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Guide for Design and Proportioning of Concrete Mixtures for Pavements

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Concrete mixtures intended for pavements have purposes and desired characteristics that are different from other types of mixtures, such as structural or mass concrete. Thus, a guide for designing concrete mixtures specific to paving, such as highways, streets, airfields, and parking lots, is necessary. This guide describes a method for designing mixtures and selecting trial mixture proportions for hydraulic-cement concrete made with and without supplementary cementitious materials, chemical admixtures, and fibers. The guide provides a method that focuses on designing the concrete mixture in the context of pavement structural design, concrete production, construction operations, and the environment in which the pavement will reside. Trial mixture proportions are for concrete consisting of normalweight aggregates and concrete with workability suitable for various types of pavement construction, such as slipform, fixed-form, and laser-guided screeding. The method provides an initial approximation of proportions intended to be analyzed to assess their performance potential for mixing, transporting, placing, screeding and consolidating, finishing, texturing, and time-of-setting. The method also considers the hardened concrete performance parameters of strength, durability, abrasion resistance, skid resistance, smoothness, and dimensional and shape stability. Methods of checking for incompatibilities of materials in given construction environments are included, as well as methods for aggregate grading optimization. Resulting proportions should be checked by preparing and analyzing trial mixtures in the laboratory, then in the field, and adjusting as necessary to produce the desired concrete characteristics. Special concrete pavement mixtures, such as pervious concrete or roller-compacted concrete, are not included in the document. This is a dual-unit document; however, paired values stated in inch-pound and SI units are usually not exact equivalents. Therefore, either system should be used independently of the other.

Keywords: aggregate optimization; aggregates; cementitious materials; fly ash; incompatibility; intermediate aggregate; mixture proportioning; mixtures; pavements; slag cement.

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CHAPTER 1—INTRODUCTION

1.1—General

This document is intended to be used as a supplement to ACI 211.1, specifically for paving concrete mixtures. ACI 211.1 provides an in-depth discussion of concrete mixture characteristics and technology. It is unnecessary to repeat this information within this guide. Rather, this guide will point out the concepts specific to paving mixtures that are not fully developed in ACI 211.1. Additionally, concepts of materials' compatibility, durability, solutions for alkali-silica and sulfate reactions, and aggregate grading optimization are more fully developed in this document. Mixtures considered in this document would be suitable as paving mixtures for airports, highways, streets, or parking lots.

1.2—Mixture design goals

The design of a concrete mixture suitable for paving includes the desired outcomes of production, construction, service life, economy, and sustainability. Material selection and mixture proportioning are the means of obtaining the goals of the mixture design, and should consider materials suitability and availability in relation with the proposed production technology and construction constraints.

Ideally, the concrete mixture design method will assist the mixture designer to (Transtec Group, Inc. 2010):

(a) Identify important performance criteria that are functions of the climate, weather during construction, service conditions, and importance of the project
(b) Identify mixture performance criteria (such as strength and durability)
(c) Identify recommended test methods
(d) Assess the impact of changes in weather, construction procedures, materials, and proportions on constructability and service performance
(e) Provide methods for aggregate blending
(f) Produce mixture proportions based on all the above
(g) Provide mixture performance criteria optimization opportunities

A successful mixture design will meet the performance criteria of the paving contractor for: the mixture's ability to be properly mixed, transported, placed, screeded and consolidated, finished, and textured without segregation within the constraints of the proposed construction operation; schedule (including weather); production technology; and material availability. A successful mixture design will also meet the performance criteria of the owner to provide sufficient strength, durability, wear resistance, skid resistance, and dimensional and shape stability while achieving economy and sustainability. These properties are interrelated. For instance, placeability and finishability are important to the integrity of the top 1/8 in. (3 mm) of the slab surface, thus affecting resistance to freezing and thawing as well as wear resistance. To achieve all these goals, the optimal combination of materials and proportions should be provided.

