The Advantages of Fly Ash Use in Concrete Structures

Nicola LONGARINI[1], Pietro Giuseppe CRESPI[2], Marco ZUCCA[3], Nicola GIORDANO[4], Giuseppe SILVESTRO[5]

[1] Ing.; Politecnico di Milano, CISE Consortium, Piazza Leonardo Da Vinci, 32, 20133 Milan, Italy; email: nicola.longarini@polimi.it
[2] Doc.; Politecnico di Milano, Department of Architecture, Built environment and Construction engineering (ABC), Piazza Leonardo Da Vinci, 32, 20133 Milan, Italy; email: pietro.crespi@polimi.it
[3] Ing.; Politecnico di Milano, CISE Consortium, Piazza Leonardo Da Vinci, 32, 20133 Milan, Italy; email: m.zucca@aol.com
[4] Politecnico di Milano, CISE Consortium, Piazza Leonardo Da Vinci, 32, 20133 Milan, Italy; email: nicola_giordano@hotmail.it
[5] MSc.; Civil Engineer, Milan, Italy; email: giuseppe.silvestro@aol.it

Summary

In this paper the use of fly ash for particular High Strength Concrete (HSC) realizations is investigated.
The use of fly ash as a partial replacement of Portland cement in HSC seems a valid solution in particular for a sustainable construction design, considering the interesting HSC performances (in terms of strength and durability) and the economic aspects (in terms of waste material's reuse from industrial process). Fly ashes have been employed in the past especially for underground structures. Nowadays, their use is under evaluation also for elevation structures.
In this paper, the most important technical regulations about the use of fly ash for the concrete mix design are discussed. The increase of the mechanical resistance, the better protection against chemical agents attacks and freezing - thawing cycles using fly ashes are also show. Moreover, in comparison to the fresh concrete, the benefits related to the minor water/cement (w/c) ratio are presented, in the same workability conditions. Additional considerations are carried out about the hydration process: the mixture produces less heat for the lowering of the C3A and C3S percentages using fly ash.
Finally, a greater concrete impermeability obtained using fly ash, due to the presence of a lower hydrolysis content, which leads to an increment of the cement paste porosity, has been evidenced.
All of mentioned benefits shows the fly ash use in the High Strength Concrete (HSC) is a valid solution against many problems interested negatively the concrete mix – design and the mix – production.

Keywords: fly ash, mix design, high strength concrete, admixture

Fly ash classification

Nowadays, despite the increase of renewable energy sources, the use of coal is the best way for electricity power production in some countries. This results in the generation of large quantities of fly ash. Furthermore, there are different types of coal and the boilers used in this process produce different types of fly ashes, such as siliceous, calcareous or silica-calcareous fly ash.

The fly ash could be defined as fine powder of mainly spherical, glassy particles, obtained from burning of pulverised coal, having pozzolanic and hydraulic properties, and consisting essentially of SiO_2 and Al_2O_3 (Table 1). It is obtained by electrostatic or mechanical precipitation of dust-like particles from the flue gases of the power plants. This product has pozzolanic properties and, for this reason, it isn't only waste material but it may be used to improve performances of other products as concrete. Before use, fly ash may be subjected to industrial processing, for example by selection and classification, sieving, drying, blending, grinding or carbon reduction, to optimize its fineness or reduce its water demand.

When using fly ash, it should be noted that, certain properties of fresh and hardened concrete may be affected, apart from the pozzolanic property effect.

Fly ash use in concrete mix design

Generally, pozzolanic additions in concrete offer undoubted advantages compared to the use of cement (Portland or admixture) only. These additions are usually defined as "type II" and they are different from those of "type I" which are mainly inert, sand and gravel properly.

The first advantage is represented by the increase of fresh concrete pumpability when a low content water and, consequently, a low content of cement, to maintain constant the water – cement ratio used.

In later time, the possibility of improving other performances by the use of fly ash, compared to concrete mixes with cement only, has been evaluated.

