

PCC Mix Design

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Research Project GC8286, Task 1
PCC Mix Design

PCC MIX DESIGN

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SUMMARY

The objectives of this project were to provide insight into whether the current WSDOT mix design procedure is adequate and effective; how PCC mix design and placing requirements can accommodate the need for PCC at distances from central mix plants that are greater than could be covered within the specified maximum 90-minute transit time, and the need for high early strength PCC for patching and other rehabilitation applications; and the precautions that should be taken when non-standard procedures are used to qualify aggregates for use in WSDOT mixes.

The majority of the project consisted of a literature review. A large volume of literature exists relating to the various mix design parameters and their effects on both plastic and hardened PCC properties. The report summarized the information.

A limited investigation of field PCC with aggregate-related durability problems was also conducted to evaluate the effectiveness of current PCC mix design and to assess the potential for long-term problems when non-standard aggregate qualification methods are used.

CONCLUSIONS

The project found that the current WSDOT mix design procedure has produced excellent PCC in almost all applications except in terms of abrasion resistance. Additional work is needed to determine the cause of the low friction values on some pavements and what can be done to improve abrasion resistance.

However, while the standard mix design procedure has worked well for standard applications, special conditions such as long transit times or high early strengths need to be addressed.

Because of the difficulty in controlling air contents when long transit times are involved, transit mixed PCC should be considered. Mixes that are more

forgiving of variability, including richer mixes, should be considered. Additional job site quality control testing is also required.

When alkali aggregate reaction is not a problem, Type III cement should be considered for high early strength PCC. Where alkali reaction is a problem, higher cement contents should be used. Any accelerating admixtures should not be used until adequate information is available about its performance.

Any time high early strength PCC mixes are used, the problem of increased heat of hydration should be considered. Increased heat of hydration can lead to thermal cracking in thick sections, especially in hot weather.

When higher strength pastes are used to qualify aggregates, additional durability tests are needed to help assure the production of durable PCC. Tests for alkali-aggregate reaction and aggregate freeze-thaw resistance should be conducted. Only when a performance history shows that an aggregate source is durable should higher strength pastes be used to qualify aggregates without additional durability testing.

Any incidents of apparent aggregate-related durability problems should be carefully investigated to determine the causes of the problems, and true aggregate durability problems should be carefully documented.

Flyash, silica fume, water reducers, and superplasticizers all affect the entrainment of air in a PCC mix. Because air-entraining is sensitive to many parameters, including mix temperature, mixing time, and agitation time, field air contents of mixes containing any of these chemical or mineral admixtures should be evaluated more often than standard mixes.

CONCLUSIONS AND RECOMMENDATIONS

ADEQUACY OF THE CURRENT MIX DESIGN PROCEDURE

The current WSDOT mix design procedure has produced excellent PCC in almost all applications except in terms of abrasion resistance. Additional work is needed to determine the cause of the low friction values on some pavements and what can be done to improve abrasion resistance.

ACCOMMODATION OF SPECIAL CONDITIONS

While the standard mix design procedure has worked well for standard applications, special conditions such as long transit times or high early strengths need to be addressed.

Long Transit Time

Because of the difficulty in controlling air contents when long transit times are involved, transit mixed PCC should be considered. Mixes that are more forgiving of variability, including richer mixes, should be considered. Additional job site quality control testing is also required.

High Early Strength

When alkali aggregate reaction is not a problem, Type III cement should be considered for high early strength PCC. Where alkali reaction is a problem, higher cement contents should be used. Accelerating admixtures should not be used until adequate information is available that documents no durability problems associated with use of the admixture.

Any time high early strength PCC mixes are used, the problem of increased heat of hydration should be considered. Increased heat of hydration can lead to thermal cracking in thick sections, especially in hot weather.

NON-STANDARD AGGREGATE QUALIFICATION

When higher strength pastes are used to qualify aggregates, additional durability tests are needed to help assure the production of durable PCC. Tests for alkali-aggregate reaction and aggregate freeze-thaw resistance should be conducted. These tests may require considerable time, which may mean that aggregate source approval may need to begin before the job is advertised. Only when a performance history shows that an aggregate source is durable should higher strength pastes be used to qualify aggregates without additional durability testing.

Any incidents of apparent aggregate-related durability problems, such as the pop-outs near Issaquah, should be carefully investigated to determine the causes of the problems. True aggregate durability problems should be carefully documented, including aggregate source, so that future construction avoids aggregate durability problems.

Flyash, silica fume, water reducers, and superplasticizers all affect the entrainment of air in a PCC mix. Because air-entraining is sensitive to many parameters, including mix temperature, mixing time, and agitation time, field air contents of mixes containing any of these chemical or mineral admixtures should be evaluated more often than standard mixes.

INTRODUCTION

Portland cement concrete (PCC) is a blend of portland cement, water, and fine and coarse aggregates. Chemical and mineral admixtures can also be used to improve PCC properties and/or economy. PCC is a desirable material for use in pavements and bridges because of its strength, durability, abrasion resistance, ease of construction, and economy. But the success of any PCC mix is dependent upon the design of the mix to economically achieve strength, durability, abrasion resistance, and workability.

SPECIAL CONSIDERATIONS IN PCC MIXES

While the general criteria of PCC mix design are strength, durability, abrasion resistance, workability, and economy, actual construction situations can include some additional considerations, including

- lower quality local aggregates,
- long haul distances, and/or
- shorter cure times.

These special considerations are described below.

The economy in PCC mixes often comes from the use of locally available aggregates to minimize hauling. Where the aggregates are of high quality and have an excellent field performance history this causes no problem. But where aggregates may be of lower quality and there is no field history to show that the use of these aggregates may cause performance problems, extra care must be taken in the mix design process to ensure an acceptable PCC mix.

Where no acceptable aggregate source and/or central mix plant exist, long haul distances may be necessary. While longer haul distances are an additional expense, in some cases a more pressing concern is time. PCC must be placed before the mix begins to set. Typical specifications require PCC to be placed within 1 to 1½ hours after the cement and water are initially mixed. (1, 2) Special mix design

procedures may be necessary when long haul distances prevent concrete from being placed within specified times.

Construction time can be more important than PCC mix economy in some instances. Repair work to pavements and bridges that have already been open to traffic is often constrained by the amount of time that traffic can be blocked. Rapid strength gain without a sacrifice in long-term performance can become one of the PCC mix design criteria.

DOT MIX DESIGN PROCEDURE

The standard PCC mix design procedure used by the Washington State Department of Transportation (WSDOT) is a "comparison to standard" procedure. Aggregate gradations and aggregate and cement quantities are specified. Water up to a specified maximum amount is used to make PCC with a specified slump. The aggregates are limited in terms of deleterious substance content and Los Angeles abrasion value. Both the flexural and compressive strength of the mix in question are compared to a mix having the same slump and made with the same cement quantity and gradations of aggregate from Steilacoom, Washington. To be accepted, the mix must achieve 14-day strengths of at least 90 percent of the Steilacoom standard.

