Beneficial Use of Fly Ash for Concrete Construction in California

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SYNOPSIS

Fly ash Class F is the predominant type of supplementary cementitious material available for the concrete construction industry in California. The demand for fly ash is driven by constructability, performance, environment, and sustainability considerations, and by regulations and standards of governing agencies. The authors analyzed supply and demand of supplementary cementitious materials and present case studies of various projects completed in California, which feature the beneficial use of fly ash. One of these projects is the continuously placed mass concrete foundation for Wilshire Grand Replacement Hotel in Downtown Los Angeles (volume of continuously placed concrete was 21,200 yd^3; registered as the Guinness record in February 2014).

USE OF FLY ASH FOR CONCRETE CONSTRUCTION IN CALIFORNIA

Historically the demand for Class F fly ash for concrete in California has been driven by constructability, performance, environmental, and sustainability considerations, among them:

- The hot and dry climate of many counties necessitating better control of workability,
- The aggressive environment of some coastal and desert areas (due to the presence of chlorides) necessitating the reduction of permeability of concrete,
- Vast lands contaminated with sulfates necessitating the enhancement of sulfate-resistance of concrete, and
- The reactivity with alkali of many siliceous aggregate deposits necessitating mitigation of deleterious expansion.

The volumes of consumption of supplementary cementitious materials (SCM) between 2015 and 2020 are set to increase due to an increase in the volume of construction and the following factors:

- California Assembly Bill AB32 requiring reducing the volume of carbon dioxide generation and limiting it by 2020 to the level of 1990 (Note: The estimated increase in consumption of Portland cement for all usage between 1990 and 2020 is approximately 2 million metric tons),
- Challenging requirements for the reduction of embodied energy of construction materials,
- Specifications of local agencies requiring both (i) the extension of service life of structures and pavements, and (ii) the reduction of consumption of non-renewable natural resources for new concrete construction,
- Rapidly growing construction of high-rise buildings, structures and tunnels for aerial and underground high-speed rail, sophisticated bridges, and water conveying and water retaining structures, all requiring high-performance concrete, and
- Rapidly growing mass concrete construction necessitating both the reduction of heat generation and mitigation of heat induced delayed ettringite formation.

The volume of consumption of SCM in California is estimated to reach in 2015 approximately 0.9 million metric tons (1 million imperial tons), which roughly corresponds to the average replacement rate of Portland cement of 10%. The estimated share of fly ash Class F is 90% of the total volume of consumption of supplementary cementitious materials. The estimated share of ground granulated blast furnace slag is 10%. The above volumes do not include significantly lesser quantities of such pozzolanic SCMs as silica fume, natural processed pozzolans, and ultrafine products derived from fly ash.

Because fly ash used in California is mostly imported from other states, should its availability decline nationwide, California may be disproportionately adversely affected. Such developments would inevitably affect price. Importing additional quantities of fly ash from Asia Pacific may stabilize pricing.

All trends noted above require the concrete construction industry to implement a holistic approach to selecting concrete mixtures and replacement rates of Portland cement with fly ash Class F, giving consideration to (i) performance, (ii) compliance with governing requirements and standards, (iii) quality of construction, (iv) constructability, (v) durability and service life, (vi) environmental aspects, among them carbon footprint and embodied energy, (vii) initial and life cycle costs, and (viii) possible stimulus credits in recognition of value added by fly ash.

Analysis of concrete production and construction practices demonstrates a relative increase in volumes of consumption of concrete containing 20-30% of fly ash Class F in the total volume of concrete produced with fly ash. Standard and project specifications by Caltrans, FAA, U.S. Air Force, U.S. Navy, California Water Resource Board, California Department of Water and Power and others requiring mitigation of deleterious expansion of concrete due to the use of reactive aggregates promoted the noted trend and made industry and designers accustom to it. These moderate (according to classification by Thomas, 2007) volumes of replacement of Portland cement with fly ash provide for good constructability and uniformity of strength of concrete as demonstrated by our case studies. Use of ternary blends of Portland cement with Class F fly ash and ground granulated blast furnace slag (GGBFS) in higher replacement volumes corresponding to 35-50% is another trend specific to Northern California, where GGBFS is available, although yet in limited quantities.

The beneficial effects of fly ash on concrete permeability, durability, and reduction of heat generation are well documented and recognized by the industry (ACI 232.2R-03; ACI 232.3R-14; Malhotra and Mehta, 2012; Taylor, 2006; Van Dam and Smith, 2011). Some of the typical concerns of contractors are related to uniformity of strength of concrete containing fly ash and to its application for flatwork and pavements specifically, where retardation needs to be considered with respect to early age cracking. Case studies presented further in this paper address these areas of performance of concrete, mostly produced with moderate volumes of replacement of Portland cement with Class F fly ash.

