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Performance of concrete with binary and ternary cement blends

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Among the many factors that govern the durability and performance of concrete in service, type of cement receives greater attention. This paper describes the characteristics of cementitious systems required to meet the diverse requirements of strength and durability of concrete and highlights the advantages of part replacement of OPC by fly ash, granulated slag and silica fume – either singly or in combination in ternary blends. Examples of successful application are cited.

Keywords: *Cements, fly ash, granulated slag, silica fume, triple blends, high performance concrete, strength, durability, rebar corrosion.*

Durability of concrete is its resistance to deteriorating agencies to which it may be exposed during its service life, or which, inadvertently, may reside inside the concrete itself. The deteriorating agencies may be chemical – sulphates, chlorides, CO_2, acids, etc, or mechanical causes like abrasion, impact, temperature, etc. The steps to ensure durable concrete encompass structural design and detailing, mix proportion and workmanship, adequate quality control at the site, and choice of appropriate ingredients of concrete. Type of cement is one such factor.

Depending upon the service environment in which it is to operate, a concrete structure may have to encounter different load and exposure regimes. In order to satisfy the performance requirements, cements of different strength and durability characteristics will be required. Such different 'types' and 'grades' of cements are achieved by subtle tailoring of its chemical composition, fineness and particle size distribution. Greater varieties are introduced by the incorporation of additives like pozzolana, granulated slag or inert fillers. These lead to different 'Specification' of cements in national or international standards. The various IS specifications on cements are listed in *Table* 1.

Table 1: Types of cement covered in IS specifications

Sr no	*Generic type*	*Title*	*IS code no*
1	Ordinary portland cements	OPC 33 grade	IS 269
2		OPC 43 grade	IS 8112
3		OPC 53 grade	IS 12269
4		Rapid hardening Portland	IS 8041
5		Sulphate resisting Portland	IS 12330
6		Low heat cement	IS 12600
7		Hydrophobic cement	IS 8043
8		White cement	IS 8042
9	Blended and composite cements	Portland slag cement	IS 455
10		Portland Pozzolana cement – Fly ash based	IS 1489 : Part I
11		Portland Pozzolana cement Calcined clay based	IS 1489 : Part II
12		Masonry cement	IS 3466
13		Super-sulphated cement	IS 6909

At the commencement of a concrete construction, the anticipated exposure conditions generally decide the 'type' of cement. Requirements of load-carrying capacity are met by the structural design of the members, which decide the required strength grade of concrete and strength 'class' of cement. From logistic and management considerations, it helps if one cement can meet the diverse performance demands. The concept of such 'ideal' multi-function cement is elucidated first in this paper, with examples drawn from the Indian cement industry.

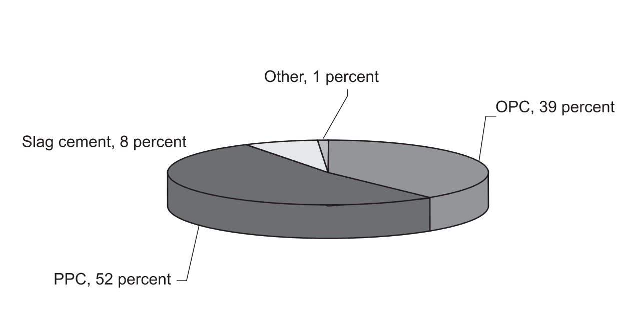

Fig 1 Production trend of different varieties of cement in India

Concept of multi-functional cement

The nomenclature and compositional details of IS specifications on ordinary Portland cements (OPC) given in *Table* 1 make the areas of application obvious. There are additional stipulations of alkali content and chloride ion concentration, which are similar to the international practice.

The general trend of production of different varieties of cement in India is shown in *Fig* 1. Cement production in India mainly centres on three types – OPC ~45 percent, Portland pozzolana cement (PPC) ~44 percent and Portland slag cement (PSC) ~10 percent, comprising 99 percent of the total. All other varieties including functionally important types such as rapid hardening cement (similar to ASTM type III), sulphate resisting cement (similar to ASTM type V) or low heat cement (similar to ASTM type IV), etc comprises only 1 percent of the total.

Two significant aspects in *Fig* 1 deserve notice. The first is that the production of PPC and PSC taken together is greater than that of OPC, which indicates gradual acceptance of such blended cements for structural concrete. The other aspect is that all other varieties, which are required to impart special characteristics of strength development or durability, comprise only one percent. On the face of it, this will appear to be surprising. In a large country like India where weather, environmental and ground water conditions vary widely in different parts, the need of functionally efficient cements should be large. This anomaly is resolved to some extent by having ordinary Portland cement, which fulfill the intents of more than one specification. These may be called 'Multi-functional' cements.

