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Sustainable Development through use of Fly Ash

N. Bhanumathidas
N. Kalidas
INSWAREB
Visakhapatnam

Synopsis:

India is a vast country with huge population. The demand is not only on industrialization and housing but also equally on infrastructure where interconnecting the whole nation through road network is one of the important ongoing activities. If the interlinking of rivers also comes true this is another dimension of development. All these projects bring in lot of pressure on the construction material, with major thrust on bricks and concrete, because of their voluminous consumption.

India is bestowed to generate more than 150 million tons of industrial byproducts annually which can best be utilised in bricks, cement and concrete. Fly ash is the major byproduct and is available in almost all parts of the nation. Hence solving the fly ash problem is tantamount to solving the major share of the issue.

In this background authors discuss the use of fly ash in bricks and concrete with special emphasis on FaL-G technology. The indicators for sustainable development are also discussed thereupon.

In view of its voluminous availability bituminous coal is used in about 95% of coal-based thermal power generation, thus generating major lot of fly ash as ASTM Class F. The technical discussions in this paper thus pertain to this class of fly ash.

Introduction:

The rapid industrialization globally has been the main source, bringing in its melee billions of tons of industrial byproducts from many chemical process industries and coal-based thermal power plants. The mineral materials mutely existing in the interior of the earth are mined out and processed into various products, may it be for fertilizers, steel or power. As per one study about 8% of the mined material is only getting converted into usable material and the remaining 92% is left as byproduct. The natural resources have been used in a squandering way without much concern on the welfare of nature and environment. The harm caused to the mother earth is insurmountable in this direction.

But every cloud has a silver lining. Many of the byproducts befit themselves for the production of building material like bricks, cement and concrete owing to the calcareous, siliceous and/or argillaceous base of the former. India generates about 150 million tons of industrial byproducts out of which about 80% can be converted into building materials. Fig 1 depicts the annual generation of various byproducts and the potential of their utilisation towards bricks and cement (1). This is the crux of the Grey Revolution submitted by INSWAREB to the Government of India in 1998, which discussed various potential opportunities to revolutionise the nation in building materials scenario.

If the byproduct scenario is analysed fly ash from coal-based thermal power plants contributes to a major share close to 66% with its annual generation of about 100 million tons. As per the projected expansion of thermal power production the fly ash generation is poised to reach to about 170 million tons by 2012, occupying about 1.7 lakh acres of land if not put to optimum utilisation. In this context the Union Ministry of Environment & Forests, brought in notification that facilitates effective utilisation of fly ash and to enhance the consumption level from the present bleak rate of 15 -18%.

Avenues of fly ash utilisation

Fly ash is one product, probably next to water, to offer multifarious performance in umpteen fields. It could be a good soil supplement with superior shear strength and engineering values for the formation of embankments, substrata of the roads etc., Fly ash offers more densification through packing effect, when added at threshold levels during the preparation of bituminous concrete, and, in turn, enhances the longevity of bituminous roads.

Its application as micronutrient is well established for increasing the yield of certain crops. The apprehension that heavy metals of fly ash leach into water and ground can be alleviated as per the studies conducted by the authors, which indicate the leaching only in the highly acidic environment at low pH below 2. However the use of fly ash as a micronutrient or as a soil conditioner has limitation on its quantitative consumption.

The extraction of metals and production of zeolites seem to be unviable on techno-economic logistics. Also such approaches do not solve accumulation problem of fly ash.

Among other materials ceramics and granites have been developed from fly ash but their economic viability is not established.

The well-established utilisation avenue of fly ash is in the manufacture of building material where value addition is also one of the criteria. Hence major thrust of discussion is given for building material viz.,

* Bricks/ blocks
* Cement and concrete

Bricks/ blocks:

India is a traditional market for clay brick with an annual demand of about 360 billion bricks. Even in the 21st century about 95% of the bricks are manufactured in unorganized sector with least mechanization under unhealthy environment and unprotective conditions. The technological advancements in clay brick industry could not make entry into Indian industry because of the socio-economic conditions prevailed and geographical nature of the country. The widespread availability of fertile topsoil through out the nation made the clay brick market as a localised one. Thus logistically clay brick cannot be marketed beyond a radius of 20 to 50 km from the manufacturing place.

