

APPROPRIATE CEMENT BINDERS FOR CONCRETE PIPE – A REVIEW

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APPROPRIATE CEMENT BINDERS FOR CONCRETE PIPE

- A REVIEW

R.K. Lewis and D.W.S. Ho

1. INTRODUCTION

The draft for comment on the revision and amalgamation of AS1342 (Precast concrete drainage pipes), and AS1392 (Precast concrete pressure pipes), to be known as The Standard for Precast Concrete Pipes (Pressure and Non-pressure) provides the industry with the opportunity to utilize fully the advances made in concrete technology since 1970. These have been associated with the introduction and development in Australia of materials such as fly ash, ground granulated blast-furnace slag (subsequently referred to as slag) silica fume and chemical admixtures such as air-entrainers, water-reducing agents, superplasticizers. Their use is critical to the optimum management of our national resources and provided they are compatible with the technical requirements of the end product, should be encouraged to be used.

The proposed standard has been drafted in a way that lends itself to the inclusion of the above materials, in that it has specific acceptance requirements. Thus defects such as size of cracks, dents, bulges etc. are defined in seven degrees of severity and the acceptability of these defects are related to pipe usage – drainage, pressure and sewerage. There are also clauses related to compliance testing in terms of cracking and ultimate load, hydrostatic pressure, water absorption, cover and dimensional accuracy. These acceptance criteria enable the wording of the standard to be given in general form. As an example it is required that the pipe be cured to produce dense hardened concrete without specifying the actual curing treatment. Poor quality of concrete due either to lack of curing or mix constituents and proportioning would not be permitted because it would not meet the acceptance criteria required by the standard.

The long-term durability of pipes is essentially controlled by Clause 2.2.1 which states that '*Cement should be one of the types specified in AS1315 as appropriate to the intended use of the pipe. Other types of cements (e.g. Blended Cements to AS1317) shall not be used unless otherwise specified*'. This infers that pipes destined for different end use would require a knowledge of the long-term performance of the binder for that environment. Thus a Type A cement having a high C₃A content would be inappropriate for use where sulfate attack is critical. The responsibility for correct choice of binder lies with the manufacturer either independently or in conjunction with the purchasing authority where particular site problems exist. The proposed standard also places restrictions on the use of chemical admixtures. Clause 2.2.4 states that '*chemical admixtures shall not be used unless otherwise specified ...*'.

Concrete pipe production in Australia is based on highly compacted, low water/cement ratio concrete having a compressive strength generally exceeding 50 MPa. For this type of concrete it would be expected that long-term durability would not be a critical factor. Nevertheless, precautionary steps should be taken. Exposure Conditions for concrete pipes and their direct physical effects on pipelines have been detailed by Gourley⁽¹⁾.

This report outlines experiences relating to durability with the use of materials currently outside the draft rules in order to explore the consequences of specifying them. The report covers in addition to binder materials such as slag, fly ash, silica-fume, the role of chemical admixtures such as water reducing agents, air-entrainment agents, and superplasticizers.

2. LITERATURE SURVEY

A literature survey from Compendex Plus (1970–1990) was done to establish research data on the use of mineral and chemical admixtures in concrete pipe production. A total of 374 papers were indexed covering concrete pipes but only four papers were related to chemical or mineral admixtures. Summaries of these are given in Appendix A. There were also 18 papers on durability and 4 on curing related to concrete pipe without admixtures and these have been

integrated into the text where appropriate. It should be noted that no paper provided any reason why chemical and/or mineral admixtures should not be used.

3. MINERAL AND CHEMICAL ADMIXTURES

Up until about 1960 concrete in Australia was made with portland cement, coarse and fine aggregate and water. From then on two major changes occurred. Firstly, chemical admixtures (air entraining agents, water-reducing admixtures and set-controlling admixtures) became normal ingredients of concrete. This was followed by the introduction of fly ash, slag and more recently silica-fume.

In this section, each of the above materials will be reviewed. Their performance will be discussed in a later section.

3.1 Mineral Admixtures

3.1.1 Fly ash

Fly ash is a by-product from burning finely-ground coal in modern steam-raising power stations and is collected as fine dust in cyclones or electrostatic precipitators. Because of its siliceous nature, it has the ability to combine with lime in the presence of water to form compounds with cementing properties. Some fly ashes also have a water reducing effect because of the shape of the constituent particles. When properly proportioned and placed, fly ash concrete generally shows improved workability, pumpability and long-term strength gain.

The properties of fly ash depend on the particular source (silica and lime contents, particle shape, fineness, etc) and trends and developments in Australian Standards have been aimed at setting requirements that ensure high performance characteristics. Potter and Guirguis⁽²⁾ have

recently reviewed the requirements of fly ash, slag and silica-fume in current Australian Standards and pertinent details are given for fly ash in Appendix B.

In terms of strength some fly ashes produce binder compounds that are less effective than the cement they are replacing i.e. they have an effectiveness factor less than unity and typically about 0.5 to 0.7. Consequently it may be necessary to replace 1 unit weight of cement with a greater amount of fly ash. The increased volume of binder produced is generally offset by a reduction in the fine sand component. This is known as the Replacement-Addition Method of proportioning.

Fly ash is also added as a direct addition to a concrete mix replacing part of the fine aggregate to maintain correct yield. This is generally done to improve workability and/or reduce bleeding of lean concrete.

The difference between the above two methods are not obvious. In the latter use, reduced water demand and increased binder content may lead to increase 28-day strength. Mix design can then be adjusted to produce common strength with savings in cement. Potter and Guirguis⁽²⁾ discussed the implications of this in relation to specification where supplementing cementing materials are not allowed. A restriction on the binder to Type A Portland Cement e.g. *'All cements shall be Type A Portland Cement in accordance with AS1315'* is commonly used. Under the superseded AS1480 Concrete Structures Code, the intention of this restriction could be circumvented by the addition of fly ash and/or slag, nominally as part of the aggregate. To guard against this a specific clause was required – e.g. *'Fly ash shall not be used in concrete'*.

In the revision of the above standard, known as AS3600, the above problem was overcome by the introduction of 'normal-class' and 'special-class' concretes. Where a definite limitation of the use of a material is required, then the concrete is specified as 'special-class' and the purchaser nominates the requirements and/or limitations. AS3600 does not apply to concrete pipes, but the same implications exist.

3.1.2 Ground granulated blast-furnace slag

The production of pig iron in a blast furnace, also produces a liquid slag which if rapidly water quenched from high temperature, most of the lime, magnesia, silica and alumina can be held in a noncrystalline or glassy state and is called granulated slag. When ground it is capable of developing cementitious and pozzolanic properties.

The hydration of slag in a portland cement mixture must await the hydration of the portland cement which provides alkalis and sulfate for 'activating' the slag component. Mehta⁽³⁾ reported on the work of Sadatsure⁽⁴⁾ and also Hogan and Mensel⁽⁵⁾ which showed that under normal conditions it takes about 3 days before the contribution of the cementitious properties of the slag to the composite system becomes noticeable.

A major difference between fly ash and slag is in the shape and texture of the particles. In contrast to fly ash which has mostly spherical particles, slag is angular and has a rough surface texture. Consequently in a given concrete mixture the workability should be superior with fly ash additions than with slag additions. Due to the chemical composition of the slag, it has a higher effectiveness factor (0.9–1.0) compared with fly ash. Requirements for blast furnace slag are detailed in Appendix C.