In this way, the "type II" addition can be used to replace (or in addition to) the cement so that it can modify the water – cement ratio, the principal parameter of concrete design. For instance, it is possible to reduce the cement content with an increase of fly ash keeping constant the water – cement ratio and the final strength of hard concrete. For this reason, in the concrete mix design procedure it is possible to talk about "equivalent binder" rather than simple cement.

Obviously, in concrete production standards such as the European standard EN 206-1, the correct procedure for maximum content and homogenization coefficient (K_{FA}). If a concrete is made using a quantity "c" of cement and a quantity "p" of fly ash, it is defined as equivalent cement (c_e) the amount of cement required to obtain the same contribution to the compressive strength given by p. The sum of the value of c_e and c of the amount of cement determines the total content of cement (c_{tot}), as shown by the following relationship:

$$c_{tot} = c + c_e = c + K_{FA}\, p$$

The European standard EN 206-1 suggests the maximum fly ash content, in order to define a limit of fly ash use as "type II" addiction. Exceeded that limit, 1/3 of the cement content, the remainder is considered as of type I addition only, so aggregates. Regarding the coefficient (K_{FA}) value for concrete admixture made with cement CEM-I, Portland cement conforming to EN 197-1, the European standard EN 2016-1 admits that:

CEM I – 32,5: K_{FA} = 0.2; CEM I – 42,5: K_{FA} = 0.4.

There is another tip suggested by the standard about fly ash use: the minimum content of cement, defined according to the class of environmental exposure, can be reduced and replaced with fly ash, at maximum as:

k × (minimum cement content - 200) kg/m^3.

Tab. 1 Normal range of chemical composition for fly ash produced from different coal types (expressed as percent by weight)

Tab. 1 Normalny zakres składu chemicznego popiołów lotnych pochodzących z różnych typów węgla (procent wagowy)

Component	Bituminous (%)	Sub-bituminous (%)	Lignite (%)
SiO_2	20-60	40-60	15-45
Al_2O_3	5-35	20-30	10-25
Fe_2O_3	10-40	4-10	4-15
CaO	1-12	5-30	15-40
MgO	0-5	1-6	3-10
SO_3	0-4	0-2	0-10
Na_2O	0-4	0-2	0-6
K_2O	0-3	0-4	0-4
LOI	0-15	0-3	0-5

