

Aesthetic durability of white concrete structures



Synopsis

This report contains guidelines on how to obtain aesthetically durable white concrete structures.

Aesthetic durability of white concrete is, for the purpose of this report, defined as »the combination of design, concrete composition and surface texture that, under a given combination of environmental loads and maintenance, creates a desired expression throughout the service life of a given structure«.

The report is based on a combination of literature, field observations and experimental investigations: the guidelines for design and maintenance are based solely on literature and field observations, whereas the guidelines for concrete composition and execution also include results from experimental investigations carried out at the **AALBORG WHITE®** Research and Development Centre (RDC).

The primary message of the report is that aesthetic durability does not mean that surfaces should remain unstained or unaltered for all time, but rather that the development of the expression should be expected, desired - even necessary - to obtain the visual effect originally intended.

The development of a continuously desirable expression is aided by taking the aspects described in this report into consideration through all phases of the design, construction and service life of a structure.

Aalborg Portland, September 2004.

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1

Introduction

The use of concrete is to some extent limited by the fact that some architects and other specifiers of building materials for structures are dubious about its aesthetic durability. This is particularly true for concrete produced from white cement. Even though an architect may desire the surface texture and colour of a white-cement-based product (in the following simply called »white concrete«), he or she may choose an alternative solution owing to a lack of confidence in the long-term aesthetic durability of white concrete.

White concrete is more sensitive to aesthetic durability. One reason is that dirt particles and growths are more visible against a light background than on the darker surface of concrete produced from grey cement. To ensure a satisfactory result, it is therefore even more important to address the aesthetic dimension properly for white concrete than it is for grey, especially in areas with a predominantly damp climate.

This realisation is paramount for the appropriate application of white concrete but is nevertheless often forgotten, as made evident by the number of aesthetically inferior constructions in countries with damp atmospheric conditions. This despite the fact that several guidelines dealing with the aspects of aesthetic durability are available, and have been so for at least 30 years [1..11,13..15,17..20,22,23,26..34].

The result is that white concrete structures with poor aesthetic durability may appear to be the rule rather than the exception, particularly in damp regions, and consequently some potential users may refrain from using these materials.

It is important to understand that weathering of and changes in the aesthetic appearance of a building are inevitable, and that the aim for any structure should be to achieve graceful and aesthetically pleasing ageing, regardless of environmental conditions [1,2,5,26].

*Courthouse in Holstebro,
Denmark*



Introduction



■ 1.1 Contents

This document contains a summary of some of the guidelines available in the aforementioned references, as well as results from experimental work, see section 1.2. The guidelines are divided into four sections:

- ▀ Design guidelines
- ▀ Guidelines for concrete composition
- ▀ Execution guidelines
- ▀ Maintenance guidelines.

These areas are interrelated, of course, and decisions regarding one will affect the number of feasible choices in the others. However, to maintain a structured approach, each area will be dealt with in separate sections of this document. Specific dependencies will be demonstrated through the examples and in the summary.

The detail and depth of each section will vary, as the depth of the available literature and experimental results covering the sections is not consistent.

In all four sections examples and illustrations are used where possible to demonstrate the effect of the recommendations compared with situations where the recommendations have not been followed. Also, actual tolerances (recommended limits) of variation for specific variables will be given, where known.

The present collection of guidelines is intended to be an aid in the design, production and maintenance of in-situ cast concrete structures and pre-cast concrete elements, but the contents may be valuable for other applications of white-cement applications as well.

Introduction

■ 1.2 Experimental work

To determine the best way of producing aesthetically durable concrete surfaces, several major experimental programmes have been carried out at **AALBORG WHITE®** Research and Development Centre, or RDC. These programmes have focused mainly on the significance of concrete composition, execution and post casting treatment.

