Aalborg Portland

White Concrete for Aggressive Environment

Evaluation Report

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1 Background

Aalborg White produces white cement which is different from white cements produced a couple of decades ago and is formulated to provide a more colour stable and durable white concrete. This new white cement is targeted at producing lasting white concrete thus enhancing the appearance of concrete structures.

Extensive laboratory testing of concrete samples using Aalborg White has been performed and today a set of the most classical test data for the cement and for different concrete mixes is available.

1.1 Objective

The objective of the present evaluation report is to evaluate the durability of the Aalborg White concrete based on the test data for white cement concrete mixes

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and reference mixes using grey cement.

1.2 Tests performed

The tests performed include two series of concrete with water/powder ratios of 0.36 and 0.45, respectively.

Reference concretes have been prepared with powder compositions corresponding to those used to build the Great Belt Link and other grey concretes. These high performance reference concretes are assumed to be well-known, well-tested, and highly durable.

For each water/powder ratio five different concrete mixes were tested:

- Pure Aalborg White (AW) concrete, with and without 2 kg/m^3 zinc stearate as hydrophobic agent
- AW concrete and 5% white silica fume, with and without 2 kg/m^3 zinc stearate
- AW concrete with 30% of the powder being white blast furnace slag.

The reference concretes are cast using low-alkali sulphate-resistant cement from Aalborg Portland, 5% normal silica fume and 15% fly ash. For the series with water/powder ratio of 0.45 also a reference concrete of AW with ordinary silica fume was tested.

The concretes had a slump of 150±30 mm and an air content of 5.9-7.0%. It was necessary to double or triple the quantity of air-entraining agent used in the mix designs containing zinc stearate as hydrophobic agent. The hydrophobic zinc stearate was added as dirt repelling agent.

The comparative laboratory tests performed were the following:

- Strength development (Compressive strength, splitting tensile strength, Modulus of elasticity)
- Adiabatic heat development
- Frost testing and air void analysis (Borås Method SS137244, DS 481 and ASTM 457-98)
- Chloride penetration testing (NT Build 492, NT Build 443)

1.3 Results of the laboratory testing

The following results were obtained from the comparative laboratory testing as referred in the Report "White Concrete for Aggressive Environment", ref. 1:

1. The ultimate strength of white concretes was similar to that of the reference concretes for both investigated water/powder ratios.

2. The initial strength of white concretes was higher than that of the reference concretes.

3. The initial heat development in white concretes without blast furnace slag was higher than that of the reference concretes.

4. Replacing 30% of Aalborg White cement with blast furnace slag reduced the heat development in relation to concretes based mainly on pure Aalborg White cement.

5. Chloride diffusion coefficients similar to those of the reference concretes were achieved by the addition of 5% silica fume.

6. The addition of zinc stearate did not affect the measured properties significantly.

7. All concretes were frost resistant, with the exception of Mix 10, containing 30% blast furnace slag and had a water/powder ratio of 0.45.

2 Conclusions of the laboratory tests

The evaluation of the durability characteristics of the different concrete mixes with Aalborg White cement is based on tests performed on special samples prepared in the laboratory.

However, the chemical analyses of the cement and the tests performed represent the usual standard methods applied to verify the durability of any concrete mix with respect to their resistance to most of the chemical, physical and biological deterioration mechanisms threatening concrete structures in aggressive environments.

Based on this information the durability of the white concretes tested is fully comparable to the durability of similar high quality grey concrete. The only real weakness found was the frost resistance of the concrete mix with 30% slag blended with the white cement. The water powder ratio is however 0.45, and concrete with slag is often seen to be sensitive to frost exposure at early age.

Short-term tests have been made at this stage and therefore the long-term behaviour cannot be evaluated. This would in particular relate to the aesthetical durability in addition to the effect already included by adding zinc stearate as hydrophobing agent. The cement itself consists of the same clinker components as grey cement and long-term behaviour of the white cement should in principle on this basis not differ significantly to that of the grey cement.

3 Scope of this durability evaluation

The durability of a concrete structure refers to the interaction between the structure and its environment. A highly durable structure can resist for a predetermined long period of time (typically 50 - 100 years) the deleterious actions imposed on it by its foreseen use and the chemical and physical actions from the surrounding environment. As an integral part of ensuring durability a foreseen level of inspection and normal maintenance are often taken into account.