OBJECTIVES

The objectives of this report are to provide insight into the following considerations in PCC mix design:

1. Is the current WSDOT mix design procedure adequate and effective?
2. How can PCC mix design and placing requirements accommodate the following special conditions:
 - a. the need for PCC at distances from central mix plants that are greater than could be covered within the specified maximum 90-minute transit time, and

- b. the need for high early strength PCC for patching and other rehabilitation applications?
- 3. What precautions should be taken when non-standard procedures are used to qualify aggregates for use in WSDOT mixes?

PCC PROPERTIES

Physically, PCC consists of coarse aggregate suspended in a matrix of fine aggregate and cement paste (cement, water, and air), as shown in Figure 1. The cement paste coats all of the aggregate particles, both coarse and fine. The properties of a PCC mix in both the plastic and hardened state depend upon the individual properties of the aggregates and the paste, as well as the interaction between them.

WORKABILITY

Workability is a general term applied to a PCC mix in its plastic state that describes how easily the mix can be handled. Workability is actually a combination of two properties: consistency and cohesiveness. Consistency describes how easily concrete flows, and cohesiveness describes the tendency for a concrete mix to bleed and/or segregate. While bleeding is generally associated with mixes that have excess water, segregation can occur in mixes that are either "too dry" or "too wet." A dry mix that tends to segregate is often called harsh. Harsh mixes are normally caused by either poorly graded aggregates or insufficient mortar.

The standard test in the United States for measuring workability actually measures consistency. This test is the slump test, ASTM C 143. Other tests for determining PCC consistency exist but are not often used in this country. Cohesiveness is not directly measured in PCC. The tendency for a PCC mix to segregate is an observed rather than measured trait. A standard test exists for bleeding, ASTM C 232, but is seldom run. The U.S. Department of the Interior, Water and Power Resources Service uses a modification of the slump test to obtain a qualitative measure of cohesiveness. After the slump of the PCC is measured in accordance with ASTM C 143, the side of the PCC is tapped with the tamping rod.

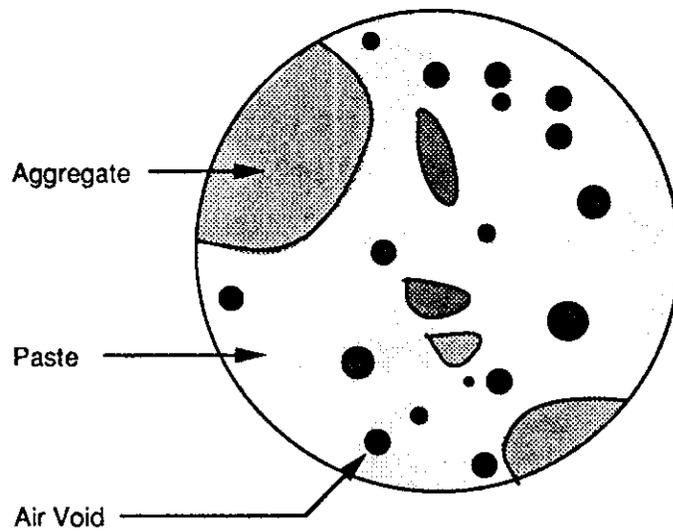
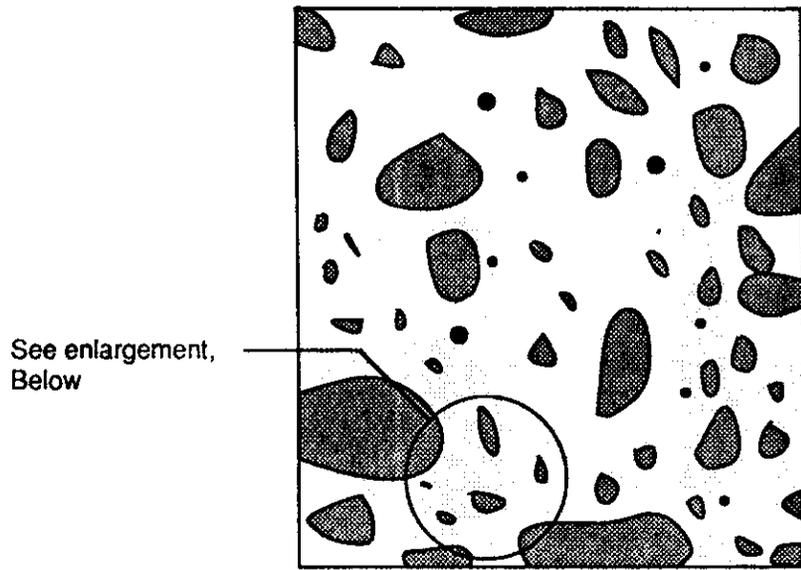


Figure 1. Cross Section of PCC Showing Aggregates Suspended in Matrix of Paste and Air Voids

The resulting behavior of the mix is defined as cohesive when the PCC holds together, or as harsh when the PCC falls apart. (3, 4, 6)

Placing

The necessary workability of a concrete mix is actually determined by three factors: placing, consolidating, and finishing. Placing is the process of getting the concrete into the formwork and around any reinforcement or unusual form shapes. This process is affected by the shape and surface texture of the aggregate and the quantity and viscosity of the cement paste. (3, 5) Smooth, rounded aggregate needs less paste to facilitate movement of the aggregates for consolidation than does rough, angular aggregate. A low viscosity paste is more conducive to aggregate movement than a stiffer paste but can contribute to excessive bleeding and/or segregation.

Consolidating

Consolidating is the process by which the PCC is made more dense by removing entrapped air. The viscosity of the paste is the most important factor affecting consolidation. Low viscosity helps consolidation, but again care must be taken to avoid bleeding and/or segregation.

Finishing

Finishing is the process of leveling the PCC to the desired degree of flatness and achieving the desired surface texture. The quantity of mortar is the major factor affecting placing, though extremely flat and smooth surfaces are also affected by the particle shape of the fine aggregate. The greater the amount of mortar, the easier the PCC is to finish. Smooth, rounded, fine aggregate finishes easier than fine aggregate produced by crushing operations. Finer particle sizes also make finishing easier.

STRENGTH

Because the aggregates in PCC generally do not touch, the strength of the PCC is related to the strength of the aggregate, the strength of the paste, and the strength of the aggregate-paste bond. The relative stiffness of the aggregate and the paste also affects PCC strength. (3)

Aggregate Strength

Aggregate is the primary constituent of PCC, typically occupying from 70 to 75 percent of the PCC by volume. (2, 7) For normal strength concrete (4,000 to 8,000 psi), aggregate strength is usually not a factor. Most commonly used aggregates have compressive strengths in excess of 8,000 psi, with some strengths as high as 30,000 psi or more. (3, 8) Many agencies (1, 2) test coarse aggregate with the Los Angeles Abrasion Test, ASTM C 131, which effectively eliminates weak aggregate. Weak, fine aggregate would probably degrade with handling and contain too many fines (minus #200 sieve) to meet gradation specifications.