3.1.3 Silica fume

Silica fume is a by-product of the manufacture of silicon or ferrosilicon alloy which are produced in submerged-arc-furnaces. In Australia, there are three sources of silica-fume. Sirivivatnanon, *et al.*⁽⁶⁾ recently reviewed the production and utilization of Australian silica-fume in concrete. The review discusses concrete properties and durability factors. An Australian standard covering silica fume materials is currently being prepared. The authors

presented a copy of the requirements of the Canadian Standard Specification (CSA, 1986). This is detailed in Appendix D.

Silica fume is a highly reactive pozzolan and a very efficient filler because of its fineness and shape. Its effectiveness factor can be as high as 5. Because of the ultra fineness of the particles the water demand of silica fume concrete is higher than that of normal concrete. This is generally offset by the use of water-reducing agents or superplasticisers.

The utilisation of silica fume in concrete is projected to be in the economic production of high strength concrete. Also, because the inclusion of silica fume reduces the total porosity and also reduces the proportion of large pores (pores greater than 0.01 microns), this type of concrete would be expected to have greater resistance to the ingress of liquids and gases. High quality concrete pipes would appear to be an area where technological gains could be achieved with the use of silica fume.

3.2 Chemical Admixtures

The use of air-entraining, set-modifying and water-reducing admixtures is well established in Australian concrete practice. Technical information is readily available on their use and Australian standards and codes of practice concerning the use of admixtures have been published (Bruere⁽⁷⁾).

In concrete pipe production it is chiefly the use of water-reducing admixtures that may be of value. Since water-reducing admixtures increase the fluidity of the cement paste they may be used to modify concrete in three ways:

Mode 1. To increase slump while maintaining constant w/c ratio and strength.

Mode 2. To reduce the water content of the mix while maintaining constant slump and so increasing strength.

Mode 3. To reduce both cement and water contents while maintaining constant slump and strength.

In addition water-reducing admixtures improve particle dispersion of cement, fly ash, slag in a concrete mix and thereby enable more efficient use of these materials.

In relation to pipe production, concrete would be modified by modes 2 and 3. Mode 2 would lead to a pipe with greater impermeability, whilst mode 3 provided it was done with consideration to there being an adequate volume of cement paste, could result in only minor changes in performance.

In relation to the use of chemical admixtures in conjunction with mineral admixtures, Lovewell and Hyland⁽⁸⁾ concluded from research and literature surveys that '*... combinations of pozzolans (including fly ash) with water-reducing agents, or with water-reducing-retarder agents, with and without air-entrainment can be used in concrete without creating abnormalities. All such ingredients should be checked for compliance of such mixes with specified quality parameters*'.

Fulton⁽⁹⁾ concluded from experiments in South Africa that water-reducing admixtures influence the behaviour of cements containing slag to the same manner and to the same degree as they influence the behaviour of ordinary portland cements.

The role of chemical admixtures was reviewed by Ashby⁽¹⁰⁾ and it was concluded that chemical admixtures do appear to aid Portland cement, fly ash and slag to act more efficiently. In addition they contribute to improved durability by water reduction. They will be further

discussed in the following section. Benefits arising when fly ash and water-reducing agents were used together were also obtained by Ho and Lewis⁽¹¹⁾.

4. DURABILITY CONSIDERATIONS

Gourley⁽¹⁾ reported on the durability of roller compacted and centrifugally spun concrete pipe. The aggressive agents which can cause deterioration of concrete by direct attack or by leading to reinforcement corrosion were reviewed, together with means of protection which can be used where concentrations are above certain levels. For concrete pipes both the external and internal conditions need consideration.

Durability factors requiring attention are sulphate and acid attacks, steel corrosion, abrasion resistance, aggressive CO₂ (in ground water). In this section each factor will be discussed with particular reference to the use of admixtures.

4.1 Water Permeability

Destructive agencies generally require the presence of moisture to enable them to penetrate into concrete. Water penetration can occur due to capillary attraction or by differential applied water pressure. In pipes both are likely to occur under certain practical conditions. The Draft Standard requires prototype testing of water absorption for sewerage and pressure pipes with the option of quality control testing if specified. The latter also applies to drainage pipes. Water absorption shall not exceed 6.5% for sewerage and pressure pipes and 8.0% for any drainage pipes. These low values of water absorption are set to ensure that water penetration into the concrete is low.

Ho and Lewis⁽¹²⁾ developed the concept of measuring the quality of concrete by determining the water sorptivity. During testing, the depth of water penetration, d , is noted visually by

splitting the specimen, and the depth is found to be related to the square root of time, t , as shown in Fig. 1. This behaviour can be represented mathematically by

$$d = d_0 + S\sqrt{t}$$

where d_0 is a constant.

In general, the value of d_0 is small and may be ignored in practice. The gradient of the straight part of the curve is defined as the water sorptivity, S , of the concrete. Good quality concrete is represented by low values of water sorptivity.

The above authors used the concept of sorptivity to study the role of cement, mineral admixtures, chemical admixtures, and curing on the durability of concrete having a compressive strength within the range 20 to 50 MPa.

Although this research work was directed towards building facades which receive intermittent wetting and drying, it is also of value for pipes. Table 1 sets out some results illustrating the following influence of constituents on sorptivity:

1. The addition of a water-reducing admixture resulted in a reduction in the sorptivity both in comparison to plain concrete or to fly ash concrete.
2. The variation in sorptivity values between different brands of Type A cement may be greater than that arising due to the partial replacement of a Type A cement with fly ash.
3. As compressive strength is increased, the differences in sorptivity values between mixes with different constituents becomes less significant.

Further Ho and Ritchie⁽¹³⁾ reported earlier work on the effects of steam curing. It was noted that the water sorptivity of steam cured concrete was greatly reduced by the partial replacement

of cement by fly ash. For plain concrete (i.e. without mineral admixtures) the sorptivity after steam curing was equivalent to about 3 days of standard moist curing whilst for fly ash concrete the sorptivity after steam curing was equivalent to that obtained after about 28-days of moist curing. Recent results with slag gave similar results to the fly ash concrete.

Hadipriono *et al*⁽¹⁴⁾ noted that water-reducing agents were commonly used in pipes and that with proper use absorption factor was reduced.

Mehta⁽³⁾ reported that work done by Manmohan and Mehta⁽¹⁵⁾ showed that additions of pozzolanic and cementitious admixtures such as rice husk ash, fly ash, and slag to portland cement were instrumental in causing pore refinement or transformation of large pores into fine pores – a process which had a far reaching influence on the permeability of hardened cement pastes. Also that Feldman⁽¹⁶⁾ using a fly ash and a slag as admixtures, and Sellevold *et al.*⁽¹⁷⁾ using silica fume as admixture have confirmed the process of pore refinement and its significance to permeability. Mehta concludes that the use of admixtures which would reduce water demand and bleeding in fresh concrete, decrease the size and number of large voids in hydrated cement paste should improve the impermeability of a portland cement concrete. The author underscores the importance of proper curing of concrete containing mineral admixtures, since without sufficient progress on the pozzolanic and cementitious reactions associated with mineral admixtures, significant improvements in strength and durability of concrete cannot be expected.

