

THE CONCRETE MIXTURE: THE KEY TO PAVEMENT DURABILITY

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INTRODUCTION

Volumes have been written on the subject of concrete durability. I have no intention of repeating what has been said but will address what I feel is the most neglected part of the subject — the non quantitative aspects. To understand the difference, we must separate durability into two different classifications:

- 1) Failure concrete due to structural problems either in the subgrade, base, or concrete strength or thickness, and
- 2) Deterioration due to aggressive action from the forces of the environment in which the pavement exists.

Solutions to structural problems are quantitative and the responsibility of the engineer. The site conditions and design objectives can be translated into formulas used to calculate measurable objectives. These criteria are reduced to specifications expressed in measurable terms. During construction, ingredients and mixtures are tested for compliance with the specified control factors. It is assumed that the formula will lead to results that will assure a durable pavement. This can be a faulty assumption even when the contractor does everything exactly as specified.

Seldom is the in-place quality of the concrete determined except for thickness to verify structural factors. There is an exception. If problems develop, samples are taken and examined microscopically to assess the cause of the problem and to fix blame. Pavements that perform exceptionally well are seldom accorded the same level of study to determine why they performed so admirably though that information is invaluable.

I will address the more illusive subject of concrete deterioration based upon environmental factors. A slide (Figure 1) from the FHWA ED-89-006, *Portland Cement Concrete Materials Manual* provides good guidelines for durability, but how can it be used?

- A. Low water-cement ratio
- B. Adequate cement content
- C. Adequate strength
- D. Proper consolidation
- E. Adequate air-entrainment
- F. Sound, clean, well graded aggregates
- G. Adequate moist curing

Figure 1 — FHWA ED-89-006 Recommendations

These are sound recommendations but are not stated in quantitative terms. They are qualitative so someone must make a judgment on what should be done. Means whereby these very important characteristics can be achieved cannot be put into formulas to produce hard numbers that will be reliable for the infinite number of materials, climatological, and abrasive service variables. They are performance oriented but only air content is measured.

Similar terms such as “clean air,” “clean water,” and “zero emissions,” have been assigned quantifiable numbers but solutions to those numbers are left to people with technical skills. It is possible to similarly quantify each of the above factors but not through formulas. To do so requires research that has been only minimally accomplished. We have recommended procedures [1] [2].

When the above guides are scrutinized, it is easy to see that there are problems because this is not an exact science. During this analysis, I don't want this to sound like the Music Man and his exhortations to the people in River City about the potential problems of children with idle hands.

- 1) **Low water-cement ratio** — How can the water-cement ratio measured in the field? Is this with just cement or cement plus fly ash or ground-granulated slag? The fly ash and slag help increase strength by reactions with the cement hydration product so water is not a factor. It is possible low water-cement ratios are more theory from calculations than beneficial fact in concrete. There is established, though neglected, research that contradicts current theories when mixtures have only portland cement as the binder. Many feel slump aids in evaluating the water-cement ratio of the concrete as delivered. I suggest they look at Note 1 of ASTM C 143 as it discourages such thinking. The average coefficient of correlation between slump and strength is about 0.30 — poor at best.
- 2) **Adequate cement content** — What is “adequate” in measurable terms? Some seem to feel if a little is good, more is better. There are many occasions where the unnecessary addition of cement contributes to shrinkage and cracking problem. There is a level at which the addition of cement is such that it can act only as a filler. It can adversely affect mix rheology.
- 3) **Adequate strength** — Which strength? Is this for structural needs or durability? As will be seen, the strength that will be produced when the mix is proportioned to be durable in the environment will be considerably greater than that required for structural requirements. While 20 MPa (3,000 psi) may be adequate for engineering needs in an intersection or where vehicles change lanes frequently, ACI 201, “Durability of Concrete” recommends 41 MPa (6,000 psi).
- 4) **Proper consolidation** — Consolidation of the in-place concrete has not been measured so how is it possible that a quantitative value can be established for this very important characteristic? It is logical that if the concrete is very dense, deterioration related to water and water-borne factors will be minimized.
- 5) **Adequate air-entrainment** — What is adequate? Because a number is in a table does that make it valid? Concrete pavements cast long before air entrainment was used to resist freeze/thaw attack are still in service in severe environments. Recent studies are showing the size and distance between the air voids is more important than their volume. How much is trapped air due to a harsh mix? And how much and what is good air? There is no means to define the difference between trapped and entrained air. There's another problem. Some

air meters cannot detect the very fine air bubbles produced by the modern air entraining agents so how does one determine the air content?