Paste Strength

The relationship between strength and water/cement ratio (w/c) has been an accepted fact since at least 1918. (3) The lower the w/c, within practical limits of about 0.20, the higher the strength of the hydrated cement paste. Because hydration is a time and temperature dependent process, (9) strength is also a function of curing. Figure 2 shows relative strength as a function of moist curing time. (10) When PCC is allowed to air dry, the rate of curing decreases substantially. High strengths are achieved with a low w/c along with sufficient moist curing to reach a high degree of hydration.

Transition Zone

The weakest area in PCC is often the transition zone between the paste and the aggregate. The maximum strength of the aggregate-paste bond is often controlled by the paste strength, and a number of factors can reduce this bond strength, including the following:

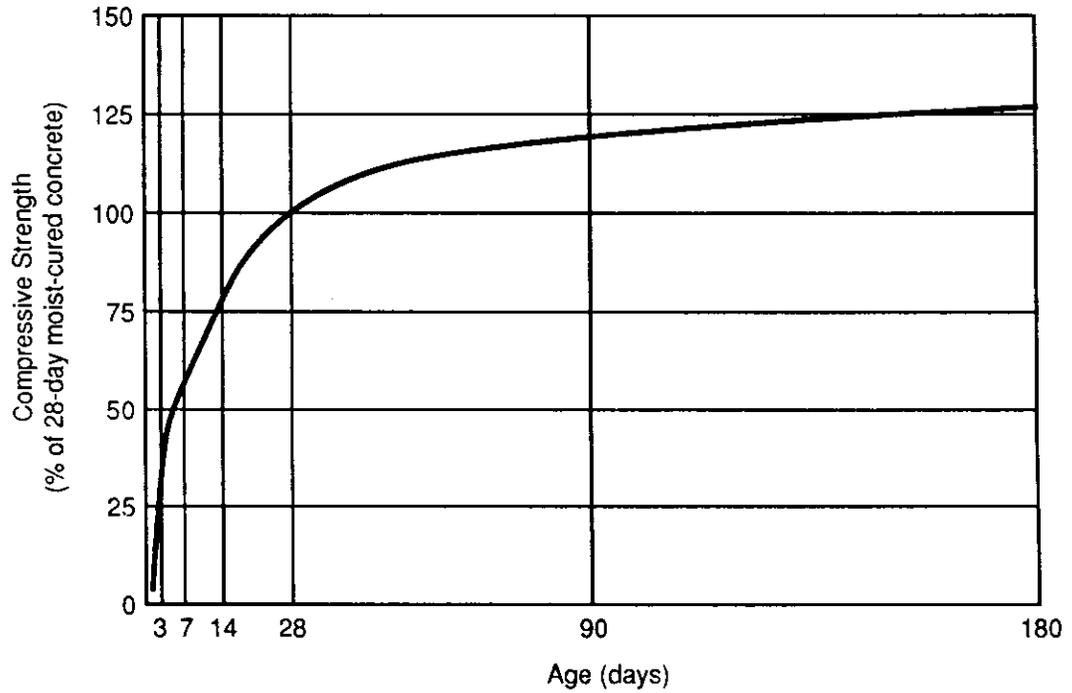


Figure 2. Percent of 28-day Compressive Strength versus Time for Continuous Moist Curing (after Reference 10)

- dirty aggregate - may not bond as well as possible,
- smooth aggregate surfaces - may not bond as well,
- dry aggregate - may absorb water from the paste and result in insufficient water for hydration at the paste-aggregate interface, and
- wet aggregate - may cause an increase in the w/c at the transition zone, resulting in lower paste strength.

Internal bleeding is often the major cause of weak transition zones. Bleed water that is trapped under aggregate particles will lead to an abnormally high w/c and weakness right at the paste-aggregate bond. This problem becomes worse with increasing aggregate size, flat or irregularly shaped aggregates, and rough aggregate surfaces.

When PCC flexural strength is a major concern, rough or crushed coarse aggregate can make the PCC stronger than gravel with the same w/c because of the improved paste-aggregate bond. The flexural strength improvement is typically about 20 percent. (4) However, angular aggregate requires more paste for the same workability. If this additional paste is provided only by an increase in mix water and not an increase in both water and cement, the resulting higher w/c could result in lower flexural strength.

Aggregate and Paste Stiffness

Aggregate is often not only stronger than the paste, it is also stiffer. Because strain compatibility must be maintained between the aggregate and the paste, this difference in stiffness can lead to stress concentrations in the paste. These stress concentrations increase with increasing differences in stiffness and with increasing coarse aggregate size. Excessive stress concentrations can lead to reduced strength.

Shrinkage can also cause stress concentrations. The paste shrinks as it dries, and this shrinkage is restrained by the aggregate. Larger and stiffer aggregates provide more shrinkage restraint (11), but this shrinkage restraint can lead to cracking at the paste-aggregate bond.

DURABILITY

Durability is the ability of PCC to withstand environmental exposure. Almost all PCC durability problems are related to moisture and moisture movement. This includes freeze-thaw damage, alkali-aggregate reactions, sulfate reactions, and expansive aggregates. While many factors can affect the severity of durability problems, one universal characteristic is PCC permeability. Decreasing the permeability will decrease the severity of, and in some cases may even prevent, durability problems. Permeability is most strongly affected by w/c and degree of curing. Low w/c and good curing practices will substantially decrease PCC permeability. (3, 4)

The other major factors affecting PCC durability are discussed below under the appropriate durability problem.

Freeze-Thaw

Freeze-thaw attacks both the paste and the aggregate in PCC. The most common type of freeze-thaw damage is in the paste. This damage can range from total disintegration of the paste phase of the PCC to mere scaling of the PCC surface. The severity of the freeze-thaw damage to the paste depends on the number and severity of the freeze-thaw cycles, the availability of moisture, and the PCC itself.

Air entraining has long been recognized as an effective method of preventing freeze-thaw damage to PCC paste, as long as the PCC is not at too high a degree of saturation. (12) An air-entraining agent is added to the PCC mix. It produces many tiny bubbles with a typical diameter of about 0.10 mm. and ranging from 0.05 to 0.20 mm. (3, 13) Volumetric air contents of 4½ to 7½ percent are normally specified to ensure frost-resistant concrete. A maximum w/c of 0.45 to 0.50 is also specified to ensure adequate strength and low permeability. (14)

Actual air content is not sufficient to protect paste from freeze-thaw damage because a small number of large voids can produce the same air content as a large

number of small voids. A maximum distance between air voids is necessary for protection. Powers defined a spacing factor, L , as the longest distance from any point in the paste to the edge of the nearest air void. (12) He assumed that the air voids were distributed in a cubic arrangement, and all of the voids were the same size. He also developed a method of measuring L in hardened concrete. That method has evolved into ASTM C 457, "Microscopal Determination of Air-Void Content and Parameters of the Air-Void System in Hardened Concrete," often called "Linear Traverse Method for Determining Air Content in Hardened Concrete." For normal air-entrained concrete, 0.20 mm is the suggested maximum recommended value for L in order to protect the concrete matrix from freeze-thaw damage. (14) Some researchers suggest that the maximum value of L be increased for special cases, such as high strength concrete made with high-range water-reducing admixtures (17), or concretes exposed to less severe freeze-thaw. (18) They generally agree, however, that a maximum L of 0.25mm will protect concrete with a maximum w/c of 0.50 from freeze-thaw damage.