Cohen⁽¹⁸⁾ quotes the work of Mehta and Gjorv⁽¹⁹⁾ who showed that there is a significant reduction of about one order of magnitude in volume of pores larger than 1000 Å when silica fume is added. Such pores comprised 6% of the total pore volume in the silica fume pastes and 60% for pastes without the silica fume.

4.2 Carbonation

Sirivivatnanon *et al.*⁽⁶⁾ reviewing the use of silica fume in concrete reported the work of Sellevold⁽¹⁷⁾ with respect to carbonation. Although the effect of limited curing on carbonation rates is more important with concretes containing silica fume, these influences are found to be more pronounced with increased replacement percentages of silica fume. However it was stated that the major applications of silica fume are in the production of high strength concretes in which case, carbonation itself should not be a major problem.

Ho and Lewis⁽²⁰⁾ showed that with limited initial curing such as 7 days the carbonation was related to the water/portland cement ratio (w/c), Figure 2. For w/c of about 0.4, the carbonation rate at a CO₂ concentration of 4% was about 1 mm per square root of time in weeks.

Comparisons between the accelerated carbonation process and that in natural environment indicated that for the later, the carbonation rate would be at least 10 times slower for building facades. For concrete pipes, where the outer pores could be blocked with moisture for longer periods than in building facades, a factor of 20 may be more appropriate. Under these conditions the depth of carbonation after 50 years would only be 2-3 mm.

With the partial replacement of portland cement with mineral admixtures, w/c would be increased resulting in higher carbonation rates. However with the type of concrete produced for concrete pipe, even a 50% increase in carbonation rate would only result in 3-4 mm of carbonation depth over a 50 year period. Thus, for pipes buried in ground or used to carry liquids, carbonation should not be a major concern.

4.3 Chloride Ion

Hatten⁽²¹⁾ states that buried concrete pipes will give satisfactory service where groundwater contains up to 20 000 ppm of chloride ion. For concentrations above this protective means should be considered – e.g. coatings. In the marine environment the various situations are more diverse and complicated. If the concrete is submerged, the rate of propagation of the steel

corrosion due to the penetration of the chloride ion will be less critical than at locations such as above or in tidal zones, or subject to severe wave action.

Durability aspects of fly ash concretes in relation to chloride are discussed by Swamy⁽²²⁾ who quotes the work of Gebler and Klieger⁽²³⁾. This study showed that fly ashes are effective in controlling the penetration of chloride ions, and that air-entrained concretes with fly ash are as effective as similar concretes without fly ash. Research to date shows that pozzolans provide excellent protection of steel reinforcement from chloride attack.

Li and Roy⁽²⁴⁾ investigated possible mechanisms of reduction in chloride ion diffusion, due to the inclusion of fly ash in the concrete mixture. They concluded that fly ash blended cement has high potential to prevent diffusion of chloride ions. This is due to the clogging of the pores by gel produced, the tortuosity in the pore structure and also to the action of multivalent cations on chloride ion diffusion in the pore solution.

With respect to slag cements, Hooton⁽²⁵⁾ states that from the international literature, the diffusion of chloride through slag concretes should be less and resistivity to galvanic corrosion should be higher. He refers to the work of Page *et al.*⁽²⁶⁾ who showed that a 65% slag paste had a chloride diffusivity of less than 10% of that of its parent portland cement. Cook *et al.*⁽²⁷⁾ showed that for a fixed binder content, increasing slag replacement reduced chloride penetration into concretes exposed to seawater. Cao *et al.*⁽²⁸⁾ found that pore solutions for a slag cement displayed better corrosion passivation characteristics than did some portland cements.

Heummen⁽²⁹⁾ discussing experiences with precast reinforced – concrete box sections for culverts and storm drains noted that cement with at least 65% slag content gave a low chloride diffusion coefficient.

For silica fume, Sirivivantnanon *et al.*⁽⁶⁾ noted that overseas research by Masurin⁽³⁰⁾ indicated that using silica fume in concrete reduced chloride penetration characteristics. The effect appears to reach a maximum at a cement replacement level of around 10%. The study reports that there appears to be no improvement in the resistance to chloride penetration at higher cement replacement percentages.

Research on silica fume by Sellevold⁽³¹⁾ noted a substantial increase in concrete resistivity which was related to the finer pore structure and lower ionic strength of the pore solution.

The corrosion of steel reinforcement depends primarily on carbonation, chloride penetration and water sorptivity. It is shown in the review of these factors that concrete made with mineral admixtures and chemical admixtures, and after adequate curing has similar or better ability to resist the destructive agencies which lead to steel corrosion, than plain concrete.

4.4 Sulphate Ion

Where attack from sulphate ion is a potential problem, Type D sulphate resisting cement is often used. According to Burnett⁽³²⁾ for a severe sulphate environment the Bureau of Reclamation would specify a sulphate resisting cement or perhaps a sulphate resisting cement plus a pozzolan. He cited the work of Kalousek *et al.*⁽³³⁾ who studied concrete for long-time-service in sulphate environment.

Davies *et al.*⁽³⁴⁾ investigated five low-calcium fly ashes for their effectiveness in improving the sulphate resistance of cement. On the basis of the ratio of the compression strength of fly ash concrete to the corresponding plain concrete specimens, it was concluded that all fly ash concretes were superior to their corresponding plain concrete specimens. Mehta⁽³⁵⁾ found that fly ashes with lower alumina content showed better resistance to sulphate attack.

Mehta^(36,37) has shown that reduction in permeability as a result of pore refinement associated with the pozzolanic reaction is equally important as the reduction in free lime and reactive alumina content. He again underscores the importance of proper curing of concrete containing mineral admixtures.

Schroder⁽³⁸⁾ reviewed recent literature on the durability of slag concretes and concluded that the vast majority of laboratory studies and all the long-term studies confirmed that cements containing slag imparted better resistance to sulphate attack. Schroder concluded, that for the best results, slag cements with more than 70% slag component are required.

Hooton⁽²⁵⁾ concluded from his research with Emery that concretes made with between 45 and 72% slag replacement of portland cement were not exhibiting any deterioration after 10.5 years in 3000 mg/l $\text{SO}_4^{=}$ sulphate solutions. Accelerated mortar bar tests, demonstrated that 50% slag replacement (with a low AL_2O_3 slag), regardless of cement C_3A content (up to 12.3%) is adequate to provide better performance than a sulphate resistant portland cement with a C_3A of 3.1%. Hooton cautioned on the general applicability of his results and recommended that each source of slag be tested to judge its sulfate resistance.

Heummen⁽²⁹⁾ also found that cement with at least 65% slag content provided resistance against sulphate attack.

Cohen⁽¹⁷⁾ reports that most publications dealing with sulphate problems also point to the benefits of silica fume in reducing sulphate attack. He quotes the work of Mather⁽³⁹⁾ who tested three high C_3A content portland cements with various pozzolanas and noted that the greatest benefit was obtained with silica fume. Recent work by Cohen and Bentur⁽⁴⁰⁾ indicated that silica fume is deleterious when the attacking solution contains magnesium sulphate.

Carlsson *et al.*⁽⁴¹⁾ reported on the addition of silica fume/chemical admixtures to concrete and noted that the resistance of the pipes against chemical attack was increased.

