Specifying Fly Ash for Use in Concrete

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Over the past several decades, the use of fly ash in concrete has had a successful track record. The performance benefits fly ash provides to mechanical and durability properties of concrete have been well researched and documented in actual structures. Currently, fly ash is used in more than 50% of all ready mixed concrete placed in the United States, yet many design professionals continue to remain overly restrictive when it comes to using fly ash in concrete.

This article addresses some optimal ways of specifying fly ash for use in concrete while ensuring that the desired concrete performance is achieved. Most of these recommendations form part of a larger NRMCA publication that should be released later in 2008. Project specifications for most commercial work in the United States are typically written as per American Institute of Architects MasterSpec format. Any cementitious material is typically addressed under Section 2.5 (Concrete Materials) of that format as follows.

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Cementitious materials: Use materials meeting the following requirements:

Hydraulic Cement: ASTM C150 or ASTM C1157 or ASTM C595

<specify type of cement required for the work; C150 – I, II, III, V; C 595 – IP, IS; C 1157 GU, HE, MS, HS, MH, LH>

Pozzolan or Fly Ash: ASTM C618

<specify class of fly ash if pertinent to the work – Class N, C or F>

Slag: ASTM C989

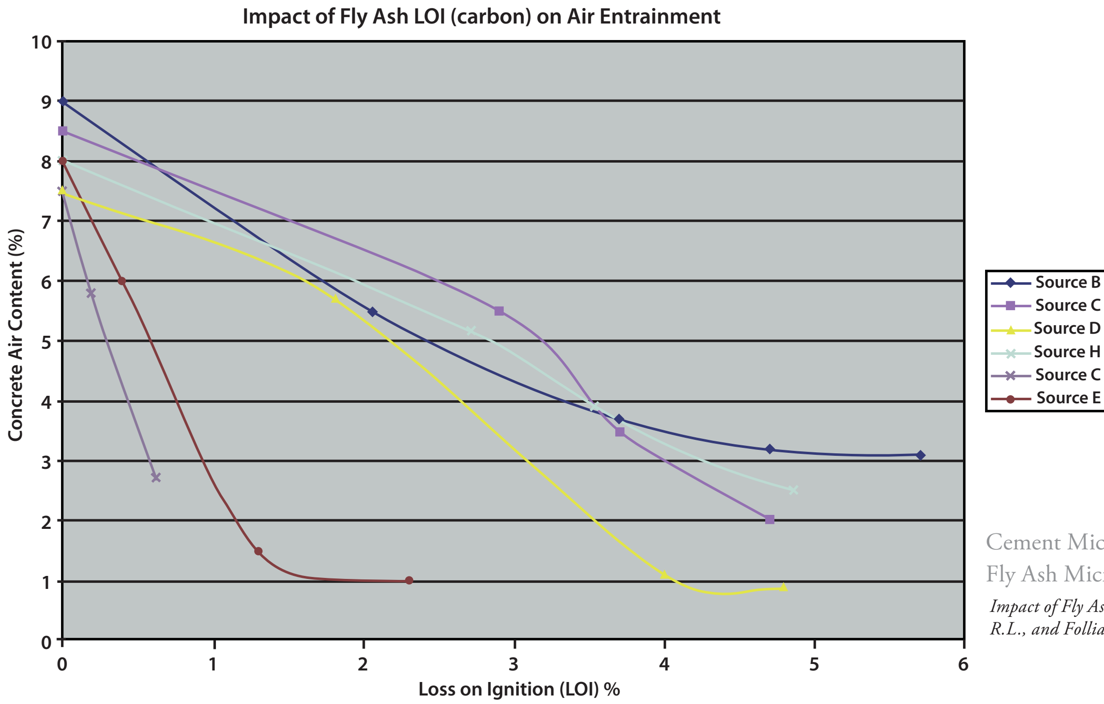
<specify grade of slag if pertinent to the work; Grade 100 or 120>

Silica Fume: ASTM C1240

The above format clearly states that fly ash has to meet ASTM C618, which is the standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. This by itself is adequate for specifying fly ash in concrete. Frequently, design professionals make it more complicated and too restrictive. Some of these restrictions, the possible rationale behind them and issues related to not having these restrictions are discussed below.