An aggressive environment usually refers to an environment which threatens the concrete structure with one or more of the following deleterious actions:

1. Chemical deterioration of the concrete
   a. alkali-aggregate reactions (AAR)
   b. sulphate attack
   c. acid attack
   d. seawater attack
2. Reinforcement corrosion
   a. carbonation induced corrosion
   b. chloride induced corrosion
3. Physical deterioration of concrete
   a. cracking
   b. frost and de-icing agents
   c. erosion
4. Biological based deterioration

The cement and concrete compositions, supplemented by the laboratory testing performed and summarised in ref. 1, have dealt with the durability of the white concrete itself when exposed in the laboratory to the above deleterious actions.

In connection with the laboratory testing of individual parameters the comparison with the reference concretes from the Great Belt Link and the other comparable grey concretes may be considered valid, as these concretes represent some of the best concretes for which such extensive tests have been made proving resistance to deterioration in an aggressive environment.

4 Evaluation of the durability of Aalborg White concrete

The potentials of Aalborg White concrete to resist the deterioration mechanisms listed in Section 2 above are evaluated in this Section.

4.1 Chemical deterioration of concrete

The tests performed provide the most important classical data on which to evaluate the durability of white cement concrete to chemical deterioration. They show in general that Aalborg White concrete has a resistance against most of these mechanisms which is equal to or better than normal grey cement concretes.

The verification of the resistance to chemical deterioration of concrete is generally based on laboratory testing and without direct verification by testing a finished structure. Even for existing structures with more or less unknown concrete composition such testing will be based on samples (cores) taken from the structure and tested in the laboratory by a combination of petrographic analysis and standard chemical tests.

The documentation available for the Aalborg White concrete test mixes has given the following results:

- The resistance against AAR, as determined by the alkalis in the concrete, is provided through the low contents of totals alkalis in the cement ($\leq 0.2\%$). The remaining protective measure relate to the choice of aggregates.

- The resistance against sulphate attack is provided mainly through the low contents of C_3A, and sustained through the high denseness of the white concrete.

- The resistance against acid attack is comparable to most other high performance concretes, although the low alkali content and the efforts towards reducing the calcium hydroxide content (adding silica fume), to reduce risks of efflorescence, are factors slightly reducing the resistance against acid attacks. This effect is considered compensated through the increased denseness of the white concrete.

- The resistance against seawater attack is an issue not directly covered by the tests made. It comprises a number of aggressive types of dissolved salts (sodium- and magnesium chloride, magnesium- and calcium sulphate, and potassium chloride and -sulphate). Only by testing the concrete under the varying marine exposure conditions (submerged, tidal, splash and atmospheric zones) can the resistance be convincingly determined. However again the adverse effects of seawater attack is considered limited through the increased denseness of the white concrete.

4.2 Reinforcement corrosion

The risk of reinforcement corrosion depends on the alkalinity of concrete. The amount of calcium hydroxide crystals in the paste provides a reserve buffer capacity for the alkalinity. Aalborg White cement is expected to provide increased buffer capacity owing to its high content of C_3S and minor contents of C_3A and C_4AF, enhancing the formation of $Ca(OH)_2$ during hydration.

Any measures leading to a reduction in contents of calcium hydroxide reduce the inherent buffer capacity for corrosion protection of the reinforcement and reduce the resistance of the concrete to withstand carbonation.

Blending Aalborg White cement - as for any other types of cement - with silica fume, fly ash or slag will reduce the pH value somewhat. This will in turn reduce the so-called threshold value for chloride induced corrosion. If, on the other hand the electric resistivity is increased through the blending of the cement or providing a concrete with increased denseness a reduced corrosion rate will take place.

When blending the cement it must therefore be a precondition that the denseness - or penetrability - of the resulting concrete is sufficiently improved to more-than compensate for the reduced inherent corrosion protection through the reduced pH-level. This also means that the risks of cracking of the concrete should be reduced.

The further beneficial effect of blending the cements may be the increased electric resistivity, which usually can be achieved. As mentioned above this will in itself reduce the rate of corrosion once corrosion has initiated, due to the reduced size of cathode, which can be activated.