The dilemma of mixture design and proportioning involves conflicting combinations of benefits and disadvantages as materials and proportions are varied. Reduction of water content will increase strength and durability while reducing shrinkage and edge slump. It may, however, negatively impact finishability and smoothness, which refers to the undulation of the concrete surface elevation, not the surface texture or skid resistance, and could reduce the ability to entrain air, thereby reducing durability. Raising the air content will increase durability, but lower strength. Use of locally available aggregate may be less expensive, but gap-graded or poorly-shaped material may negatively impact finishability, smoothness, and edge slump. Increased water content may increase workability and finishability, but decreases strength and durability. Material incompatibilities will further complicate the issue. The intent of this guide is to find a way through these issues and produce successful mixture designs.

Mixture design criteria taken into consideration in this guide include:

a) Slump
b) Air content
c) Strength
d) Resistance to freezing and thawing
e) Sulfate attack
f) Alkali-silica reaction
g) Modulus of elasticity
h) Thermal expansion and contraction
i) Shrinkage
j) Warping
k) Curling
l) Abrasion resistance
m) Setting time
n) Permeability
o) Corrosion resistance of reinforcing steel

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

Abs = absorption of an aggregate
AEA_{adj} = adjustment of water requirement for use of air-entraining admixture
DRD_{avg} = dry-rodded density of combined CA and IA aggregate
DRD_{CA} = dry-rodded density of coarse aggregate
DRD_{FA} = dry-rodded density of fine aggregate
DRD_{IA} = dry-rodded density of intermediate aggregate
f_c = compressive strength
f_c' = specified compressive strength of concrete
f_{cr}' = required average compressive strength of concrete used as the basis for selection of concrete proportions
$Fly\ ash_{adj}$ = adjustment of water requirement for use of fly ash
G_{admix} = specific gravity of admixture
$G_{CA,OD}$ = oven-dry specific gravity of coarse aggregate
$G_{CA,SSD}$ = saturated surface-dry specific gravity of coarse aggregate
G_{cem} = specific gravity of cement
G_{cm} = specific gravity of cementitious material
$G_{FA,OD}$ = oven-dry specific gravity of fine aggregate
$G_{FA,SSD}$ = saturated surface-dry specific gravity of fine aggregate
$G_{fly\ ash}$ = specific gravity of fly ash
$G_{IA,OD}$ = oven-dry specific gravity of intermediate aggregate
$G_{IA,SSD}$ = saturated surface-dry specific gravity of intermediate aggregate
G_w = specific gravity of water
$HRWRA_{adj}$ = adjustment of water requirement for use of high-range water-reducing admixture
k = regression factor
M_{admix} = mass of admixture
$M_{admix\ water}$ = mass of water in admixture
$M_{AEA\ water}$ = mass of water in air-entraining admixture
M_{agg} = mass of total aggregate
$M_{base\ water}$ = mass of base water
$M_{batch\ water}$ = mass of batch water
M_{CAadj} = mass of coarse aggregate shape water adjustment
$M_{CA,OD}$ = mass of oven-dry coarse aggregate
$M_{CA,SSD}$ = mass of saturated surface-dry coarse aggregate
M_{cem} = mass of portland cement
M_{cm} = mass of cementitious material
M_{FAadj} = mass of fine aggregate shape water adjustment
$M_{FA,OD}$ = mass of oven-dry fine aggregate
$M_{FA,SSD}$ = mass of saturated surface-dry fine aggregate
$M_{fly\ ash}$ = mass of fly ash
$M_{fly\ ashadj}$ = mass of fly ash water adjustment
$M_{IA,OD}$ = mass of oven-dry intermediate aggregate
$M_{IA,SSD}$ = mass of saturated surface-dry intermediate aggregate
M_{SFadj} = mass of silica fume water adjustment
M_{slag} = mass of slag cement
$M_{slagadj}$ = mass of slag cement water adjustment
M_{TCM} = mass of total cementitious materials
M_{water} = mass of total design water
$M_{WRA\ water}$ = mass of water in water-reducing admixture
MC = moisture content, aggregate
N = number of test results in a data set
RD_{fiber} = relative density of fibers
S = standard deviation of f_c
SCM_{adj} = adjustment of water requirement for use of SCM
$Slag_{adj}$ = adjustment of water requirement for use of slag cement
V = absolute volume of a component
V_{admix} = absolute volume of admixture
V_{air} = absolute volume of air
$V_{CA,OD}$ = absolute volume of oven-dry coarse aggregate
V_{cm} = absolute volume of cementitious material
$V_{FA,OD}$ = absolute volume of oven-dry fine aggregate
$V_{FAvoid\ content}$ = absolute volume of fine aggregate void content
V_{fiber} = absolute volume of fibers
$V_{fly\ ash}$ = absolute volume of fly ash
$V_{IA,OD}$ = absolute volume of oven-dry intermediate aggregate
V_p = absolute volume of paste
w = water content
WRA_{adj} = adjustment of water requirement for use of WRA
wt = weight
ρ_{water} = density of water