Even in one location, the performance requirements on the cement in a structural application may overlap with those of a number of specifications. A pre-stressed concrete member made of M40 or M50 grade concrete will require cement of higher strength class (for example OPC 43 or 53 grades). For early transfer of pre-stress or pre-cast construction, the compressive strength of concrete at early ages should be correspondingly high. Concrete of high strength grade (based on 28 days strength) may ensure this; otherwise cement having 'rapid hardening' properties will be required. To reduce the chances of corrosion of High Tensile Strength (HTS) wires and bars, the chloride ion content in the cement should be extremely low (< 0.05 percent). If such a structure is exposed to sulphate-bearing environment, the cement should have 'sulphate resisting' properties. If the aggregates to be used are likely to be reactive, the alkali content of the cement should be sufficiently low (< 0.6 percent). If the concrete section is thick, low heat generation is preferable. Thus, if a single cement can satisfy all these performance requirements of the construction than such a multi-functional cement is the ideal cement.

Features of an ideal cement composition

Cement is only an intermediate product; its quality manifests through the performance of concrete (or mortar/grout) in which it is used. Since properties of concrete are influenced by a large number of factors related to its constituents, workmanship, service environment and test protocol, very few properties of concrete have one-to-one correspondence with those of cements. In order to establish the features of an ideal cement composition, it is necessary to identify the more pertinent characteristics of cement. The next task is to set optimum levels of these properties.

Strength and generation of heat due to hydration are examples where cement properties are more relevant. Compressive strengths of cement and concrete have correlation in that, for given aggregates and identical mix proportions, higher the strength of cement result in higher concrete strength[1]. Heat rise in concrete is closely related to the heat of hydration of cement, the latter being the only source of rise in temperature in fresh concrete.

Among the chemical characteristics, C_3A and alkali contents of cements have somewhat well defined relationship with chemical durability of concrete[2]. The magnitude of expansion in mortar or concrete specimens, made with aggregate which have potential for alkali-silica reaction (ASR), depends upon the alkali (Na_2O and K_2O) content in the cement is quite clear. In view of such dependence of ASR activity on cement alkali, limit of alkali content as 0.60 percent (Na_2O-equivalent) has served as a reliable guideline. Apart from its role in setting characteristics, the importance of C_3A content in cement is in relation to sulphate resistance. Lower C_3A content (less than five percent) is prescribed for sulphate-resisting cement for use in sulphate-bearing environment. There is considerable interaction between sulphate and chloride ions, when present simultaneously. In such situations, the role of chloride ions in promoting corrosion of reinforcement takes precedence. Some research work has shown that higher C_3A content in cement imparts greater resistance to corrosion of steel in concrete. This is achieved by 'chloride-binding', that is, fixation of part of chloride ions by C_3A in the cement and forming calcium chloro-aluminates. In such a situation, only the free part of the total chloride ions would be available for corrosion process. Codes of practices for concrete constructions like IS 456 : 2000 recommend the use of cement having moderate C_3A content (between five to eight percent) in such situations.

Another important parameter, incorporated in many specifications, is of chloride content in cement. During the pyroprocessing in cement manufacture, material temperature of the order of 1450^{o}C is reached inside the kiln. At this high

Table 2: Performance characteristics of OPC 53 grade cements

Characteristics		*Average values*			
Type	*Details*	*Plant A*	*Plant B*	*Plant C*	*Plant D*
Physical characteristics	*Compressive strength, MPa*				
	1-day	17	21	20	23
	3-day	39	38	42	41
	7-day	50	48	51	52
	28-day	60	64	62.5	64
	Heat of hydration, Cal/gm				
	7-day	62	59	53	63
	28-day	70	68.5	67	72
Chemical	Alkalis, Na_2O-equivalent, percent	0.46	0.35	0.52	0.30
	C_3A, percent	3.05	4.0	5 – 8	6 – 7.5
	Chlorides, percent	0.036	0.038	0.02	0.01

temperature, chloride (or sulphates or alkali) ions, if present in the raw materials or fuel, will volatalise. Since the exhaust gases and dust are recycled into the kiln, chloride ions are found in cement clinker. More chloride can be introduced with chemical gypsum. In order to limit the total amount of chloride in concrete, contribution from cement has to be restricted in reinforced and prestressed concrete constructions. Hence, the limit of chloride contents in cement is mentioned in the specifications.