Limitations on quantity of fly ash

This is perhaps the most frequently applied restriction governing the use of fly ash in a concrete specification. When fly ash was originally used in concrete in the 1970s, there was some basis for restricting its use. However, after extensive research and several decades of successful utilization of fly ash, there is no basis for a restriction on the quantity of fly ash that should be permitted to be used in concrete. Some may say that the ACI 318 Building Code restricts fly



Cement Micrograph

Fly Ash Micrograph (note spherical particles)

Impact of Fly Ash LOI (Carbon) on Air Entrainment Hill, R.L., and Folliard, K.J. (2006)

ash use to 25% of total cementitious content. However, that is inaccurate. The new ACI 318-08 Building Code in Chapter 4 defines very severe freeze-thaw exposure (Exposure Class F3) as concrete exposed to freezing and thawing cycles that will be in continuous contact with moisture and exposed to deicing chemicals. For concrete structural members subject to Exposure Class F3, there is a limitation on the quantity of supplementary cementitious materials, expressed as a percentage of the total cementitious materials, as follows:

1. Fly ash or other C618 pozzolans – max: 25 percent
2. Total of fly ash or other pozzolans and silica fume – max: 35 percent
3. Combined fly ash, pozzolan and silica fume – max: 50 percent with fly ash or pozzolan not exceeding 25 percent and silica fume not exceeding 10 percent
4. Ground granulated blast-furnace slag – max: 50 percent
5. Silica fume – max: 10 percent

The primary reason for these limits in the Building Code is to minimize the potential for deicer-related surface scaling that can subsequently compromise the concrete cover over reinforcement and initiate corrosion earlier than expected. There is no technical reason to extend this maximum 25% limit for other applications. It is seen that for adequate resistance to alkali silica reaction (ASR) with some types of aggregate and for sulfate resistance, more than 25% of fly ash frequently is required. Also, with greater quantities of fly ash, the durability of concrete related to resistance to ASR, sulfate attack and chloride-induced corrosion is further enhanced. Further, the use of fly ash in concrete supports sustainable construction.

While it is true that greater quantities of fly ash can delay setting and early strength gain, these could be addressed to a large extent through the effective use of chemical admixtures. The concrete producer can evaluate the setting and early strength-gain characteristics of concrete containing fly ash under varying ambient conditions to assure the contractor that these needs will be achieved. It should be left to the concrete producer to optimize concrete mixtures to accommodate different quantities of fly ash.

Prescriptive limits on fly ash amounts do not help concrete performance in any way and may actually limit the improvement in concrete durability.

Limitations on the loss on ignition (LOI) of fly ash to less than x% (x = 2 is typically 2 or 4)

Most commercially available fly ashes will not meet this specification limitation, so in effect, this requirement will prevent fly ash use. In fact, C618 already has a LOI limit of 6%.

LOI is a measure of unburnt carbon in fly ash. Certain forms of unburnt carbon can absorb air-entraining admixtures and affect air entrainment of concrete. So, some may argue that by restricting LOI contents, the air-entrainment problems due to fly ash can be reduced. However, that is inaccurate. Figure 1 illustrates that at the same LOI, different fly ashes can lead to different performance related to generating the necessary air content. In fact, the low-LOI fly ash in that study was more sensitive to air entrainment than the higher-LOI fly ash. The reason for this is that certain fly ashes have finer carbon, which, in spite of lower LOI, can have a more significant effect on air entrainment. So, restricting the LOI of fly ash to 2% or 4% does not eliminate the problems with air entrainment.

The issue is not the LOI but rather the variability of carbon content and type at a given source. If the carbon content and type varies frequently (even as often as during the day) in an unpredictable manner, then it will be challenging for the concrete producer to supply air-entrained concrete with consistent levels of entrained air. This is really a quality-control issue that the fly ash marketer and concrete supplier have to resolve through frequent testing. The fly ash marketer can do a quick indicator test every four truckloads and supply that information to the concrete producer when delivering the fly ash load. The concrete producer can adjust the air-entrainment dosage on that basis and confirm the air content of the produced concrete. Some of the indicator tests are LOI, mortar air content and fly ash foam index test.

Specifying a maximum LOI limit does not resolve the air-entrainment problems related to fly ash use and might in fact provide a false sense of security because these effects may not be determined before concrete is placed in the structure.