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," https://

www.concrete.org/store/productdetail.aspx?ItemID=CT13. Definitions provided herein complement that source.

mass (weight)—this usage is provided as an aid to understanding for users of the U.S. customary system in which "mass" refers to pounds mass, but is often erroneously called "weight", which is mass multiplied by the acceleration of gravity.

stress ratio—ratio of maximum applied flexural stress to modulus of rupture.

vibrator trails—localized areas of segregation characterized as mortar-rich and often with a compromised air-void system.

CHAPTER 3—BASIC PROPERTIES

3.1—Desired properties

This section presents concrete behavior that is desired during production, construction, and service life as related to specific concrete mixture properties and components. Regarding production and construction, a major factor to be considered is workability. In this document, workability includes ease of mixing, transporting, placing, screeding and consolidating, finishing, and texturing. Hardened concrete performance properties of interest include strength, durability, skid resistance, smoothness, and dimensional and shape stability (resistance to excessive warping, curling, or both). Desired properties are addressed in the mixture design phase either by being specified in the contract documents, or by a decision made by the contractor/producer. If the property is specified, then the contractor/producer should work within the specification, but may elect to further enhance the property in the mixture design. If the property is not specified, the contractor/producer may still choose to add requirements/additives for the mixture.

3.2—Workability

3.2.1 *Effects of concrete components*

3.2.1.1 *Effects of water*—A major factor affecting the workability of a concrete mixture is water content. Increasing the water content will increase the flow and compactability of the mixture, but will usually also reduce strength while increasing segregation, bleeding, and permeability (Mindess et al. 2003). Workability decreases with time as water from the mixture evaporates, is absorbed by the aggregate, and reacts with cementitious materials during the initial chemical reactions. Increases in ambient temperatures will accelerate these effects because higher temperatures increase both the evaporation and hydration rates (Mindess et al. 2003).

3.2.1.2 *Effects of aggregate*—Effects on all aspects of workability are related to aggregate particle shape and surface texture, nominal maximum size, and grading. The more rounded and smooth the aggregate, the lower the water requirement; thus, rounded river gravels and sands would be preferred in this regard. The particle shape of the fine aggregate is especially important to finishability. Increased finishability will result in less hand manipulation of the surface, producing a smoother-riding pavement, as discussed in 3.2.5 and 3.6. Regarding ease of mixing, more rounded and smoother aggregate may shorten mixing time. Also, as aggregate becomes flatter, more elongated, or both (failing a 3:1 shape ratio requirement per ASTM D4791), issues arise regarding increased paste content. In some specifications, the recommended maximum limit of flat and elongated aggregate is 15 to 20 percent. Cubical or well-rounded particles are more mobile under vibration and flow more easily around dowel baskets, chairs, and reinforcement. Angular aggregate, such as manufactured sand, can sometimes cause the surface of the concrete to tear as the mixture moves through the paver.