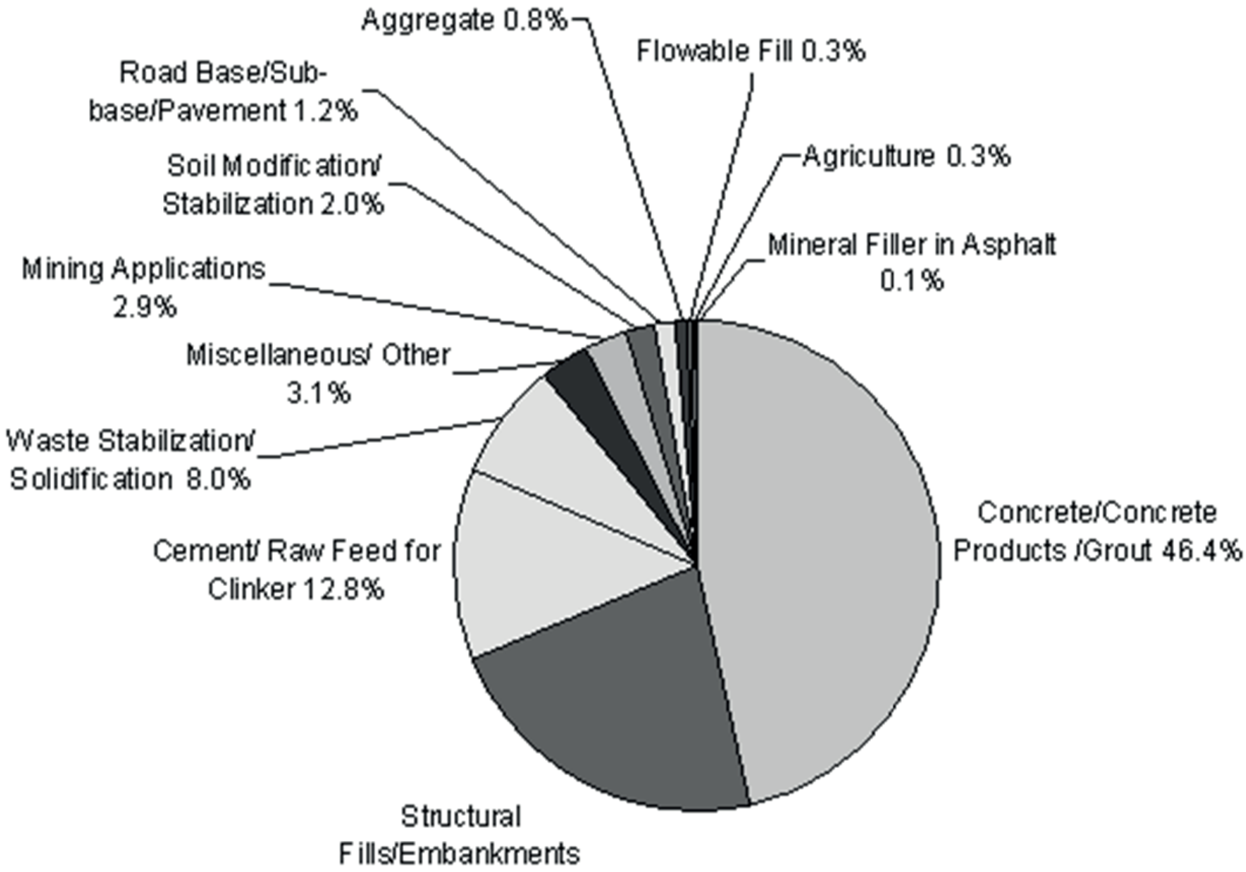

Fig. 1 Common applications of fly ash in the US. - American Coal Ash Association (ACAA). 2006 coal combustion product (CCP) production and use. Aurora, CO: American Coal Ash Association; August, 2007

Rys. 1 Typowe zastosowania popiołu lotnego w USA - American Coal Ash Association (ACAA). 2006 coal combustion product (CCP) production and use. Aurora, CO: American Coal Ash Association; August, 2007

Furthermore, the application of this coefficient K_{FA} to concrete for exposure classes "XA2" and "XA3", with a risk of sulphate attack, is not recommended.

Determination of mechanical strength

The compressive strength of a concrete depends mainly by the water / cement ratio and the concrete hydration degree (a) which is, however, difficult to assess and, therefore, it is preferred to consider the time of hydration (indicated by t). Considering that the temperature remains constant during the period of hydration, either when additives don't modify the kinetics of hydration either when the curing is developed in a wet environment, the concrete compressive strength, given at the hydration time t*, can be expressed as :

$$R_c = A (w / c) ^\wedge B$$

where w = water present in the mixture, c = cement present in the mixture, A and B = constants to be determined experimentally dependent on the hydration time and the type of cement.

In the presence of fly ash it is:

$$R_c = A [w / (c_{tot})] ^\wedge B$$

Workability

The workability is the property of fresh concrete and mortar of determining the easiness that they are mixed, packaged and casted.

Generally, the addition of mineral particles improves the properties of concrete but sometimes it reduces the workability.

Indeed, the addition of fine dust raises the surface area and consequently the water request. However, it is verified, in some cases, the addition of fine dust such as the blast furnace slag (made in certain proportions) is able to decrease the amount of mixing water.