Fly ash-lime bricks had been introduced about two decades back in India in the interest of bringing to fore alternate products. The conventional technology for the production of these bricks involved the import of heavy duty press and autoclave that had increased the project cost. The thermal energy involved in autoclaving was added to the cost of production. These had cascading effect on the ultimate cost of the product making the same cost-prohibitive when compared to clay brick. Notwithstanding the good quality, the survival of fly ash-lime bricks had become questionable and slowly the manufacturing units reached to closure.

FaL-G Technology:

Bricks and blocks:

This is at this juncture that FaL-G technology developed during fall of 80s could attract the industry. FaL-G is the product name christened to a cementitious mixture composed of fly ash (Fa), lime (L) and gypsum (G), that sets, hardens and forms water impervious matrix with hydrated mineralogical phases akin to those in hydrated portland cement. The FaL-G technology is based on two principles viz.,

- The fly ash-lime pozzolanic reaction does not need external heat under tropical temperature, and

- The rheology and strength of fly ash-lime mixtures can be greatly enhanced with the addition of gypsum.

This dispensed away the need for heavy-duty press and autoclave equipment, and also made the process energy-efficient, thus bringing down the cost of the project as well the product. More than 1200 FaL-G brick/block production centers, operating successfully through out the nation manufacturing about 3.6 billion bricks or equivalent volume of blocks, are the testimony for the acceptance of the technology as well as the product.

FaL-G Chemistry

Pozzolan-lime mixtures have been used in ancient-roman structures. Therefore the chemistry of pozzolan-lime has its roots in the civil engineering practices of the last two millennia. In the absence of any instrumentation techniques to analyse the raw materials or end products, the empirical formulae were based purely on practical experience and engineering judgment of the quality of the product. After the advent of ordinary portland cement (OPC) pozzolan-lime science and material had become obsolete. Since 1960s the confidence in OPC concrete as the durable material has been shaken and, at the same time, pozzolan-lime mixtures had been under reinvestigation for the sound principles of material science and associated durability.

With this background, FaL-G technology was developed in India, with an innovative composition, which utilises the formation of calcium sulphoaluminate hydrates for early strength development that is achieved through addition of gypsum. Hence gypsum has as much significant role in FaL-G technology as it has in Portland cement. Authors discussed, in their comprehensive book, various studies in the development of this technology (2).

In fly ash the reactive aluminate phase exists as aluminosilicate in glass/ amorphous form in association with reactive silica. This phase, however, is passive and needs an appropriate activator. This is where gypsum plays a crucial role. Due to the affinity between alumina and sulphate ion, the latter is capable to destruct/ dissolve the glass and activate alumina. This contributes for the formation of ettringite, simultaneously facilitating the availability of reactive silica for further reactions those contribute for later strength and densification. Thus gypsum acts as an accelerator in FaL-G in enhancing the early reactions and as well accelerating the formation of calcium silicate hydrates (3).

Aluminate of portland cement exists in highly reactive calcium aluminate (C_3A) phase and tends to hydrate aggressively forming C-A-H, which has feeble strengths. This formation prevents further hydration of cement, thus making the product commercially unviable. When gypsum is added to ground clinker, sulphate ion, due to its affinity with alumina, diverts the same towards ettringite formation, thus preventing direct hydration of calcium aluminate. With gypsum addition the portland cement undergoes systematic hydration with sequential formation of hydrated mineralogy. Thus in portland cement gypsum acts as a set regulator. It is interesting to note the dual role of gypsum as set retarder and strength accelerator in blended cements (4).

The comparison of strengths between fly ash - lime mixes and FaL-G mixes is given in Table 1. The lime reactivity strength of fly ash also enhances in association of gypsum as given in Table 2.