A more well-graded aggregate has been shown to decrease segregation, which can cause honeycombing. For traditionally-graded mixtures, it is recommended that when coarse aggregate graded from No. 4 to 1-1/2 in. (4.75 to 38 mm) is specified, the coarse aggregates should be furnished in at least two separate sizes, with the separation at the 3/4 in. (19 mm) sieve. For No. 4 to 2 in. (4.75 to 50 mm) material, the separation should be at the 1 in. (25 mm) size. Such separation is not necessary when the specified nominal maximum size of coarse aggregate is 1 in. (25 mm) or less (MoDOT 2011). A more well-graded aggregate has been shown to increase finishability and smoothness. Being well graded, the larger particles will not lock with others because of less direct contact under vibration and finishing. Tearing of the concrete surface through the paver is associated with gap-graded mixtures, which are typically deficient in the No. 8 to No. 30 (2.36 to 0.59 mm) sizes. Coarser fine aggregates are recommended to reduce the occurrence of shrinkage cracking and joint raveling. Mixtures that are too sandy or where the fine aggregate is too fine may appear sticky.

Whether to use the traditional two-aggregate blend (coarse and fine), or to optimize the grading with three or more aggregate products, is driven by the benefits of a well-graded combined aggregate. These benefits can include the following:

a) Enhanced finishability, leading to higher smoothness incentives

b) Less day-to-day variability, leading to less intermittent problems of edge slump, segregation, and strength variation

c) Less shrinkage cracking

d) Less joint raveling

For example, MoDOT allows a 50 lb/yd^3 (23 kg/m^3) reduction in cement content if an optimized grading is used (MoDOT 2011).

However, potential constraints of using more than two aggregates to optimize grading should also be considered. These constraints could include, but are not limited to, economics, available stockpile space at the plant site, increased time needed for the plant to measure a batch, and increased water demand or paste content if the additional aggregate source contains deleterious materials or undesirable particle shapes. The cost of bringing in a third or fourth aggregate or blending two fine aggregates is often offset by a cement reduction or higher smoothness bonus, or less penalties for excessive cracking (USAF 1997).

The largest nominal maximum size (NMS) consistent with workability should be used to minimize shrinkage cracking and provide the most economical concrete. For two-aggregate systems, however, the choice of a large NMS is often overruled by such factors as availability (for example, a 3/4 in. [19 mm] NMS may be the most readily available coarse aggregate), potential for segregation, desirability for smoothness pay factor incentive, enhancement of flexural strength, and potential for freezing-and-thawing deterioration of aggregate.

NMS of the aggregate affects production and construction operations. As with particle shape, smaller NMS will result in shorter mixing times. Slipform pavers generally have problems with placing and consolidating aggregate with NMS of 2 in. (50 mm) and greater. Tearing of the concrete surface through the paver is associated with larger NMS aggregate. As NMS decreases, there are fewer low spots produced under the finishing pan and, as NMS and the proportion of coarse aggregate increases, the potential for segregation in stockpiles or mixtures increases.

3.2.1.3 *Effects of cement*—Although less important to workability than other components' properties, the characteristics of the cement may also affect workability. For example, the increased specific surface area caused by cement fineness associated with Type III cements means they will have a lower workability at a given water-cementitious materials ratio (*w*/*cm*) than a Type I cement (Mindess et al. 2003).

3.2.1.4 *Effects of supplementary cementitious materials*—The workability of concrete is usually enhanced by the inclusion of fly ash or slag cement for several reasons. First, the specific gravity of fly ash and slag cement is typically lower than portland cement, so a 1:1 mass substitution of supplementary cementitious materials (SCMs) for cement will result in an increase in paste volume, thus increasing plasticity and cohesiveness of the mixture. If fly ash is added to increase the total cementitious content, the increase in fines can compensate for aggregate deficiency in the smaller particles—for example, coarse sand. Second, the rounded fly ash particle shape and the nature of the slag cement usually allows for a reduction in water content (ACI 211.1; Richardson 2015). The water demand can be lowered by as much as 3 to 5 percent (PCA EB001; ACPA 2003a). Although fly ash and slag cement both improve workability, fly ash has the greater effect. In hot weather, however, some fly ashes may cause early stiffening and loss of workability of the mixture, as discussed in 3.8 and 4.3. Silica fume will markedly increase the water requirement and stickiness at dosages above 5 percent by mass of cement because of the high surface area. Silica fume is not typically used in concrete for pavements, as discussed in 4.3 and 5.4. Bleeding may be reduced when SCMs with finer particles are used, especially if water demand has been lowered. Slipform low-slump mixtures with higher fines contents may not bleed, and necessitate prompt curing practices, special curing methods after finishing, or use of finishing aids.