- 6) **Sound, clean, well graded aggregates** — It is possible to determine if an aggregate source is sound using standard procedures. Cleanliness can be measured. But, how is the "well graded" characteristic measured? The concrete industry separates two size ranges of coarse and fine aggregates on the 4.75 mm (No. 4) sieve. When Duff Abrams introduced his water-cement ratio theory, he pointed out that it is only the combined gradation that really counts. The asphalt industry measures optimum gradation on the 0.45 power chart but there is no similar standard for concrete.
- 7) **Adequate moist curing** — There are quantitative measurements for moisture retention under laboratory conditions. There is no field measurement though such a method can reasonably be developed and used.

The problem is not so insurmountable as what I have said would indicate. Concrete is such a versatile road-building material that it is durable in spite of some of the things we do with it. Too, the length of time the concrete must be durable must be borne in mind. We are not talking about 10 years - 40 years is more appropriate. We do need better guidelines about how to achieve our durability objective and how recommendations in Figure 1 can be applied with minimal research.

The concrete that should be examined has been in place and already served well for 40 actual years in real world service. The only laboratory work will be the examination of the best performing pavements and ask the investigators why the concrete performed so well. One senior petrographer for a large federal agency told me that only once in his years of experience was he asked to determine why a piece of concrete was good.

My purpose is to provide a better foundation that a knowledgeable concrete technologists can use to develop concrete mixtures that will be durable in nature's many environments. These recommendations are based upon my many years' experience in the field and observations of concrete and concrete pavements in differing parts of the world. Once one learns the language, a pavement can "talk" to you through its surface condition language.

CURRENT PRACTICES

We need to scrutinize the traditional concrete pavement process to appreciate how that process contributes to the durability problem.

1. The materials specifications are based upon broad national or state-wide tolerances that are sometimes politically motivated. On occasions a high cement factor is specified to be "safe" in case the mix is not well proportioned. The low bidder selects his resources based primarily upon price,
2. Mixture proportioning is often relegated to repeating long outdated practices or even by predetermine quantities that "make it easy for contractors to bid." By-weight proportions, either furnished by the State or developed following an easy-to-apply formula are used throughout the project,
3. Equipment for mixing, delivering, placing, compacting, and finishing the pavement is selected by other people without consideration for the characteristics of the mixture to be used,
4. The selected mix is held inviolate throughout the project even when materials may vary within the extremes of the tolerances and site conditions may change, and,
5. The concrete is accepted based upon tests of materials taken before the mix is placed in front of the paving machine.

This system is not "engineered". It more or less just happens according to the way it has been done for many years. The contractor generally uses state supplied mix proportions or follows the traditional local practices. Though State personnel point out that the contractor may recommend his own mix, few contractors choose that option. If a change is suggested by the contractor and problems occur, the problems belong to the contractor. If he uses the state supplied mix, the state is responsible.

During the construction, the only adjustments to the mix are to correct for moisture in the aggregates. In the mean time, aggregate gradations are allowed to vary within the limits of the broad tolerances. It should be obvious that fixed weights of materials that are allowed to vary under broad tolerances will lead to variable products. Ride characteristics may change, edge sloughing may become a problem, and finishing be difficult. Despite these problems, the mix is not adjusted because a new one would have to be developed and processed through a time consuming, outmoded approval process. There is no wonder that we have "lemons" as does the automobile industry.

ENGINEERING THE MIXTURE FOR DURABILITY

"Engineering" is defined in my dictionary as "the transformation of materials available in nature to products usable by man." That definition indicates that selection of the proper materials and proportioning is the purest form of engineering though it is done by one often classified as a "technologist."

It is possible to profile a durable concrete composite. There are things we know about the factors that affect durability and current research is in progress to augment what we now know. Unfortunately few academic studies adequately describe the characteristics of the mix ingredients and the proportions so they can be correlated with materials in the field and the data used. Cement, sand, and stone are looked upon generically though aggregate particle size and shape and the cementitious materials chemical and physical data are needed to evaluate the research. Not all research is of value. We field types need information that can be used in practical terms. On occasions, we have found the mixes used to prove important academic findings were not realistic for the construction they were purported to represent. The data led to faulty conclusions.