From the discussions above, the following characteristics of cements can be held to be more important:

- Compressive strength: It is required for appropriate strength grade of concrete. For a particular strength of concrete required, higher strength of cement will allow lower cement content in the concrete mix. In India, 53 grade OPC is preferred for most applications involving medium to high strength concrete.
- Low heat of hydration: Apart from mass concrete, even in general constructions in tropical climates, low heat generation is an advantage, so that the problems associated with hot weather concreting are minimised
- Low chloride content: Although a limit of 0.1 percent is set, restricting to less than 0.05 percent is ideal.
- Low alkali content: Total alkali, calculated as Na_2O + $0.658 \times K_2O$), should not exceed 0.6 percent in case of reactive aggregates.
- Restricted C_3A content: Restricting it between 5 to 8 percent is a good compromise when both sulphates and chloride ions are present; keeping it below 5 percent is ideal for sulphate resistance.

Examples from Indian cement industry

There are difficulties in satisfying all these requirements simultaneously. Higher compressive strength of cement is achieved by increasing the potential C_3S content and C_3A (in place of C_4AF) content in the clinker. For this, the lime saturation factor (LSF) and Alumina-Iron ratio (A/F) ratio in the raw mix or kiln feed is maintained at appropriately high levels. The resultant cement has to be ground finer. High C_3S and C_3A contents and greater fineness of grinding, however, increase the heat of hydration of cement. To control the heat of hydration without sacrificing strength characteristics, the kiln feed composition has to be optimised. This involves maintaining the LSF and A/F ratio within a narrow optimum range, which are arrived at after repeated trials with the raw materials at hand. Adequate burnability of the raw mix has to be ensured, so that free (uncombined) lime (CaO) in the clinker is minimised. Use of mineralisers is made, where necessary. The grinding process should ensure required particle size distribution of cement, more particularly the fractions passing 3 micron and 45 micron size sieves[2]. Modern grinding mills achieve this without resorting to a high (Blaine) fineness.

Control of alkali level is accomplished mostly by the choice of raw materials, whose individual alkali levels are low. In fact, if the raw materials contain alkali in significant amounts, it will be difficult to produce low-alkali cement, in an energy-efficient manner. Control of alkali, alumina and Fe_2O_3 in the kiln feed thus is an important exercise. Taken together, these affect smooth operation of the kiln, burnability of the raw mix, setting and early strength characteristics, and the colour of the cement. To reduce C_3A content, A/F ratio is to be lowered. Often this will call for a different set of raw materials, that is, the correctives and additives to maintain the required level of flux.

By way of example, characteristics of the cements produced in four modern, million tonne dry process plants in India is given. In this paper, these will be identified as Plants A, B, C and D. These plants are located in the North, South and West of India. The main production is of 53 Grade OPC, conforming to IS 12269. Other products are sulphate-resistant cement (IS 12330) and fly ash based Portland pozzolana cement (IS 1489 - Part 1). Essential characteristics of the OPC 53 grade cements from these four plants are summarised in *Table* 2**.**

The production in each batch is carefully controlled through control of raw materials and fuel, kiln feed, kiln operations and grinding. Consequently, the variation in cement characteristics is narrow. Indian Standards do not specify strength at 1 day, but market forces demand compressive strength of at least 16 MPa and preferably 20 MPa. This is attained in cements from all the four plants.

Although it is not intended to describe the production process in this paper, some details of the raw materials are given in *Table* 3 for one cement plant (Plant A). Limestone along with Laterite or Marl and iron sludge in required proportions are used as raw materials. Fluorspar (CaF_2 ~ 28

Table 3: Chemical analyses of raw materials

Material	*Plant A*			
	CaO	*SiO_2*	*Al_2O_3*	*Fe_2O_3*
Limestone	50.2	5.6	1.2	1.8
Laterite	1.5	14.3	23.8	31.9
Marl	29.4	30.3	11.8	7.4
Sandstone	2.6	90.3	2.7	1.3
Iron sludge				88.0

Table 4: Composition of kiln feed and clinker for OPC 53 grade (Plant A)

	Oxides	*Kiln feed*	*Clinker*
Chemical analyses	CaO	43.32	66.24
	SiO_2	11.77	21.52
	Al_2O_3	4.03	5.65
	Fe_2O_3	2.83	4.43
Moduli	LSF	1.093	0.95
	AM	1.43	1.37
	SM	1.72	2.20
Phases	C_3S		53.39
	C_2S		21.42
	C_3A		8.0
	C_4AF		12.56

percent) is used as mineraliser at 0.5 percent. Sandstone having lower iron and alumina content is used in place of Laterite or Marl for the manufacture of sulphate-resistant cement from the same plant.