Technological flexibilities:

FaL-G technology has been successfully practiced with even low quality of lime and gypsum that are obtained as by-products from other industries. However for any such industrial byproduct it should be ensured that the other ingredients are not deleterious for FaL-G chemistry. In the modified version of FaL-G technology OPC has been used as a substitute for lime without disturbing cost economy. Also some fly ashes those did not meet Indian Standard Specifications, have been successfully used to make FaL-G products. Mehta's comment on FaL-G technology in this context is note-worthy (5): "By disregarding the standard chemical and physical requirements for use of fly ash in the cement and concrete industries, it is found that tailor-made blends of even non-standard fly ashes with lime and gypsum or with Portland cement produced adequate strength on normal curing".

Once optimum FaL-G is synthesised as the cementitious media, it can bind any aggregate and the product has lot of options, leverages and flexibilities. For example, FaL-G can bind various fine aggregates such as sand, crusher dust, pond ash, and so on. Due to such flexibilities, FaL-G bricks/blocks offer plausible terms of techno-economic logistics as follows:

- FaL-G bricks can be produced with compressive strength of 10-35 MPa, water absorption of 8-15% and coefficient of softening at 0.85 to 0.95.
- It is feasible to produce FaL-G bricks at places where the brick price prevails at Re 1.25 or more even by procuring fly ash from distances of 150-300 cm.
- It is easy to manoeuvre the production cost of FaL-G bricks by playing with FaL-G to sand/crusher dust ratio whereby strength can be brought down from as high as 25-30 MPa to 8-15 MPa so much so the production costs.
- FaL-G production is simple with manufacturing steps viz., casting and curing, and hence the total production cycle spans at 7-10 days with minimum capital deployment in comparison to clay brick.
- As FaL-G brick production does not require drying and sintering the activity is close to perennial one unlike in clay brick, which is compelled for stoppage during monsoon.

For concrete:

When compared to neat strength of OPC paste the strength of FaL-G is almost at 50%. However this does not preclude the use of FaL-G as a media for concrete as long as proper measures are taken to compensate the cementitious input. Accordingly, after various studies, FaL-G concrete was developed by using 1.5 units of the same against every one unit weight of OPC input. The data below on FaL-G concrete give some indications:

Mix by wt	w/cm	Compressive strength (MPa)		
		7day	28day	180day
1.5:2:4	0.57	11.6	16.5	30.5
1.5:1.5:3	0.57	14.5	21.1	42.8

Above strengths infused confidence based on which about 200 m^2 roof slab and 85 rmtr beams were cast with FaL-G concrete way back in 1991 and that is the monumental structure of *FaL-G Mansion* in Visakhapatnam. However to make the concreting more versatile with FaL-G, a blend of OPC and FaL-G, Portland: FaL-G, was developed. It was interesting that 30:70 blends yielded strengths at par with neat OPC at later ages. This facilitated to practice conventional mix designs for parallel grade strengths. For various mix designs strengths achieved were about 25 to 30 MPa on 28 day and about 40 to 50 MPa on 90 day. About one km road in black cotton soil area was laid. About 250 m^3 of structural concrete has been used in various constructions.

FaL-G has gone through various transformations as above, and the development of FaL-G in cement route made the formulation synonym to High Volume Fly ash Concrete (HVFC) popularly promoted by Malhotra and team of Canada Centre for Mineral Energy and Technology (CANMET), Ottawa. While HVFC uses typically 50 to 56% fly ash, FaL-G (HVFC) uses 60 to 70%. Another distinct contrast is that HVFC advocates expensive chemical admixtures to compensate the delayed rheology of fly ash, whereas, to meet the same need, FaL-G (HVFC) promotes addition of gypsum, commensurate to fly ash quantity, for early strengths, and use of roller mixer for controlled rheology.