Finally, an important general comment relates to the effect of cracking in the concrete. The risk of early age cracking should be reduced through appropriate measures during execution and after-treatment. But it is a natural and fully legitimate phenomenon that reinforced concrete cracks during service. Such cracks are mainly due to normal service loading where the tensile strength of the concrete is overcome and the reinforcement is engaged to take over the tensile forces. In addition, concrete shrinks, and for hyper-static structures temperature changes and also shrinkage causes sectional forces that may lead to cracks. These cracks are all so-called load induced cracks or cracks due to imposed deformations. The location of such cracks and their crack widths shall be controlled through an intelligent design and layout of the reinforcement.

4.2.1 Carbonation induced corrosion

Carbonation of concrete is an issue usually being more of concern for ordinary building structures and prefabricated building components than for large infrastructures in aggressive environments.

In general the quality of concrete used for infrastructure constructions have adequate resistance against carbonation due to the relatively low water/binder ratio and the rather large concrete cover.

4.2.2 Chloride induced corrosion

The available laboratory test data have studied the ingress of chlorides in detail, based on two different types of exposure and test methods, the Rapid Chloride Migration test (CTH-Method) and the Bulk Diffusion test with profile grinding. Both test methods are standardised as NordTest methods. For the bulk diffusion test the chloride profiles have been reported as chloride concentration in $\%Cl^-$ by weight of concrete. The CaO content in each layer was measured to monitor the variation of paste concentration over the depth of the specimen. The converted results allow for a direct comparison between different mixes compensating for possible variations in Calciumoxide concentration e.g. as a result of variations in aggregate content.

Within the recognised variations in results obtained for apparent diffusion coefficients, there seem to be fine agreement between the reference concretes and most of the trial mixes for both series of concrete. The only discrepancy is found for the trial mixes made with pure Aalborg White cement, where the apparent diffusion coefficients seem on the high side, 2-3 times higher than the corresponding reference mixes and mixes with both Aalborg White and silica fume. It must however be noted, that if the reference mix was free of silica fume, its diffusion coefficient would be higher too.

5 Physical deterioration of concrete

Physical deterioration of concrete is to a large extent dependent on the concrete strength. It has been convincingly shown, that there are no problems in achieving the necessary strength of the Aalborg White concretes as seen from a load carrying point of view.

5.1 Cracking

Two types of cracks shall be considered, early age cracking (cracking before full strength gain) and cracks during use (load induced cracks and drying shrinkage cracks).

Early age cracking is much influenced by the strain capacity of the concrete at early ages. Therefore, the amount of autogenous shrinkage as well as the heat that develops during initial hydration of the cement is an important issue to have clarified for the different realistic levels of water/binder ratio. For many structures placed in an aggressive environment, cooling pipes or other precautions are required to reduce the heat developed during hardening and hence reducing the risk of cracks formed in the concretes´ early age. The implications of the hydration heat development and provisions against cracks being formed are being evaluated in a separate report.

5.2 Frost and de-icing agents

The available test data have given a clear overview of the frost resistance of the white concretes. For the low water/binder ratio of 0.36 there seems to be no problem for all the mixes tested. This corresponds to the general experience that low water/binder ratio concrete with air entrainment does not pose any frost problems, even for the very severe Swedish Borås test method.

For the high water/binder ratio of 0.45 the mix with Aalborg White blended with 30% slag shows inadequate frost resistance in these early age tests. This corresponds to the experience, that slag cement concrete has reduced frost resistance if a low water/binder ratio has not been ensured in the final structure.

For the high water/binder ratio there also seems to be a beneficial effect of adding the hydrophobic admixture in the form of zinc stearate.

An interesting observation - as seen in many other cases - is that some mixes that passed the physical test method failed in the classical testing based on specific surface and spacing factor. For the samples with high water/binder ratio and the cement blended with slag the situation was just the opposite; they passed the specific surface and spacing factor but not the physical test.

5.3 Erosion and abrasion

Erosion and abrasion resistance of concrete is generally closely linked to the concrete strength and this does not seem to indicate any special problems.

5.4 Biological based deterioration

Such deterioration is generally transformed to either a physical deterioration caused by vegetation or roots growing into the concrete member or expanding in joints, or as chemical deterioration caused by bacteria developing typically an acid environment such as the sulphide reducing anaerobic bacteria in sewers developing sulphuric acid which dissolves the concrete.

Such types of deterioration do not seem to indicate any special problems for white concrete compared to the reference grey concrete.

6 References

1. ref. 1:White Concrete for Aggressive Environment, Aalborg Portland, September 2003.