4.5 Soft Water Attack

Soft water corrodes cement-bonded products. The main cause of the aggressiveness of natural waters is the presence of dissolved carbon dioxide and humic acid. There appears to be little one can do to improve significantly the soft water resistance of structures themselves other than to impregnate them with solutions of magnesium or zinc fluosilicate or other chemicals, or by applying an appropriate coating. Kruger and Visser⁽⁴²⁾ experimented on mortar prisms and fibre-cement pipes made with portland cement, and with blends incorporating slag, fly ash and milled quartz. They concluded that soft water resistance of portland cement-bonded products can be significantly improved by replacing 30 to 40% of the cement with fly ash and then autoclaving them. Also the soft water resistance of both autoclaved and unautoclaved fibre-cement pipes could be improved by replacing 50% of the cement with slag.

4.6 Abrasion

The severity of abrasion depends on the size, hardness, and quantity of solids being moved through the pipe. Bealey⁽⁴³⁾ reported only one instance of an abrasion problem over the past 14 years in America and that was related to water carrying boulders 0.3 to 0.6 m in diameter. Abrasion can be reduced by increasing the compressive strength and quality of the concrete. Perkins⁽⁴⁴⁾ reported that he had come across only one case of severe damage to the invert of underground pipelines and this was in a sugar beet factory. Several centimetres had been worn away over about 2 years. Perkins concluded that if the concrete had been of the quality normally found in concrete pipes to British Standard Requirements, the damage would have been much less severe.

For concrete floors Chaplin⁽⁴⁵⁾ studied the effects of incorporating flyash and slag on Abrasion Resistance. The work showed that the use of blended cements is not detrimental provided that

the floor is well cured, but when curing is inadequate, blended cements give lower abrasion resistance results than those obtained with ordinary portland cement.

Butler and Asby⁽⁴⁶⁾ studied the effect of fly ash and slag as binder components on the abrasion resistance of concrete. For water-cured concrete having a 28 day strength of about 40 MPa, the abrasion resistance was similar for all binders, except that the portland cement/slag binder without a chemical water-reducing admixture had a slightly lower abrasion resistance. Air storage resulted in a decreased resistance for all mixture types, but the authors stated that inconsistencies in the results made it inappropriate to draw further conclusions.

A similar result would be expected for concrete pipes.

4.7 Acid attack

Acid causes attack on and removal of material from a concrete surface. Attack by acid in ground-water is controlled mainly by concentration, pH value and the rate of replenishment. Coatings applied to the outside surface will usually provide adequate life expectancy. Further protection can be provided by a sacrificial layer of concrete (by increasing the cover) which delays the onset of acid attack to the pipe itself.

The end result of the generation of hydrogen sulphide in sewer lines is the progressive corrosion of the sewer by sulphuric acid. To withstand this severe attack it is necessary to apply protective measures, ranging from the use of calcareous aggregates, high quality concrete, to protective coatings and linings.

In Australia, the occurrence of sulphuric acid attack has been successfully combated by means of sewer design and operation measures. These are directed at preventing the formation of H₂S and its discharge into the air space of the sewer, by providing adequate ventilation and preventing moist precipitations.

The above approach to reduce of acid attack would be equally appropriate when the concrete incorporated mineral and chemical admixtures.

5.0 CURING

In most cases, the benefits described earlier that are derived from the use of mineral admixtures are obtained through the development of pozzolanic reaction. This reaction could only proceed if 'proper' and adequate curing is maintained. This is to be expected since curing results in a reduction in the volume of large pores making it more difficult for the destructive agencies to enter the concrete. Steam-curing would assist in mineral admixtures achieving their potential earlier.

Chemical water-reducing agents which achieve a reduction in water demand also lead to reduced volume of large pores.

Steam curing is often used for partial or full curing of concrete pipes. The ACI Recommended Practice for Steam Curing⁽⁴⁷⁾ states that a minimum curing period is generally used for concrete sewer and concrete pipes, whilst for pressure pipes the American Water Works Association specifications are cited which require longer curing periods up to a total of 32 hours. In the summary section it is stated that the curing cycle chosen should be the most economical one which produces the desired strength at the required time.

Soroka *et al*⁽⁴⁸⁾ studied the effect of short-term steam-curing on later-age strength. It was confirmed that steam curing affected adversely concrete later-age strength. It was concluded, however, that under short curing periods and moderate temperatures this adverse effect was primarily due to the lack of supplementary wet-curing and not necessarily to such physical factors as increased porosity, internal cracking etc. Accordingly, under such conditions,

supplementary 7 days wet-curing was found to virtually eliminate the adverse effect of steam-curing on concrete strength. In the experiments reported the steam was applied either 1/2 or 1 h after mixing and the maximum chamber temperature was held from 2 to 5 h at 60° and 80°C.

Lewis⁽⁴⁹⁾ reported on the effect of cement characteristics on strength of steam cured concrete. With respect to additional fog-curing the ratio of the steam plus fog-cured strength to fog-cured strength varied between 98 and 124 per cent depending on the cement used – the latter being associated with those cements which show considerable long-term strength development under standard moist curing conditions.

The proposed Australian Standard requires the concrete to be cured to produce dense hardened concrete.

6.0 CONTROL TESTING

The standard details acceptance requirements for drainage, sewerage and pressure pipes which endeavour to safeguard 'Quality' of the concrete product. These requirements are for prototype and Quality control testing. Thus cracking load is determined for all pipes for both prototype and quality control, but many of the other tests are required for prototype testing only whilst quality control testing is done only if specified. Nevertheless the test requirements do exercise a degree of control over the manufacturing process in respect to mix design, manufacturing techniques and curing.

According to Gowripalan *et al.*⁽⁵⁰⁾ investigations of the methods based on water absorption to assess the effects of curing are numerous, but a completely reliable field method has yet to be developed. The absolute value of absorption depends on the specimen dimensions, the method of conditioning the specimen, and the testing technique.

Bealey⁽⁴³⁾ in a state of the art paper on concrete pipes, makes the following comment about the absorption test. *'Initially used as a quality control test for thin-wall concrete drain tile to ensure adequate resistance to leaching action, absorption testing has been gradually applied without any substantiating research to larger pipes with thicker walls as an indicator of durability. Precast concrete pipe specifications require absorption not to exceed a maximum of 8.5 to 9 per cent, and pipe is normally produced with absorption significantly less'*. In Australia, a much lower allowable water absorption value is required for concrete pipes.

The proposed pipe standard details the test method to obtain the water absorption of cores secured from pipes. It is held that consideration should be given to up-grading the requirements given in Table 9 so that absorption testing is mandatory for all pipe types. Consideration should also be given to the sample dimensions. Because of the varying wall thickness of pipes, the ratio of surface area to volume will not be constant. This can influence the total water absorbed and give apparent absorption values within the allowable whilst the actual water absorbed into the concrete could be higher. For example, assume that water penetrated during the test 20 mm from all surfaces. Thus a 40 mm long core will be fully saturated whilst a longer core (say 100 mm) will have a dry inner portion. This would give a lower total absorption to the total mass of the concrete.

To remove this anomaly, the standard should require that in pipes having a wall thickness greater than 50 mm, the thickness of the test core for absorption testing should be limited to 50 mm from the inner surface of the pipe.