FaL-G (HVFC) concrete for water tanks and VAMBAY project:

During laboratory studies M20 grade concrete was developed by proportioning the mix at 1:1.5:3 by weight, as stipulated by the department in the tender schedule. The durability studies conducted on 28-day specimen as per *ASTM C 1202: Rapid Chloride Permeability Test* were quite encouraging with very low Coulomb value at 240 as against 3,500 - 4,000 Coulombs obtained on corresponding OPC concrete. This indicates that, notwithstanding slow rate of strength gain, the concrete becomes impermeable at the early age, a striking and positive feature to prevent ingress of any chemicals or air pollutants into the concrete. Data of lab trials are as given in Table 4.

Panchayatraj department of Andhra Pradesh has taken the initiative to construct water tanks with FaL-G concrete and so far about 40 water tanks of different capacities are constructed. The latest one has a capacity of 2.5 lakh litres. Non-destructive and RCPT tests have been conducted on different water tanks and a summary of the data is given in Table 3.

Subsequently about 4,000 houses at VAMBAY scheme, Vijayawada, are designed with FaL-G concrete as framed structures with a plinth area of about 21 m^2 and separate area for utilities. In view of black cotton soil, the structure is designed with pile foundation having a pile depth of 3 mtr and 230 mm dia. The piles are connected with precisely designed plinth beams over which the basement is constructed.

FaL-G concrete has been deployed right from pile foundation through the columns upto the beams and slab. For homogeneity and better workability the FaL-G concrete has been prepared in roller mixer. Due to effective attrition under heavy rollers the gel formation, associated with good workability, has been achieved at a w/cm of 0.35 to 0.38. The slumps attained for concrete are in the range of 25 to 30 mm. The striking benefit of FaL-G concrete lies in yielding good flow when subjected to vibration, despite low slump. This peculiar phenomenon facilitates to eliminate chances for voids and honeycombing. The super fines of concrete help in better finish of the structural element provided proper formwork is used. The fine and smooth finish of the ceilings offers aesthetic appearance and also facilitates to avoid plastering, thus saving costs on this count.

As a quality control measure specimens were cast everyday using the field concrete and tested at corresponding ages of curing. This exercise facilitated feedback on the uniformity in dosing and homogeneity in concrete preparation. For testing purpose a site laboratory was also set up and every day number of samples were tested. The range of compressive strengths (MPa) and chloride permeability of concrete specimens is shown in Table 4.

Fly Ash in Cement and Concrete:

Technologically the performance of fly ash has been established way back in 1948 in the construction of Hungry Horse dam in the United States (6). Utilisation was upto 32% and two phenomena were counted for its use viz.,

- Reduced water demand to achieve the required workability
- Reduced heat of hydration of the concrete.

There after these intricate properties were availed to address the durability problems of concrete resulted out of high early strength cements, developed and used during post-second world war period. Fly ash has become an imminent input of cement/ concrete in many high-profile structures, where service life of the structure has to be guaranteed at minimum 100 years. Euro tunnel, UK; Akashi Kaikyo bridge, Japan, Confederation bridge, Canada, Petronas Towers, Malaysia are some among many where fly ash has been used just for durability criteria. Three Gorges dam, China is the new addition to this list.

Simultaneous to various global developments Indian cement and concrete industry realised that fly ash contributes for various performance phenomena of concrete and enhances the long term durability of structures. This has triggered off the production of *Portland Pozzolan Cement (PPC)*, fly ash blended cement, to an amazing growth to about 45% during 2003, as against a production figure of about 13% during mid of 90s.

Hydration chemistry

OPC consists of mainly four mineralogical phases, which undergo various stoichiometric reactions upon hydration. While the hydration of C_3A and C_4AF does not contribute for surplus $Ca(OH)_2$, the hydration of C_3S and C_2S invariably release surplus $Ca(OH)_2$ to the tune of 39% and 18% respectively upon complete hydration, which is identified as the possible cause for deleterious reactions, ultimately leading to early distress of concrete.

As per the established data, the hydration of OPC yields approximately 75% strength rendering mineralogical phases. The balance 25% is $Ca(OH)_2$ that is vulnerable for deleterious effects rather than contributing for the strength. Nevertheless *the same $Ca(OH)_2$ is a resource for pozzolanic reactions of fly ash to form secondary hydrated mineralogical phases, contributing for additional strength, more so at late ages*. Like insulin for sugar complaint in human system, fly ash works as an insulin to the lime complaint of concrete system (2).

