Enhancing Durability of Concrete Structures using Mineral Additives as Sustainable Alternatives for Portland Cement and its Quality Control Procedures

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***Abstract*— The construction industry is consistently under tremendous pressure to increase productivity in a sustainable way without compromising for quality. This paper contents several contemplative sections covering technical, commercial and practical aspects relevant to the use of sustainable alternatives for Portland Cement such as GGBS and Fly Ash. The properties of concrete containing GGBS and Fly Ash vary with the proportion of the material used in relation to the total cement content. As a general rule the increase in the proportion of GGBS or Fly Ash reduces the water demand, extends the setting time and the initial rate of gain of strength is slower. Potential durability of concrete made with these mineral additives is generally greater than that of normal OPC concrete. Concrete durability tests generally being specified worldwide for assessing the durability attributes and quality control of concrete are rapid chloride per meability test, water absorption, water permeability, chloride migration coefficient, porosity, capillary absorption etc. The three principal mix design criteria that affect durability of concrete are maximum free water/cement ratio, proportions of mineral additions used and the minimum cementitious content. The test conditions for durability parameters are normally based on a test age of 28 days. The use of GGBS or fly ash in concrete as supplementary cementitious material not only extends technical advantages to the properties of concrete but also contributes to the environmental pollution control.**

I. INTRODUCTION

Attack on concrete can be resisted by isolating it from deleterious materials or by making it resistant to them. Isolating concrete from the aggressive agents is not always possible, particularly when it is cast in situ, as it may not always be possible to apply an isolating membrane around the component or to ensure that the membrane remains intact. The most practical solution may be to use a concrete that resists both physical and chemical attack. However, the appropriate cementitious material for the situation must be chosen and the concrete must be of suitable quality.

The permeability of concrete has an important influence on chemical resistance in all exposure conditions: the lower the permeability is the better in all cases. The penetration of chloride into concrete is difficult to avoid in chloride-laden atmospheres. The general practice of using Portland cement concrete with a water/cement ratio below 0.45 with reinforcing steel at least 75mm from the surface, does not always prevent chloride-induced corrosion of embedded steel. To prevent corrosion, the level of chloride at the steel needs to be minimised, i.e. the penetration rate to be reduced.

II. METHODS OF REDUCING CHLORIDE PENETRATION RATE

Resistance to chloride penetration is influenced by the cement chemistry and concrete quality. In general, Portland cement with a high C_3A content is more resistant to chloride penetration than Portland cement with a low C_3A content. This is partly due to the influence of alumina in the binding of some chloride during mixing and placing. Differences in Portland cement composition have been reported to result in differences in chloride diffusion coefficient of the order of 10 times.

Concretes containing Pulverised-Fuel Ash (PFA) and ground granulated blast furnace slag (GGBS) are highly resistant to penetration by chlorides, due to their increased binding capacity and refined pore structure. Service life two to three times longer is estimated for concretes made with PFA or GGBS of equal water/cementitious material ratio. This difference is greater when comparisons are made on the basis of strength grade, because blended cement mixes need a lower water/cement ratio to achieve strength equivalence at 28 days.

Normal grade structural concretes containing Fly Ash, GGBS or Silica Fume mixes can all achieve very high chloride resistance compared with Portland cement concretes. The main methods of reducing the penetration of chlorides are tabulated below:

TABLE I. MEASURES FOR REDUCING CHLORIDE PENETRATION

Approach	Methods
Concrete mix design	Selection of cement type Water/Cement ratio Use of mineral additions such as GGBS, Fly Ash & Silica Fume
Other measures	Controlled permeability formwork Coatings Hydrophobic treatment of the concrete

III. Mineral Additions

The use of mineral additions are as old as that of concrete construction. There are three main types of mineral addition in concrete construction: ground granulated blastfurnace slag (GGBS), pulverised-fuel ash (PFA, often referred as fly ash), and silica fume (SF, also referred as microsilica).