7.0 MANUFACTURE OF PIPES

This paper does not deal specifically with manufacturing techniques for concrete pipes. However a cautionary note is warranted, at least to those who maybe new to admixtures. Admixtures influence the properties of the fresh and hardened concretes and these have been well documented. Pipe producers should be aware of the difference between blended and

portland cement mixes in order to avoid problems during production. Major differences are that some mineral admixtures may:

- (a) slow strength development, and therefore necessitate longer overall periods for steaming,
- (b) lower the heat of hydration, thus requiring more energy to bring pipe to required temperature during curing,
- (c) require extra quality control procedures over raw materials.

8.0 SUMMARY

The use of fly ash, ground granulated blast-furnace slag, silica fume and water-reducing agents is critical to the optimum management of our national resources and should be encouraged.

The detailed review of the influence of chemical and mineral admixtures on the durability of concrete indicates that benefits can arise due to use of fly ash, ground granulated blast-furnace slag, silica fume, water-reducing agents and air-entrainment. Whilst there is only limited supporting research data for concrete pipe products, there is no apparent reason why the benefits of this technology should not also be applied to pipe production, provided upper limits on the percentage of mineral admixtures in the binder are defined.

It must be acknowledged, however, that certain applications may require particular properties of the cementitious binder in the pipe. Since the end use of the pipe is governed by the purchasing authority, the pipe standard must provide for the purchaser to specify particular cement types or combinations for special applications.

It is recommended that pipes for all applications should comply with absorption limits as specified and that the thickness of cores for absorption testing should be limited to 50 mm from the inner surface of the pipe.

9.0 REFERENCES

1. Gourley, J.T. (1988). 'High Quality Concrete in Corrosive Waters'. Seminar – The Technology of High Quality Concrete, Cement and Concrete Association of Australia, Melbourne, July.

2. Potter, R.J. and Guirguis, S. (1990). 'Developments and Trends in Australian Standards and Specifications for Fly Ash, Slag and Silica-Fume'. Concrete for the Nineties. International Conference on the use of Fly ash, Slag, Silica Fume and other siliceous materials in concrete, Leura, Australia, Sept.
3. Mehta, P.K. (1983). 'Pozzolan and Cementitious By-products as Mineral Admixtures for Concrete – A Critical Review'. American Concrete Institute, SP-79, 1, pp. 1–46.
4. Sadatsure, K., (1978). 'Practical Properties of Slag Cements Prepared with a Series of Classes of the Gehlemite – Akermanite System'. Cement Association of Japan, 32nd Meeting, pp. 57–58.
5. Hogan, F.J. and Mensel, J.W. (1981). 'Evaluation for Durability and Strength Development of a Ground Granulated Blast Furnace Slag'. Cement, Concrete and Aggregates, 3(1), pp. 40–52.
6. Sirivivatnanon, V., Cao, H.T., Baweja, D. and Hassell D. (1990). 'Production of Australian Silica Fume and its Utilization in Concrete'. Concrete for the Nineties. International Conference on the use of Fly ash, Slag, Silica Fume and other siliceous materials in concrete, Leura, Australia, Sept.
7. Bruere, G.M. 'Admixture Chemistry'. Seminar on Admixtures, Concrete Institute of Australia, April, 1982.
8. Lovewell, C.E. and Hyland, E.J. (1971). 'Effects of combining two or more admixtures in concrete'. Ctte A2-E5, Highway Res Bond 50th Ann Meet, Washington, D.C., Jan.

9. Fulton, F.S. (1974). 'The properties of portland cements containing milled granulated blast-furnace slag'. Monograph, The Portland Cement Institute (South Africa), Johannesburg.
10. Ashby, J.B. (1990). 'Australian Concrete Containing Chemical Admixtures and Fly ash and/or Ground Granulated Blast Furnace Slag'. Concrete for the Nineties. International Conference on the use of Fly ash, Slag, Silica Fume and other siliceous materials in concrete, Leura, Australia, Sept.
11. Ho, D.W.S. and Lewis, R.K. (1987). 'The Water Sorptivity of Concretes: The Influence of Constituents under Continuous Curing'. Durability of building Materials, 4, pp. 24–252.
12. Ho, D.W.S. and Lewis, R.K. (1984). 'Concrete Quality as Measured by Water Sorptivity'. Civ. Eng. Trans. Eng. Aust., CE26(4), pp. 306–313.
13. Ho, D.W.S. and Ritchie, D.J. (1988). 'The Quality of Cover Concrete Achieved by Different Curing Techniques'. Paper 3.1. Proc. Second Australian/Japan Workshop on Durability of Reinforced Concrete Structures'. Highett, Australia, Nov.
14. Hadipriono, F.C., Larew, R.E. and Lee, O. (1988). 'Service Life Assessment of Concrete Pipe Culverts'. J. Transportation Engineering, 114(2), pp. 209–220.
15. Manmohan, D. and Mehta, P.K. (1981). 'Influence on Pozzolanic, Slag, and Chemical Admixtures on Pore Size Distribution and Permeability of Hardened Cement Pastes'. Cement, Concrete and Aggregates, 3(1), pp. 63–67.
16. Feldman, R. (1981). 'Pore Structure Formation During Hydration of Fly Ash and Slag Cement Blends'. Proc. Symposium on Fly Ash Incorporation in Cement and Concrete Material Research Society. Ed. S. Diamond, pp. 124–133.

17. Sellevold, E.J., Bager, D.H., Jensen, E.K. and Krudsen, T. (1981). 'Silica Fume Cement Pastes – Hydration and Pore Structure'. Proc. Nordisk Mini Seminar on Silica and Concrete, Dec., 32 pages.
18. Cohen, M.D. (1990). 'A look at silica fume and its actions in Portland cement concrete'. Indian Concrete Journal, **64**(9), Sept., pp. 429–438.
19. Mehta, P.K. and Gjorv, O.E. (1982). 'Properties of Portland Cement Containing Fly Ash and Condensed Silica Fume'. Cement and Concrete Research, **12**(5), pp. 587–596.
20. Ho, D.W.S. and Lewis, R.K. (1987). 'Carbonation of Concrete and its Prediction'. Cement and Concrete Res., **17**(3), pp. 489–504.
21. Hatten, N.H. (1986). 'Concrete Pipe Durability'. Seminar – Pipes, Poles and Piles, Concrete Institute of Australia, April.
22. Swamy, R.N. (1990). 'Fly ash concrete – potential without misuse'. Materials and Structure, **23**, pp. 397–411.
23. Gebler, S.H. and Klieger, P. (1989). 'Effect of fly ash on the durability of air-entrained concrete'. ACI, SP-114, **1**, pp. 453–475.
24. Li, S. and Roy, D.M. (1986). 'Investigation of Relation Between Porosity, Pore Structure and Cl⁻ Diffusion of Fly Ash and Blended Cement Pastes'. Cement and Concrete Research, **16**(5), pp. 749–759, Sept.