Typical chemical composition of the kiln feed and clinkers of OPC 53 Grade for the plant A are given in *Table* 4.

From the details in *Table* 2, it may be seen that ordinary Portland cements of 53 Grade (IS 12269) from the four plants, A, B, C and D also meet the functional requirements of,

- Rapid hardening (early strength) properties as per IS 8041,
- Low heat of hydration as per IS 12600,
- Low alkali content as stipulated in IS 269, 8112 and 12269,
- Low chloride content as per IS 269, etc, and
- Low C_3A content as per IS 12330; it can be brought down to be within five to eight percent (moderate sulphate resistance, ASTM type II), if needed.

These cements describe the concept of ideal, multi-functional cements. Such a cement is ideal from durability considerations as per the exposure conditions in the Indian sub-continent and much of the Middle-East countries.

Role of additives in ideal cement systems

Ordinary Portland cements of such characteristics described above can be made when suitable raw materials – mainly limestone, are available. On the other hand, OPC clinker and cement that is manufactured by a majority of cement plants can result in satisfactory 'cement systems' with judicious use of pozzolanic and/or hydraulic additives obtained from industrial wastes. Fly ash from coal-fired thermal power stations, granulated blast furnace slag from steel industries and silica fume from ferro-silicon alloys or silicon metal industries are prominently used as additives to cement and concrete the world over, for making concrete more durable. Such combinations are the ideal cement systems for durable concrete. The durability advantage with such cement systems are described below mainly in relation to use of fly ash. However, the discussion is equally valid for use of granulated blast furnace slag and silica fume. The optimum dosages, in each case, are different.

Durability advantage

Since industrial wastes are relatively lesser-known materials than cement, it is possible to have questions on their long-term effects on concrete. Doubts about effects of fly ash and granulated slag on durability of concrete had initially inhibited their full use in structural concrete. However, experience over the years and continuous research has actually revealed positive effects on durability. Corrosion of reinforcement, sulphate attack, heat of hydration and alkali silica reaction (ASR) in concrete are the major issues of durability. Use of fly ash, granulated slag or silica fume is known to be beneficial in all such cases. These are supported by well - documented case studies and performance records reported from foreign sources[3-7]. Data and case studies on Indian experiences with indigenous materials have been presented earlier, hence only the salient trends are enumerated below[8,9].

Corrosion of reinforcement

Beneficial effects of supplementary cementing materials like fly ash, slag and silica fume on reducing the incidence of corrosion of reinforcement in concrete is due to the following factors[8,9]:

1. Formation of a denser microstructure of the calcium silicate hydrate (CSH) due to additional hydration products formed by pozzolanic reactions.
2. Modification of the pore structure of the cement paste: The products of reaction of fly ash or slag particles taking place within the capillary pores of the cement hydrate may block some pores and make them discontinuous. The average pore size becomes smaller, although the total porosity may remain the same. Such pore modification and pore blocking are more pronounced in case of silica fume.
3. Increased impermeability of concrete: This results from denser microstructure of the cement paste, increased volume of reaction products and improvement in the workability of concrete, which permits fuller compaction.
4. Lower electrical conductivity of concrete: Addition of fly ash, slag or silica fume increases the resistance to the flow of (electrochemical) corrosion currents in concrete.
5. Increased chloride binding: Presence of aluminate phases in fly ash or slag encourages binding of chloride ions in the pore solutions. Chloride binding is also aided by adsorption on the surfaces of the fly ash or slag particles.
6. pH value of the pore solution in concrete is maintained.

This issue is discussed here in some length in order to dispel unfounded apprehensions among some construction agencies on use of blended cements. It is erroneous to suggest that because calcium hydroxide liberated by cement hydration is consumed in pozzolanic reactions, pH value of concrete would be reduced to such an extent that passivity around reinforcing steel is destroyed. Recent tests have shown that pozzolana like fly ash and silica fume or granulated slag affect the pH of cement mortars only marginally and the actual pH level remains high enough for continuation of protective environment for the steel reinforcement[4,10,11]. Alkalinity in pore solutions in the cement paste is not due to $Ca(OH)_2$ alone; alkalis, aluminate and silicate hydrates and excess calcium ions over what is required to combine with silica in cement and pozzolana also contribute to the alkalinity. This is borne by the fact that pH value of hydrated cement paste is in the range of 13 or more, while that of saturated $Ca(OH)_2$ solution is only 12.5.