There are two steps to be taken in engineering the mix for durability. First we need to determine what affects those factors that influence durability. Then we examine the materials and the construction process to see how they fit into the system. This subject can be a large volume so I will touch only on highlights that are not generally well understood. For example: cement types and their applications and the importance of proper curing are well established so I will not deal with them.

FACTORS AFFECTING DURABILITY

Permeability: Permeability is technically not a durability problem but failure to consider its importance can lead to premature deterioration of a portland cement concrete pavement. Permeability is caused by the occurrence of pores left by water channels, voids due to poorly compacted concrete, and cracks. If the total water content is low, the mixture has good rheological properties for placement, and the concrete is properly compacted; permeability will be low. The combined aggregate distribution can have an influence upon permeability.

Impermeable concrete is the concrete's best protection. It is possible that low permeability was a characteristic that has made old concretes perform well. Permeability can be measured by the AASHTO Chloride Permeability test or the boil test described in ASTM C 462.

Figure 2 is a segment of a core with a dense aggregate distribution. The particles tend to block the movement of water through channels. Figure 3 is a segment of a core B that has an abundance of mortar that can contain many water channels. The concrete in Figure 2 was cast in 1928 and the gradation was representative of the combined ASTM C 33 of the time. That specification required that "the sand be predominately coarse particles." Figure 3 represents concrete cast in 1988 and is typical of what we observe in most concrete cast today when fine sand may be used. Strength, adequate for highway loading, can be produced with either sand but the durability of the concretes will be different.

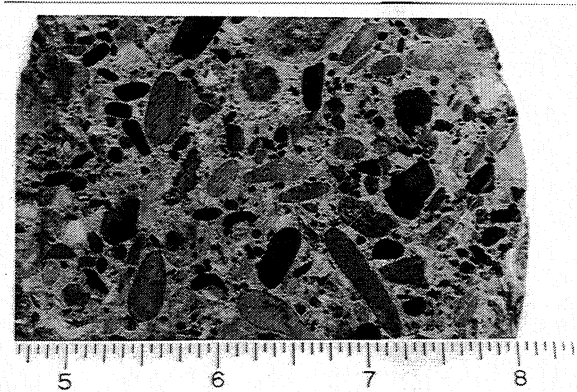


Figure 2 — Concrete with a dense aggregate distribution

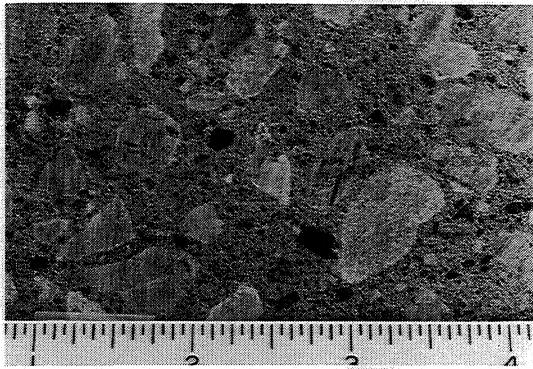


Figure 3 — Concrete with a poor aggregate distribution

The keys to low permeability are: low total water, well graded combined aggregate, good mixture rheology, and high in-place relative density.

Freeze/Thaw: Freeze/thaw resistance is important even in areas where there are but a few cycles of freezing and thawing. It's control is fairly well understood so there will be minimal discussion. Concrete deterioration in a freezing environment is often accentuated by uncontrolled use of salts to prevent the formation of ice. The primary deterrent to such deterioration is not only air content but also low water-cementitious materials ratio, and low permeability.

Increased concrete strength improves freeze/thaw resistance. However, the benefit of higher strength is based upon the water-cement ratio with a low water content. Strength can be increased but durability can decrease. While many highway designs allow the minimum required strength to be 3000 psi, the specification of that strength in areas subject to severe freeze/thaw can contribute to early deterioration. A maximum water-cement ratio of 0.45 is recommended for pavements in severe freeze

areas. When the field verified water-cement ratio is 0.45, the concrete strength, as measured by the cylinder test, will be about 5,500 psi. Since water-cement ratio cannot be measured in the field that quality should be evaluated based upon the strength produced in the field. If the concrete is judged acceptable because the strength is 3,500 psi, there is little doubt that the water-cement ratio was more than the specified 0.45 but that can't be proven by field test. It is probably closer to 0.60. The strength specified should reflect the more important criteria of durability and therefore be set at 5,000 psi. This procedure has been adapted by the American Concrete Institute in ACI 318, "The Building Code."