As told before, using fly ash in the mix design for concrete, leads to a significant improvement of fresh concrete properties, such as workability and pumpability so that allows to optimize the water – cement ratio. In fact, the obtained mixtures are more homogeneous with a low risk of particles segregation and water bleeding. This improvement is due to the ash spherical shape that enables particles to flow each other more easily, reducing the friction between the particles. Furthermore, that form is able to minimize the surface – volume ratio of the particles reducing the demand for water. It depends by the particles form because the spherical shape allows obtaining a higher packing density than irregular shapes particles, which follows a

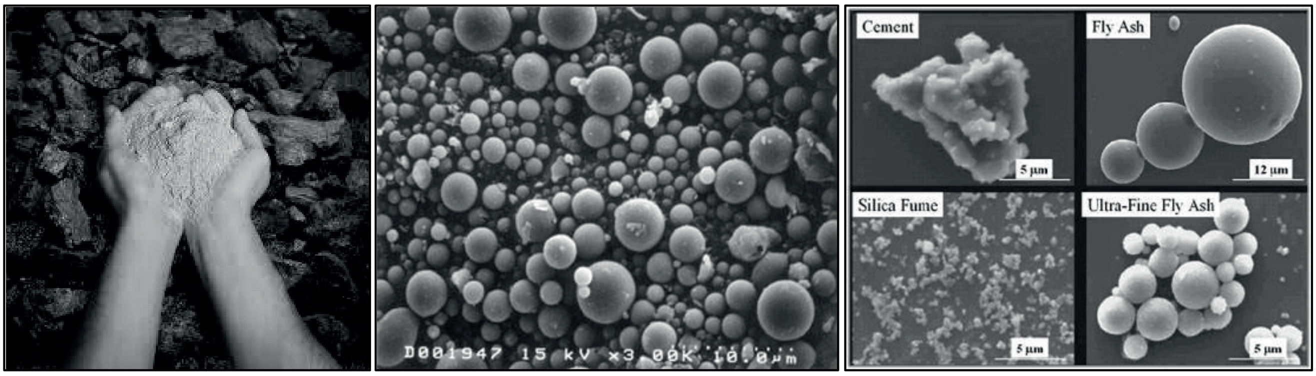

Fig. 2 Fly Ash, electronic microscope photos
Rys. 2 Popioły lotne, zdjęcia z mikroskopu elektronicznego

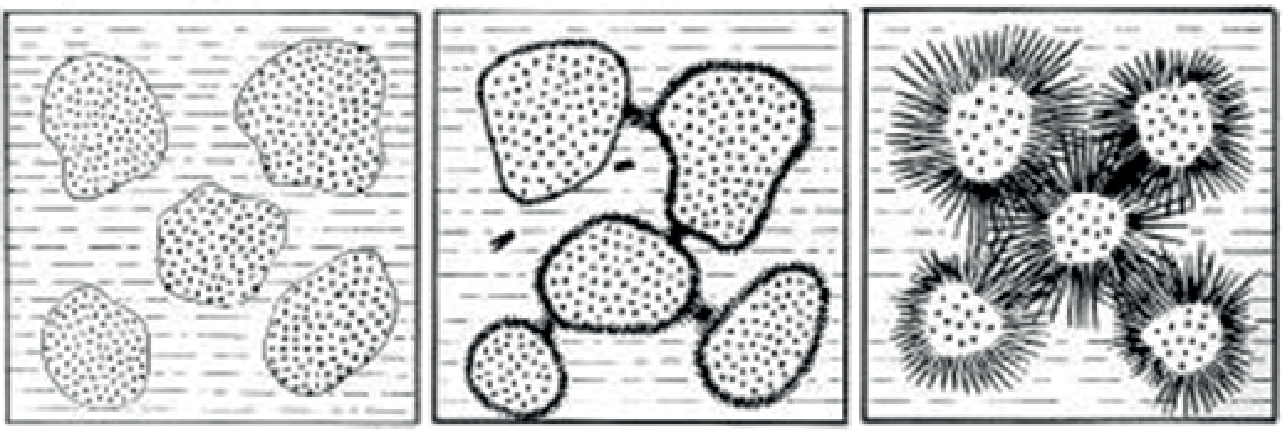

Fig. 3 Three steps of concrete hydration – (Enco Journal, prof. M. Collepardi)
Rys. 3 Trzy stopnie uwodninia betonu – (Enco Journal, prof. M. Collepardi)

lower water demand in equal condition of workability. The spherical and regular geometry, as well as the small size, of vitreous ash allows the mobility of particles better than the others inside the mix, admitting to reduce water demand, in contrast to what happens with other fine dusts, with the exception of the cement. This effect rises if the content and fineness of ash increase. It can be said that fly ashes bring benefits to concrete mixes, in terms of workability and surface finish, when used in mixtures poor in fine aggregates.