The term D-cracking is normally used to describe freeze-thaw damage that is caused by aggregates, and it can occur even in properly designed, air-entrained PCC mixes. (15) Susceptible aggregates are usually sedimentary rocks and can be found in either ledge deposits or gravels. Knowing the specific rock type is not sufficient for identifying D-cracking aggregates; instead, the pore volume and pore size distribution are the most significant factors. Because D-cracking often starts at the bottom of a PCC slab, ten or more years may pass before it appears on the surface. Severe D-cracking can reduce a strong PCC slab to little more than a compacted granular base. (16)

Alkali-Aggregate Reaction

Alkali-aggregate reaction is a chemical reaction between the alkali (basic) environment in the cement paste and the silica in the aggregate. This reaction results in expansion, which in a brittle material like PCC can cause failure. While

any silica aggregate can react with alkali, the reaction is normally too slow to cause problems. However, glassy, amorphous, or microcrystalline silica may react at a rapid enough rate to cause expansion in the PCC. Because expansion is volumetric but the reaction generally occurs on the aggregate surface, particle size affects the severity of the reaction. Coarse aggregate, unless it is porous enough for the reaction to occur inside the aggregate as well as on the surface, generally does not cause deleterious expansion. Material fine enough to pass the number 200 sieve may react with the alkali environment, but expansion is seldom a problem. The reaction may occur so rapidly that the reaction product is included in the hydrating paste, or the expansion may be accommodated by porosity in the paste. The worst expansion problems generally occur when the reactive aggregate is sand-size, especially 1 to 5 mm. (3) Though the most severe reactions may be detected in the first few years after the PCC has been placed, slower reactions may not be apparent until ten years or longer. Alkali-aggregate reactions can also contribute to micro-cracking, which may accelerate freeze-thaw damage.

A number of standard tests exist for identifying alkali-reactive aggregate, ASTM C 227, ASTM C 289, ASTM C 586, and ASTM C 342, but they are either slow or not completely reliable. A reliable, accelerated test method has recently been developed (20) and verified to use the same mechanism as slower standard tests (21), but time is required before this test becomes well accepted.

The best way to avoid alkali-aggregate reaction problems is to only use aggregate with a field history of no problems. When potentially reactive aggregate must be used or the reactivity potential is uncertain, low alkali cements or mineral admixtures (pozzolans) that reduce the alkalinity of the cement are recommended. Problems can still occur though, especially if the concrete is used in an alkali environment. Cathodic protection of bridge decks may also defeat the purpose of low alkali cements by concentrating alkalis at the reinforcing steel. (19)

Sulfate Reaction

Sulfate reaction is the reaction of the cement paste with sulfates from the environment. Two distinct sulfate reactions actually occur: reaction with calcium-aluminates in the cement paste, which results in expansion, and reaction with calcium-silicates, which dissolves a portion of the paste and results in a loss of strength and stiffness. The second reaction generally requires higher sulfate contents and is most severe when sulfates of magnesium are present. Often, micro-cracking caused by expansion from the first reaction leads to increased permeability, which permits sufficient sulfate contamination for the second reaction to occur.

While most soils contain some sulfate in the form of gypsum, their low sulfate content of 0.01 to 0.05 percent is usually harmless to concrete. Higher sulfate contents, usually in the form of magnesium and other alkali sulfates in excess of 0.1 percent (150 mg/liter SO_4 in water), are necessary to cause detrimental sulfate reactions. Other sources of sulfates include ammonium sulfate from agricultural fertilizers, sulfuric acid from high-sulfur coal burning, industrial wastes, seawater, and acid rain. (3)

The best protection from sulfate attack is to eliminate the source of sulfate. As this is not always possible, low-permeability concrete is essential. Low permeability is achieved through high cement content, low w/c, proper consolidation, and good curing. Adequate concrete thickness is also important, as this permits gradual sacrifice of the surface exposed to sulfates without compromising the structure. These precautions are especially important when the concrete is exposed to alternating wet-dry cycles or one surface of the concrete is wet while another is dry. The evaporation of water from concrete exposed to sulfate increases the sulfate content.

Two grades of sulfate-resistant cement are available. Type II has moderate sulfate resistance and is recommended for placing against soils with a sulfate content below 0.2 percent or 1500 ppm in water. Type V is sulfate-resistant for

placing against soils with a sulfate content up to 2.0 percent or water solution below 10,000 ppm. (14, 22) These cements achieve their sulfate resistance primarily by limiting the calcium aluminate content. This provides protection from the expansive reaction but not from disintegration of the calcium silicates associated with high sulfate contents. Additional protection is achieved when the calcium-hydroxide content is also reduced. For very severe sulfate exposure, the use of blast-furnace slag cement or pozzolans is recommended in addition to low calcium-aluminate contents. (3)

Expansive Aggregates

Aggregates are composed of both solid materials and pores. The pores can be either isolated or interconnected, and the interconnected pores can have considerable effect on long-term durability. Aggregate with a large quantity of pores with radii less than 5×10^{-3} mm. can expand and contract upon wetting and drying, similar to clay soils. Though the magnitude of the volume change is considerably less than that of clay soils, this volume change in coarse aggregate can cause problems in a relatively brittle material such as PCC. The problems are worst in aggregate such as shale and chert, but can also occur in argillaceous limestones and dolomites, some sandstones, and fine-grained volcanic rocks. (23)

Problem aggregate is often identified by ASTM C 88, which uses wet-dry cycles in a saturated sodium or magnesium sulfate solution to determine the resistance of the aggregate to disintegration. The salt solution accelerates the disintegration process of the aggregate. Problem aggregate may also fail the Los Angeles Abrasion test, ASTM C 131. Because of the inherent variability of gravels, problem aggregate in gravels may be difficult to identify with these tests.

Expansive aggregate may appear as pop-outs in concrete surfaces and not cause any structural problems at all. Freeze-thaw can attack expansive aggregate, leading to D-cracking. Because of high porosity, some expansive aggregate containing non-crystalline silica may be susceptible to alkali-silica reaction. The use

of de-icing salt or other types of salt contamination may also increase an expansive aggregate problem. Any of these complications can change expansive aggregate from cosmetic surface pop-outs to structural damage.

ABRASION RESISTANCE

Abrasion resistance is important to pavement PCC for surface friction. New pavement and bridge deck construction is often given a tined finish. When wear causes a loss of that finish, surface friction decreases. As wear continues to remove mortar between the coarse aggregate, surface friction often continues to decrease. In extreme cases, abrasion can include the coarse aggregate, resulting in rutting. Standing water in the ruts can lead to hydroplaning.

Abrasion resistance of the coarse aggregate is normally assured by specifications controlling maximum loss in the Los Angeles Abrasion test, ASTM C 131. Abrasion resistant paste is much more difficult to provide.