Theoretically, the rate of chloride penetration is determined mainly by the diffusion coefficient for chloride ions. The cement matrix of concrete is a composite material through which most of the transport of the chloride takes place, and so it is the matrix that determines the diffusion coefficient. Matrix properties depend on initial composition, over time this may change and be reflected in changes in the diffusion coefficient. Reactive minerals such as Fly Ash, ground granulated blast furnace slag etc cause the matrix to become less permeable to chloride by reducing the pores.

The main benefits of mineral addition are:

- a possible reduction in the rate of chloride ingress by a factor between say 3 and 10
- similar or higher threshold level of chloride content
- similar or lower rate of corrosion

The disadvantages of mineral addition are:

- lower strength at early age
- requires more care with curing
- requires more care with mix design to achieve acceptable workability

IV. Ground Granulated Blast furnace Slag

Blast furnace slag is a by-product of the production of iron from ore. The quality of the iron is controlled by monitoring the composition of the slag and so the by-product is also controlled. Molten slag is tapped from the blast furnace and granulated by pouring it through fine water jets at high pressure. At this stage it may resemble a coarse sand. It can then be interground with Portland cement clinker, or ground separately (to produce GGBS) to be preblended by the cement producer or supplier separately for blending in the mixer. GGBS has 'latent hydraulicity and will react on its own with water though very slowly. When mixed with Portland cement and water the reaction is accelerated by the presence of sulfates and alkalis. The GGBS particles are angular and tend to be single-sized with a fineness similar to Portland cement. The specific gravity is about 2.9. GGBS usually forms 40-70% of the binder.

GGBS reacts in water, increasing pH, generating heat and developing a particle to particle cementatious bond in very much the same way as Portland cement. This intrinsic hydraulicity distinguishes GGBS form pozzolanas.

The intrinsic reaction is slow compared to Portland cement and for practical reasons the 'latent' hydraulicity must be activated. The activation is the result of the GGBS coming into contact with the alkalis or sulphates that are present in Portland cement. These activators react chemically with the GGBS 'disturbing' the structure of the glass; releasing reaction products for hydrate formation and continuation of the hydration process.

The rate, nature and extent of formation of the hydrates are influenced by:

- Composition Portland cement
- Composition of GGBS
- The fineness of the two component
- Temperature

V. Fly Ash

Fly Ash is also known as Pulverised-fuel ash (PFA) is a byproduct of coal-fired combustion furnaces used worldwide for electricity generation. It is the fine ash precipitated from the flue gases. The type and quality of the ash depends on the type of coal burnt. PFAs are classified as either high-calcium (CaO > 10%) or low-calcium (<10%). The calcium level is determined by the type of coal burnt and generally PFA is either classified as Type F, produced from anthracite or bituminous coal, or Type C, produced from lignite or sub-bituminous coal. Type F ashes tend to have a low CaO content (<10%) while Type C have high CaO contents (>10%). The low-calcium ash is pozzolanic, with alkali-soluble silica and alumina reacting with calcium hydroxide in solution. On its own, it will not react with water.

PFA particles are usually spherical and of a similar size range to Portland cement grains. The specific gravity of PFA is about 2.3 compared with 3.15 for Portland cement. So for a given weight of PFA the volume is about 35% greater. PFA is commonly used in proportions of 20-30% by weight of binder (Portland cement + PFA) although proportions up to 50% have been used in specific applications.

VI. Influences of Mineral additions on Concrete Properties

The properties of concrete containing GGBS or Fly Ash vary with the proportion of the material used in relation to the total cement content. As a general rule the increase in the proportion of GGBS or Fly Ash reduces the water demand, extends the setting time, and the initial rate of gain of strength is slower. The strength and durability can be greater but in some situations greater emphasis must be put on the need for adequate curing procedures.

A. Water Demand

For concretes with an equal slump, lower water content is required when GGBS or PFA is used.

B. Setting Time

The setting times of GGBS or Fly Ash concrete are longer than for the equivalent OPC mix. This delay is mainly due to the slower initial rate of reaction between the GGBS or Fly Ash and water, compared to that of OPC. The effect is magnified at higher percentages of GGBS or Fly Ash. In certain situations this can be advantageous, for example in minimizing the occurrence of cold joints. However in periods where Ambient temperature is reduced, such as during the winter months it may cause practical difficulties particularly with floor slabs and the delay between placing the concrete and applying the final trowelled finish.