Loss of air during placement or air variation are of concern in some areas. Significant differences have been found between concrete as delivered, at the point of placement, and in hardened concrete examined petrographically. Air loss can be attributed to many factors and a number of studies are underway to determine these factors. In somewhat harsh mixes, trapped air is measured by the air meter but it may be expelled during placement and mechanical consolidation. Air can be best retained by using a uniformly graded combined aggregate in a cohesive mixture which responds well to vibration or movement. Also, if there is a deficiency in material passing the 600 micron (#30) sieve, entrained air may not be stable.

There are pavements and sidewalks in freeze/thaw areas which do not display spalling problems but were cast long before air entraining agents were introduced. These castings should be evaluated. It is anticipated the strengths will be over 6000 psi and the permeable voids by the boil test will be less than 12%.

The keys to freeze/thaw resistance are: Closely spaced small air voids, ultimate compressive strengths of 40 MPa (6,000 psi) or higher, well graded combined aggregate, low permeability, and good curing.

Shrinkage: Shrinkage affects durability in that the resulting cracks provide channels through which water and deleterious materials can migrate. Shrinkage is based upon the characteristics of the paste - the cement, water, air, and mix temperature. The lower the total water, the less the shrinkage. At a constant water-cement ratio, the less the cement, the more durable the concrete.

The keys to reduced shrinkage are: Low total water, low cement factor, low water-cement ratio, uniformly graded combined aggregate gradation, and minimal sharp and elongated particles.

Reactive materials: Reactive materials include sulfates and alkali reactivity. In both cases, care must be taken in selection and use of materials including the cement. A number of recent studies have indicated that the use of selected types of pozzolanic materials can reduce the problems caused by both problems.

The keys to reactive materials are: Proper selection of cement type and aggregates, low permeability to reduce the potential for water penetration, low water-cement ratio, and use of a properly selected pozzolanic material in the mixture.

Abrasion Resistance: Abrasion resistance is important for all wearing surfaces. Tires slip sideways about 6 mm (1/4") during a 90 degree turn and the churning action, especially on wet pavement, is highly abrasive. Response to abrasion occurs on a progressive basis. Initially, resistance is based upon the water-cement ratio, finishing, and curing. The strength of the paste and curing has the most affect on initial abrasion resistance. As the paste wears, the fine and coarse aggregates are exposed and become the primary lines of defense against further wear. Where there is a high incidence of hard coarse 9.5 mm to 1.18 mm (3/8" to No. 16) sieve size sand particles there will be little abrasive wear. Figure 2 is representative of such a concrete. Concrete that has a high incidence of 1/2" and larger coarse aggregate particles and fine sand tend to wear rapidly. Figure 3 is typical of concrete that abrades rapidly after the surface skin has been worn away.

Erosive wear is similar to abrasion but it is defined as "the progressive disintegration of a solid by cavitation, abrasion, or chemical action." The problem is a disruption in flow leading to a concentration of physical or chemical attack at certain locations in a concrete member. The forces of liquids can be such as to undermine a surface and force larger pieces of aggregate out of the concrete. Where drainage water flows adjacent to a highway, erosion should be considered.

The keys to reduced abrasive or erosive wear are: Over 40 MPa (6,000 psi) compressive strength, well graded combined aggregate, low water content, hard and dense aggregate that does not contribute to slipperiness, and air consistent with the exposure conditions.

Highway Roar: Highway roar is a relatively new subject. I first heard of it during a RILEM workshop in Helsinki in 1992 but heard more on return to the U.S. During a visit to a new highway outside of Helsinki, we traveled over an open graded asphalt. There was no roar. The new concrete highway was a dense exposed aggregate with many particles in the 9.5 mm size range. It had been cast in two layers. My hosts said that concrete strength was 70 MPa (14,500 psi).

Upon return to the United States and during the drive home on concrete pavement, I listened for roar and found everything from quiet to severe roar. That was at night so I returned to the highway and examined the differences in surface conditions. From those observations, I developed a theory and tested it on other highways and found that theory to be logical and accurate.

From my observations, roar is primarily caused by one of two happenings. First, rapid application of pressure on a small void on the surface followed by a mild explosive escape of the air when the pressure exceeds the load confining the air can sustain, e.g. the tire covering the void. I refer to this a exploding balloon theory. The second possibility is the noise created by the loss of the suction created by removing the pressure on the pressurized air in the void. The key to the theory was the quiet while driving over the open graded asphalt. The voids were present but there was no pressure build-up because there were openings under the surface aggregates to relieve the air pressure.