The abrasion resistance of the mortar portion of PCC is improved through a decrease in the w/c and good curing. In addition, non-air-entrained PCC is improved by repeated power finishing. The increase in surface consolidation along with increased evaporation of bleed water is believed to improve abrasion resistance with repeated finishing. (24)

The finishing of air-entrained PCC must be minimized to avoid a loss of entrained air near the surface. Surface scaling, discussed above under freeze-thaw, is aggravated by wear, and the combination of traffic and inadequate air-entraining can allow abrasion to cause significant loss and result in a loss of surface friction.

Increased abrasion resistance has been reported with the use of fly-ash (FA) (25) and silica fume. (34) Possible explanations include increased strength in comparison to normal PCC and reduced loss of entrained air at the surface. The reduced loss of entrained air could be due to easier consolidation of the FA and

silica fume PCC and the higher viscosity of pastes containing FA and silica fume, which help retain entrained air.

Abrasion resistance in mixes not subject to freeze-thaw has been increased by the use of fine aggregates produced by crushing. (34) However, the additional finishing necessary when crushed material is used for fine aggregate could cause problems in PCC exposed to freeze-thaw.

MIX DESIGN

The ability of a PCC mix to achieve the desired properties depends mainly upon the materials used to produce the PCC. A description of the principal PCC ingredients and their effect on mix properties is given below.

WATER

Water influences all PCC properties. Workability improves with increased water content, as the mix changes from a stiff to a flowing consistency, but segregation can occur at higher water contents because of the reduced cohesiveness of the mix. Strength depends upon w/c. Increasing the w/c lowers strength while increasing permeability, which leads to lower durability. Drying shrinkage is also related to water content, with typical shrinkage on the order of 2.5×10^{-4} in/in for PCC with 250 lb water/cu.yd to 6.5×10^{-4} in/in for 450 lb water/cu.yd. (4) The water content of a PCC mix is normally determined by workability requirements.

CEMENT

Cement is normally the most expensive ingredient in PCC, and therefore, mix economy dictates minimizing cement content. Because of the fine nature of cement, an increase in cement content requires a slight increase in water content to achieve the same consistency. Mixes with a high cement content (often called "rich" mixes) are generally more cohesive than mixes with a low cement content ("lean" mixes). The minimum cement content of a PCC mix is often determined by strength requirements after the necessary amount of water has been estimated. The minimum cement content for strength and durability may also be specified by experience.

A variety of cements are available for use in PCC. The major difference between these cements lies in their chemical composition and the reaction products that are created when the cements hydrate. The major reaction products of

portland cement are tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and calcium ferroaluminate (C_4AF). Typical quantities of these products and their influence on the PCC mix are given in Table 1. Portland cements contain an excess of calcium oxide (CaO). This provides a basic environment and helps the reactions to proceed faster. Gypsum is added to portland cement to control flash set, and other compounds are often present as contaminants. (3)

Though not a type of portland cement, calcium aluminate cement is often available. It is often used in refractory mortars and concretes. The principal types of cement and their influence on PCC mixes are described below.

Type I-II

This is the "normal" portland cement. While there is a difference between Types I and II, ASTM C 150, there is sufficient overlap in the specifications for a cement to often meet both specifications.

Type III

Type III is often called "High Early Strength" cement. Its early strength is higher, though its long-term strength may be slightly lower, than Types I or II. Type III cement produces significantly higher heat of hydration, which can lead to thermal cracking. Thermal cracking can present problems when low permeability is important. Type III cement is also often ground finer than normal cement. This increases the rate of reaction but can also cause a slight increase in the water requirement for the same workability.

Type V

This cement is used to resist sulfate attack. Its gain in strength is slightly slower than that of normal cement, but its ultimate strength can be higher.

Calcium Aluminate Cement

Though not a portland cement, calcium aluminate cement (also called high alumina cement or cement fondué) is sometimes used to repair PCC structures. This is because the cement gains strength very rapidly and is very strong.

Table 1. Constituents of Portland Cement (after Mehta (3))

PCC Composition				
Compound	C ₃ S	C ₂ S	C ₃ A	C ₄ AF
Effect of Compound				
Reaction Rate	Medium	Slow	Fast	Medium
Early Strength	Good	Poor	Good	Good
Ultimate Strength	Good	Excellent	Medium	Medium
Heat of Hydration	Medium	Low	High	Medium
Percent Composition by Cement Type				
Type I	45-55	20-30	8-12	6-10
Type II	40-50	25-35	5-7	6-10
Type III	50-65	15-25	8-14	6-10
Type V	40-50	25-35	0-4	10-20

Compressive strengths of 6,500 psi in 24 hours for w/c of 0.45 are not unusual. Calcium aluminate cement is also quite resistant to acid and sulfate environments. (3, 4)

Problems occur with calcium aluminate cement when it is used in a warm, moist environment. The reaction products created by hydration break down to yield a weak, porous structure. The reduction in strength can be as much as 50 percent over a 20-year period at 68°F. The reduction at higher temperatures is greater and more rapid; for example, after 90 days at 104°F strength may only be 33 percent of the 28-day strength. Such an environment can easily be achieved in patches under a bridge deck overlay during a warm summer.

AIR

Both entrapped and entrained air can be present in PCC mixes. Though most entrapped air is removed by proper consolidation, typically 1 to 2 percent by volume of the total mix typically remains. (10) This air has no benefit to the mix.

Entrained air is necessary to give the paste freeze-thaw resistance. Air-entraining admixtures are used to produce air contents of 4½ to 7½ percent. The amount of entrained air produced by a given dose of admixture is sensitive to a variety of factors including but not limited to temperature, duration of mixing, consistency, cohesiveness, fine aggregate gradation, fines content, duration of vibration during placing, and the presence of other admixtures.

Duration of mixing, consistency, and cohesiveness are somewhat related in their effect on air content. Sufficient mixing must occur to produce the air bubbles initially, and the air bubbles are easier to produce in less stiff mixes. Over-mixing can lead to a loss of entrained air. Mixes that are very fluid also lose air easily unless the paste is quite cohesive. In general, decreasing the slump from 4 inches to 1 inch decreases the air content about 1 percent. Slumps over about 6 inches tend to lose air easily.

Fine aggregate is important for the retention of entrained air. Sizes from the No. 30 to No. 100 sieves have the greatest influence. This size range is especially effective in providing a "three-dimensional screen" to trap the air bubbles. Finer particles, however, tend to decrease the air content of PCC mixes. These fines may be in the form of silts from "dirty" aggregates, excess cement in rich mixes, mineral admixtures, or coloring agents. They tend to inhibit the formation of entrained air bubbles, though these same fines may help retain air voids that are produced because of the influence of fines on cohesiveness.

Air content generally decreases as temperature increases, and this effect is increased by an increased slump. Careful monitoring of air content is necessary when PCC is placed in hot weather to maintain an adequate amount of entrained air.

Vibration during placing decreases air content. While vibration is quite effective in eliminating entrapped air, excessive vibration and work on the plastic PCC can lead to a loss of entrained air as well.

