WHITE CEMENT CONCRETE FOR CONSTRUCTIONS IN AGGRESSIVE ENVIRONMENTS

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ABSTRACT

The White Portland cement (WPC) studied is characterised by high strength and low alkali, low C_3A and low Fe_2O_3 content. Owing to such properties, concrete with high resistance to alkali-silica reactions and sulphate attack can be produced. When cured under the same conditions, fully hydrated WPC concrete results in a low capillary porosity compared to grey cement concrete commonly used in aggressive environments; the dense matrix of WPC concrete provide good resistance to chloride penetration and increases the chloride binding by the C-S-H phase. Experimental results confirm that WPC can be used to produce concrete being at least as durable as the grey High Performance concretes used in the Danish "Great Belt Link" and "Øresund Link" infrastructure projects. This paper describes the ideas behind using WPC in aggressive environments; experimental results confirming the strength and durability of WPC are presented and WPC concrete in relation to aesthetic and traffic safety is discussed.

Keywords: White Portland Cement, Aggressive environment, Durability, Freeze-thaw resistance, Chloride penetration, Aesthetic, Traffic safety.

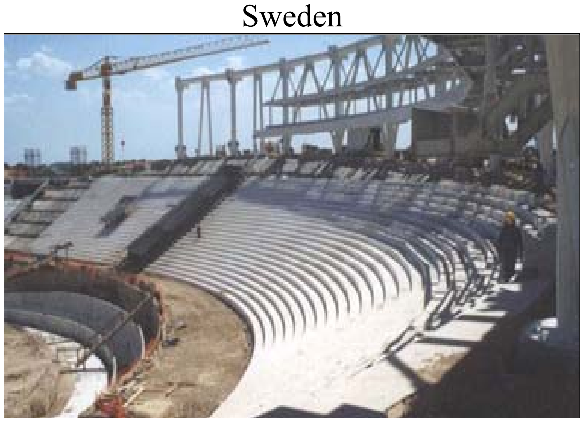
INTRODUCTION

White Portland cement (WPC) concrete today like grey concrete has many construction applications, e.g. in architectural facade elements and surface coverings, though white concrete is only used to a very limited extent for construction elements that are subjected to aggressive environments. There is, however, increasing interest world-wide in using white concrete in aggressive environments, for example in bridge construction, providing architectural freedom, and for infrastructure traffic safety elements e.g. bridge parapets.

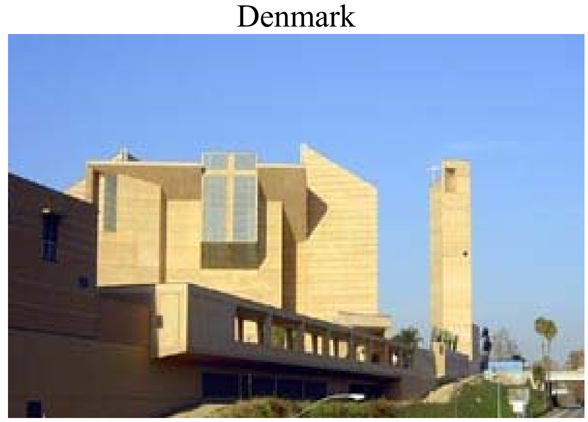
In Fig. 1 examples of structures made by WPC concrete from around the world are shown, giving an impression of how the material can be used for making white or coloured structures.

Arlanda Airport (control tower), Sweden

Holstebro Court, Denmark



Stadio de La Plata, La Plata, Argentina



Our Lady of the Angels (Cathedral), Los Angeles, USA

Fig. 1 Examples of the usage of white cement concrete.

The usage of WPC in concrete for constructions in aggressive environments is obvious owing to its superior properties in respect to strength and durability. A barrier hindering the use of white cement concrete in such environments is the perception among many decision-makers, that white concrete is less durable than grey concrete. However, the chemical composition of WPC is ideally suited for the production of high strength - high performance concrete with the added feature durability. To demonstrate the strength and durability of WPC a large experimental study was conducted at the Research and Development Centre (RDC) at Aalborg Portland, Denmark.

This paper presents the experimental results confirming the presumption that WPC can be used for high-performance concrete to be placed in aggressive environments. Aesthetics issues and parameters to consider when making and casting WPC concrete are discussed. The use of WPC concrete to improve traffic safety is described at the end of the paper.