C. *Heat of Hydration*

Similar grades of concrete containing GGBS or PFA generally have lower heats of hydration than OPC mixes. The lower heat of hydration reduces the early age temperature rise in hardening concrete. With increasing GGBS or PFA levels the temperature rise reduces, but the benefits decrease as the cement content, placing temperature, section size and ambient, or curing, temperature increases.

The reduced temperature rise is mainly attributable to the slower hydration rate, compared with that of OPC. The slower release of heat combined with reducing ambient temperature results in a reduced strength gain at an early age when compared to OPC. This may require an extended period before striking formwork or removal of props especially when casting thin, exposed sections with high percentages of GGBS or PFA at times when ambient temperature is reduced particularly in winter months.

D *Strength Gain*

GGBS and Fly Ash affect the rate of strength gain of concrete in much the same way. The early rate of strength gain is slower than that of OPC concrete of similar grade. In the long term the strength is usually higher due to increased development at later stages.

VII. DURABILITY OF CONCRETE CONTAINING GGBS OR FLY ASH

The use of GGBS leads to the enhancement of intrinsic properties of concrete in both fresh and hardened conditions. The major benefits of suitably cured concrete containing GGBS are the reduced heat of hydration, refinement of pore structures, reduced permeability and Increased resistance to chemical attack.

Sufficiently cured concrete containing good quality fly ash shows dense structure which offers high resistivity to the infiltration of deleterious substances.

It is also recognised that the addition of fly ash contributes to the reduction of the expansion due to alkali-aggregate reaction. The dilution effect of alkali and reduction of the water permeability due to dense texture may be one of the factors for reduction of alkali-aggregate reaction.

Although GGBS and fly ash are industrial waste, its use in concrete significantly improve the long term strength and durability and reduce heat of hydration. In other words good GGBS or fly ash will be an indispensable mineral addition for high performance concrete.

Durable concrete made with GGBS or PFA in most respects the potential durability is greater than that of OPC. This is due both to the continued hydration of the GGBS or PFA, which subsequently reduces the porosity and the permeability of the paste structure and to modify the chemistry of the cement matrix.

For concrete containing GGBS the hydration reactions the influence the durability in two ways:

- Pore size distribution - With increasing percentage of GGBS the pores become smaller. Fully hydrated pastes contain more gel pores and fewer capillary pores than OPC pastes thereby reducing the permeability.
- Diffusivity of aggressive ions - GGBS concrete have higher resistance to ionic diffusion than OPC and the resistance increase as the percentage of GGBS increase.

All these factors have a bearing on sulphate resistance, carbonation, alkali-silica reaction, chloride penetration and reinforcement corrosion.

A. *Influences on Durability*

It is generally recognised that the durability of concrete is related not only to its strength but its permeability in respect of gases and liquids, its resistance to penetration by chloride ions and sulphate ions. The physical properties are governed by the porosity and pore size distributions which in turn are determined by the water/cement ratio and the quantity and distribution of gel produced during the hydration process. It must also be recognised that the compaction and curing of the concrete can also have a major influence on its permeability

B. *Sensitivity to Curing*

Concrete containing GGBS or PFA is more sensitive to inadequate curing than OPC concrete. In all concrete, durability and strength performances are reduced if the concrete is allowed to dry out at an early age and hydration process is arrested. The critical region with respect to curing sensitivity is the cover to reinforcing steel. Again the most vulnerable are the thin section.

C. *Permeability*

In well-cured concrete the water permeability of concrete containing GGBS or Fly Ash will be ultimately lower than that of OPC concrete of a similar grade.

D. *Protection of Steel Reinforcement from Chloride Ingress*

Protection of steel depends on the maintenance of an alkaline environment which renders the steel passive and upon the rate at which moisture , oxygen and, if present chloride ions can penetrate to reach the steel. GGBS or Fly Ash concrete is substantially more resistant to chloride ion penetration than OPC whether compared on cement content or grade. Concrete containing 50% GGBS and over have been proved, without exception ,to be more durable than OPC.