28-day strength requirement

In general, concrete containing fly ash has a slower rate of strength development and often results in a higher later-age strength than with portland cement concrete. In some projects, there may not be a need for a 28-day strength requirement for members or classes of concrete that will not have anticipated construction or service loads applied at 28 days. For example, specifying 8,000-psi compressive strength to be achieved at 56 instead of 28 days for columns will result in highly optimized mixtures. A later-age strength requirement when feasible will permit a higher quantity of supplementary cementitious materials, reduce the total cementitious content (paste volume) and therefore reduce the potential for cracking while improving long-term concrete durability. Many projects have been successfully completed where the specified strength had to be attained at 56 days.

If there is a need to obtain information about the acceptability of concrete strength at an earlier age, one might use a percentage of the specified strength at the designated earlier age or an accelerated curing procedure in accordance with ASTM C684. This will allow for necessary quality-control actions if necessary.

Limitation on mixture proportioning, such as replacing "1.2 pounds of fly ash per pound of cement"

This mixture-proportioning approach was popular when fly-ash use in concrete was in its infancy and the use of chemical admixtures was not very prevalent. The objective was to achieve 28-day strength equivalent to a portland cement concrete mixture with some sources and types of fly ash, cement, aggregates and chemical admixtures. It was understood early on that there is no magic replacement ratio of cement with fly ash. The optimum replacement level will depend on the strength targets at different ages, the properties being targeted, climactic conditions, the use of admixtures and cement and fly ash sources. The concrete producer must be allowed to tailor concrete mixture proportions to satisfy strength, durability and fresh properties such as workability, setting time, etc.

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Limitations on the class of fly ash or supplementary cementitious material

Some specifications only permit the use of C618 Class F fly ash. In many parts of the country, good quality Class C fly ash is also available. In some regions, a good quality Class N pozzolan, such as calcined clay, is also used. Slag cement may be the preferred supplementary cementitious material in some markets. Concrete producers will generally not stock more than one or two types of supplementary cementitious materials. Project specifications must address local availability and experience to allow fly ash and pozzolans meeting C618, slag meeting C989 and silica fume meeting C1240 in the specification.

It is true that Class F fly ash is more effective in increasing concrete's resistance to ASR and sulfate attack. However, rather than disallowing Class C fly ash, durability can be ensured through a performance specification as discussed below:

When fly ash was originally used in concrete in the 1970s, there was some basis for restricting its use. However, after extensive research and several decades of successful utilization of fly ash, there is no basis for a restriction on the quantity of fly ash that should be permitted to be used in concrete.

Requirement for Class F fly ash for resistance to Alkali Silica Reaction (ASR)

Design professionals often specify prescriptive requirements such as quantities of Class F fly ash, slag, low-alkali cement, the use of a non-reactive aggregate, etc., to avoid ASR-related distress in structures. Class C fly ash may not be allowed. Concrete resistance to ASR can be ensured by incorporating the performance option provided below in the concrete specification:

Alkali silica reactivity – If the aggregate is deemed reactive as per Section XX.X and for structural concrete members that will be moist in service, submit documentation qualifying the proposed cementitious materials used with the aggregate by ASTM C1567 tests with an expansion after 14 days of exposure less than or equal to 0.1%.

C1567 is a standard test method for determining potential alkali-silica reactivity (ASR) of combinations of cementitious materials and aggregate. Generally, fly ash, silica fume and slag are used to mitigate problems associated with deleterious ASR, with increasing levels typically leading to improved resistance. If the aggregate is deemed reactive, the concrete supplier can perform ASTM C1567 tests with different types and proportions of supplementary cementitious materials and choose the combination that yields a 14-day expansion lower than 0.1%. For example, if 25% fly ash A shows expansion below 0.1%, the concrete supplier should use at least 25% of that fly ash in the mixture proportions. This is a better approach because more than 70% of the aggregates are typically found to test as potentially reactive to ASR by the ASTM

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C1260, Potential Reactivity of Aggregates (Mortar-Bar Method). Most of the aggregates that test to be potentially reactive show good field performance. Disallowing Class C fly ash on the basis that the aggregate fails the C1260 test or even the C1293 concrete prism test is not a good approach. The use of C1567 test limits allows the possibility of using Class C fly ash at different dosages while ensuring that the concrete can attain resistance to ASR.

> With greater quantities of fly ash, the durability of concrete related to resistance to ASR, sulfate attack and chloride-induced corrosion is further enhanced. Further, the use of fly ash in concrete supports sustainable construction.