BACKGROUND

White Portland cement clinker is characterised by having a much lower iron content compared to other cement clinker, and is therefore harder to burn[3]. Since iron forms high density, low volume FH_3 phase, a lower iron content results in a higher relative volume of the hydrate phases and thereby a lower capillary porosity. Lower porosity again results in higher strength and lower permeability. Recent studies[1] confirms that some of the iron is incorporated in the C-S-H structure and reduce its chloride binding capacity. The chloride binding capacity of the C-S-H phase in WPC is therefore higher compared to ordinary Portland cement (OPC).

The WPC used in these studies, see Table 2, is also characterised by low alkali and low C_3A content. Using these properties, concrete's with high resistance to alkali-silica reactions (ASR) and sulphate attack can be produced. Furthermore the low alkali content of this cement used, results in a higher chloride binding at any total chloride content[1].

It is thus expected that concrete structures built with low-alkali Portland cements, with low C_3A content and low iron content (i.e. white Portland cements), will result in a longer service life compared to structures made by comparable low-alkali sulphate resistant cement. This is of major interest when making structures subjected to a chloride and sulphate-containing environment.

The advantages and disadvantages, in relation to concrete durability, of the WPC used in these studies are summarised in Table 1.

Table 1 Properties of the WPC used compared to OPC.

	Advantage **(+)**	**Disadvantage** **(-)**
Low alkali	• Reduced risk of ASR	
Low Al_2O_3	• Increased resistance against sulphate attack	• Lower chloride binding by alumina phases
Low Fe_2O_3	• Relatively lower capillary porosity • Higher chloride binding in the C-S-H phase	• Harder to burn

Together with the possibility of making concrete with a very high ultimate strength and a rapid strength development, white cement is ideal for making durable high performance concrete with the added architectural freedom of colour. The experimental study described in this paper confirms that WPC can be used for high performance and highly durable concrete. It is shown that WPC concretes are *at least as durable* as the grey high performance concretes used in the Danish “Great Belt Link”, see Fig. 2, and “Øresund Link” projects, both among the largest bridge construction projects in the world. The concrete used in these two infrastructure projects were based on “Low-Alkaline Sulphate Resistant Portland Cement” (LASRC), ASTM type-V; major studies were carried out to ensure the durability and performance of these concretes and are today still considered as being "state-of -the-art" high performance concretes.

Fig. 2 Great Belt Link (free span of 5328 ft. (1624 m)), Denmark.

EXPERIMENTAL

The composition of the two cements used for concretes examined in the experiments, respectively a WPC ASTM-type V and a Low-Alkaline Sulphate Resistant Cement (LASRC) ASTM-type V, are shown in Table 2.

Table 2 Properties of cements examined (more information on www.aalborg-portland.dk).

Id.	ASTM-type	Corrected Bogue composition						Na_2O_{eq}
		C_3S	C_2S	C_3A	C_4AF	$CaSO_4$	Lime	
WPC	V (white)	64.9	22.4	4.5	1.0	3.6	2.15	0.23
LASRC	V (grey)	52.8	29.8	3.9	7.0	3.5	1.24	0.39

The strength development of the cements examined is shown in Table 3. Measurements were carried out on mortar cylinders according to EN-196.

Table 3 Strength development of cements examined according to EN-196, psi.

	1 day	2 days	7 days	28 days
WPC	2640 (18.2 MPa)	4470 (30.8 MPa)	7590 (52.3 MPa)	10390 (71.6 MPa)
LASRC	1320 (9.1 MPa)	2520 (17.4 MPa)	5110 (35.2 MPa)	8300 (57.2 MPa)

CONCRETE MIX DESIGN

To prove the durability of WPC, 16 different concretes were prepared in two groups, having water-powder ratios of respectively 0.36 and 0.45. In the following, only concretes with water-powder ratios of 0.36 are considered. The powder combinations and designations of the concretes investigated are shown in Table 4. The WPC concretes are designated Mix 1, Mix 2, Mix 3, Mix 4 and Mix 5, and the reference concrete Ref. 1; the reference concrete having a mix design similar to the concrete used for the "Great Belt Link" connection, as mentioned before.