Engineering characteristics and durability are two important features for concrete performance, which can be addressed by fly ash through this mechanism.

Engineering characteristics:

Effect of fly ash in concretes is more pronounced in flexural strength than on compressive strength as shown in table 5. Portland pozzolan cement (PPC) is showing high rate of increase in flexural strength. Improved bond at the transition zone may be attributed as one of the significant contributions for this phenomenon

Modulus of elasticity is low at early ages and high at later ages for fly ash-blended/ PPC concrete. Contrarily, creep strains are high at early ages that decrease progressively at later ages. *For concretes without fly ash, modulus of elasticity is high and creep is low that results in restrained extensibility of concrete, leading to cracks owing to drying shrinkage and thermal shrinkage. This phenomenon is more surfaced in concretes when large inputs of high grade cements are used.*

Intrinsic soundness and volume stability of concrete depend on the above characteristics, which, in turn, depend on materials those have gone into concrete as well the concreting practices including the mix design. Thus it is essential to judiciously select the material and design the mix proportions with an ultimate target on the holistic performance of concrete. Strength is only one of the many parameters, but it should not be the main target. Mehta has analytically discussed various consequences of using high-grade cements and adopting reductionistic concrete practices. One of the final recommendations is to use complementary cementitious material for durability criteria (7,8).

Durability

In the context of durability the following are noteworthy**:**

a) Permeability is the prime cause for the problems of concrete associated either with leaching of lime, leading to porosity, or with several types of chemical attacks.

b) Surplus $Ca(OH)_2$ released out of cement plays as the host to initiate and invigorate chemical reactions when reactive chemicals such as SO_2, CO_2, O_2, Cl^- ingress into permeable concrete.

c) Transition zone is the crucial area in concrete, which influences the micro cracking and durability of concrete. Incidentally, for a variety of reasons, transition zone is the weakest link in general and it is more so in permeable concretes.

d) The lime released from the hydration reactions (of cement) migrates to coarse aggregate together with bleed water, and settles at the interface zone in between the cement paste and coarse aggregate. Depending on the type of cement used, this surplus lime may get transformed partly or totally into mineralogy with progress in hydration. Whereas in high C_3S cements with higher fineness, in view of rapid release of lime, this zone gets thickened progressively

This is where the addition of fly ash becomes significant. When fly ash is present in the concrete, the lime in the transition zone gets converted into hydrated mineralogy, strengthening the bond between cement paste and aggregate. Pozzolanic reactions of fly ash with hydrated lime in transition zone are associated with two physical effects viz., *pore-size refinement and grain-size refinement. While pore-size refinement contributes for impermeability of concrete, grain-size refinement influences the transition-zone towards densification thereby minimising chances for micro cracking. Such improved microstructure of cement paste mitigates various chemical attacks and contributes for durability of concrete.*

Holistic Performance for Durability

Fly ash in PPC offers the holistic performance towards durability enhancement of a concrete in multiple ways:

- Reduction in heat of hydration, *generated out of OPC hydration chemistry*, and minimisation of thermal stresses;

- Absorption of surplus lime *released out of OPC* to form into secondary hydrated mineralogy;

- Pore refinement and grain refinement due to the secondary hydrated mineralogy, thus, contributing for impermeability and enrichment of transition zone;

- Improved impermeability of the concrete, resulting in increased resistance against the ingress of moisture and gases; thus ultimately leading to durability enhancement.

- Due to the various phenomena as above the fly ash concretes become chemically resistant as shown in Table 6.

This holistic performance addresses the issues of multiple needs in a single go, which otherwise need various inputs, as shown in the figure 2. *There is no product comparable to fly ash to render such holistic performance towards durability of concrete. Particularly on the aspect of enriching the transition zone between aggregate and cement paste fly ash is the unique and cost-effective solution. ASTM has included C1202, the method for rapid chloride ion permeability, as one of its specifications to rate the performance of concrete in qualitative terms.*

Chloride Permeability and Electric Resistivity:

Table 7 shows fall in chloride permeability for fly ash blended concrete in comparison to that of control. The data clearly delink durability from strength, which is a performance of increase in fineness of fly ash and its quantity. Even with 45 % fly ash the concrete is showing 28-day strength matching for M-20 grade.