3.2.1.5 *Effects of air*—Entrained air increases the paste volume while acting as a lubricant to improve the workability of concrete (Scanlon 1994). Entrained air is particularly effective in improving the workability of lean mixtures with a low cement content that otherwise might be harsh and difficult to work, and of mixtures with angular and poorly-graded aggregates (PCA EB001). Excessive amounts of entrained air, however, can make a mixture sticky and difficult to finish, may reduce concrete strength, and may increase permeability. Allowable upper limits are a function of many factors, but typically are in terms of 8.0 to 9.5 percent (ACI 211.1).

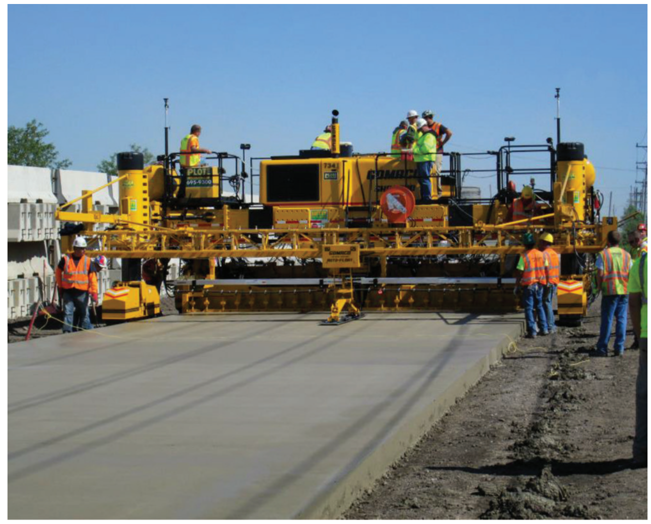

Fig. 3.2.4a—Slipform paver (courtesy of GOMACO Corp.).

3.2.1.6 *Effects of water-reducing admixtures*—Water-reducing admixtures (WRAs) are used to increase workability, reduce water demand, or both, although the rate of slump loss may not be reduced, depending on the chemistry of the admixture (PCA EB001).

3.2.1.7 *Effects of set-modifying admixtures*—Set-retarding admixtures reduce the early rate of hardening and permit concrete to be handled and vibrated longer (Scanlon 1994; ACI 212.3R).

3.2.2 *Ability to be mixed*—The concrete mixture should be able to be mixed successfully with the mixing equipment intended for the project. Successful mixing entails production of a batch that is uniform throughout and achievable in a minimum amount of time. Occurrences of cement balls, clumps of fibers, rocky portions, and so forth, should be minimized. Smaller-sized rounded aggregate mixtures may not break down fiber bags as easily as other mixtures. Thus, fiber balls may appear more often. The variety of mixers that may potentially be used in a given project should be taken into consideration.

3.2.3 *Transportability*—Transportability is the concrete's ability to be transported from the mixer to the delivery vehicle and into the forms successfully and without harmful segregation. The mode of transportation should be considered, along with haul distance. Paving concrete for highways is hauled in dump trucks, agitator trucks, or transit truck mixers. Care should be taken to minimize segregation. Low-slump mixtures suitable for slipform paving may resist segregation, but mixtures intended for form-and-place paving may require greater slumps, which may lead to a greater risk of segregation.

3.2.4 *Placeability*—Placeability is the concrete's ability to be conveyed from the delivery vehicle into forms without harmful segregation. Placeability is affected by slump, which is a measure of fluidity. Slump is commonly specified in the contract documents with the inclusion of minimum/