For all concretes the weight-percentage of aggregate was 38% pit sand 0/2 class E, 13% crushed granite 2/8 class E and 49% marine rubble 8/16 class, A; aggregate classes according to Danish standard (A: applicable for aggressive environment; E: applicable for extra aggressive environment). The fractions of paste volume, aggregate skeleton and water content was held constant. Plasticiser and super-plasticicer were used to adjust workability to achieve a target slump of 6 in. (150 mm). The target air-content was 6%.

In Mix 3 and Mix 4 zinc stearate, a hydrophobic agent, was added as an extra powder because of its dirt repelling properties. It was however necessary to double or triple the quantity of air-entraining agent in the mixes containing zinc stearate; later production experiments showed that calcium sterate was easier to use and did not influence the air content.

Table 4 Concrete mix design.

		Ref. A	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
LASRC	%	80					
WPC	%		95	100	95	100	70
Fly Ash	%	15					
White Silica Fume	%		5		5		
Silica Fume	%	5					
White Blast furnace slag	%						30
Zinc stearate	lb/yd^3				3.4 (2 kg/m^3)	3.4 (2 kg/m^3)	
Total Powder content	lb/yd^3	659 (391 kg/m^3)					
Water content	lb/yd^3	236 (140 kg/m^3)					
Plasticicer	% of powder weight	0.5					
Super- plasticicer	% of powder weight	0.5-0.8					
Sand (0-2 mm)	lb/yd^3	1127 (669 kg/m^3)					
Stone (2-8 mm)	lb/yd^3	386 (229 kg/m^3)					
Stone (8-16 mm)	lb/yd^3	1455 (863 kg/m^3)					

INVESTIGATIONS

The studies were carried out from August 2001 to March 2003. The following parameters were investigated:

- **Fresh concrete properties** (air content, slump, density).
- **Strength properties** (compressive strength, tensile strength, E-modulus).
  The strength properties were measured on 3.94 in. x 7.87 in. (100 mm x 200 mm) cylinders according to DS 423.23 (Danish Standard). Compressive strength was measured after 1, 2, 7, 14, 28, 90 and 365 days of maturity (equivalent at 68°F (20°C)). Splitting tensile strength and E-modulus were measured only on Ref. 1, Mix1, Mix 2 and Mix 3, after 1, 2, 7, 14 and 28 days of maturity.
- **Freeze/thaw resistance** (according to SS137244 - Swedish Standard)
  - Concrete discs of 5.91 in. in diameter were mounted in a rubber ring and insulated with polystyrene. A 3% NaCl solution was poured onto the free concrete surface before subjecting the sample to frost-thaw cycles between -4°F and +68°F (-20°C - 20°C). The amount of material scaled from the surface was weighed after 7, 14, 28, 42 and 56 cycles. According to SS137244 the evaluation was based on the criteria shown in Table 5:

Table 5 SS137244 evaluation criterias, lb/ft^2 (SI: kg/m^2)

Frost resistance	Requirements
Very good	Average scaling after 56 cycles < 0.02 lb/ft^2 (0.1 kg/m^2)
Good	Average scaling after 56 cycles < 0.04 lb/ft^2 (0.2 kg/m^2) or Average scaling (AS) after 56 cycles < 0.1 lb/ft^2 (0.5 kg/m^2) and $AS_{56}/AS_{28} < 2$
Acceptable	Average scaling (AS) after 56 cycles < 0.2 lb/ft^2 (1.0 kg/m^2) and $AS_{56}/AS_{28} < 2$
Unacceptable	The above requirement are not met

- **Heat development** (adiabatic).
- **Chloride ingress** (according to NT-Build 492 and NT-Build 443 - Nordic Test Methods).
  - NT BUILD 492 (known as the CTH method) describes a method for determining chloride diffusion coefficient of concrete at a given maturity. Concrete discs are lined with rubber and placed in an experimental set-up where one end is in contact with an anolyte (0.3 mol NaOH) and the other in contact with a catolyte (10% NaCl in 0.1 mol NaOH solution). By applying a potential of typically 30V across the disc for 24 hours, chloride ions are driven through the concrete. The penetration depth is subsequently measured and the chloride diffusion coefficient is calculated. Chosen limits when evaluating the degree of chloride resistance is shown in Table 6.

Table 6 Chosen limits for evaluating the degree of chloride penetration using NT BUILD 492, m^2/s.