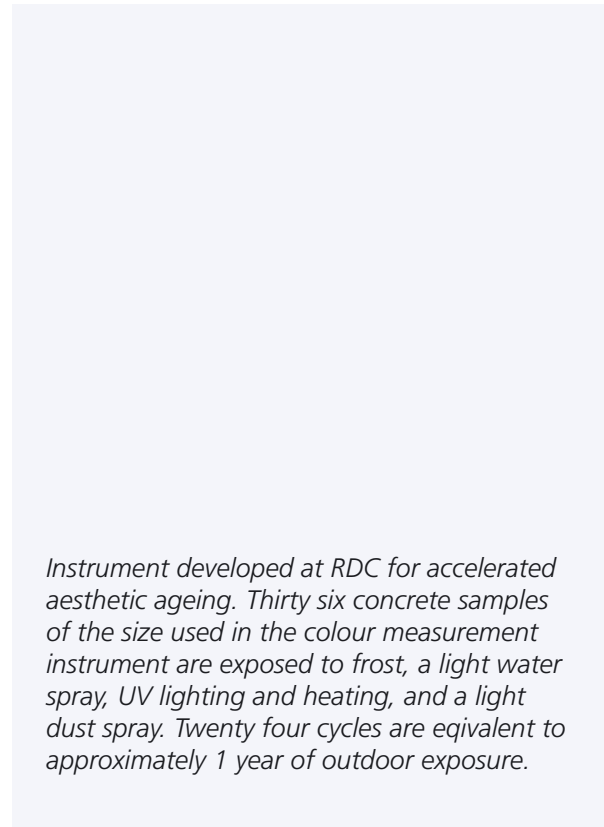
The work includes measuring the impact of variations in concrete composition on initial surface colour [12] as well as outdoor and accelerated exposure testing.

For all these investigations samples were colour-measured to obtain an objective and reliable evaluation of the effect of variations in composition or different responses to exposure. Results are shown as Hunter L values, which indicate reflectance: 100% is pure white, 0% is black.

The results from these investigations are used both to exemplify the guidelines given in the literature, and to provide actual limits for acceptable variations and other directly applicable information.



Instrument specifically developed at RDC for the aesthetic evaluation of concrete. The surface colour of 25×35×7 cm concrete tiles is measured at 96 points and the mean used for evaluation.



Instrument developed at RDC for accelerated aesthetic ageing. Thirty six concrete samples of the size used in the colour measurement instrument are exposed to frost, a light water spray, UV lighting and heating, and a light dust spray. Twenty four cycles are equivalent to approximately 1 year of outdoor exposure.



2

Design guidelines

There are three levels in the design of a structure that all interrelate, but can nevertheless be described separately [5]:

- ▀ General shape and placement of the structure - relates to local wind patterns, shading from other buildings or vegetation, etc.
- ▀ Detailing - relates to localised run-off patterns for rainwater, staining from other materials, etc. Includes the engineering design (shape, location of construction joints, etc.)
- ▀ Surface texture - relates to the inherent ability of the surface to conceal minor colour variations, or lack thereof, permeability, etc.



■ 2.1 General shape

Overall shape is decisive for the impression created by the building from a distant viewing position ~ 50 metres plus.

The overall shape and orientation of any structure influence how different parts are affected by the weather patterns in the particular location where it is situated, under the influence of nearby structures, vegetation, topographical features and the direction of the prevailing wind [5].

This means that the concrete surfaces are subjected to unevenly distributed amounts of water, sun, airborne particles, etc., for the entire duration of the structure's service life [7].

For tall buildings the environmental load on the upper part of the building will be very different from that on the lower parts. A high-rise building in an urban environment is exposed to traffic-generated particles at its base and much cleaner air (and more water) at its top [2,5].

In consequence, regardless of whether it is desired that a uniform expression should be maintained for all areas of a structure or the natural patina of ageing is preferred, it is necessary to:

- A. Create a building shape that takes local conditions into account.
- B. And/or create details to obscure or emphasise the boundaries between differently affected areas.
- C. And/or select a surface texture that ages evenly regardless of the differential climatic loading.