CASE STUDIES - USE OF FLY ASH IN CONCRETE PAVEMENTS

In 2006 – 2007 the authors performed for Caltrans comparison evaluation of strength development of various concrete mixtures with moderate (25%) and high (not less than 50%) volumes of replacement of Portland cement with such SCMs as Fly ashes Class F and C, GGBFS and blends of fly ashes with GGBFS (Rufino 2008). Results of the evaluation of strength gain of concrete containing 25% of fly ash as a replacement for Portland cement are presented in Table 1. According to the conditions of the evaluation, control and test concrete contained the following materials and were proportioned as follows:

- Type II/V Portland cement (moderate heat of hydration),
- Class F fly ash with calcium oxide content of 8%,
- Siliceous coarse and fine aggregates mined in Southern California (decomposed granite type), maximum aggregate size was 25-mm (1-inch),
- Type A normal range water reducing admixture,

- Total cementitious content of 350 kg/m3 (590 lb/yd^3), which corresponds to median cementitious content used by the industry for production of pavement concrete,
- Design slump was 4 inches, and
- Mixes were not air entrained.

The test concrete mix with moderate volume replacement of Portland cement with fly ash Class F demonstrated good workability, reduction in water requirement of 4% compared to the control mix and acceptable 28-day compressive strength (94% of the control mix). In 90 days strength of the test mix was equal to the strength of the control mix and in 180 days exceeded it by 4%. In early age (up to 10 days, which corresponds to the average time during which new freeway pavements are opened to traffic after placement) strength of the test mix was 83%-86% of the strength of the control mix.

Table 1 - Comparison Laboratory Testing for Caltrans

Concrete Proportions			Compressive Strength, MPa (psi) Ratio of Strengths of Test and Control Mixes						
Cementitious Material, kg/m^3 (lb/yd^3)		W/CM							
Portland Cement Type II/V	Fly Ash Class F		3 days	7 days	10 days	28 days	56 days	90 days	180 days
350 (590)	-----	0.50	21.2 (3070) control	28.8 (4180) control	32.3 (4680) control	35.7 (5180) control	37.1 (5380) control	38.0 (5510) control	38.9 (5640) control
262.5 (442.5)	87.5 (147.5)	0.48	17.8 (2580) 84%	23.9 (3470) 83%	27.8 (4030) 86%	33.5 (4850) 94%	35.2 (5100) 95%	38.0 (5510) 100%	40.6 (5880) 104%

Tables 3 and 4 present summaries of flexural strength uniformity studies performed during construction of airfields in Sacramento and San Diego International Airports. Concrete for Sacramento Airport contained 20% of Class F fly ash (Table 2) and concrete for San Diego Airport contained 25% of Class F fly ash (Table 3) by the total weight of cementitious material. Content of calcium oxide in both fly ashes was less than 10%. Minimum content of fly ash was selected for mitigating expansion of the production blend of slow reacting siliceous aggregates and limiting it to 0.10% (ASTM C1567). Production mixes were developed on the basis of laboratory established relationships "Flexural Strength (MOR) Versus Water-Cementitious Materials Ratio (W/CM)." Specified MOR was 4.5 MPa (650 psi) in 28 days. Both concrete mixes were proportioned for required MOR of 5 MPa (725 psi). Mixes were designed for placing concrete using slip-forming technique. Slump was limited to 38 mm (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 produced with following materials: (i) Cementitious blend – Portland cement Type II/V and fly ash Class F, (ii) Aggregate – siliceous, 25-mm (1-inch) maximum size combined gradation, continuously graded with optimized coarseness and workability factors, (iv) Chemical admixtures – normal range Type A polymer-based water reducer and air-entraining agent.