25. Hooton, R.D. (1990). 'Applications and Durability of Slag Cements in Concrete'. Concrete for the Nineties. International Conference on the use of Fly ash, Slag, Silica Fume and other siliceous materials in concrete, Leura, Australia, Sept.
26. Page, C.L., Short, N.R. and Holden, W.R. (1986). 'The Influence of Different Cements on Chloride Induced Corrosion of Reinforcing Steel'. Cement and Concrete Research, 16(1), pp. 79–86.
27. Cook, D.J., Hinczak, I., Jedy, M. and Cao, H. T. (1989). 'The Behaviour of Slag Cement Concretes in marine Environment – Chloride ion Penetration'. American Concrete Institute, SP-114, 2, pp. 1467–1483.
28. Cao, H.T., Baweja, D. and Roper, H. (1990). 'Corrosion Characteristics of Steel in Solutions Derived from Cement and Blended Cements'. Cement and Concrete Research, 20(3), pp. 325–334.
29. Heummen van, P.H. (1984). 'Half-century Experience with Precast Reinforced-Concrete Box Sections for Culverts and Storm Drains in Netherlands'. Transportation Research Board, 1001, Washington CD.C., pp. 112–114.
30. Masurin, S.L. (1986). 'Chloride ion Penetration in Conventional Concrete and Concrete Containing Condensed Silica Fume'. Second International Conference of Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete. American Concrete Institute, SP91, pp. 1119–1134.
31. Sellevold, E.J. and Nilsen, T. (1987). 'Condensed Silica Fume in Concrete: A World Review'. Supplementary Cementitious Materials for Concrete, V.M. Malhotia Ed. CANMET, Canada, pp. 166–243.

32. Burnett, G.E. (1974). 'Concrete Pipe in High Sulfate Soils Found in Excellent Condition after 34 years'. Amer. Conc. Inst., 71(2), pp. 80–81.
33. Kalousek, G.L., Porter, L.C. and Benton, E.J. (1972). 'Concrete for long-time service in sulphate environment. Cement and Concrete Research, 2(1), Jan., pp. 79–89.
34. Davis, R.E., Carlson, R.W., Kelly, J.W. and Davis, H.E., (1937). 'Properties of Cement and Concrete Containing Fly Ash'. ACI Proc., 33(5), pp. 577–612.
35. Mehta, P.K. (1980). 'Performance Tests for Sulphate Resistance and Alkali-Silica Reactivity of Hydraulic Cements'. Durability of Building Materials and Components – ASTM STP691, pp. 336–345.
36. Mehta, P.K. (1981). 'Sulfate Resistance of Blended Portland Cements Containing Pozzolans and Granulated Blast Furnace Slag'. Proc. Fifth International Symposium on Concrete Technology, University of Nuero Leon, Mexico, pp. 35–50.
37. Mehta, P.K. 'Durability of Concrete Exposed to a Marine Environment – A Fresh Look'. Concrete Workshop 88, Concrete Institute of Australia, W.G. Ryan Ed.
38. Schroder, F. (1968). 'Blast-Furnace Slags and Slag Cements'. Proc 5th Int. Symp. Chem. Cem., Tokyo, IV–3, pp. 149–199.
39. Mather, K. (1982). 'Current Research in Sulphate Resistance on the Waterways Experimental Station'. George Verbeck Symposium of Sulphate Resistance of Concrete, ACI, SP–77, pp. 63–74.

40. Cohen, M.D. and Benture, A. 'Durability of Portland Cement-Silica Fume Pastes in Magnesium Sulphate and Sodium Sulphate Solutions'. *Jr. Amer. Conc. Ins.*, **85**, pp. 148–157.
41. Carlsson, M., Hope, R., and Pedersen, J. (1986). 'Use of Condensed Silica Fume (CSF) in Concrete'. *ACI Special Publication, Detroit, SP-91*, pp. 1013–1030.
42. Kruger J.E. and Visser, S. (1990). 'Comparative Resistance to Soft Water Attack of Mortars and Fibre-cement Products made with OPC and Blends of OPC and Milled Quartz, PFA and GGBS'. *Durability of Building Materials and Components, Proc. 5th International Conference. Brighton, UK*, pp. 639–650.
43. Bealey, M. (1984). 'Precast Concrete Pipe Durability : State of the Art'. *Transportation Research Record 1001, Washington D.C.*, pp. 88–94.
44. Perkins, P.H., (1979). 'Portland Cement Concrete Underground Pipelines'. *Transportation Engineering Journal of ASCE*, **105(5)**, Sept., pp. 577–588.
45. Chaplin, R.G. (1986). 'The influence of cement replacement materials and other factors on the abrasion resistance of industrial concrete floors'. *Technical Report 568, Slough, UK, Cement and Concrete Association.*
46. Butler, W.G. and Ashby, J.B. (1985). 'The Influence of Curing Environment upon the Properties of Concrete Made Using a Variety of Portland Cement Supplements'. *ACI-Rilem Symposium 85, Monterrey, Mexico*, pp. 197–217.
47. Anon, (1969). 'Proposed ACI Standard – Recommended Practice for Atmospheric Pressure Steam Curing of Concrete'. *J. ACI*, **66(8)**, Aug., pp. 629, 646.

48. Soroka, I., Jaegermann, C.H. and Bentur, A. (1978). 'Short-term steam-curing and concrete later-age strength'. *Materials and Structures*, **11**(62), March-April, pp. 93–96.
49. Lewis, R.K. (1968). 'A summary of investigations of steam curing of concrete related to cement characteristics', *Constructural Reveiw*, **41**(3), March, p. 18.
50. Gowripalan, N., Cabrera, J.G., Cusens, A.R., and Wainwright, P.J. (1990). 'Effect of Curing on Durability'. *Concrete International: Design and Construction*, **12**(2), Feb., pp. 47–54.

Table 1. Water Sorptivity of Various Concrete Mixes

| Brand- Type A cement | Cement content (kg/m ³) | Fly ash (kg/m ³) | Chemical admixture | Water content | Compressive strength at 28 days (MPa) | Water Sorptivity after 7 days curing (mm/h ^{0.5}) |
|----------------------------|---|---------------------------------|-----------------------|------------------|--|---|
| A | 405 | – | – | 171 | 45 | 3.5 |
| | 373 | – | Water-reducing | 156 | 49 | 3.0 |
| | 293 | 74 | – | 159 | 49 | 4.0 |
| | 284 | 71 | Water-reducing | 148 | 47 | 2.5 |
| B | 401 | – | – | 177 | 47 | 5.0 |
| | 296 | 74 | – | 166 | 46.5 | 5.5 |
| A | 316 | – | – | 178 | 38 | 5.5 |
| | 303 | – | Water-reducing | 163 | 38 | 4.5 |
| | 243 | 61 | – | 166 | 35 | 7.5 |
| | 241 | 60 | Water reducing | 155 | 38 | 6.0 |
| B | 310 | – | – | 178 | 38 | 6.5 |
| | 239 | 60 | – | 168 | 35 | 8.0 |