As per Aitcin (9) Rapid chloride-ion penetrability test gives a fair idea about the interconnectivity of fine pores in concrete that are too fine to allow water flow. He further emphasized good correlation between water permeability and chloride permeability.

Based on the charge passed in Coulombs, the durability criteria can be graded as follows:

Charge passed Coulombs	Chloride penetrability rating	Durability grading
> 4000	High	Very poor
4000-2000	Moderate	Poor
2000-1000	Low	Good
1000-100	Very low	Very good
<100	Negligible	Excellent

These data also highlight the resistivity of the concrete to electric charge manifested in Coulombs, which means that lesser the Coulomb value higher the resistivity. Kurgan et al have done considerable studies on chloride ion penetration and electrical resistivity on concrete specimens, with and without complementary cementing materials, and established close linear correlation between these two parameters (10). Electric charge is the basic activity, in the presence of moisture and oxygen, to initiate corrosion of the reinforcement, thus a concrete resistive to electric charge is also resistive to corrosion.

Chloride Diffusivity:

Chloride diffusivity is one of the key issues in establishing the ability of concrete to withstand the chloride-rich environment. Bamforth, through the surveys on chloride concentration levels in various structures in service, established that blended cement concretes performed well (11). As per him *the effective diffusion coefficients for portland cement concretes were found to be at a level that would not afford protection when used with practical levels of cover*. In an extensive study he further developed a service life prediction method that considers the surface chloride level, the chloride corrosion threshold concentration, the effective diffusion coefficient and the cover to reinforcement. He concluded that for portland cement concrete unreasonably high cover with high grade concretes is essential whereas with fly ash and slag concretes the normal cover with average grade of concrete is sufficient to achieve similar performance (12).

Richardson, giving a summary of various observations and data, highlighted the low diffusivity of blended concrete, and referred Fookes' observation that in the severest microclimates blended cements were necessary, otherwise a cover of over 200 mm would be required (13).

Can there be more tangible data and explanations to prove that fly ash blended concrete is more resistive to corrosion in comparison to OPC concrete!

Sustainable Development:

Sustainable development is defined as the " Development, which meets the needs of the people without compromising the ability of future generations to meet their own needs" (14).

Fly ash utilisation complies with various indicators of sustainable development viz.,

- Conservation of non-renewable natural resources through byproduct utilisation viz., 3,500 tons of fertile top soil for every million bricks, and 1.5 tons of limestone for every ton of clinker.
- Conservation of thermal energy and equivalent fuel: about 200 tons of coal for every million bricks and about 120 kg of coal for every ton of clinker.
- Protection of ecology and environment, and abatement of pollution.
- Abatement of CO_2 @ 270 tons for every million bricks, and about 1.0 ton for every ton of clinker.
- Enhancement of structures' life that contributes for an improved GDP of the nation.

Conclusions:

Fly ash is a renewable resource with multi-faceted technical virtues, which made it as the most sought out material in bricks and concrete for various high profile constructions. Fly ash based blended cements are a boon to construction industry. On durability criteria IS 456:2000 insists on the use of blended cements.

