

Concrete with Reduced Portland Cement Clinker Content for Pavements

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ABSTRACT

Reduction of content of Portland cement is one way to reduce carbon footprint and improve sustainability of concrete construction. During the past decade concrete containing 15-25% fly ash Class F by the total weight of cementitious material has been extensively used in California for construction of pavements, structures, and buildings. The authors, who were involved in the development and implementation of moderate and higher-volume supplementary cementitious material (also referred to as SCM) concrete summarize laboratory and field experience, and illustrate it with examples of pavement projects built in California. The paper discusses factors determining the quality of concrete pavements with higher volumes of replacement of Portland cement with SCM and provides recommendations on special quality control procedures.

Keywords: concrete pavement, carbon footprint, Portland cement, fly ash, ground granulated blast furnace slag

1 SCM AVAILABLE IN CALIFORNIA

Traditionally the demand for supplementary cementitious materials (SCM) for concrete in California has been driven by constructability and performance considerations, among them:

- The hot and dry climate of many counties necessitating better control of workability and heat generation of concrete
- Abundance of lands contaminated with sulfates necessitating the use of sulfate-resistant concrete
- The reactivity with alkali of many siliceous aggregate deposits necessitating mitigation of deleterious expansion

Starting in 2012, this demand is set to increase significantly driven by environmental regulations requiring optimal reduction of content of Portland cement or its clinker constituent to reduce the carbon footprint of concrete. Agencies and research institutions have been focused on the dominant concept of using higher volumes of SCM, such as fly ash, ground granulated blast furnace slag (also referred to as GGBFS) and processed natural pozzolan, for achieving substantial reduction in Portland cement clinker content. However, less consideration has been given to construction specifications, concrete practice, constructability, and quality control procedures.

The main type of SCM used in California is fly ash Class F. GGBFS is imported from Asia in limited quantities. Silica fume and metakaolin are used for special applications, for example high-strength or low-permeability concrete.

2 STATE-OF-PRACTICE

Driven by the necessity of mitigating potential reactivity of local aggregates, content of fly ash Class F in concrete for pavements typically has been 20% to 25% by the total weight of cementitious material.

Tables 1 and 2 present condensed data of uniformity studies performed during construction of airfields in San Diego and Sacramento International Airports. Concrete for Sacramento Airport contained 20% fly ash (Table 1) and concrete for San Diego Airport contained 25% of fly ash (Table 2) by the total weight of cementitious material. Production mixes were developed on the basis of laboratory established relationships “Flexural Strength (MOR) Versus Water-Cementitious Materials Ratio.” Specified MOR was 650 psi in 28 days. Both concrete mixes were proportioned for design MOR of 725 psi. Mixes were designed for placing concrete using slip-forming technique. Slump was limited to 1.5-inch, air was entrained in the amount of 3% to enhance workability. Both airfields were built in non-freeze-thaw areas. Concrete was proportioned as follows: (i) Cementitious blend – Portland cement Type II/V and fly ash Class F, (ii) Aggregate – siliceous, 1-inch maximum size combined gradation, continuously graded with optimized coarseness and workability factors, (iv) Chemical admixtures – normal range polymer-based water reducer and air-entraining agent.

Table 1 - Flexural Strength (MOR) Uniformity Studies, Sacramento Airport

Evaluation of Data	Age, days			
	3	7	14	28
Number of sets	64	170	200	263
Average MOR, psi	551	611	664	727
Minimum MOR, psi	455	495	490	610
Maximum MOR, psi	645	740	795	900
Standard deviation, psi	41	44	47	51
Coefficient of variation, %	7	7	7	7

Field experience confirmed that strict quality control of materials, production, and testing assured good uniformity of MOR of concrete with fly ash.

Field experience demonstrated the necessity of pretesting of concrete in the beginning of production shift and adjusting the dosage rate of air entraining admixture to assure uniformity of air content. Influence of fly ash on air entrainment can be forecasted by its pretesting for foaming index. Compatibility of fly ash with Portland cement and chemical admixtures should be pre-evaluated during concrete mix development preconstruction studies. We recommend that during preconstruction studies the fly ash used for laboratory trial batching be tested (analyzed) for its chemical and mineral composition, fineness and physical properties. Such express-certification of fly ash (or other SCMs) involves, for example, X-ray fluorescence (XRF) analysis for elemental composition and X-ray Diffraction (XRD) analysis for amorphous and crystalline phase content and identification of crystalline phases. This signature record should be further used during construction for reactive and proactive quality control.

Pavements built with concrete containing 20% - 25% fly ash Class F had good quality. Proper construction practice and early-entry saw cutting of contraction joints allowed to control and prevent cracking.