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, MPa (psi)	3.9 (569)	4.3 (620)	4.6 (668)	5.1 (746)
Minimum MOR, MPa (psi)	3.1 (455)	3.4 (490)	4.0 (585)	4.2 (615)
Maximum MOR, MPa (psi)	4.9 (710)	5.1 (735)	5.5 (795)	6.4 (925)
Standard deviation, MPa (psi)	0.33 (48)	0.32 (47)	0.34 (49)	0.37 (53)
Coefficient of variation, %	8	8	7	7

Table 3 - Flexural Strength (MOR) Uniformity Studies, San Diego Airport

Evaluation of Data	Age, days			
	3	7	14	28
Number of sets	64	170	200	263
Average MOR, MPa (psi)	3.8 (551)	4.2 (611)	4.6 (664)	5.0 (727)
Minimum MOR, MPa (psi)	3.1 (455)	3.4 (495)	3.4 (490)	4.2 (610)
Maximum MOR, MPa (psi)	4.5 (645)	5.1 (740)	5.5 (795)	6.2 (900)
Standard deviation, MPa (psi)	0.28 (41)	0.30 (44)	0.32 (47)	0.35 (51)
Coefficient of variation, %	7	7	7	7

Analysis of data presented in Tables 3 and 4 demonstrates that the average flexural strength achieved was equal to or slightly exceeded the design strength of 5 MPa (725 psi). Minimum flexural strength was 4.21 MPa (610 psi) and exceeded the minimum strength allowed by FAA and equal to 0.93 of the specified strength (4.17 psi or 605 psi). For both projects coefficient of variation calculated as the percent ratio of the batch-to-batch sample standard deviation to the average strength was equal to 7%. For evaluating coefficient of variation after provisions to ACI standards (ACI 214-11) specified flexural strength ($MORc$) of 5 MPa (650 psi) was correlated to specified compressive strength ($f'c$) of 35.9 MPa (5210 psi) using the previously established by the authors physical relationship between actual flexural and actual compressive strengths of concrete with aggregates mined in California: $MORc\ (psi) = 9\sqrt{f'c\ (psi)}$.

The coefficient of variation is rated after provisions of ACI 214 as very good. It shall be noted that one of the factors contributing to the reduction in batch-to-batch variation of strength was the consistency of characteristics fly ash Class F.

Workability, retention of slump within time, content of entrained air and requirement in air-entraining agent, finishability, time of stiffening/setting and gain of strength of production concrete mixes, including strength development in early age, were evaluated by field trial batches immediately prior to the start of construction to reconfirm consistency of performance with the one observed during laboratory trial batches. In order to prevent from possible plastic shrinkage cracking and early age cracking of hardened concrete in the course of concrete production and pavement construction:

- Aggregates in stockpiles were continuously moist conditioned,
- Moisture content of aggregates was strictly controlled by direct testing to assure that it was at or above their physical absorption,
- As finishing aids contractors used evaporation retarders,
- Curing compound was applied immediately upon completion of finishing and texturing, and rate and uniformity of its application was continuously controlled,
- Rate of moisture evaporation above the surface of concrete was controlled using portable weather stations, and
- Time of beginning of pavement shifts was selected with consideration for minimizing the rate of evaporation from concrete.

In order to assess on a daily basis the air-entrainment and adjust, if needed, the dose of air-entraining admixtures the first three loads of central mixed concrete were tested prior to their delivery to the field with non-agitating trucks.

CASE STUDIES – USE OF FLY ASH FOR HIGH-STRENGTH CONCRETE

For construction of the The Century, a 146 meters (480 feet) high condominium building in West Los Angeles, the contractor used concrete mixes containing 10% to 25% of fly ash, depending on concrete application in structures. The supplier developed the mixes with consideration for constructability considering along with the specification age strength needs in controlling stiffening/setting time and rapid development of early age strength when dictated so by pace of vertical forming, removal of formwork and reshoring. The project schedule was intense and provided for one week cycle per floor. Concrete used for gravity columns and moment frame columns, beams and shear walls with specified compressive strength of 55.2 MPa (8,000 psi) to 69.0 MPa (10,000 psi) contained 10% of fly ash by the total weight of its blend with Type II/V Portland cement.

Design W/CM was 0.36. Congested reinforcing steel condition and concerns with strength of 25-mm (1-inch) maximum size local siliceous aggregates dictated the use of 9.5 mm (3/8”) maximum size aggregate (60% by absolute volume of coarse and fine aggregates). Concrete mix contained polycarboxylate high-range water reducer. The design allowed for the use of set controlling admixture, when required so by ambient temperature and anticipated duration of delivery time. Acceptance ages were: concrete designed for compressive strength of 55.2 MPa (8,000 psi) – 90 days and concrete designed for compressive strength of 69.0 MPa (10,000 psi) – 365 days. Table 4 presents results of evaluation of strength data for the 69.0 MPa (10,000 psi) mix obtained in the course of construction.