The presence of other admixtures can either increase or decrease the amount of entrained air produced by a given dosage of air-entraining admixture. Combinations of admixtures, especially when the admixtures come from different suppliers, should be carefully tested. (26)

Though entrained air tends to decrease compressive strength in comparison to non-air-entrained PCC with the same w/c, entrained air improves the workability. Mixes with identical cement contents and slump show that the strength penalty from entrained air is partially offset by the lower water requirement for workability. (3)

Air-entrained PCC tends to be very difficult to trowel to a smooth finish. The mix tends to stick to the trowel, and continued troweling often causes tears in the surface. PCC flatwork requiring entrained air for freeze-thaw durability should normally receive a broomed or tined finish for improved surface friction.

AGGREGATE

Aggregate is the major portion of PCC mixes, and because aggregate generally costs less per unit quantity than the other ingredients, aggregate has a major effect on mix economy. Because aggregate often occurs naturally, variability must be accommodated in PCC mixes. To reduce variability, aggregate is generally divided into coarse and fine aggregate with the No. 4 sieve (4.76 mm). Coarse aggregate with a maximum aggregate size exceeding 3/4 or 1 inch may be further divided to permit reblending.

Coarse Aggregate

Coarse aggregate affects strength, stiffness, durability, and abrasion resistance to some degree, but these properties are influenced to a greater extent by the mortar fraction of the PCC. Only in the cases of weak, soft, poorly shaped, or non-durable aggregates does coarse aggregate merit major consideration for these properties. Workability and volume stability, however, can be closely related to coarse aggregate.

Workability generally increases as the percentage and size of the coarse aggregate increases. This is due to the reduced amount of paste required to coat coarse as opposed to fine aggregate particles. Coarse aggregate surface texture also affects workability. Rough surfaces from crushed material require more paste than smooth gravels for the same workability.

Coarse aggregate has a major influence on thermal expansion and contraction. In general, stronger aggregate tends to produce PCC with higher coefficients of thermal expansion. Limestone typically produces PCC with expansion rates of 3 or 4 x 10⁻⁶in./in. F°, while granite produces 5 x 10⁻⁶in./in. F° and quartzite produces 7 x 10⁻⁶in./in. F°. Coarse aggregate tends to restrain drying shrinkage in PCC. As the coarse aggregate content increases, shrinkage is reduced, which is important for applications such as pavements.

Fine Aggregate

Fine aggregate or sand, along with paste, must fill the voids between the coarse aggregate particles. Fine aggregate varies from relatively coarse, with little material in the smaller size range, to finer materials. Fineness modulus, 0.01 times the sum of the quantities individually retained on the Nos. 4, 8, 16, 30, 50, and 100 sieves, is used to evaluate the relative coarseness or fineness of a sand. Fine sands typically have values around 2.50, while coarse sands may have values of 2.90 or higher. Higher quantities of coarse aggregate can be used with fine sands to produce PCC mixes with the same workability, but as the quantity of material passing the No. 100 sieve increases, additional paste is needed to coat individual particles. (3, 10)

CHEMICAL ADMIXTURES

Chemical admixtures are often used to alter the properties of PCC mixes. A variety of admixtures are available, and care must be taken to ensure that combinations of admixtures are compatible.

Air-Entraining

Air-entraining admixtures belong to a chemical class of materials called surfactants, which includes such common materials as soaps and detergents. A wide variety of chemicals entrain air in PCC, with varying degrees of success. The most common air-entraining agents are forms of vinsol resins, though alkyl sulfonates, sulfonated lignins, sulfonated hydrocarbons, and various protein salts and compounds made from animal fats and vegetable oils have also been used. Many claims have been made concerning specific air-entraining agents producing "better bubbles." Because of the complex balance among the air-entraining agent, specific cement chemistry, PCC mix proportion, aggregate type, mixing, placing, and finishing, the best air-entraining for a specific application may often be a matter of trial and error. (26)

Accelerating

Many chemicals are known to accelerate the rate of strength gain in PCC, including alkali hydroxides, silicates, fluorosilicates, organic compounds, and a number of calcium salts. Calcium chloride is the best known and most used of these. Higher cement contents and higher temperatures are also known to have an accelerating effect.

Accelerating admixtures not only accelerate the rate of early strength gain but also decrease the set time. While this can be an advantage in cold weather, decreased set time can be a disadvantage in warm weather when accelerating admixtures are being used to achieve high early strength. Accelerating admixtures also tend to increase the rate of heat evolution at early ages, which can lead to thermal cracking in thick sections.

Calcium chloride improves early properties, including abrasion and freeze-thaw resistance, because of increased early strength. But long-term strength and durability are often reduced. Calcium chloride tends to decrease the freeze-thaw, alkali-aggregate, and sulfate reaction resistance of PCC. The presence of chlorides accelerates the corrosion of reinforcing steel and can also lead to expansive reactions with aluminum and zinc (as in galvanizing) embedded in PCC.

Another calcium salt, calcium formate, causes accelerating effects in PCC similar to those caused by calcium chloride, though higher doses are required. Calcium formate also tends to increase early drying shrinkage.

Calcium nitrate, calcium nitrite, and calcium thiosulfate have also been used as accelerators. Little research has been conducted to determine the long-term effects on durability of these admixtures.

Formaldehyde and paraformaldehyde have been found to accelerate PCC setting. Small amounts of finely ground hydrated portland cement have been found to be as effective as calcium chloride in accelerating setting, probably by serving as reaction initiation sites in the PCC mix. (27)

Water Reducing

Water reducing admixtures are used to decrease the quantity of water in a PCC mix. This use can have three purposes: to increase strength by holding the cement content constant while decreasing water, to increase economy and reduce the shrinkage and heat of hydration by decreasing both cement and water, and to improve workability with no change in mix proportions. Applications often include a combination of the above purposes.

Most water reducing admixtures are composed of lignosulfonates, hydroxycarboxylic acids or carbohydrates. Other chemical groups are possible, but these are the most common. All of the above compounds also tend to retard the set of the PCC mix and are sometimes combined with accelerating agents in commercial admixtures to counteract the retarding effect. Because of the retarding effect, large overdoses, two or three times the recommended dosage, may substantially delay set and reduce early strengths. Delayed set can also increase plastic cracking because of evaporation before setting.

Lignosulfonates tend to entrain air, and defoaming agents are often added to reduce this tendency. Making air-entrained PCC with lignosulfonate-based water reducers containing defoaming agents may require job-site adjustments in mix proportions.

The water reducing effect is greatest when the admixture is added after the PCC has been completely mixed. This makes control of the desired slump difficult. More predictable results are obtained when the PCC is initially mixed with half of the mixing water, followed by addition of the water reducer in about 25 percent of the total mixing water. The remaining 25 percent of the mixing water is used as needed to achieve the desired slump.

Lignosulfonates tend to reduce bleeding in fresh PCC mixes, while hydroxycarboxylic acids increase bleeding. Some carbohydrates increase and others decrease bleeding. Finishers should be aware of the admixtures used in the PCC

mixes they are working on so that they can proceed with the finishing operations at the proper times.