From many field observations since then, there is little roar where there is a dense surface — either concrete or small aggregate particles. Where there is heavy texture and near gap graded mixtures and where the surface mortar and that between the large particles has been eroded, there is roar.

I understand there are plans to use the European system that provides for two layer construction. In that case, the top layer is cast with a finer coarse aggregate, a higher strength, and the surface is removed by retarders. There are two reasons why I feel this is not wise. First, a well cast and properly cured concrete surface provides years of valuable life to the concrete. Good mixes, compaction, and curing are essential. Possibly there has been too much tying that created roar with high speed traffic. Second, the desired aggregate density can be cast into the concrete to quiet the roar and also improve the density of the concrete through its entire depth to provide long-term durability. The proportioning of mixtures for uniform, high aggregate density is not new. That has been done by the architectural concrete industry for many years.

CONSTRUCTION RHEOLOGY

If the laboratory tests indicate a mixture will produce the specified strength and have all of the properties needed for durability but the contractor has trouble placing and finishing it, that mixture will not perform as intended and not be durable. A paving spread is the final part of the manufacturing process [4]. As in any manufacturing process, all the parts and materials must fit if there is to be a good solution. If the parts don't fit, there will be problems.

The workability of concrete is often discussed but never measured. What is "workability"? It is not measured by slump. The response of concrete during mechanical placement and compaction does not respond as it does during a slump test. The settlement of concrete after the cone is removed is not comparable to the reaction of concrete in a paving machine or under high frequency, energetic vibration. Slump measures consistency of the batch being tested — not workability. Identical slumps from two successive batches of concrete do not assure the two batches will produce the same results and have equal workability.

A uniformly graded, well proportioned mixture will respond instantaneously to the action of a properly selected vibrator. The mixture will "melt" down rapidly and appear almost as a fluid in the zone of influence. This occurs even with low slumps. Good concrete mixtures have good rheological properties and have excellent "workability" characteristics.

ACI Committee Report 309, *Behavior of Fresh Concrete During Vibration* includes a chart by Ritchie [3] describing the factors that affect the rheological properties of concrete. Ritchie's chart (Figure 4) does not include the reference to "Adhesion". We have added this to reflect the effect of external influences upon a mixture. Excessive adhesion of a mixture to a chute, bucket, paving machine, or under a finishing tool is undesirable. Adhesion or "stickiness" interference must be overcome if the mixture is to perform well in the field and avoid edge sloughing after a slip-form machine passes.

Simply put, a mixture to perform well in a paving machine must be stable, cohesive, and respond well to the compaction equipment. With poor rheological properties, a mix can segregate during placement, respond sluggishly to the vibrators, sometimes honeycomb on the edges, and at other times sag and leaves a low place in the roadway. The better the mix, the smoother the surface. If a mix is too "bonny" the screed can't level it and the carpet drag can turn over aggregate. If it is too fatty, the screed drags and the edges sag.

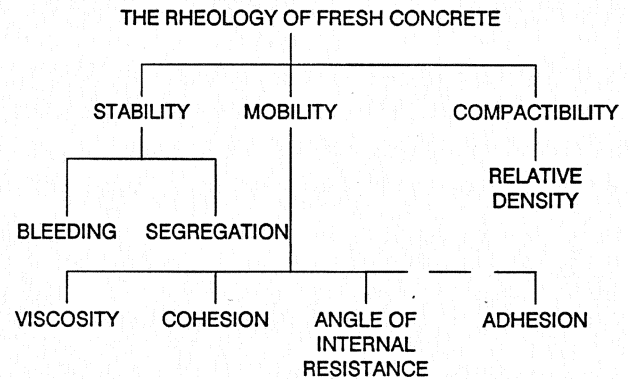


Figure 4 - Modified Rheology Chart by Ritchie

Stability is influenced by the two factors. However, in a paving operation, the tendency to use very high coarse aggregate factors and mixture with poor rheological properties can contribute to poor compaction and high coarse aggregate densities with voids at the edges and bottom of a pavement.