Table 4 – Compressive Strength Uniformity Studies, The Century

Evaluation of Data	Age, days		
	28	90	365
Number of sets	51	138	41
Average strength, MPa (psi)	60.3 (8,750)	68.4 (9,921)	76.3 (11,066)
Minimum strength, MPa (psi)	41.6 (6,030)	56.1 (8,140)	69.6 (10,095)
Maximum strength, MPa (psi)	70.1 (10,160)	83.6 (12,120)	84.8 (12,295)
Standard deviation, MPa (psi)	5.03 (730)	4.90 (711)	4.16 (603)
Coefficient of variation, %	8	7	5

Evaluation of strength data demonstrates that the coefficient of variation improves with age, which among other reasons may be explained by the moderate strength of the local siliceous rock source somewhat stabilizing strength. Evaluation of the field data versus the requirements of ACI 214 suggests that the coefficient of batch-to-batch variation at 90 days meets the standard for very good variation and at 365 days the standard for excellent variation.

CASE STUDIES – USE OF FLY ASH FOR MASS CONCRETE FOUNDATION

Wilshire Grand Replacement Hotel in Downtown Los Angeles is the tallest building west of Chicago currently under construction. The building will be 73 stories high above five levels of parking structure and 335 m (1100 feet) tall. The concrete foundation for this building was constructed on February 16-17, 2014 within 18.5-hour continuous placement. Some facts about construction of the foundation are summarized below:

- Total volume of concrete continuously placed was 16208 m^3 (21,200 yd^3),

- Concrete was designed for compressive strength of 41.4 MPa (6,000 psi) in 90 days and produced with local siliceous aggregates, Portland cement Type II/V, fly ash Class F and mid-range water reducing admixture,
- Cementitious blend contained 25% of fly ash by the total weight of cementitious materials, design W/CM was 0.40,
- Concrete was supplied from 8 batch plants (two ready mix companies),
- 263 ready mix trucks delivered 2,120 concrete loads,
- Concrete was placed from the street level into the pit by 13 pumps,
- For better and more convenient placement of concrete two additional redistribution pumps were installed in the pit,
- Depth of foundation was 17.5 feet,
- Thermal control was achieved by controlling the initial temperature of concrete, cooling concrete with chilled water by pumping it through 0.5-inch diameter pipes installed at 4-foot on center, and thermal insulating the surface,
- Compliance of both maximum absolute temperature of concrete and maximum temperature difference to the provisions of the thermal control plan were continuously monitored,
- Concrete sampling stations were located at each of street level pumps and equipped to provide for standard initial curing temperature environment (ASTM C31),
- Quality control included, among others, continuous verification of batch weights of materials, its consistency and amount of water added in the field (control of consistency and adjustments to water content were performed at staging area immediately prior to delivering concrete to pumps), random sampling of concrete and fabricating cylinders at frequency not exceeding 115 m^3 (150 yd^3), and a more frequent verification of initial fresh concrete temperature and plastic properties,
- A total of 168 sets resulting in 1008 cylinders, proportionally representing volumes of supplies of each of the plants, were tested for compressive strength at 7, 28, 56, and 90 days.

The replacement rate of Portland cement with fly ash was selected with considerations for performance, constructability, thermal control and required productivity (as affected by the discharge rates of Portland cement and fly ash during batching)

Results of statistical evaluation of 90-day strength of concrete produced by each plant and all plants combined are provided in Table 5.

Table 5 – Compressive Strength Uniformity Studies, Wilshire Grand Replacement Hotel

Evaluation of data	Supplier 1					Supplier 2			All plants
	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 1	Plant 2	Plant 3	
Number of sets, two cylinders each	27	21	35	15	11	33	23	3	168
Average strength, MPa (psi)	50.0 (7256)	50.6 (7335)	51.2 (7426)	51.3 (7433)	51.4 (7458)	50.0 (7252)	50.7 (7358)	48.8 (7070)	50.6 (7340)
Min strength, MPa (psi)	45.6 (6615)	46.8 (6790)	47.3 (6865)	47.4 (6875)	49.0 (7100)	46.1 (6690)	47.7 (6910)	47.6 (6905)	45.6 (6615)
Max strength, MPa (psi)	54.0 (7830)	58.3 (8460)	55.9 (8110)	57.2 (8290)	53.8 (7795)	54.1 (7840)	55.4 (8030)	51.0 (7390)	58.3 (8460)
Standard deviation, MPa (psi)	1.74 (253)	2.50 (363)	1.97 (286)	2.66 (385)	1.46 (212)	1.99 (288)	1.78 (258)	N/A	2.10 (305)
Coefficient of variation, %	3.9	4.9	3.8	5.2	2.8	4.0	3.5	N/A	4.2

All sets of test demonstrated strength exceeding the minimum specified in 90 days. Range of coefficient of batch-to-batch sample standard deviation for individual plants was limited to the range of 2.8% to 5.2%. Coefficient of variation for all batch plants was 4.2%. Excellent uniformity of concrete among other factors was benefitted by control of (i) composition and performance of intermingled fly ash Class F and (ii) proportions of concrete. Absolute maximum temperature and maximum temperature difference within the mass foundation were within the limits specified by thermal control plan.

