environmental considerations at the time of construction include ambient temperature; fluctuation of ambient temperature; precipitation; relative humidity; solar radiation and wind. All these factors influence the rate of hydration and strength gain, as well as moisture loss and the onset of uncontrolled cracking. The FHWA currently has a study with Transtec, Inc, to investigate the influence of these factors from the time of placement through the first 72 hours of life. Guidelines are being developed to keep stresses within the pavement slab below critical levels at which uncontrolled cracking will occur. In essence the aim is to control the pavement condition so that strength development always exceeds stress development during the early age.

Over the long-term life of the pavement, temperature and moisture variations will produce compressive (increasing temperature and moisture) and tensile (decreasing temperature and moisture) stresses, which will result in overall expansion and contraction, respectively, of the concrete. Contraction of the concrete will lead to increased joint and crack openings, and greater difficulty in maintaining adequate load transfer.

Temperature and moisture gradients through the thickness of the pavement will cause non-uniform expansion or contraction of the concrete, internal stresses, and result in curling and warping in jointed concrete pavement slabs. Additional cracking can result when these deformed slabs are subjected to loading. The influence of all aspects of temperature and moisture variation must be included during the pavement design phase, through consideration of such things as transverse joint spacing, percent reinforcing and the use of load transfer devices.

The University of Washington is currently investigating the effects of curling and warping on long-term pavement performance in a study for the FHWA.

INFLUENCE OF CONSTRUCTION

Our job is not finished once good mix and pavement designs have been obtained. To be successful, the construction process must then get in place what was designed (see Table 2). First, the concrete produced must equal the concrete designed during the laboratory phase. Next, the quality of that concrete must be controlled throughout production. The site must be well prepared prior to the start of paving, including uniformity of any supporting layers and placement of reinforcing and/or dowel baskets. The concrete must be delivered to the site at a rate consistent with the speed and demands of the paving train, to avoid stops and starts. The equipment must be well maintained and in good shape with a well trained crew to enable consistent placement and consolidation.

Proper finishing must be carried out for smoothness (and its effect on dynamic loads and ride). The texturing must be adequate for friction and durable to withstand wear. Proper curing must be applied to prevent uncontrolled cracking and obtain strength at the surface. Finally, joints must be sawed in a timely fashion to control cracking and provide equal opening of all transverse joints.

SUMMARY

Although this paper is intended to be a discussion of the various aspects of concrete materials and mix design which must be considered to produce durable, long-lasting pavements, it should be apparent from the forgoing that the other aspects of rigid pavement design and construction must also be considered. When selecting materials and designing the concrete mix, the characteristics, influence on performance and interaction of the various components must be well understood. Further, the materials tested in the laboratory must be the same ones used on the job.

The pavement type being constructed will influence the structural requirements placed on the concrete, so the mix and pavement design processes should go hand-in-hand. The environment at the site can make or break a project: in the short term, the construction process must compensate for any environmental conditions that will be harmful to the concrete during the first several days of hydration and strength gain; in the long-term, the concrete and pavement must be designed to withstand the temperature and moisture regimes (including freeze-thaw cycling) in which they will be placed.

Finally, the construction process must control the quality of the concrete produced; adequately prepare the site; time activities to produce constant paving rates; provide good consolidation and finishing; timely and adequate curing, and timely joint sawing.

Following all these steps from materials selection through construction will assure durable concrete pavement with excellent long-term performance.

TABLE TITLES

TABLE 1 - The Influence of Materials and Mix Design on Concrete

TABLE 2 - The Influence of Other Factors on PCC/Pavement Properties

TABLE 1 The Influence of Materials and Mix Design on Concrete

CATEGORY	CHARACTERISTICS	AFFECTED PCC PROPERTY
Aggregates	Maximum size	paste vol %, shrinkage
	Gradation	same
	Soundness	durability; including F/T resistance
	Angularity/shape	
	Surface Texture	
	Thermal Coefficient	
	Alkali Reactivity	
	Hardness	
Cements	Fineness	rate of strength gain; permeability
	Chemical composition	Rate of strength gain; sulfate resistance; AAR susceptibility
Additives/ Admixtures	Air entraining	F/T resistance of the paste
	Water reducing/ plasticizing	Water content; W/(C+P); workability; finishability; shrinkage
	Pozzolans	rate of strength gain; permeability; AAR susceptibility
	Fibers	bleeding; toughness; cracking; crack opening
W/(C+P)	Level of:	workability; finishability; segregation; shrinkage; cracking; strength; permeability

TABLE 2 The Influence of Other Factors on PCC/Pavement Properties

CATEGORY	CHARACTERISTICS	PROPERTY AFFECTED
Pavement structural design & performance	Design strength	flexural, tensile strength; crack resistance
	Joint/crack spacing - JPCP - JRCP - CRCP	tensile stress & transverse cracking; load transfer efficiency & need for load transfer devices
Environment -short term	Temperature, relative humidity; solar radiation; wind	strength gain; moisture loss; tensile stress and random crack susceptibility
-long term	Temperature; moisture; F/T cycling	slab size; slab shape (curling & warping) and slab support; joint/crack opening; durability
Construction	Control of materials and mix	quality & uniformity of PCC
	Site preparation	uniformity of PCC in place; smoothness
	On-time PCC delivery	same as above
	Equipment & crew quality	same as above
	Finishing	smoothness
	Texturing	surface friction and noise
	Curing	moisture loss; temperature and moisture gradients; strength gain; crack susceptibility
	Timing of joint sawing	randon cracking; uniformity of joint/crack opening

REFERENCES

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