Diffusion coefficient	Resistance to chloride penetration
$< 2 \times 10^{-12}$ m^2/s	Very good
$2 – 8 \times 10^{-12}$ m^2/s	Good
$8 - 16 \times 10^{-12}$ m^2/s	Acceptable
$> 16 \times 10^{-12}$ m^2/s	Unacceptable

- NT BUILD 443 describe an accelerated method for determining chloride diffusion profiles in concrete at a given exposure time. Chloride diffusion coefficients and surface chloride concentration can be determined from these profiles. Samples are cast in 7.9 x 7.9 x 7.9 in. (20 x 20 x 20 cm) blocks and allowed to cure for 28 days at 68°F (20°C). The blocks are then halved and immersed into a 16.5% NaCl solution for respectively 35 and 180 days. After exposure, a 2.95 in. (75 mm) hole is ground into the cut surface; the hole is ground in steps of 0.04-0.08 in. (1-2 mm) into a depth of about 0.55 in. (14 mm). Ground material from each layer is vacuumed and stored in plastic bags. The material is analysed for Cl and CaO contents after which the chloride profile can be constructed; by measuring the CaO content in each layer, any variation in paste concentration can be disregarded. The chloride diffusion coefficient is calculated from the measured chloride profile using non-linear regression to Fick´s second law of diffusion.

RESULTS

COMPRESSIVE STRENGTH

The compressive strength development to 365 days of maturity is shown in Fig. 3. The WPC based concretes show rapid strength development in the early age, compared to the LASRC based concrete; the 2 day strength of the white concretes, except from Mix 5 which contain 30% slag, is higher than the 7 day strength of the reference concrete. The 365-day strength of the white concretes, except from Mix 5, is at the same level as for the reference concrete.

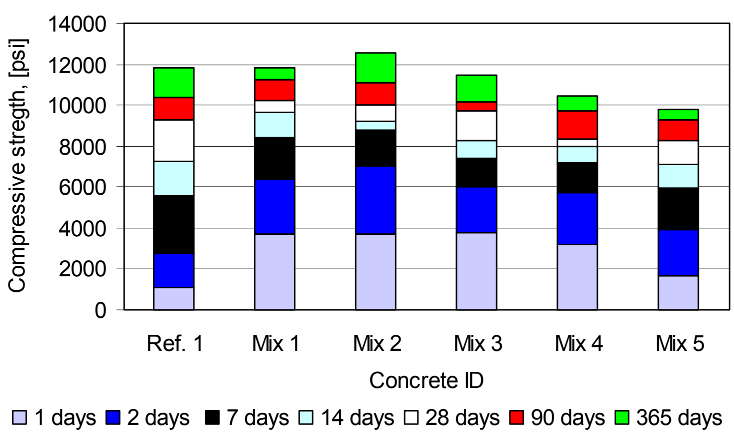


Fig. 3 Compressive strength development.

The addition of zinc stearate for Mix 3 and Mix 4, has only a minor influence on the strength development.

SPLITTING TENSILE STRENGTH

The splitting tensile strength development, measured on concrete cylinders, is shown in Fig 4. The early strength of the WPC concretes are considerably higher than for the reference concrete. After 2 days, the splitting tensile strength of WPC-based concretes was similar to that of the reference concrete at 7 days. After 14 days the splitting tensile strength of the concretes was similar.

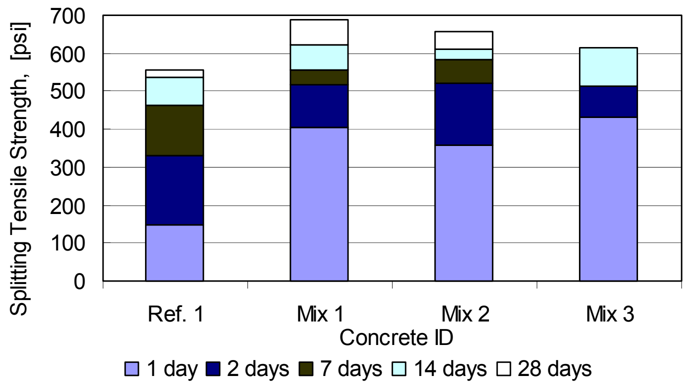


Fig. 4 Splitting tensile strength.

ELASTICITY MODULE

The development of elasticity module is shown in Fig 5. As for the development of splitting tensile strength, the elasticity module shows high initial values compared to the reference concrete. The 2-day modulus of elasticity for the WPC-based concretes was similar to that of the reference concretes after 7 days. After 14 days the modulus of elasticity was similar.