Depending upon the reactivity of fly ash, only a limited amount, and not the entire calcium hydroxide is consumed due to pozzolanic reactions. All the $Ca(OH)_2$ in concrete cannot be consumed simply by addition of 20-30 percent fly ash. Stoichiometry indicates that equal weights of lime ($Ca(OH)_2$) and active silica combine in pozzolanic reactions. The amount of $Ca(OH)_2$ liberated in hydration is about 25 percent by weight of cement. For example, if there is 400 kg of OPC in the mix, 100 kg of $Ca(OH)_2$ will be liberated, which will require 100 kg of active silica for chemical reaction. Indian fly ashes contain about 55 percent SiO_2, out of which only 20 to 25 percent are in glassy form. Hence, addition of 100 kg of fly ash (that is, 25 percent of OPC), will consume only about 14 percent of $Ca(OH)_2$; and 86 percent will remain unconsumed to provide alkalinity. This calculation is in line with the fact that all of $Ca(OH)_2$ in concrete was shown to be consumed only when 30 percent of silica fume was used, which is mostly active silica. Even then the pH was above 12[4]. The results are reproduced in *Fig* 2. Comparing the relative reactivity, it may be inferred that addition of up to 10 percent silica fume will have similar effect on depletion of $Ca(OH)_2$ ions in the pore solution as with 30 to 40 percent (or even higher) of typical Indian fly ashes. Hence, there may not be undue reduction of pH value.

In high alumina cement (HAC), which has been used in reinforced and prestressed concrete constructions in cold countries, there is no $Ca(OH)_2$ in the hydrated phases of HAC system, yet the pH value of pore solution in high-alumina cement paste is between 11.4 and 12.5[12]. In Beijing, China, the author was shown flyovers built with calcium sulpho-aluminate cement, which is low-energy cement. Again, there is no $Ca(OH)_2$ in its hydrated phase. Adequate pH value in the pore solution of concrete is needed for protection of reinforcement against corrosion, and presence of $Ca(OH)_2$, undiminished or in some reduced quantity, is not *per se* important. Much more $Ca(OH)_2$ can be depleted due to atmospheric carbonation, primarily caused by poor quality control.

Alkali–silica reaction (ASR)

In his pioneering work on ASR, Stanton had postulated more than six decades ago that incorporation of pozzolana could reduce the expansion due to alkali-silica reaction in concrete[13]. Subsequent studies by many others have supported such beneficial actions by use of fly ash. The mechanism involved is that a high proportion of the alkalis available in the pore solution is imbibed and 'bound' into the structure of the hydrates formed. CSH formed due to reaction of fly ash, slag or silica fume has a lower C/S ratio than the hydration of OPC and can accommodate more alkalis in solid solution[14]. The amount of fly ash or granulated slag has to be high – generally greater than 20-25 percent in case of fly ash and more than 50 percent in case of slag. At lower dosages the alkalis in fly ash or slag, which are generally greater in percentage than in OPC, can augment the pore solution alkali and results in no benefit.

It is noteworthy to recall the substantial amount of research work carried out in India on the beneficial role of blended cements in alleviating expansion due to ASR[15,16]. Basic research carried out in NCB established the role of commercial blended cements in reducing the expansion due to ASR. Accordingly, mass concrete constructions like dams were advised to adopt blended cement, for example, PPC with fly ash proportion 20 percent or higher, when aggregates were suspected to be reactive. Because of such data, use of fly ash or slag, or blended cements made with them, to alleviate ASR in concrete is now an accepted practice in India.

Sulphate resistance

Concrete structures exposed to seawater or sulphate – bearing soils, sub-soils and ground water may suffer deterioration during their service-life due to 'sulphate attack'. The sulphate ions can react with calcium hydroxide and alumina – bearing phases of hydrated cement. This leads to formation of expansive salts like calcium-sulpho-aluminate hydrate (ettringite) and calcium sulphate (gypsum). These result in expansion, spalling, cracking and loss of strength of concrete.