- Bleeding can delay slab finishing, contribute to surface blemishes and leave an excess of high water-cement ratio paste on a surface. Bleeding is affected by the gradation of the sand and the balance of finer particles in the mixture.
- Segregation during casting causes voids in paving that increase permeable voids and blemishes that must be patched. When segregation occurs during placement due to poor aggregate gradation and shape, it leads to honeycomb on the edges and a higher than desirable amount of voids inside a mixture. Where the segregated aggregate is on the top of the concrete, and the surface is rough with aggregate particles are turned over by a carpet drag.

Mobility is especially important for placement with a paving machine. The contractor has no control over the mixture characteristics once it is placed on the ground.

- Viscosity is measured in the paste. It must provide a proper balance of cementitious materials, entrained air, admixtures, and water. It should be stable during placement and be in sufficient quantity to coat all particles and also fill minor voids between the aggregate particles. False or flash set of a cement completely removes the viscosity of that portion of the mixture that is serving as a lubricant during placement.
- Cohesion is the antithesis of segregation. It starts with a stable mortar and ends with aggregate distribution which effectively uses the mortar. Aggregate particle distribution in portland cement concrete is almost as important as for asphalt. When the combined gradation of the aggregate is poorly distributed, there can be but two classes of materials — rocks and mortar. If the gradation varies within the limits of ASTM C 33, AASHTO, or equal grading standards to provide a

coarser coarse aggregate gradation — the mix is very harsh and bony. At other times, there is a surplus of fines and over mortared mix is not dimensionally stable as the edge form slip by the concrete. In a paving machine, the edges sag behind the skirt.

- The aggregate particle angle of internal resistance reflects the effect of particle shape and texture upon placement. Rounded and cubically crushed particles provide good workability. Elongated slivers and rod shaped particles cause placing and finishing problems. In pavements, they can cause major problems by interfering with vibrator action and cause voids and honeycomb. Rounded or cubical intermediate aggregate 9.5 mm to 1.18 mm (3/8" to No. 16) contribute to improved mix rheology.
- Adhesion describes the relationship of a mixture to its external environment. A mixture must flow and respond to vibrator equipment. It should not dampen the effect of the vibrator or produce a surplus of fat which will roll under the finisher's trowel. In paving work, it can retard the movement of the screed and cause a wavy surface.

Compactability is the ultimate objective. It is facilitated by good stability and mobility. If a mixture is sluggish, as found with over sanded mixtures, or bony, as with sharp edged, poorly graded coarse aggregate, it does not respond well to the vibrator. The quality of the in-place concrete will be reduced and the contractor's placement costs increased. When the materials are optimized, the concrete can be readily compacted to achieve its maximum density and provide good durability.

AFFECT OF THE AGGREGATE

Traditionally, little attention is given to the aggregate portion of the mixture as long as it meets the requirements of the specifications. Though occupying about two-thirds of a mixture volume, aggregate is looked upon generically. Tolerances are so broad that it is possible under some standards to meet a specification requiring 25 mm (1-inch) coarse aggregate and produce a material that is finer than that allowed under a specification for 19 mm (3/4-inch) aggregate. There is no requirement for day-to-day gradation uniformity. Note 8 in ASTM C 33 recommends the supplier deliver a consistent product but Notes are not enforceable under ASTM standards. ASTM C 33 provides that if a material fails to meet grading requirements, it may be used if it has a proven history of producing consistent strength. In other words, that portion of a concrete mixture that occupies a major portion of the mix volume is produced with minimally effective standards.

There are trends in the standards writing organizations to use performance standards for the combined gradation. It is being recommended that the engineer specify only the nominal maximum aggregate size and that the supplier furnish a uniform combined aggregate gradation. The specifier should also require compliance with the ASTM requirements for non gradation related quality in the specification.

It has been said that concern for the combined aggregate gradation is new and innovative and contrary to everything done in the past. That is not true. At the time Duff Abrams presented the water-cement ratio theory he said that it was the combined aggregate that was important. Later Treval Powers wrote of Abrams “. . . he abandoned the notion that concrete is a mixture of mortar and coarse aggregate, pointing out that the whole aggregate, fine and coarse combined, should be considered as one even though fine and coarse aggregate are proportioned separately.”

Many tests have shown that a well graded mixture can reduce water requirements, improve rheological properties, provide better ride, and should be more durable.