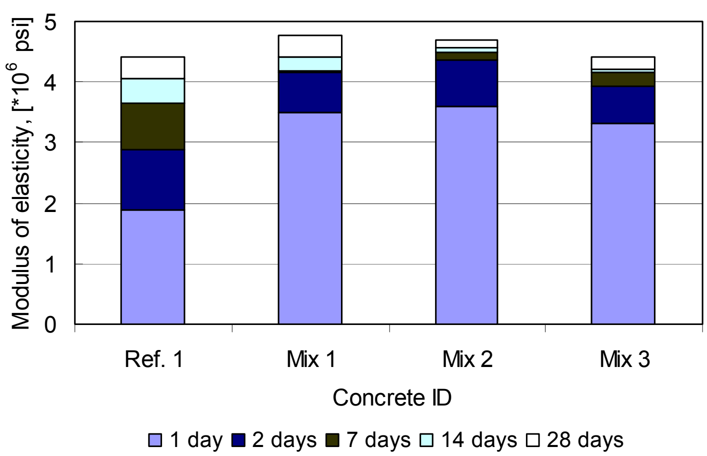


Fig. 5 Development of elasticity module.

HEAT DEVELOPMENT

Heat development was measured using Adiabatic calorimetry, and the *Freiesleben* model[2] was fitted to the results using non-linear regression, see equation (1):

$$Q(M) = Q_\infty \cdot \exp\left[-\left(\frac{\tau_e}{M}\right)^\alpha\right] \tag{1}$$

where Q(M) is the heat developed (cal/g powder (SI: kJ/kg powder)) at maturity M (h), Q_∞ is the final heat developed, τ_∞ is a characteristic time constant (h), and α is a curvature parameter (-). The principle of this model is described in ASTM C 1074-98.

The adiabatic heat developments are shown in Fig. 6 and the corresponding property parameters are listed in Table 7.

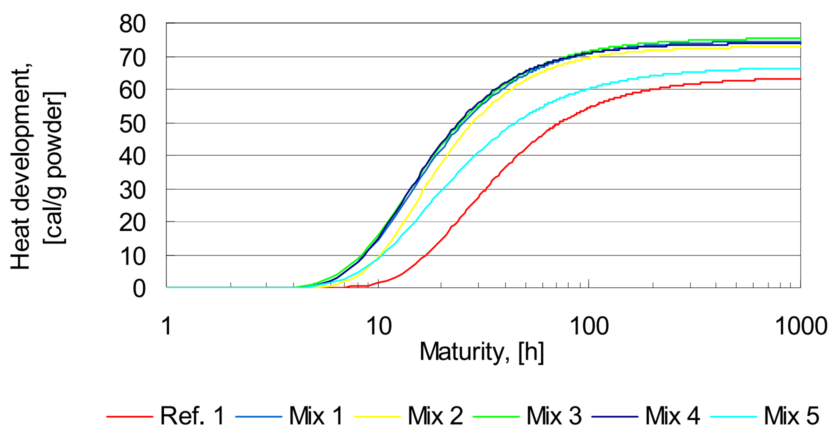


Fig. 6 Adiabatic heat development.

Table 7 Property parameters describing adiabatic heat development.

	Ref. 1	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Q_∞ (cal/g powder)	63.6	74.6	72.8	75.5	73.9	66.7
τ_e, (h)	26.5	13.9	15.6	13.5	13.4	17.3
α, (-)	1.39	1.49	1.63	1.45	1.58	1.29

The WPC-based concretes develop more heat than Ref 1. This is most pronounced in the early age, and can be seen on the fitted parameter τ_e, which is almost twice as high for Ref. 1 as for the WPC-based concretes. The final heat development for the white concretes is higher than for Ref. 1. Replacing 30% of the cement with slag (Mix 5) reduced the final heat development by some 8 cal/g powder.

The high development of heat can be opposed by several initiatives if necessary: cold concrete, cooling pipes (which often have to be used anyway in large constructions), retarding the concrete chemically, etc.

FREEZE - THAW TESTING

In Fig. 7 the results of frost resistance tests, according to SS137244, are shown. All concretes can be classified as having a *very good* frost resistance according to Table 5. This confirms that concrete having a low water/powder-ratio is not vulnerable to frost action.