C_3A content in sulphate-resisting OPC (SRPC) is required to be less than 5 percent and ($2C_3A + C_4AF$) less than 25 percent. Use of appropriately formulated blended cements

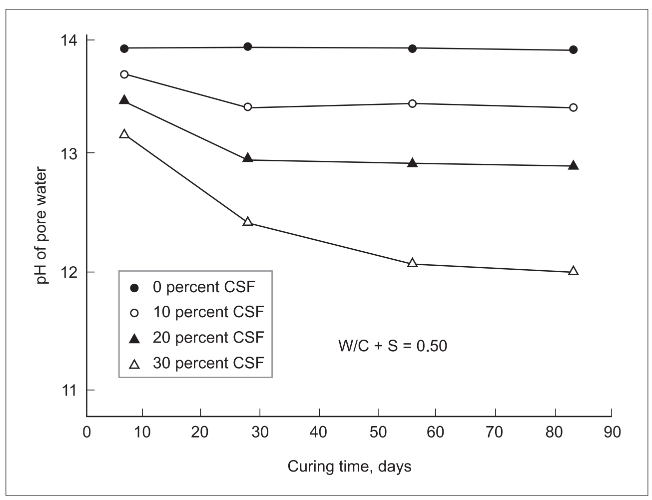

Fig 2 Effect of silica fume on the pH value of pore water solution[4]

as PPC or PSC are also recommended in IS 456 : 2000; ACI 318 and British practice (BRE Digest 250) to combat moderate sulphate attack. The resistance to sulphate attack is enhanced by the presence of fly ash or slag. The following mechanisms are involved in the same[17]:

1. Reduced C_3A content : As fly ash or slag replaces the amount of OPC in concrete, the net C_3A in the cement system goes down, even if the OPC component has high C_3A content.
2. Reduction in calcium hydroxide in the system: Pozzolanic reaction consumes part of $Ca(OH)_2$ released by the hydration of Portland cement. The amount of calcium hydroxide in the hydrated cement matrix decreases.
3. Pore modification: Reduction in larger pores and greater presence of finer pores in the cement paste decreases the permeability of concrete. Ingress of water carrying sulphate ions and other chemicals becomes more difficult.

Heat of hydration

The extent of generation of heat of hydration, at least in the early part of use, is reduced to the extent that OPC is replaced by pozzolanic additives. Addition of silica fume can reduce cement content in the concrete mix and thereby the heat generation substantially. Secondary C-S-H formation due to pozzolanic reaction or slag hydration takes place only at a later date, hence initial rate is lower. This is a clear advantage in case of mass concrete or thick concrete sections like dams, bridge piers, massive columns in high rise structures, etc.

Soundness of cement

Another source of delayed expansion in concrete is due to hydration of free (uncombined) lime; MgO and calcium sulphate phases in cement. This is known as 'unsoundness' of cement. National specifications prescribe accelerated tests like Le Chatelier and autoclave to detect potential unsoundness of cement. When raw materials and process parameters are likely to result in unsoundness of cement, the known remedy is the use of fly ash and slag. Experience of PPC and PSC produced commercially in India show that incorporation of pozzolana or slag has improved the soundness in all cases[17]. This is an important consideration for the manufacture of blended cements in India, especially when high–MgO limestone is encountered.

Modes of use

Fly ash or granulated blast furnace slag can be used in cement and concrete in two different ways. Fly ash or slag can be used in the manufacture of Portland pozzolana cement (PPC) or Portland slag cement (PSC) in the cement plant, by blending or inter-grinding with cement clinker and gypsum. Alternately, fly ash or ground granulated slag can be added to OPC and other ingredients of concrete in the concrete mixer at the construction site, prefab factory or RMC plant. The prevalent practice in any country depends upon the way the industry has grown. For example, in USA and UK, the practice is to add fly ash (or granulated slag) in the concrete mixer with cement and other ingredients of concrete. In many European countries and, in India to a large extent, the trend is to manufacture factory-blended pozzolana or slag cements.

Apart from commercial considerations, which are not similar in every country or every situation, both the approaches have some distinct technical advantages, which have been enumerated elsewhere[8]. Taking into account all the aspects, it may be observed that use of factory –blended cement, with quality and proportion of fly ash or granulated slag decided in consultation with the customer's requirements wherever necessary, is a better option in the present context. Adding fly ash or slag at the concrete mixer may be adopted, if necessary infrastructure for producing quality concrete with fly ash exists at the project site. This practice is also helpful, when the required proportion of the additions is larger than in commercially produced blended cements. It must be noted that more than 80 percent of the cement produced in India is used in constructions adopting labour-intensive practices and small capacity site mixers. Thorough blending of cement and the additives at such sites is not possible. In such a situation, blended cements are the best option. It is customary to add silica fume with other ingredients of concrete at the mixer stage, the world over. Only two countries – Iceland and Canada produce factory-blended silica fume cement.