Heat of hydration

The hydration of Portland cement is an exothermic process, in which the heat determines an increase of the fresh cement temperature. A partial replacement of cement with fly ash, when the kinetics of hydration appears to be much slower than that of the cement, implies a lower heat development and a consequent raise in temperature. Ashes from bitumen, characterized by a low content of calcium, are more effective than those with a high content of calcium (called sub-bituminous ashes) reducing the rate of temperature increase. In massive civil constructions, a partial substitution of cement with fly ash, in percentages between 40% and 70%, leads to a great reduction of the thermal stresses generated during the concrete curing tasks.

Hydration and mechanical strength

Addition of fly ash in mix design of concrete leads to a change in the rate of hydration and in the subsequent development of mechanical strength. Partial replacement of cement with ashes generates a slowdown in the hydration process of the cement during the initial stages of that process. Reactions involving pozzolanic fly ash take place only when hydration process of cement has already started (Figure 3 – after the second step); it happens when a sufficient amount of calcium hydroxide, which reacts with the silica contained in the ashes, is generated.

The period of curing where ashes behave as a material inert practically depends on the reactivity of the system. Precisely, it depends on the content of amorphous silica and on the specific surface area, as well as on the curing temperature of concrete dough. Accordingly, all the beneficial effects, brought by the introduction of ashes in terms of hard concrete mechanical strength and reduction of permeability, are only manifested at later time. The developed resistance rate of hardened concrete with ashes, depends on various factors, the most important ones are the fineness of the ash used, the content of amorphous silica, the average size of particles, the proportions in which they were added, the environmental temperature and the possible use of chemical additives modifying other characteristics. In many researches it is shown the concrete with ash additions get an higher mechanical strength than the others, even though it needs more time to reach the final strength. Moreover, the addition of mixtures of ashes rich in fine fractions leads to an increase of the final strength without affecting the short term development rate. There are many factors which influence in a negative way the strength development and impermeability of concrete, for instance the presence of large dimensions pores in the hardened concrete and some micro-cracks generated at the interface between the cement paste and aggregates.

Using of fly ashes tends to minimize these effects because they act both from physical and chemical points of view. The first acts through the filling of large pores with the fine and very fine particles, the second products of the pozzolanic reaction tends to redefine the structure of pores by reducing the development of micro-cracks at the transition zones. Mechanical properties and durability of concrete are conditioned by density and microcracks formation at the contact zone between the cement paste and aggregates. In conventional concrete, based on Portland cement, the transition zone has a density less than the remaining mass of material and an higher content of calcium hydroxide crystals. For this reason, the formation of micro cracking phenomena is easier than in other areas because the shrinkage induced by changes in temperature and humidity, between cement paste and aggregates is different. It is clear from the foregoing points, that the interface area of cement paste - aggregates is the most critical in terms of hardened concrete mechanical strength. Using of fly ash improves the mechanical strength and durability of concrete as it leads to an increase of the mechanical strength of the area of the interface by changing the structure.

Resistance to chemicals attacks

The resistance to chemicals aggressive is strongly influenced by the decomposition state of the cement paste which is due to internal chemical reactions occurring to the paste already hardened. Acid solutions react with the calcium hydroxide and generate a water-soluble compound which leaches from the concrete getting an high-porosity damaged material. As result by the reactions, there is a drastic decrease of the chemical concrete resistance and the water-soluble sulphates reacting with the $Ca(OH)_2$ leads to the formation of calcium–sulpho–aluminate, also called "ettringite". That reaction is characterised by a volume increase and, when it occurs in the matrix already hardened, it involves in a physical disgregation of the concrete. The addition of fly ashes leads to an increase of the concrete resistance to particularly aggressive chemicals attack, as water-soluble sulphates. In fact, the reaction of pozzolanic ashes, at first, consumes the calcium hydroxide, which is one of the main causes of the vulnerability of concrete to chemicals, and secondly it leads to a significant porosity of the paste decrease resulting in a minor permeability to chemicals aggressive. By replacing about 15% of the weight of cement with fly ashes, like subbituminous type, the concrete resistance is considerably increased specially when the concrete is exposed to the action of solutions by Na_2SO_4 and $MgSO_4$, in less than 10% concentration.