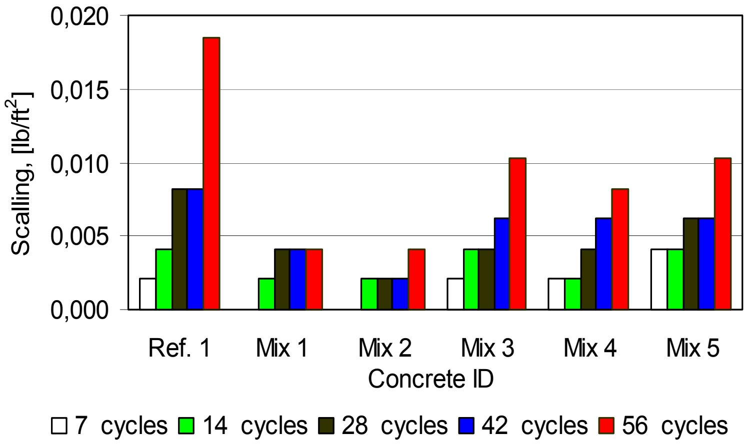


Fig. 7 Freeze-thaw resistance after SS137244.

CHLORIDE TESTING

In Fig. 8 effective chloride diffusion coefficients determined from measured chloride profiles are shown; the concretes were exposed at a maturity of 28 days and examined after respectively 35 and 180 days of exposure. The diffusion coefficients of the concretes based on WPC and 5 % micro-silica (Mix 1 and Mix 3) are comparable to those of the reference concrete (Ref. 1). When no silica fume is used (Mix 2 and Mix 4) the diffusion coefficient is considerably higher than for the reference concrete. The diffusion coefficient of Ref. 1 is expected to be at the same level as Mix 3 if no silica-fume had been used.

The addition of zinc stearate (Mix 3 and mix 4) had only a minor effect on the ingress of chlorides.

When adding 30% slag (Mix 5), the diffusion coefficient became lower than the concrete made of WPC (Mix 2) but higher than that of Ref. 1.

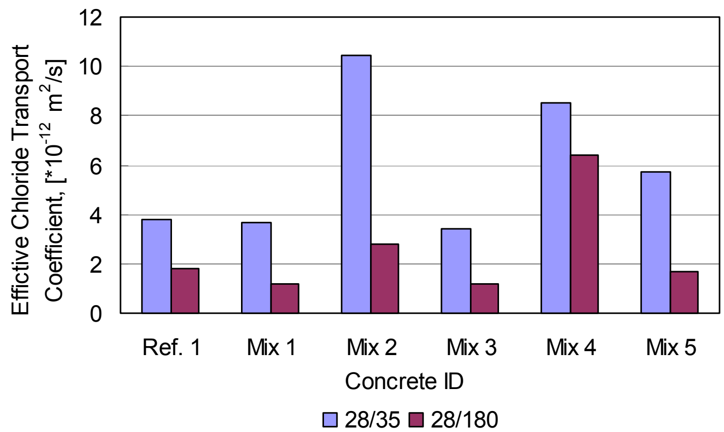


Fig. 8 Effective chloride diffusion coefficient measured by profile grinding.

In Fig. 9 results from CTH measurements are shown; the measurements were carried out on all the examined concretes after 28 days maturity and for some concretes after 56 and 180 days. The results are comparable to those shown in Fig 8, just scaled up, wherefore the conclusions are the same.

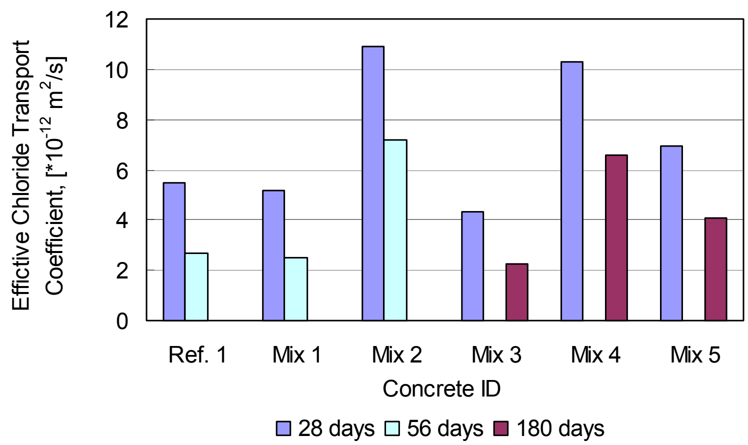


Fig. 9 Effective chloride diffusion coefficient measured by the CTH method.