DEVELOPING THE MIXTURE MODEL

The foregoing has described the objectives for a well engineered mixture. Now that data must be translated into usable terms. The first thing to recognize is the requirements that two entirely different strengths need by determined. First is that for structural needs. The second is for durability. It is also important to identify the means for measuring that strength. Durability has been evaluated only based upon compressive strength. If the engineer still wants flexural strength tests, both tests should be run. Through use of statistics it will be possible to determine the relationship between the two and eventually settle on one. The relationship

will vary based upon materials sources and aggregate nominal maximum size.

Table I is a summary of the factors affecting durability. Once the requirements are determined, it is possible to develop a means to assure durability. A number of these factors are mutually supporting. The first measurable factor is the 40 MPa (6,000 psi) compressive strength. That strength will not have to be produced at 28-day age. Generally, a 35 MPa (5,000 psi) 28-day age concrete, if properly proportioned and cured, will produce 6,000 psi within 6 months. A pozzolan will aid in attaining the ultimate strength of 40 MPa (6,000 psi) due to its potential for improved long-term strength gain.

This sets a requirement for 35 MPa (5,000) psi at 28-days. A maximum water-cement ratio of 0.45 will produce field tests with adequate over-strength to comply with 5,000 psi the requirement. This is not the end. A 0.45 water-cement ratio can have 148 to 178 l/m³ (250 to 300 lbs/cy) of water. This difference would allow the cement factor to vary from 335 to 395 kg/m³ (565 to 665 lbs/cy). However, an objective is to have a low total water and low paste. That rules out the mix with the higher total water and cement. 148 l. (250 lbs) of water is reasonable for a well conceived paving mixture.

	Permea- -bility	Freeze/ Thaw	Low Shrink	React. Materl.	Abrasion Erosion	Max. Dense
Total Water	x		x		x	x
W/C Ratio	x	x	x	x	x	
Entrained Air		x			x	
High Density	x					
6,000 psi	x				x	
Pozzolan				x		
Permeability		x		x	x	
Aggr. Grade.	x	x	x		x	x
Low Paste	x	x	x		x	
Rheology	x	x	x	x	x	x

Table I – Factors Affecting Durability

The next problem is how to develop the mixture with the low water content. That can be resolved by a solution to other needs — a well graded aggregate. When the combined aggregates are blended to produce the maximum density, there will be less need for paste. The asphalt industry's 0.45 power chart (Figure 5) can serve as a guide. Concrete combined aggregate grading should be similar but with reduced amounts passing the No. 16 and finer sieves. We have suggested other alternatives and software is available to help perform the calculations.

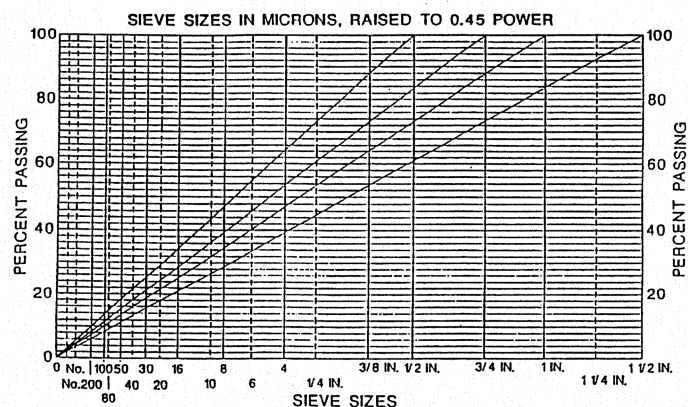


Figure 5 – 0.45 Power Chart

The final factor left is the in-place density of the concrete. That cannot be measured in standard wet-cast test specimens. High density is the product of properly placed and compacted concrete. That can be done by qualifying the paving machine with special attention to the vibration equipment. The results will be produced when the mixture has good rheological properties. Good rheological properties start with a uniform combined aggregate gradation. It is a simple matter to verify the relationship between a mixture and the proposed vibrator by preparing batches with differing mix characteristics, inserting the vibrator, turning on the power and watching the mix movement. In the optimum condition, a 1-inch slump concrete will virtually disintegrate when the power is turned on and take an almost thixotropic set when the vibration energy is removed. This helps achieve density while avoiding edge slough.

CONCLUSIONS

The qualitative requirements for durable concrete can be met using sound, properly applied technology. The methods outlined herein are not new. Many can be found in the first issue of the Portland Cement Association's DESIGN AND CONTROL OF CONCRETE. For the desired level of durability to be achieved, engineers must become more conscious of the factors that affect performance other than to sustain their anticipated load.

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