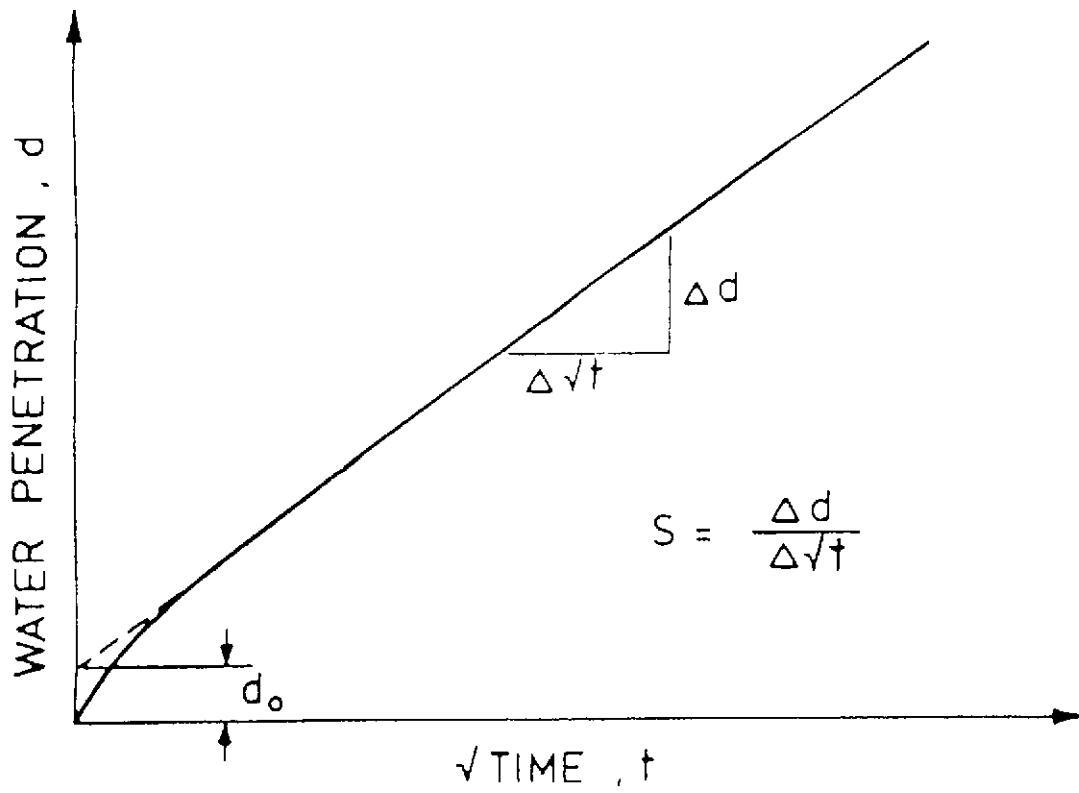


Fig. 1. General relationship between depths of water penetration and time.

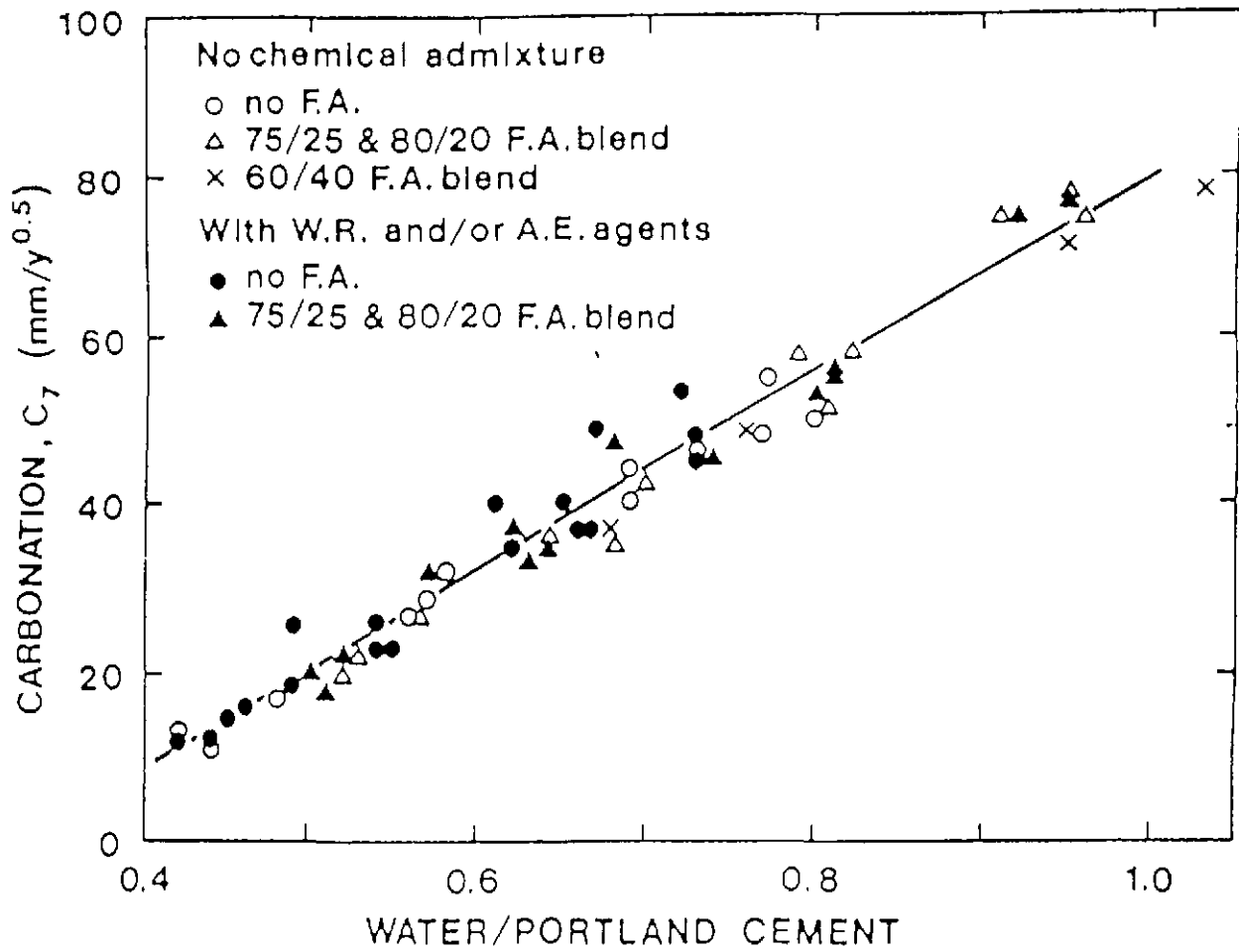


Figure 2. The Influence of Water to Portland Cement Ratio on Carbonation Under 4% CO_2 .

APPENDIX A

Summary of relevant papers from Literature Survey

- A 1. Heummen van, P.H. (1984). Half-century Experience with Precast Reinforced-Concrete Box Sections for Culverts and Storm Drains in the Netherlands. Transportation Research Record No. 1001, Washington DC, pp. 112–114.

Paper gives the experiences with precast reinforced-concrete box sections for culverts and storm drains. Discusses principal aggressive factors and their influence on durability. To manufacture a durable concrete product the author lists the following factors: dense concrete, adequate curing, sufficient cover and applying portland/blast furnace cement. The cement should consist of at least 65% slag content. This type of cement also resists sulfate, and concrete made with it has also low chloride diffusion coefficient. Because of this excellent experience, box sections are now also used for collecting sewers, effluent return basins, and tunnels under embankments.

- A 2. Carlsson, M., Hope, R., and Pedersen, J. (1986). Use of Condensed Silica Fume (CSF) in Concrete. ACI Special Publication, Detroit, SP-91, pp. 1013–1030.