Summarising the results from the two chloride tests, it can be concluded that chloride diffusion coefficients similar to that of the reference concrete can be achieved by addition of 5 % silica fume. The experiments also points to the conclusion that WPC has the same properties as LASRC concerning resistance towards chloride ingress.

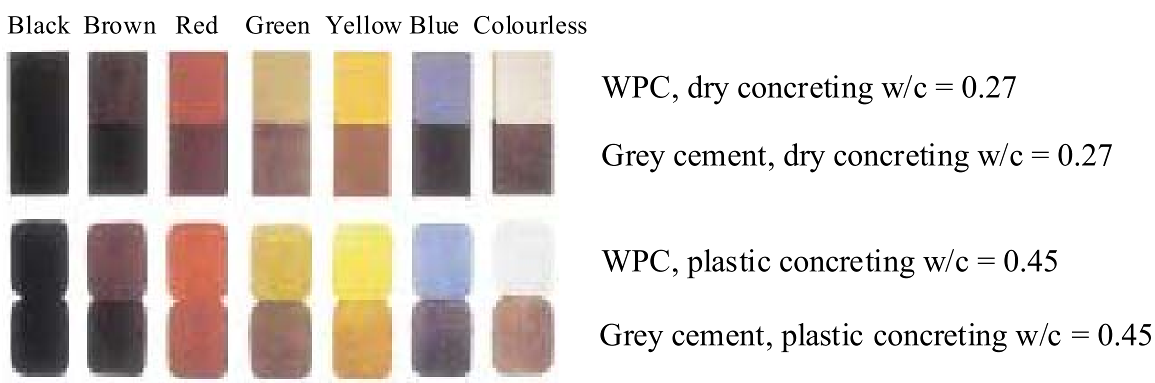
AESTHETICS

From an aesthetic point of view WPC concrete contribute with the freedom of colour providing both the architect and the owner of the structure a choice. Thus the perception among many people that concrete is boring and drab to look at, might be changed.

The high purity of the chalk used to make white cement results in a clear bright appearance of the final concrete product. This bright appearance provides the architect with the option of making structures that speak for themselves with natural and environmentally friendly surfaces without the need of special surface treatment (e.g. paint).

Coloured concretes can be made by addition of synthetically produced inorganic pigments, which most often are limeproof, alkali-resistant, weather resistant and non-fading. By choosing aggregate with the same properties as the pigments, various expressions can be made, and only imagination sets the limit.

When producing white or light coloured WPC concrete special care has to be taken compared to ordinary grey cement concrete. Details in the surface appears more clear, which is why the entire operation including mixing, casting, and controlling the hardening process must be followed closely. To get the best out of WPC as a material it is necessary to gain knowledge and experience before starting out large construction projects; it is not sufficient to just replace the grey OPC with WPC in the production process if success has to be obtained. When this is said, companies around the world are capable of making and handling WPC concrete with great success, without more effort than making grey OPC concrete. Some factors influencing the final expression of the white concrete surface are: concrete mix design, mixing procedure, handling, form work, hardening process, design, etc. As an example it is shown in the figure below that the shades of coloured concrete not only depends on the cement used, but is also influenced by the water/cement ratio.



TRAFFIC SAFETY

From a traffic safety aspect WPC concrete is favourable. Traffic light is reflected much better on a white surface compared to a grey. Especially when the concrete surface is wet white concrete reflects the light considerably better than a grey surface, see Fig. 10. Thus, in areas with sparse light, e.g. in tunnels, at night or in rainy conditions, white concrete can be used to improve traffic safety. In Fig. 10 different examples of the use of WPC concrete for traffic elements are shown.

As maintenance is an often overlooked topic in new structures, painted concrete traffic elements can profitably be replaced by WPC concrete, since no repainting has to be carried out. An example of a painted grey OPC concrete road barrier is shown in Fig. 10; this well-known look could be changed using WPC concrete.