It should be pointed out that the intrinsic hydration reactions, which influence the long-term performance of concrete, are similar, irrespective of whether fly ash, silica fume or slag was added at the cement plant or in the concrete mixer at site.

Use of silica fume and triple-blends

Silica fume is used in India for high performance concrete, requiring high strength, greater impermeability and durability or both[18]. As a result, its use for normal concrete mixes (≈ M20 to M40 range) has not received due attention. There is much to be gained in using silica fume at about 5 to 7 percent of cement by weight in such mixes. It results in saving of cement content, increased durability and corrosion resistance, higher strength, increased pumpability; all of which are vital in every construction.

To give an example, M40 concrete for flyover projects in Delhi have used cement about 400 kg/m^3. In another project, M45 pavement quality concrete for highway construction was designed with 350 kg/m^3 cement and 28 kg/m^3 silica fume (8 percent of cement). The 28 day strength in the latter case was in excess of M50 grade concrete. But for the restriction of minimum cement content in the code at that time, cement content of 300 to 325 kg/m^3 would have sufficed. For M20 to M35 grades, 260-300 kg cement along with 5 percent silica fume is adequate.

Triple-blends

The above description may convey the idea that silica fume, or other cement replacement additives are to be used with OPC only. That is not strictly true and ternary mixtures comprise efficient cement systems. The primary incentive of adding limited amount of silica fume – for example 5 percent, with

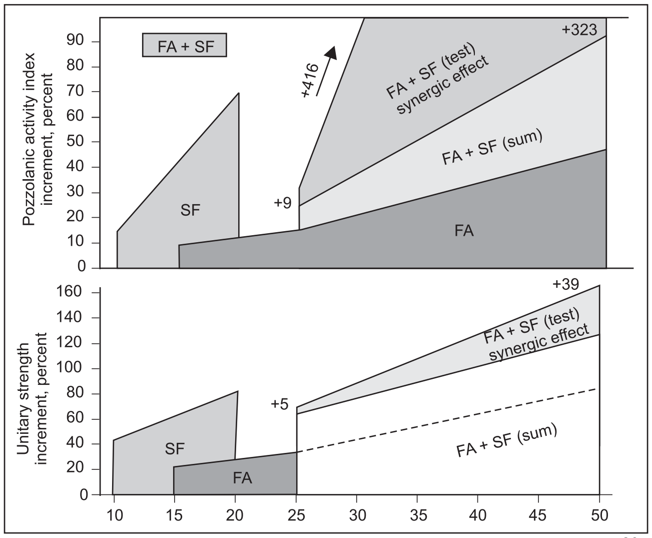

Fig 3 Synergic effect of silica fume (SF) and fly ash (FA) on OPC[20]

fly ash - cement mixes was to ensure high early strength[19]. Research has, however, shown that ternary mixtures of OPC, silica fume and fly ash result in synergic action to improve the microstructure and performance of concrete[20]. From *Fig* 3, it can be seen that, when both silica fume and fly ash are used, the resultant enhancement of strength or pozzolanic activity was greater than superposition of contributions of each, for the respective proportions. Such synergic effect results from strengthening the weak transition zone in aggregate-cement interface, as well as segmentation and blocking of pores.

In another case, a mixture of 32.5 percent OPC, 60.5 percent slag and 7 percent silica fume was found to result in compressive strength of 50 MPa at 48 hours, when cured at 38^{o}C, and higher at higher temperatures[21]. The improved performance was due to smaller pore size and lower porosity. Addition of 22.5 kg silica fume to 300 kg cement + 350 kg fly ash mixes of self compacting concrete (SCC) resulted in high early strength (21 MPa at 3 days and 45 MPa at 28 days) along with increase in cohesiveness[22]. Use of silica fume in SCC mixes can dispense with the use of viscosity modifying agents (VMA).

Some test results of concretes made with ternary blends are shown in *Tables* 4 and 5. In one case, cementitious materials of about 400 kg/m^3 were made of either OPC or OPC and ground granulated blast furnace slag (GGBS). The latter mix also contained 10 percent silica fume. Water/cementitious ratios and workability were similar in both the mixes[23]. Results reproduced in *Table* 5 show that compressive strengths from 28 days onwards were higher for the mix with triple-blend. Significant improvements in durability parameters like abrasion resistance, permeability, chloride diffusion, electrical resistivity and sulphate expansion were noticed[23].