The strength of hardened PCC made with water reducers is generally greater than that of control mixes at all but the earliest ages (one week or less). The actual strength difference depends on the w/c and mix proportions. Durability can be improved with a lower w/c because it gives a lower permeability. Entrained air is necessary for freeze-thaw durability, and when use of a water reducer causes inadequate air-entraining, freeze-thaw durability can be a problem. Proper inspection and control during construction is important. (5)

Superplasticizing

Increasing the workability of PCC without increasing the water content is called plasticizing. Increases in slump on the order of 2 or 3 inches is possible with water reducing admixtures, but greater increases from higher dosage rates are not recommended. Larger increases in workability are possible with superplasticizers. These admixtures can increase slump 6 inches or more.

Superplasticizers are different chemically than water reducers and are generally classified as sulfonated melamine-formaldehyde condensate (SMF), sulfonated naphthalene-formaldehyde condensate (SNF), modified lignosulfonates (MLS), and others, including sulfonic-acid esters and carbohydrate esters. Combinations of these general classifications are possible.

Mix designs using superplasticizers generally require a higher sand content to prevent segregation and severe bleeding. The additional sand requirement may be 5 percent or more of the total aggregate quantity (sand as a percent of total aggregate is increased 5 percent, while coarse aggregate is reduced 5 percent). Fine sands (fineness modulus values of 2.3 - 2.6) are preferred to coarse sands (fineness modulus values of 2.8 - 3.1).

Superplasticizers generally work by dispersing the cement particles in the mix water. This can lead to more complete hydration of the cement and a finer pore

structure in the hardened PCC. This dispersing affect can wear off quite quickly, and substantial loss of slump can occur in the fresh mix.

Superplasticizers based on SNF can be similar to water reducers containing lignosulfonates in terms of entraining air and requiring the incorporation of defoaming agents. In addition, superplasticized PCC can lose entrained air easily during placing, consolidation, and finishing. Repeated doses of superplasticizer to maintain workability, while seldom detrimental to strength, can aggravate the loss of entrained air. Careful control is required to produce properly entrained PCC.

Other than problems in maintaining an adequate amount of entrained air, durability appears to be either improved or unaffected by the use of superplasticizers. Improved durability may be due, in part, to the lower w/c possible with superplasticizers. Some researchers report that the entrained air spacing factor, L , increases with the use of superplasticizers. Additional research is needed to quantify the required L for superplasticized PCC. (28)

Set Retarding

As mentioned under "Water Reducing Admixtures," many of the chemicals that have a set retarding effect also serve as water reducers. The same advantages and problems that are associated with water reducers that do not contain accelerating agents apply to the use of retarding admixtures. Continued agitation of mixes containing retarders for the purpose of allowing longer hauling times may decrease the entrained air. Long agitation times can also lead to uncertainty about whether a loss of slump is due to evaporation of water or early hydration reactions. (4, 5)

MINERAL ADMIXTURES

Because portland cement contains more calcium than is necessary for complete hydration, any admixture that supplies silica for reaction with excess calcium can advantageously affect PCC mixes. The most common admixture

sources of silica are flyash and silica fume. These materials can be either used to replace a portion of the portland cement in a mix, or as an addition to the portland cement. Particles of both flyash and silica fume tend to be spherical, and when they are used to replace portland cement they can improve the workability of the mix. But because both of these mineral admixtures are substantially smaller than the No. 100 sieve, the use of these materials in addition to the normal amount of cement requires a water reducing or superplasticizing admixture to retain workability without adding water.

Flyash

Flyash results from the collection of dust produced by burning fossil fuels. The exact chemical content is very dependent upon the source of the fuel and the characteristics of the burning process. Therefore, changes in mix properties are likely when a flyash source is changed.

Flyash normally has a particle size distribution similar to that of normal portland cement, and therefore the effect on the finishing characteristics of a PCC mix is similar to what would be achieved by increasing the cement content. Flyash also improves the bleeding resistance and cohesiveness of the PCC.

Typical flyash use ranges from 10 to 30 percent of the weight of the cement in a PCC mix. Flyash has also been used as replacement of 25 percent or more of the cement. Many agencies permit the use of flyash as a partial cement replacement, i.e., replacing 10 percent of the cement with twice the amount by weight of flyash. Because, like cement, some flyashes contain calcium oxide, the best proportion of flyash for a particular PCC mix must be determined for the flyash source being used.

Flyash tends to delay setting and also to decrease early strength, especially in mixes containing flyash as a cement replacement. The reduced early strength gain is accompanied by reduced heat of hydration, which is an advantage in large sections.

Strengths at later periods, normally 56 days and later, are equal to or greater than control mixes without flyash.

The use of flyash can affect the required dosage of air-entraining admixtures necessary to achieve proper air-entraining. Instances of erratic air contents have been reported when flyash has been used, but careful monitoring and control can overcome the problem. (25)

Flyash reduces the permeability and the alkalinity of the PCC. This results in increased resistance to freeze-thaw in properly air-entrained PCC and increased resistance to sulfate and alkali-aggregate reaction. Though reduced alkalinity can lead to increased corrosion of the reinforcing steel, the lower permeability tends to compensate for this. Increased corrosion in flyash PCC has not been conclusively demonstrated. (3, 29)

Silica Fume

Silica fume, or more properly, condensed silica fume, is created by electric arc furnaces as a byproduct of the production of silicon or ferrosilicon alloys. Gaseous silicon oxidizes as it cools and condenses into tiny spheres that are collected rather than released into the atmosphere. The particles are approximately 100 times smaller than cement particles.

Silica fume is typically used at a rate of 5 to 20 percent of the weight of cement in a PCC mix. Silica fume is more expensive than cement, and instead of being used as a cement replacement silica fume is used along with low w/c mixes to produce very strong PCC. Silica fume PCC mixes usually contain some form of water reducing or superplasticizing admixture. Bleeding is substantially reduced by the addition of silica fume. Silica fume mixes tend to appear sticky to finishers, and experience is very important in producing acceptable flatwork. Extra care must be taken to avoid plastic cracking when evaporation potentials are high.

Because of its small particle size, silica fume tends to react quickly with free calcium in PCC mixes. Unlike flyash, silica fume does not necessarily reduce early strength, though substantial strength gain continues to occur after 28 days.

Silica fume mixes are very impermeable, which can significantly increase durability. But controlling entrained air can be quite difficult. The freeze-thaw durability of properly air-entrained silica fume PCC appears to be good, but some researchers suggest an upper limit of 10 percent silica for freeze-thaw resistant PCC. The surface scaling resistance of silica fume PCC may not be as good as that of conventional PCC. (29, 30)

Other Pozzolanic Admixtures

Other pozzolanic admixtures exist, including diatomaceous earth, rice husk ash, ground blast furnace slag, and materials produced from volcanic rocks and minerals. The materials consist of fine particles the size of cement particles and smaller. To be an effective pozzolan, silica from these materials must easily dissolve in the basic environment of a PCC mix. Many of these materials are ground to achieve the small particle sizes, and the angular shapes from grinding are not as beneficial to workability as the spherical particles in flyash and silica fume. (29)

MIXING, PLACING AND CURING

A PCC mix must not only be properly designed, it must also be mixed, placed, and cured. Errors in any of these steps can reduce the strength, durability, and abrasion resistance of the PCC.