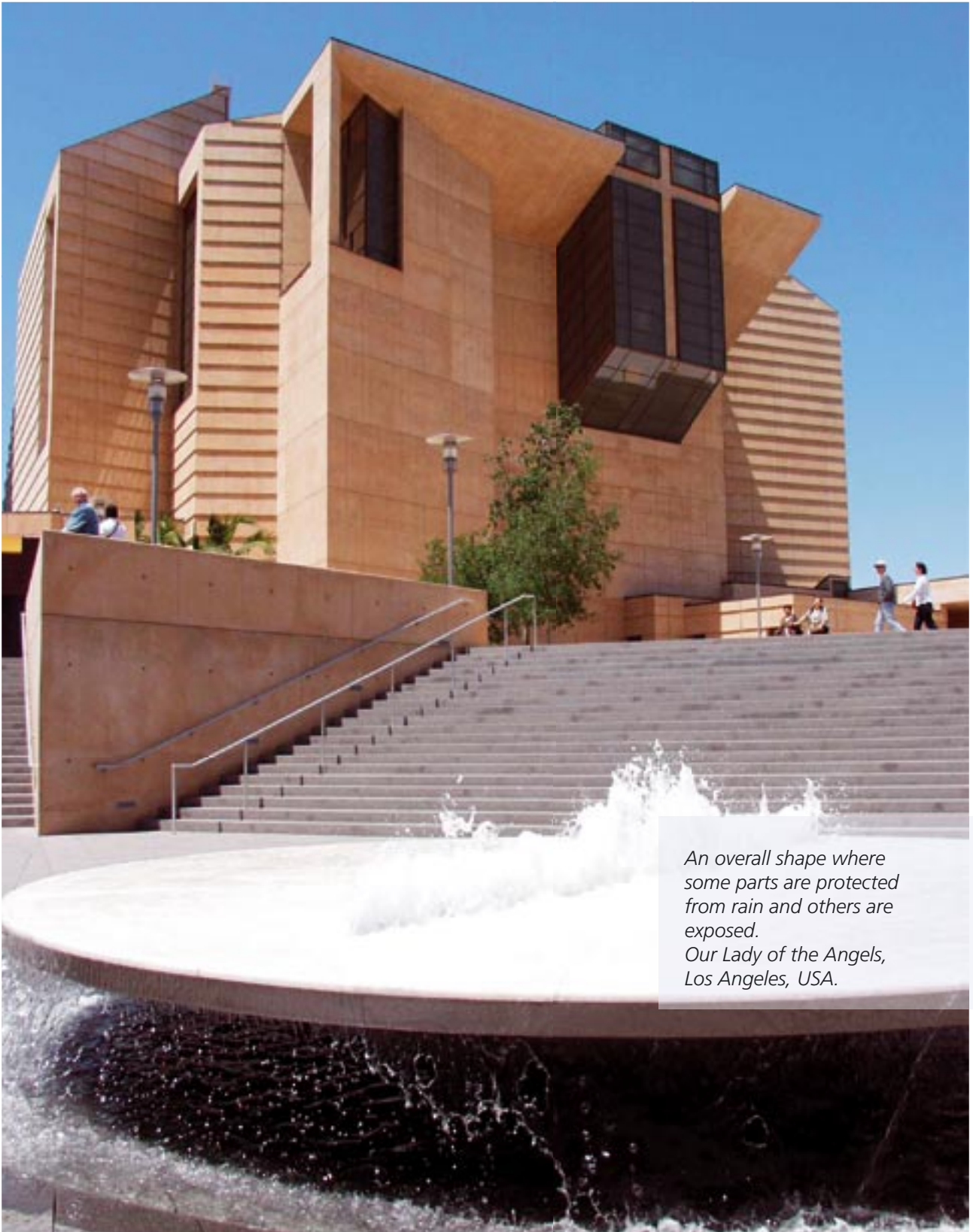
It is not possible - or even desirable - to give general guidelines for option A, but for options B and C please refer to sections 2.2 and 2.3.

*Arlanda control tower, Stockholm, Sweden.
Image by courtesy of Cementa.*



AALBORG WHITE®

Design guidelines



*An overall shape where some parts are protected from rain and others are exposed.
Our Lady of the Angels,
Los Angeles, USA.*



Design guidelines

■ 2.2 Detailing

Detailing is decisive for the impression created by a building from an intermediate position ~ 10 to 50 metres.

There are two major objectives when designing details for a concrete structure:

- ▀ Obtaining the desired architectural expression, style and function (in terms of both practical function, such as supporting other parts of the structure, providing shelter, etc, and other functions such as how it feels and is generally experienced).
- ▀ Removing water or distributing it in a desirable way on the surfaces.

These equally important objectives may or may not impose opposing demands on the design.

Viewing distance should be considered when choosing details, since very small details are a waste of resources if the observer will be too far away to distinguish them. Similarly, large details are impossible to see in their entirety, if the observer will be very close to the structure [19].