Table 5: Concrete with OPC, GGBS and silica fume

	Mix A	*Mix F*
Mix proportions		
OPC, kg/m^3	405	200
GGBS, kg/m^3	-	190
Silica fume, kg/m^3	-	40
w/c	0.43	0.44
Test results		
Slump, mm	60	80
Flow, mm	410	400
Compressive strength, MPa:		
7 days	52.5	44.5
28 days	61.0	69.5
6 months	76.0	86.0

European Standards on cement EN 197-I allow ternary or even quaternary blends in the manufacture of composite cements. IS specifications on cement are yet to permit multi-blends, *Table* 1. Examples of applications of ternary blends in large concrete constructions include 2.167 km long Tsing Ma bridge at Hong Kong and the Storebaelt Link in Denmark, comprising 8 km of eastern tunnel, 7 km long eastern bridge and the western bridge[24]. High performance concretes in both applications were made with a triple blend of OPC, fly ash and silica fume. The 200 m tall towers for Tsing Ma bridge, which were slip formed, were made of concrete with 25 percent OPC, 70 percent ground granulated slag and 5 percent silica fume. Long term strength of 100 MPa and low permeability – 500 Coulombs in rapid chloride permeability test (ASTM C1202) were envisaged.

Nearer home, M60 concrete for pile and pile cap in Bandra-Worli Sea Link project used ternary blend of OPC, fly ash and silica fume. The mix proportions are shown in *Fig* 4.

Concrete for abrasion-resistance in intake structures and tunnel lining for Tala hydro-electric project in Bhutan was made with Portland slag cement (PSC) and silica fume. An additional advantage was improved resistance to alkali – silica reaction with reactive aggregates encountered[25]. To withstand the acidic nature of reservoir water in a hydro-electric project in the North Eastern part of India, concrete with mix of PPC and silica fume with water-cement ratio of 0.35 was suggested for the upstream face, so as to have very low permeability of 500 coulombs in RCPT (ASTM C1202) test. Minimum compressive strength was not specified. Some ready mix concrete plants in the eastern sector use fly ash for part replacement of Portland slag cement as the binder system, the performance requirements being ensured by appropriate mix design.

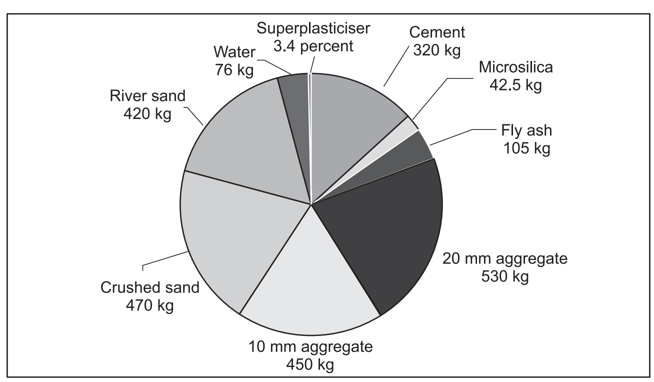

Fig 4 Concrete mix proportion for pile and pile cap in Bandra-Worli Sea Link project

Current practice

IS 456 recommends the use of blended cements like PPC and PSC, or mineral admixtures like fly ash, granulated slag and silica fume, for improving durability of concrete. Reservations in many agencies in the public sector are also being removed. Recent constructions in many prestigious projects like Delhi Metro, atomic power projects and others have used concrete containing fly ash or granulated slag. Use of fly ash and slag are particularly resorted to in case of aggressive foundation conditions and for making self compacting concrete (SCC). Such applications are well documented in the technical literature[26]. Present day concrete codes like IRC 21, IS 456 and IS 455 are, however, not very explicit about using ternary mixtures for cement systems. The use of ternary mixtures should be encouraged.

Concluding remarks

1. With favourable raw materials in judicious raw mix design and due control in plant operations, it is possible to produce ordinary Portland cement (OPC) having all the desirable characteristics to make concrete durable under different conditions of exposure during its service life. The details of such ideal cement, produced by some cement plants in India are described.

2. In absence of such ideal OPC, ideal cement systems can be obtained by use of fly ash, granulated slag or silica fume in requisite amounts as part replacement of OPC. Both blended cements like PPC or PSC, or cement substitution in the concrete mixer at site can be adopted. The Indian experience with such ideal cement systems is described.

3. Ternary blends of OPC with silica fume and fly ash or granulated slag are particularly useful to render greater durability to concrete. Limited Indian experience with such triple blends is discussed.

4. IS Specifications on cements and concrete codes like IRC 21, IS 456 or IS 455 are, however, not very explicit about using ternary mixtures for cement systems. The use of ternary blends should be encouraged for ensuring greater durability in constructions.

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