There are many research documents published and unpublished on the subject of chloride ion penetration, the majority of which confirm that the concrete containing over 50%GGBS has much improved resistance than OPC or SRC. In some instances it is reported to have a superior performance to micro silica or silica fume.

E. *Alkalinity*

Despite the reduction in calcium hydroxide, caused by the secondary reaction of GGBS hydration, the pH of the cement paste remains at an adequately high level, well in excess of that which would affect the passivity of the steel.

F. *Carbonation*

Carbonation depends on the degree of curing and generally correlates with standard strength and the percentage of GGBS or Fly Ash within the mix. Under good or similar curing conditions GGBS or Fly Ash concrete and OPC concrete show similar results for similar grades of concrete.

G. Sulphate Resistance

The use of GGBS is recognized in various standards throughout the world as an alternate to Sulphate Resistant Portland Cement (SRPC)

Where the GGBS is at least 65% then the sulphates resistance will always be greater than OPC . Depending on the concentrate of sulphate in the ground then GGBS can have replacement levels more high in order provide the appropriate resistance to sulphate.

H. Alkali Silica Reaction (ASR)

GGBS is widely accepted worldwide as a means of reducing the risk of dangerous impacts on concrete owing to alkali silica reaction in concrete.

I. Abrasion Resistance

Numerous factors influence abrasion resistance of floors and the most significant of these being strength and trowelling intensity. When compared on the basis of strength, GGBS or Fly Ash concrete have a slight edge over OPC concrete in terms of abrasion resistance.

VIII ENGINEERING PROPERTIES GGBS & FLY ASH

A. In-situ Strength Development

The strength development of GGBS concrete varies, depending on the in situ temperature during the early life of the concrete. The extent to which the long term strength impaired is appreciably less in GGBS or Fly Ash concrete and the strength development may be appreciably greater than an OPC equivalent in long term.

B. Flexural or Tensile Strength

The flexural or tensile strength of GGBS or Fly Ash concrete when expressed as a proportion of compressive strength is generally reported to be marginally higher than that of OPC concrete.

C. Elastic Modulus

The effect of GGBS and PFA in concrete mixes is usually to increase the ultimate modulus, but the magnitude of the increase is generally negligible in terms of design.

D. Creep

Under conditions of no moisture loss lower creep values will be found when using GGBS of Fly Ash in concrete of similar grade. This is usually associated with the greater strength gain of the GGBS and PFA concrete whilst under load

E. Drying Shrinkage

For most practical situations where drying shrinkage is moderate, the behaviour of GGBS or Fly Ash concrete is usually similar to that of OPC.

IX MIX DESIGN, PRODUCTION AND CONSTRUCTION

A. Mix Design Procedure

The design of any concrete mix essentially consists of selecting the proportions of the materials available to meet the required specified properties. The most common properties are:

- Compressive strength
- Workability
- Durability

B. Compressive Strength

The performance of GGBS or Fly Ash concrete will depend on the OPC and aggregates used in the manufacture of the concrete. There will almost certainly be a slower strength development at an early age, depending on method of mix design method adopted. No changes in design margin are required to that of OPC concrete.

C Workability

Concrete containing GGBS or Fly Ash generally requires less water than OPC for a given workability. Mixes can appear more cohesive for a measured workability and the amount of water required to effect a change in workability is less than that for OPC concrete. These minor changes in the fresh properties generally improve the handling, placing and finishing of the concrete on site.

D. Mix design Philosophy

For the proportioning of mixes incorporating GGBS or Fly Ash the design procedure depends on the users requirements and the availability of background data. Whatever method is adopted there are basically two alternative approaches.

- Modification of an existing OPC mix design
- User opts for a specific design technique for GGBS or Fly Ash

Whatever approach is used, trial mixes are essential in order to confirm that performance criteria is met.

Major factors influencing design criteria for concrete containing GGBS or Fly Ash are as follows

E. Specification Requirement

Special construction requirements. E.g. slip forming, secant piling, cut off walls etc.