Limits on the available alkali of fly ash

ASTM C618 used to have an optional limit on the available alkali content of fly ash. Research indicated that there was no good correlation between the measured available alkali content and the performance of the fly ash to mitigate ASR. This limit has been deleted from C618 and it is not measured by marketers of fly ash. This requirement, however, continues to remain in some project specifications. However, if the total alkali of fly ash is high (> 5% Na2O equivalent), the fly ash has not been found to be effective in controlling ASR. These high-alkali fly ashes, when tested with reactive aggregate, will exceed the ASTM C1567 expansion limits. Therefore, there is no need for a separate limit on the total alkali content of fly ash.

The requirement of a certain quantity, type of fly ash or another supplementary cementitious material for resistance to chloride ion penetration

For concrete exposed to chlorides (deicing chemicals, marine exposure), it is well known that fly ash, silica fume and slag can increase resistance to deterioration related to the corrosion of reinforcing steel by reducing chloride ion penetrability of concrete, with increasing levels typically leading to improved performance. However, it is not advisable to invoke prescriptive proportions, type and choice of fly ash, silica fume and slag to attain the improved performance.

The ASTM C1202 test, which really measures the electrical conductivity of concrete, provides a rapid indication of concrete's ability to resist chloride ion penetration. By requiring a low C1202 coulomb level, the design professional ensures that the concrete mixture will have a potential for low chloride ion penetrability without establishing prescriptive limits on the quantity, choice and types of fly ash, slag or silica fume. If the test option is used, it will need some necessary lead time for developing and testing one or more mixtures. Depending on the criteria, a value of 1,500 to 2,000 coulombs at 28 days might be selected as the criterion. The test samples must be standard cured for seven days, followed by 21 days of curing in 100-degree water. For standard laboratory curing, the test period should be extended to at least 56 days to recognize the benefit provided by fly ash. The use of C1202 test criteria provides freedom to the concrete producer to optimize mixture proportions while ensuring that concrete of low chloride ion penetrability is used.

Note that the C1202 test has a high testing variability and is not very suitable for the testing of samples obtained at the jobsite. It is suggested to be used primarily to qualify concrete mixtures. For critical projects, if the design professional is interested in the use of C1202 criteria for concrete acceptance, a more rigorous statistical approach is appropriate, as discussed in Reference 8.

Requirement for Class F Fly ash for resistance to sulfate attack

For different levels of sulfate exposure, the 318 Building Code has w/cm, compressive strength and cementitious type requirements. Concrete containing Class C fly ash is not known to be very effective against sulfate attack. Therefore, engineers prescribe only Class F fly ash for concrete exposed to sulfate environments. The new 318-08 Code adopts a more progressive approach and allows a performance-based evaluation of the proposed cementitious materials by ASTM C1012. The code also permits the evidence of past successful field performance to be used. The use of C1012 criteria ensures that the concrete is resistant to sulfate attack and does not restrict the use of Class C fly ash or any other material. The one disadvantage of this approach is the considerable lead time needed, since tests progress for six months to one year.

The use of silica fume without any other supplementary cementitious material

A concrete specification that requires the use of, say, 7% silica fume without any other supplementary cementitious material may not be an optimized mixture for the application. The design professional should focus on the intended performance requirement (permeability, resistance to ASR, sulfate attack, etc.) and allow the concrete producer to combine supplementary cementitious materials judiciously to attain target performance levels. The use of a lower quantity (3% to 4%) of a highly reactive pozzolan such as silica fume with fly ash or slag can lead to optimum early age strength, fresh concrete properties and significant long-term durability benefits.

Reference to water to cement ratio (w/c)

It is common for concrete to have supplementary cementitious materials such as fly ash and slag that are included in the

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calculation of w/cm. The ACI 318 Building Code has limitations on the maximum water-to-cementitious-materials ratio (w/cm) for various durability requirements. Referring to w/c may be misleading, and this should always be referred to as water-to-cementitious-materials ratio (w/cm).

Minimum cementitious content requirements

ACI 301 and 302 recommend minimum cementitious material content (not cement) for floor slabs only, primarily to improve finishability. There is no technically valid reason to include a minimum cementitious content for other structural elements, provided the performance requirements for that element are achieved. Even for floor slabs, the finishability can be determined by placing trial slabs rather than the prescriptive minimum cementitious material content approach, which does not necessarily ensure good finishability. Also, a high minimum cementitious material content frequently leads to non-optimized mixtures, high paste contents, higher shrinkage, high temperatures due to heat of hydration and associated cracking. ■

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