Mixing

PCC can be produced at a central mix plant, truck mixed, or mixed on-site in a mobile mixer. The highest quality PCC (most consistent in properties) is generally produced at a central mix plant, and this method of PCC production is often preferred. Truck mixing can be much more variable, with segregation and poor control of slump being common problems. Uniformity tests should be made at the

beginning and end of the discharge from truck mixers. These tests should include separating the concrete into coarse aggregate and mortar fractions according to ASTM C 172 and determining the unit weight of the mortar, ASTM C 138, and the weight of the coarse aggregate in a cubic foot of PCC. The mortar unit weight should not vary by more than 0.8 percent from the average, and the coarse aggregate weight should not vary by more than 5 percent from the average of the beginning and end of the discharge weights. Excessive variations can often be reduced by reducing the quantity being mixed. (6) PCC from a mobile mixer is quite sensitive to the calibration of the mixer feeds and the uniformity in the aggregate stockpiles. Moisture control may require sprinkling, covering piles to reduce evaporation and provide protection from rain, and consistently portioning the piles material for charging the mixer. (31)

Placing

"Placing" is a general term covering the specific processes of placing the PCC into the desired position, consolidating it to remove voids, and finishing it to achieve the desired surface. Care must be taken during the placing process to avoid causing the PCC to segregate, including depositing the mix as closely as possible to where it is needed. Excessive movement of the PCC in the forms can lead to segregation of the coarse aggregate, especially in mixes where paste has little cohesiveness.

Consolidation is the process of removing voids from the in-place mix and is normally achieved with the use of vibrators. Care must be taken during vibrating to avoid segregation of the paste and also excessive loss of entrained air, though some air is normally lost during vibration. (3, 26) In the past, PCC was consolidated by tamping, which may have made placement of leaner mixes in flatwork possible without segregation. (32, 33) Such methods are prohibitively labor intensive today.

Superplasticized PCC tends to consolidate itself with little need for vibration. However, care should be used in vertical sections to provide sufficient vibration to release entrapped air adhering to reinforcing and form walls.

Curing

Curing is necessary to ensure adequate hydration of the portland cement. Various methods of curing exist, including ponding, covering the PCC with wet burlap, covering the PCC with plastic sheets, and applying a film-forming curing compound. Ponding is rarely used today because of the labor intensity involved. When wet burlap is used, care must be taken to keep the burlap moist. Plastic sheeting and burlap are seldom used for periods longer than one week in most construction operations. Curing compounds have the advantage that they stay in place until worn off, usually providing curing longer than one week. The use of both resin- and water-based curing compounds has been found to produce better abrasion resistance of PCC than 7-day plastic sheet curing followed by drying. (24)

APPLICATIONS TO WSDOT'S MIX DESIGN PROCEDURE

ADEQUACY OF CURRENT MIX DESIGN PROCEDURE

The WSDOT PCC mix design procedure is based on strength, and therefore the adequacy of the procedure must be based on whether the procedure produces durable and, when necessary, abrasion resistant PCC.

Durability

Selected WSDOT personnel were asked if they were aware of any instances of non-durable PCC. The only cases of non-durable PCC were probably due to inadequate amounts of entrained air or poor construction procedures. Even PCC placed before the use of air-entrainment was often reported to be free of durability problems. Where alkali-reactive aggregates or sulfate environments were known to exist, adequate precautions had been taken to avoid durability problems.

Non-WSDOT uses of PCC were investigated to determine if potential problem aggregates existed. Questionnaires sent to city and county personnel throughout Washington reported excellent durability in most cases. Most of these agencies relied on WSDOT-approved PCC mixes. A few cases of possible aggregate-related durability problems were found, but these were not serious. The worst problem identified was a coarse aggregate near Issaquah that had an unusual rate of pop-outs.

Abrasion Resistance

An analysis of skid data from state PCC pavements showed a number of sections with very low friction values. Low friction can be caused by aggregates that tend to polish, loss of mortar between coarse aggregates at the surface, and/or high traffic combined with the use of studded tires. Further work is needed to determine if this problem could be eliminated through changes, such as fine aggregate gradation, in the PCC mixes.

ACCOMMODATION OF SPECIAL CONDITIONS

Long Transit Time

Long transit times can cause problems because of loss of workability and also because of loss of entrained air. Loss of workability can be attributed to either hydration of the portland cement in the mix or loss of mix water caused by evaporation. The actual cause can be hard to determine at the job site, and retempering to regain slump can be detrimental to the PCC.

Loss of entrained air can be reduced by intermittent rather than continuous agitation, but segregation can become a problem without continued agitation. The variability in air content is likely to increase as hauling time increases.

Set retarders can be used to delay slump loss due to hydration, but set retarders can make control of air content more difficult. The combination of a set retarder and a long transit time can make control of air content especially difficult.

Transit or on-the-job mixing can be used to avoid long transit times. Mixes need to have higher cement contents to offset the higher variability associated with transit mixing. Additional job site testing is needed to ensure that the concrete quality remains adequate.

High Early Strength

High early strength can be achieved by increasing the cement content, using Type III cement, and using accelerating admixtures. The advantages and disadvantages of each of these methods are discussed below.

Increasing the cement content without increasing the mix water causes a decrease in the setting time. This may or may not cause problems, depending upon the application. An increased cement content makes a more cohesive paste, which is generally desirable. Increasing the cement content also increases the PCC cost, though this is seldom the most critical factor in repair applications.

Type III cement increases early strength without accelerating the setting rate. Because of the higher C_3A content, Type III cement should not be used in sulfate environments.

Accelerating admixtures accelerate both the rate of strength gain and the setting rate. These are a less expensive method of obtaining a high early strength than increasing the cement content, but there is insufficient information on the effects of most accelerating admixtures on long-term durability.

Any form of acceleration causes increased heat evolution. This can be a problem in thick sections, and full-depth pavement repairs using any form of acceleration should be avoided on hot days.

NON-STANDARD AGGREGATE QUALIFICATION

Aggregate that fails to produce adequate strength in mixes identical to Steilacoom aggregate mixes can still produce adequate strengths if higher strength pastes are used. Higher strength pastes can be produced by using higher cement contents, reducing water by using a water reducing admixture, or using a mineral admixture to augment the cement. Higher cement contents are more expensive, and the economies of using local aggregates rather than hauling aggregate in must be weighed against the higher cement cost. Water reducing admixtures can lead to problems in controlling air content, and the retarding effect of some admixtures can lead to increased plastic shrinkage cracking. The use of flyash requires strength comparisons at greater than the current 14 days to take advantage of the effect of the flyash. Silica fume is expensive and is probably not an economical substitute for hauling in good aggregate in most cases.

Perhaps the greatest risk in using non-standard methods to qualify aggregates is that durability is not directly tested except in cases where aggregate-related durability problems are known to exist. Non-durable coarse aggregates are probably currently excluded from use because they do not pass the Los Angeles Abrasion

test, ASTM C 131. Aggregates with a few problem particles may pass this test, but the weak aggregates probably serve as fracture initiation points in the compressive strength test. A stronger paste can hide a few weak aggregate pieces. Aggregates that are weaker because of higher porosity can lead to freeze-thaw or alkali reaction problems.

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