Hyatt Tower, Chicago, Illinois, USA, and surrounding structures.



Design guidelines



One solution for removing water is to incorporate the necessary details into the design elements used to create the architectural expression, another to hide the water removal features so that they do not interfere with the features creating the desired architectural expression [5,7].

Concealed systems using drainage tubes however may become blocked and so cease to function as intended [7].

Another method is to use water flow to accentuate architectural features by ensuring that dirt is deposited in places where it enhances design features rather than obscuring them [7].

It is especially important to consider the removal of dirt and water from roofs carefully [2,5]. A lot of dirt accumulates on roofs in dry periods and is washed down when it rains [2].

One way of handling this dirt is by using eaves, or metal sills to protect the top of the facades [5,7]. Another option is to ensure that the dirty water does not leave the roof by preventing it from running off and collecting it in gutlets [2].

Profiled form liners facilitate the creation of patterned or profiled surfaces. These liners are normally made of plastic, polyurethane or foamed polyurethane. The quality of finish and the number of times these liners can be used vary [19,24].

Detailing, surface texture and concrete composition interrelates - if the design details require a porous surface in order to obtain the desired effects by absorbing of water and dirt in certain locations, the surface texture and concrete composition must promote this behaviour.

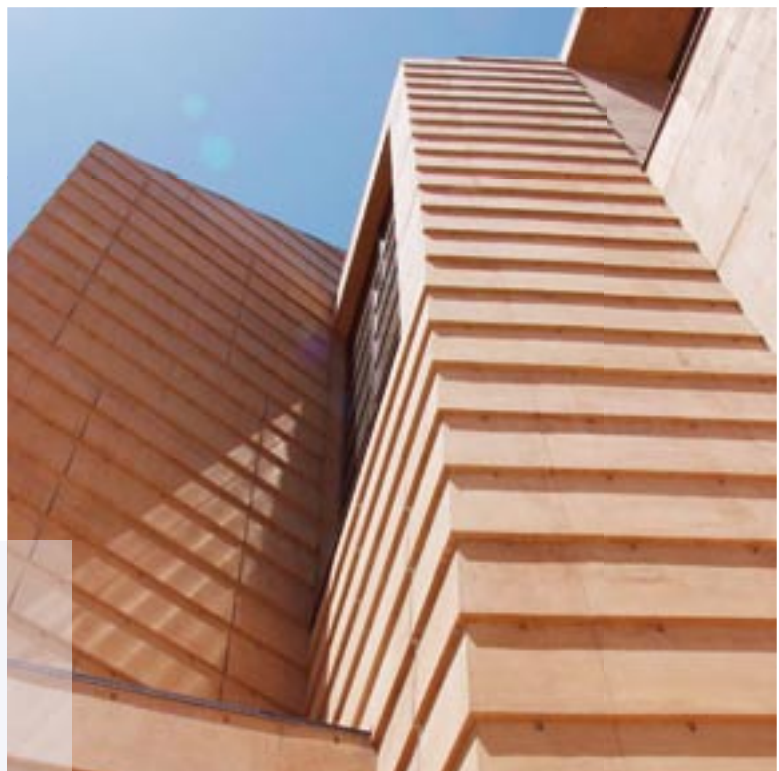
Gullet intended to throw off the rainwater from a balcony at the Salk Institute in San Diego, USA.



Design guidelines



*Polished surfaces that promote water run-off combined with deep joints where dirt is deposited.
Industrial complex, Greve, Denmark.*



Facade composed of large sloping sections. Water will run to the bottom of each section and deposit the dirt along the edge, accentuating rather than obscuring the design. Our Lady of the Angels, Los Angeles, USA.



Design guidelines



Dirty water running off the roof and onto the facades of an industrial complex, Hørsholm, Denmark.



Design guidelines

Having or not having protection against waterborne dirt deposits from a roof or other horizontal surface makes all the difference - concrete artwork, Gandrup, Denmark



*Eaves with gutlets protecting the facade.
Conference centre, Vedbæk, Denmark.*

Design guidelines

Maintaining a uniform expression over time is very difficult. But since the environmental load on different parts of the building varies as described in section 2.1, it can be advantageous to vary features aimed at removing water differently on different parts of the structure if it is desired to maintain a uniform expression:

To maintain the same expression on two areas, treat them differently [2].