Table 2 - Flexural Strength (MOR) Uniformity Studies, Sacramento Airport

Evaluation of Data	Age, days			
	3	7	14	28
Number of sets	86	184	53	188
Average MOR, psi	569	620	668	746
Minimum MOR, psi	455	490	585	615
Maximum MOR, psi	710	735	795	925
Standard deviation, psi	48	47	49	53
Coefficient of variation, %	8	8	7	7

3 NEXT STEPS

Higher volumes of replacement of Portland cement with SCM provide for more efficient reduction of carbon footprint of concrete. When Portland cement is replaced with high volumes of fly ash, additional technical benefits include:

- Significant reduction of water requirement
- Reduction of heat generation upon hydration
- Reduction of permeability
- Reduction of expansion caused by reactive siliceous aggregates
- Improvement of sulfate resistance
- Prevention of formation of calcium carbonate efflorescence, etc.

It is known and expected that high-volume replacement of Portland cement with fly ash Class F retards setting and slows down strength gain of concrete [1, 2]. Retardation of strength gain is illustrated by data presented in Table 3. Such retardation is highly undesirable because it increases risk of plastic shrinkage and plastic settlement cracking of fresh concrete. It also increases risk of cracking of hardened concrete in early age due to volume changes. Some of the strategies mitigating the retardation include:

- Selecting optimum combination of Portland cement and fly ash among the available materials (with consideration for the most efficient proportions)
- Decreasing water to cementitious material ratio (within a practical range)
- Selecting efficient water reducing admixtures enhancing strength gain without inhibiting the ability of using low-slump mixtures suitable for slip-forming
- Using accelerators not effecting adversely volume changes of concrete
- Proportioning concrete with consideration for constructability, acceleration of construction, and cracking resistance of pavements
- Controlling minimum temperature of concrete during cold weather periods
- Pretesting concrete during preconstruction studies for setting time, strength gain in early age and maturity

- Pre-placement evaluation of development of tensile stresses and tensile strength of concrete (for example, utilizing Hiperpav III software)
- Protecting pavements from moisture losses for longer time periods
- Protecting pavements from significant temperature changes caused by ambience in early age

Replacement of Portland cement with GGBFS enhanced strength of concrete in 28 days, however, noticeably slowed down the early age gain of strength. Therefore the above recommendations related to the scope of preconstruction evaluation of concrete and to construction practices allowing for mitigating early age strength gain should be implemented when pavements are built with concrete containing high-volumes of GGBFS or high volumes of mixtures of fly ash Class F and GGBFS.

Preconstruction concrete development studies should become an integral part of overall quality control protocol. For pavement concrete with high volumes of replacement of Portland cement with SCM we recommend amending quality control protocols with at least the following procedures:

- Obtaining identifying characteristics of SCMs during preconstruction studies, and tracking uniformity of their chemical and/or mineralogical composition and performance in concrete in the course of construction of specific project
- Pretesting concrete for setting time and for rate of strength gain (maturity) in the field at ambient conditions anticipated during construction
- Considering age of cracking of concrete and induced stresses determined in accordance with ASTM C1581 as one of the characteristic used for comparison of efficiency of cementitious blends in concrete
- Implementing cracking management protocols specific to concrete with high volumes of SCM
- Monitoring setting and strength gain of concrete in pavement using embedded sensors for better control of optimal time of saw cutting

Table 3 – Comparison Laboratory Testing of Concrete Containing High Volumes of SCMs

Concrete Proportions (*)					Compressive Strength of Concrete, average of 3 cylinders, psi						
Cementitious Material, lb/yd ³			Water gal/yd ³ W/C	Water Reducer (type)	Ratio of Strengths of the Test to the Control Mix at Equivalent Age						
Portland Cement Type II/V	Fly Ash Class F	GGBFS Grade 120			3 days	7 days	10 days	28 days	56 days	90 days	180 days
590 (control)	-----	-----	35.5 W/C=0.50	Normal range	3070 control	4180 control	4680 control	5180 control	5380 control	5510 control	5640 control
442.5 (-25% of control)	147.5	-----	34.1 W/C=0.48	Mid range	2580 84%	3470 83%	4030 86%	4850 94%	5100 95%	5510 100%	5880 104%
295 (-50% of control)	295	-----	31.3 W/C=0.44	Normal range	1830 60%	2350 56%	2890 62%	4040 78%	4810 89%	5170 94%	5970 106%
295 (-50% of control)	147.5	147.5	34.0 W/C=0.48	Normal range	1950 64%	2910 70%	3610 77%	4900 95%	6190 115%	6680 121%	6890 122%
295 (-50% of control)	-----	295	36.4 W/C=0.51	Normal range	1890 62%	3460 83%	4240 91%	5910 114%	6550 122%	6630 120%	7200 128%
337 (-43% of control)	337	-----	30.0 W/C=0.37	Mid range accelerator	2250 73%	3110 74%	3140 67%	4900 95%	5590 104%	6070 110%	6700 119%
337 (-43% of control)	337	-----	25.0 W/C=0.31	High range	2910 95%	-----	3300 71%	5680 110%	6290 117%	7200 131%	7700 137%

NOTE: (*) Concrete mixes were designed for slump of 4.00 inches and were non air-entrained.
Concrete contained siliceous aggregates with 1-inch maximum size combined gradation.

REFERENCES

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