Although CSF is mostly used for increasing concrete strength, it also confers other advantages such as improved durability-related properties. In the manufacture of concrete pipes, the addition of CSF is shown to increase the external load bearing capacity of the pipes by 40%. The resistance of the pipes against chemical attack is also increased considerably. Concrete pipes containing only about 5% CSF have 2-3 times longer service life than ordinary pipes when exposed to sulfates.

The CSF admixture added included a chemical admixture and a mineral filler

- A3. Hadipriono, F.C., Larew, R.E., and Lee, O. (1988). Service Life Assessment of Concrete Pipe Culverts. *J. Transportation Engineering*, 114(2), March, p. 209-220.

The durability and service life of concrete pipe culverts are discussed. The study reported includes the analysis of important enabling and triggering events that have caused or have the potential to cause the deterioration of concrete pipes. Amongst the enabling events is listed improper/insufficient use of admixtures.

Admixtures commonly used for concrete pipes are: air-entrainment, water reducing, and set accelerating agents. Air-entrainment agents are used to increase freeze-thaw resistance. Water reducing agents are used to improve workability. With proper use of this agent, segregation and honeycombing problems may be reduced, compressive strength increased and the absorption factor reduced.

In triggering events, acid attack, sulfate attack and abrasion are discussed.

- A4. Kruger, J.E., and Visser, S. (1990). Comparative Resistance to Soft Water Attack of Mortars and Fibre-cement Products made with OPC and Blends of OPC and Milled Quartz, PFA and GGBS. *Durability of Building Materials and Components. Proc. 5th International Conference, Brighton, UK, Nov. p. 639-650.*

Experiments were done on mortar prisms and fibre-cement pipes, using various binder combinations under aggressive soft water containing 500 ppm CO₂. The soft water resistance of both autoclaved and unautoclave (water cured) fibre-cement pipes could be improved by replacing about 50% of the ordinary portland cement with slag. A blend of 60% OPC and 40% flyash gave a similar result to 100% OPC when cured under water. For water cured products it was possibly due to improved impermeability whilst for autoclaved pipes to the formation of aluminium tobermorite and hydrogarnet.

APPENDIX B

Specifications for Fly Ash
(Ex Potter, Reference 2).

| | AS 3582 - Part 1 to be published | | | BS 3892 Part 1 (1982) | ASTM C618 (1987) | |
|---|-------------------------------------|-------------|------------|----------------------------------|------------------------------|---------------------------------|
| | Fine | Medium | Coarse | | F | C |
| Fineness | | | | | | |
| % pass 45 μ m | \geq 75 | \geq 60 | \geq 40 | | | |
| % ret'd 45 μ m | \leq 4 | \leq 6 | \leq 12 | \leq 12.5 | \leq 34 | \leq 34 |
| LOI max. % | \leq 1.0 | \leq 1.0 | \leq 1.0 | \leq 7.0 | \leq 6.0 | \leq 6.0 |
| Moisture content max. % | \leq 3.0 | \leq 3.0 | \leq 3.0 | \leq 0.5 | \leq 3.0 | \leq 3.0 |
| SO ₃ max. % | \leq 4.0 | \leq 4.0 | \leq 4.0 | \leq 2.5 | \leq 5.0 | \leq 5.0 |
| MgO | see Note | see Note | see Note | \leq 4.0 | - | - |
| Autoclave expansion | \leq 1.5% | \leq 1.5% | \leq 1.5 | - | \leq 0.8% | \leq 0.8% |
| Available alkali content | arbitrary | arbitrary | arbitrary | - | \leq 1.5% | \leq 1.5% |
| Relative density | no limits | no limits | no limits | - | - | - |
| Relative water requirement | no limits | no limits | no limits | not exceed 95% of that for pc | maximum that for Pozz. | 105% of cement act. index |
| Relative strength | no limits | no limits | no limits | - | - | - |
| Additional Requirements in Other Standards | | | | | Yes | Yes |
| Silica dioxide | No | No | No | No | Yes | Yes |
| Soundness | No | No | No | No | Yes | Yes |
| Uniformity | No | No | No | No | Yes | Yes |
| Multiple Factor | No | No | No | No | Yes | Yes |
| Drying Situation | No | No | No | No | Yes | Yes |
| Uniformity | No | No | No | No | Yes | Yes |
| Cement Alkali | No | No | No | No | Yes | Yes |

Note: If MgO > 4.0%, fly ash is acceptable provided autoclave expansion does not exceed 0.8%.

APPENDIX C

Specifications for Ground Granulated Blastfurnace Slag
(Ex Potter, Reference 2).

| | AS 3582 - Part 2 to be published | BS 6699 (1986) | ASTM C989 87(a) (1987) |
|--|---|---|---------------------------------------|
| Fineness Index (specific surfaces) | NS | ≥ 275 m ² /kg | 20% max. ret'd 45 μm sieve |
| LOI max. % | ≤ 3.0 | ≤ 3.0 | - |
| Sulphide sulphur max % | ≤ 1.5 | ≤ 2.0 | ≤ 2.5 |
| SO ₃ max. % | See Note 1 | - | 4.0 |
| Magnesia as MgO max. % | ≤ 15.0 | ≤ 14.0 | - |
| Alumina as Al ₂ O ₃ max. % | ≤ 18.0 | - | - |
| Total iron as FeO max. % | ≤ 1.5 | - | - |
| Manganese as Mn ₂ O ₃ max. % | ≤ 2.0 | ≤ 2.0% | - |
| Chloride ion as Cl ⁻ | See Note 2 | - | - |
| Insoluble residue max. % | ≤ 2.0 | ≤ 1.5% | - |
| Slag activity (Relative strength) | by agreement (cement being used) | 3 day - 3 MPa 28 day - 22 MPa (70% ggbfs: 30% cement being used recommended) | @ 7 & 28 day (reference cement) |
| Class content | NS | Yes | No |
| Setting | NS | Yes | No |
| Soundness | NS | Yes | No |
| Chem modulus | NS | Yes | No |
| Moisture content | NS | Yes | No |

Note 1: When slag blended with cement, SO₃ level not to exceed that given for blended cement.

Note 2: To be determined and reported

APPENDIX D

SILICA FUME – Specifications from Canadian Standard Specification (CSA, 1986)
 (Ex Sirivivatnanon *et al.*, Reference 6).

| Property | Specification | Frequency of Determination |
|---|---------------|----------------------------|
| SO ₂ (maximum) | <1% | Lot or 100 tonne |
| Loss on Ignition | <6% | Lot or 100 tonne |
| Silicon Dioxide (SiO ₂) | >85% | Lot or 500 tonne |
| Moisture Content | <3% | Lot or 100 tonne |
| Accelerated Pozzolanic Activity Index (Portland cement at 7d. min % of control) | >85% | Lot or 1000 tonne |
| Autoclave expansion | ± 0.2% | Lot or 1000 tonne |
| Fineness (% retained on 45 micron sieve) | <10% | Lot or 100 tonne |
| Density - Uniformity requirements | | |
| Maximum variation from average | 5% | |
| Maximum percentage retained on 45 µm sieve | 5% | |

Can be exceeded - dependent on expansion characteristics in combination with Portland cement