Resistance to freeze-thaw cycles

The concrete resistance to freeze-thaw cycles depends on several factors including the formation of an appropriate system of micro-pores that ensures entrapment of an appropriate amount of air, the cooling rate, the curing conditions, the type and conformation of the cement matrix and the possible presence of anti-freeze salts. The adding of fly ashes, results in a lowering of the freezing temperature of water into the concrete pores, because of the redefinition of these pores, resulting in a raise of concrete durability. However, ashes inside the concrete tend to reduce the amount of entrained air and, as the amount of ashes represents a fundamental parameter, it is good to keep under observation the distribution of pores in which the air remains.

Conclusion

In this paper the main advantages in the fly ash use in concrete admixtures is described. As it has been seen, the use of waste ashes made by thermal power stations turns out to be not only in an improvement of intrinsic properties of concrete as mechanical strength, workability, durability and resistance to chemicals attacks and freeze cycles, but also an interesting solution in the perspective of a sustainable design which uses waste materials of a production process hardly reusable. Finally, it is important to underline the fly ash are used in concrete, the potential for leaching of trace elements is very low. This is due to the constituents of fly ash being encapsulated in the matrix of the concrete.

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Zalety wykorzystywania popiołów lotnych w strukturach betonowych

W pracy tej zbadano wykorzystanie popiołów lotnych w szczególności w realizacji Betonów o dużej wytrzymałości – HSC. Wykorzystanie popiołów lotnych jako częściowe zastąpienie cementu portlandzkiego w HSC wydaje się być prawidłowym rozwiązaniem w szczególności w projektowaniu zrównoważonych konstrukcji, biorąc pod uwagę interesujące osiągi HSC (pod względem wytrzymałości i trwałości) i aspektów ekonomicznych (pod względem powtórnego użycia materiałów odpadowych z procesów przemysłowych). Popioły lotne były stosowane w przeszłości szczególnie w strukturach podziemnych. W dzisiejszych czasach, oceniane jest ich użycie również w strukturach elewacyjnych.

W artykule przedyskutowano najważniejsze techniczne regulacje odnośnie użycia popiołów lotnych w projektowaniu mieszanek betonowych. Wzrost wytrzymałości mechanicznej, lepsza ochrona przed atakiem czynników chemicznych a także przed zamarzaniem – cykle rozmrażania z użyciem popiołów lotnych zostały również zaprezentowane. Ponadto, w porównaniu ze świeżym betonem, zaprezentowane są korzyści związane z mniejszym stosunkiem wody do cementu, dla tych samych warunków obrabialności. Dodatkowe rozważania są przeprowadzone na temat procesu hydratacji: mieszanka wydziela mniej ciepła wraz dla zmniejszającego się udziału C3A i C3S przy użyciu popiołów lotnych.

Ostatecznie, uzyskano większą nieprzepuszczalność betonów używając popiołów lotnych, z powodu obecności mniejszej zawartości hydrolizy, co prowadzi do przyrostu porowatości pasty cementowej.

Wszystkie wspomniane zalety pokazują, że wykorzystanie popiołów lotnych w Betonach o wysokiej wytrzymałości (HSC) jest prawidłowym rozwiązaniem rozwiązującym wiele problemów wpływających negatywnie na produkcję mieszanek betonów – ich projektowanie i mieszanie.

Słowa kluczowe: popioły lotne, projektowanie mieszanki, beton wysokiej wytrzymałości, domieszka