F. Placing and Compacting

Concrete containing GGBS or PFA may appear more cohesive and less workable than similar slump concrete using OPC. It is acknowledged that concrete containing GGBS or PFA behave in a different manner than concrete manufactured with OPC.

G. Form Work pressures

Form-work pressures are likely to be higher from concrete mixes containing GGBS or PFA due to higher placing rates and slower setting times.

H. Plastic Cracking

Plastic cracks can occur in concrete in the first few hours after placing. This is typically two or three hours in OPC concrete. When GGBS or PFA is used this time period can be increased due to the slightly slower setting rate.

I. Early age Cracking

This is not considered to be a problem with concrete containing GGBS or Fly Ash. It is more likely to occur in concrete containing high level of microsilica.

J. Finishing

Due to improved workability, flow characteristics and increase in paste volume the surface finish of GGBS or PFA concrete is generally easier to control than concrete containing OPC.

K. Curing

As with all concrete to get the best out of it, a correct curing regime is essential.

X. DURABLE CONCRETE SPECIFICATION

The QC tests generally being conducted to verify the durable concrete performance containing GGBS or Fly Ash are Rapid Chloride Permeability Test, Water Absorption Test, ISAT Capillary Absorption Test and DIN Water Permeability test. The specification generally being adopted for producing durable concrete structures are as follows.

The test conditions for durability parameters are normally based on a test age of 28 days. This is, of course, arbitrary. Just as concrete continues to gain strength after 28 days so the continuing hydration of the cementitious phase continues to reduce the permeability of concrete and increase the durability test values.

Rapid chloride permeability (RCP) is a commonly specified durability parameter. For test specimens which are fully water-cured, typical test values may be expected to change as indicated in Table III. These are for a range of aggregates and normally designed mixes. The values depend on the materials used and the quality of the mix design process. Variations, both higher and lower, may be expected according to circumstances.

TABLE II. GENERAL SPECIFICATION FOR DURABLE CONCRETE

Test Description	**Standard**	**Limit**
Chloride Ion Penetration	AASHTO T-277	1200 coloumbs
Water Permeability	DIN 1048	8mm
Initial Surface Absorption	BS1881 Part 5	0.15ml/m^2/sec
30 min Absorption	BS 1881 Part 122	1.5%
Mix Design	***Specification***	
Minimum Cement Content	400 kg/m^3	
Maximum free Water/Cement Ratio	0.40	
Minimum Characteristic Strength	40 N/mm^2	

Other durability parameters based on some function of permeability (i.e. various absorption or penetration tests) may be expected to show improved properties at later ages, but probably not to the extent of the RCP values.

TABLE III. TYPICAL RAPID CHLORIDE PERMEABILITY VALUES (CIRIA C577, 2002)

Free Water/Cement ratio	**0.4**		**0.45**	
Test Age (days)	***28***	***90***	***28***	***90***
Cementitious Material	***Normal rapid chloride permeability values (coulombs)***			
OPC	3500 - 5000	3000 - 4000	5000 - 7000	4500 - 6000
SRC	5000 - 7000	4500 - 6000	6000 - 8000	5500 - 7000
OPC with 50 - 70% GGBS	1000 - 1500	500 - 1000	1500 - 2000	1000 - 1500
OPC with 20 - 25% Fly Ash	1000 - 2000	500 - 1500	1500 - 2500	1000 - 2000

XI. CONCLUSIONS

Concrete is the most consumed man made material in the world and cement is the vital ingredient in the production of concrete and in order for the concrete to be sustainable concrete the best available option is the use of industrial wastes such as Fly Ash, GGBS etc in suitable proportions as partial replacement of cement.

Durable concrete specifications are needed to be implemented for the quality control during the construction phase of the projects and in particular for those projects which are in marine/coastal environment.

Mineral additions such as Fly Ash & GGBS are recognized as the best available options to arrive at appropriate limiting threshold values stipulated for durable concrete. Use of durable concrete can help in constructing valuable long term assets.

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