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Table 1: Comparison of strengths between FaL and FaL-G mixes

Source	Strength MPa			
	Fly ash + Lime		FaL-G	
	7-day	28-day	7-day	28-day
LT Fly ash 1	9.0	17.9	25.0	32.0
LT Fly ash 2	11.0	15.8	20.0	25.8
HT Fly ash 1	2.6	7.8	8.4	24.0
HT Fly ash 2	3.3	4.9	6.5	24.8

Table 2: Lime Reactivity strengths MPa

Fly ash	without gypsum		with gypsum	
	10 d	90d	10d	90d
FA 1	2.8	6.4	5.2	10.8
FA 2	7.7	11.9	11.9	19.3
FA 3	9.1	15.9	17.7	21.7

Table 3: Strength, RCPT and NDT results on water tanks and concrete:

Core results

Age of specimen	Strength (MPa) Cylinder	Eq cube	Cl^- permeability (Coulombs)
270 days	29.0	32.4	326
240 days	24.4	28.8	336
240 days	22.6	26.7	390
90 days	24.8	27.7	207
90 days	26.0	29.1	132

NDT results:

Comp Strength MPa	Ultrasonic pulse velocity km/sec
25	4.25
24	4.19
28	4.27
32	4.45

Table 4: Data of lab trials and field specimens:

	Compressive strength MPa	Chloride permeability, Coulombs
Lab trials:		
3-day	7.1	-- --
7-day	15.1	-- --
28-day	29.0	240
90-day	41.8	45
Field specimens:		
3-day	4.5 to 5.5	-- --
7-day	13.0 to 15.0	-- --
28-day	18.0 to 25.0	1000 -1200
90-day	30.0 to 35.0	400-600

Table 5: Comparative strengths of OPC and PPC:

Type	Comp. Strength, MPa				Flexural strength, MPa			
	7d	28d	180d	360d	7d	28d	180d	360d
M 20								
OPC	30.7	40.7	41.0	44.0	4.6	4.7	5.2	5.8
PPC	22.7	40.0	44.0	52.8	2.8	5.2	8.0	9.2
M40								
OPC	54.0	63.0	67.8	71.0	5.6	6.8	8.3	8.7
PPC	42.2	63.0	72.7	78.0	5.7	7.2	8.4	9.6

Table 6: Comparative strengths, MPa, of M 40 concrete with different cements under various environment

Cement type	56-day NC	56-day sulphate	56-day acid	56-day sea water	120-day NC	120-day sulphate	120-day acid	120-day sea water
OPC	68.3	67.7	60.0	56.0	69.1	53.4	58.2	55.8
PPC	65.9	66.5	59.2	61.0	73.1	71.4	65.1	64.8
PSC	62.5	62.7	50.1	59.5	66.8	62.5	63.0	59.2

NC: Normal curing
Base clinker is same for all the above cement

Table 7: Results of fly ash blended concrete:

OPC	Fly ash	Comp Strength MPa				Chloride permeability (Coulombs)			
		28d	90d	180d	360 d	28d	90d	180d	360d
100	---	43.3	47.2	51.4	54.7	3852	2451	2251	1912
65	35	35.1	53.7	58.4	67.9	2529	313	166	155
55	45	28.7	51.0	54.3	59.7	2358	230	92	58