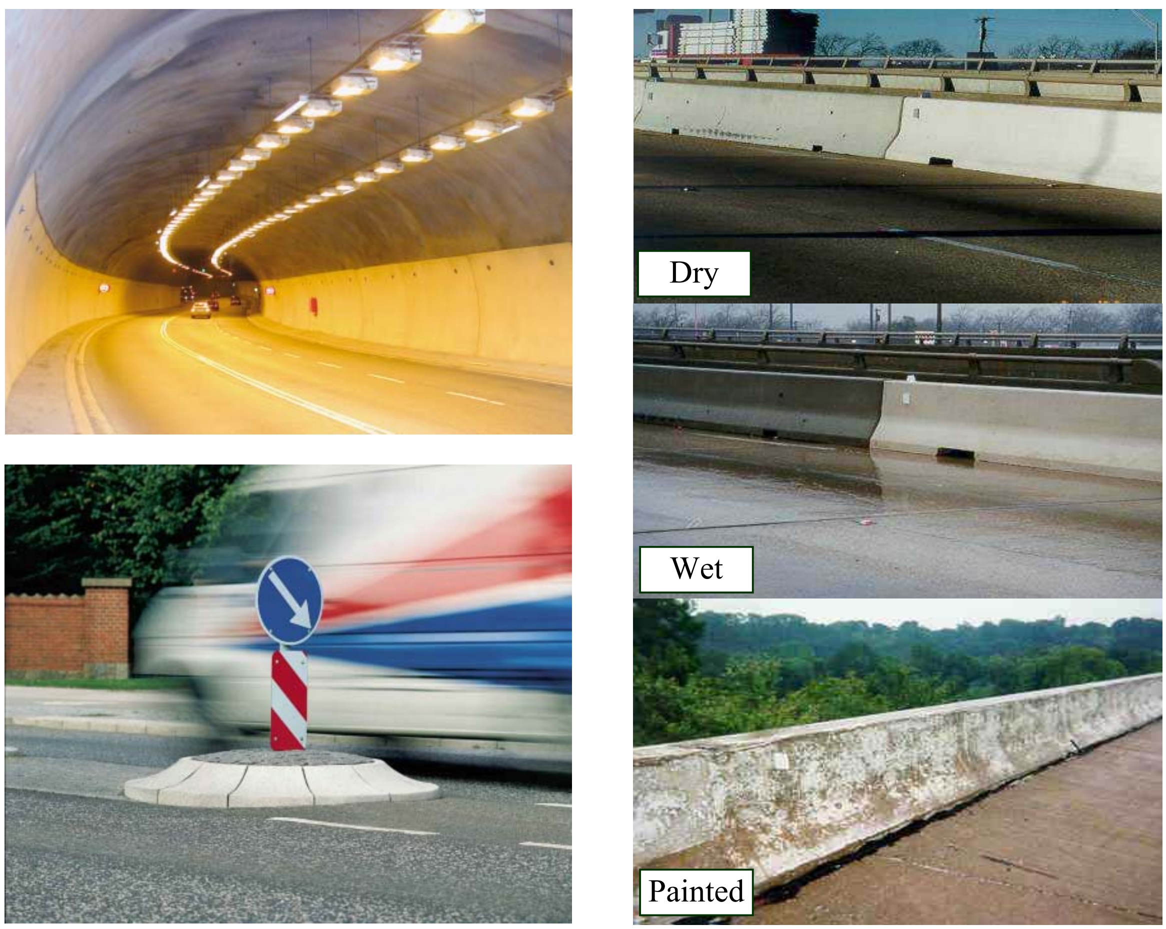


Fig. 10 Above left: Tunnel lined with white concrete, Norway.
Below left: Refuge, Denmark.
Above and middle right: White concrete road barriers in respectively a dry and a wet condition, USA.
Below right: Painted grey concrete road barrier, USA

CONCLUSION

The following conclusions are based on the experimental survey described in this paper:

1. The 365-day strength of WPC concrete was similar to that of the reference concrete.

2. The initial strength of WPC concrete was higher than that of the reference concrete.

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

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

5. Chloride diffusion coefficients similar to those of the reference concrete 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.

The overall conclusion from the experimental tests is, that concrete based on WPC and silica fume has at least as good properties in respect to strength and durability as concrete normally used in construction placed in aggressive environments (where normally silica fume or a mixture of silica fume and fly ash is used).

WPC concrete provides increased architectural freedom in relation to colour, and traffic safety can be improved compared to that given by ordinary grey cement concrete.

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