LESSONS LEARNED

For enhancing quality and service life of structures and pavements and controlling cost of construction, all effects of fly ash on fresh and hardened concrete need to be accounted for during project design, preconstruction mix development, and construction phases. Summary of these effects is provided below in Table 1 (ACI 232.2R-03; Taylor, 2006; Van Dam and Smith, 2011; Thomas, 2007):

Table 1 – Summary of Effects of Fly Ash Class F on Properties of Concrete

Property/Characteristic/Attribute	Effect of Fly Ash Class F
Water requirement	Decreases with an increase in addition rate
Workability	Improves
Setting time	Extends with an increase in fly ash content, especially at lower temperatures
Heat of hydration	Reduces with an increase in substitution rate of Portland cement
Bleeding	Reduces when the addition of fly ash is accompanied by reduction of water content
Air entrainment and air-void system	May increase the demand in air-entraining agent, may affect stability of the air-void system
Strength	Slows early age strength gain with an increase in substitution rate and decrease in temperature, enhances long-term strength
Permeability	Reduces
Expansion due to alkali-silica reaction	Reduces
Sulfate resistance	Improves
Resistance to carbonation	Decreases with an increase in addition rate

The effect of fly ash Class F on rates of setting and strength gain of concrete in early age shall be considered in selecting the best suited construction practices, when possible retardation may impact:

- Time within which fresh concrete retains the ability to transfer hydraulic pressure on formwork
    - Pace of vertical forming may need to be optimized
    - Height of lifts may need to be optimized
    - Design of formwork should account for effects of fly ash
- Potential for plastic shrinkage cracking of flatwork and pavements (which may be affected by both the extended setting and limited rate of bleeding)
    - Maximum allowable rate of moisture evaporation used in evaluating the risk of plastic shrinkage cracking needs to be reduced with the decrease of rate of bleeding (ACI 308-11)
    - In planning for finishing and curing of exposed flat surfaces special consideration shall be given to the use of evaporation retarders upon finishing, timely initiation of curing, and selecting method of curing allowing for the most efficient water retention,
- Potential for settlement cracking of plastic concrete
    - Proper vibration protocol shall be implemented to eliminate settlement above reinforcing steel and load transferring devices, especially when setting time is extended,
- Time period before removal of forms, shores, and reshoring

    - May need to be extended,
- Early age cracking of flatwork and pavements
    - The development of tensile stresses and tensile strength in concrete pavements, potential for cracking in early age and best mitigation strategies should be evaluated prior to placement, for example by using simulation software (one example is Hiperpav III software),
    - Flatwork and pavements must be protected from moisture losses for longer time periods,
    - Time of saw cutting of contraction joints shall be optimized, etc.

It is equally important to optimize the content of fly ash and proportions of concrete with consideration for constructability. The best results can be achieved when concrete during preconstruction studies is pretested for setting time and early age strength gain at temperatures anticipated during construction.

Uniformity of strength of concrete is another important consideration. FAA and many transportation agencies calculate payments to contractors for completed pavements based on uniformity of both flexural strength and thickness. Uniformity of strength also impacts the required strength of concrete, which is calculated as the specified strength plus standard deviation multiplied by standard safety coefficients. For the same specified strength an increase in standard sample deviation requires concrete suppliers to design concrete for a higher required strength. Analysis of multiple pavement projects performed demonstrates that control of composition and performance of fly ash by suppliers combined with control of concrete proportions and assurance of uniformity of mixing allow for good uniformity of concrete.

CONCLUSIONS

The optimum fly ash content varies depending among others on locally available materials, concrete application, and ambient temperature during construction. High volumes of Portland cement replacement with fly ash may be suitable for many applications provided the needed rates of setting and early-age strength gain can be met. It is equally important to (i) optimize content of fly ash for concrete exposure conditions and durability, concrete application, required rates of stiffening/setting and early age strength gain, temperature during construction and initial curing, and construction practice and to (ii) optimize construction practice for the content of fly ash.

Case studies of construction using concrete with moderate content of fly ash Class F confirmed that proper quality control of fly ash and concrete proportions allow for very good uniformity of strength.

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