Concrete Grade: M20 with cementitious content 300kg/m^3

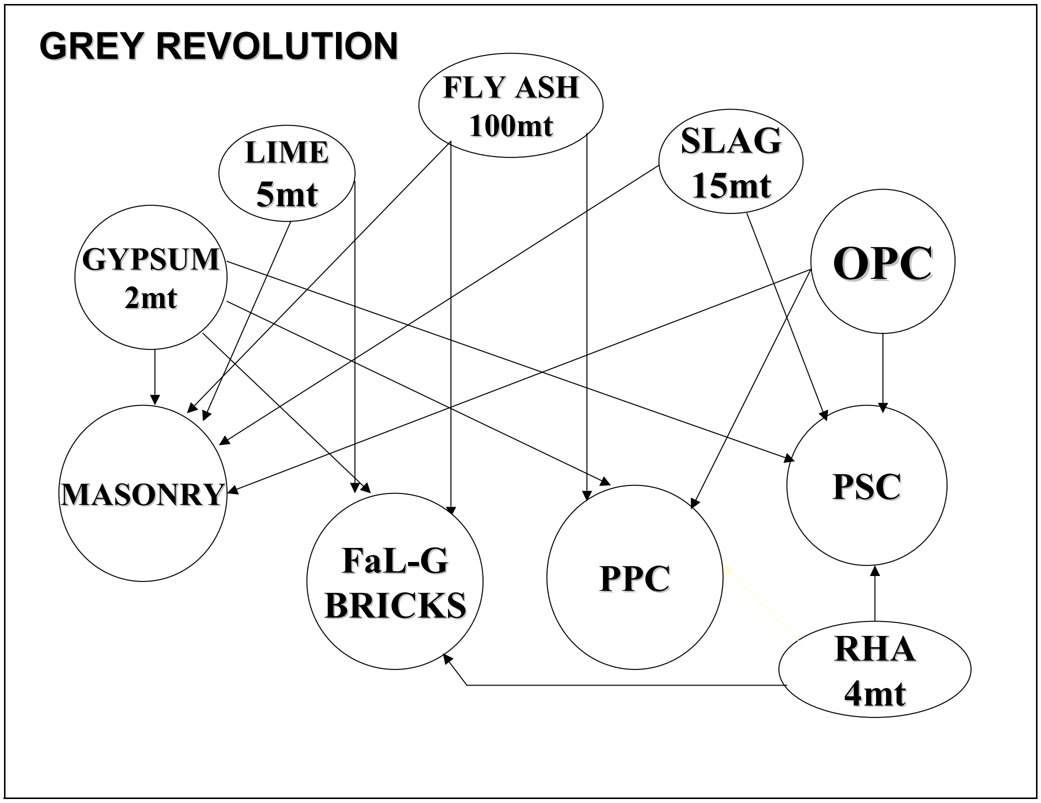

Fig1: Byproduct generation and utilisation

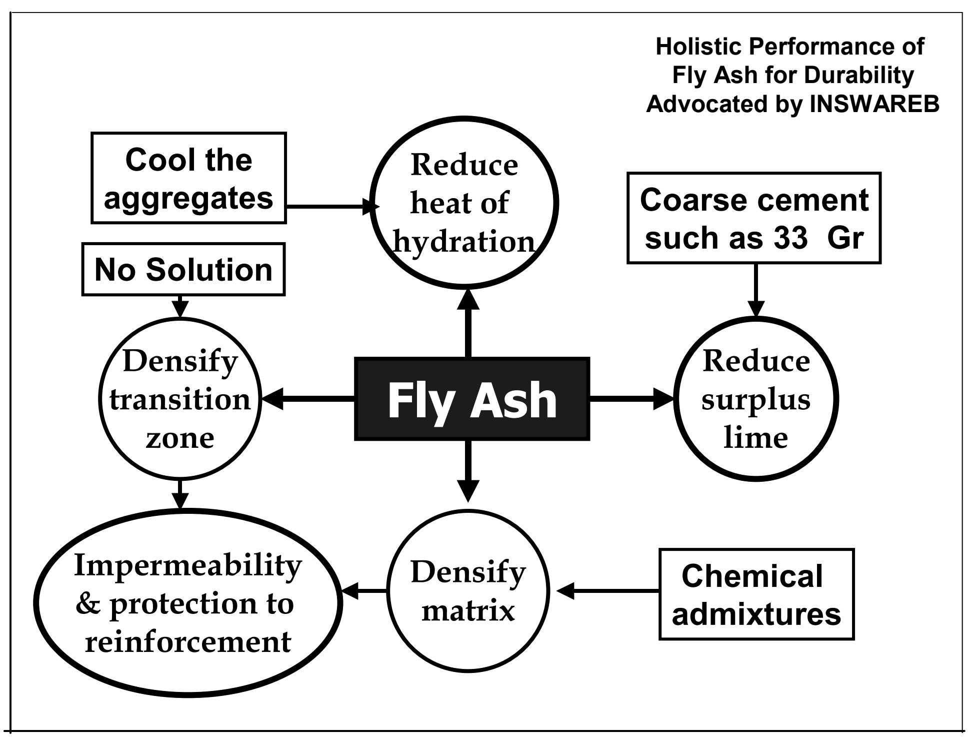

Fig 2: Holistic Performance of Fly Ash in Concrete