The specific design elements (both horizontal and vertical) that can be used to handle water flow are [2]:

- Extended projections
- Small projections
- Ribs and grooves
- Changes of plane

It is difficult to fully anticipate the effect of ageing on a specific design, but it might help to ask the following questions:

For this particular design detail, on this particular section of the structure (exposed to a certain load), where will the water come from? How much water will there be and how often, and where would I like the water to go?

The answer to these questions should make it easier to identify the necessary water control features in the design, and therefore the possibilities for obtaining the desired architectural expression in an aesthetically durable fashion.

Easy access to all surfaces should be possible to permit later cleaning of and repairs to the structure [2].



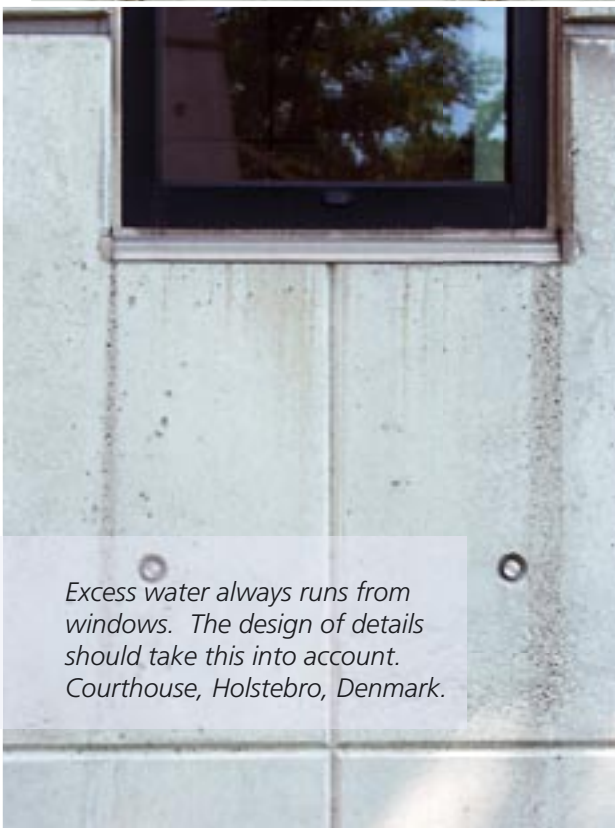
Detail elements at Hyatt Tower, Chicago Illinois, USA: extended projections, small projections, grooves and changes of plane.



Design guidelines



Design features causing concentrated water flow over some surface areas and less on others should take into account where this water - and the dirt it carries - is deposited. Housing Complex, Aalborg, Denmark



Excess water always runs from windows. The design of details should take this into account. Courthouse, Holstebro, Denmark.

Design guidelines



Three different surface expressions from the same concrete composition, left to right: exposed aggregates, polished and acid-etched.

■ 2.3 Surface texture

Surface texture is decisive for the impression created by a building from a close position ~ 0-10 metres.

The wide variety of different textures makes it possible to create almost any expression desired.

There are however three main concerns with regard to aesthetic durability when selecting a surface texture:

- ▶ How well should the surface texture conceal or emphasise dirt and other deposits?
- ▶ To what extent should the surface promote the removal of dirt and other deposits?
- ▶ What aesthetic and other functions should the surface fulfil, i.e. how should it look, feel and generally be experienced, and how should the features develop over time (organic growths, polishing by abrasion, chipping of edges, etc.) ?

A very smooth texture combined with a very dense concrete surface will very much promote the removal of dirt by rain or washing, but will also leave any dirt that is nevertheless deposited visible on the surface [2,7].

A very rough, uneven and porous surface will accumulate a lot of deposits [7,13] and promote algae growth, etc., but will also make it much harder to see dirt deposits [2,5,22].

The choice of surface texture should be based on the expected load (which is influenced by both general shape and detailing as described in sections 2.1 and 2.2), the colour and porosity of the concrete composition, and, the desired maintenance intervals [7].

Again, as described in section 2.2: *To maintain the same expression on two areas, treat them differently.*

Design guidelines



Grey concrete painted white. Even minor damages are clearly visible, and significantly changes the perception of the material away from what is intended.



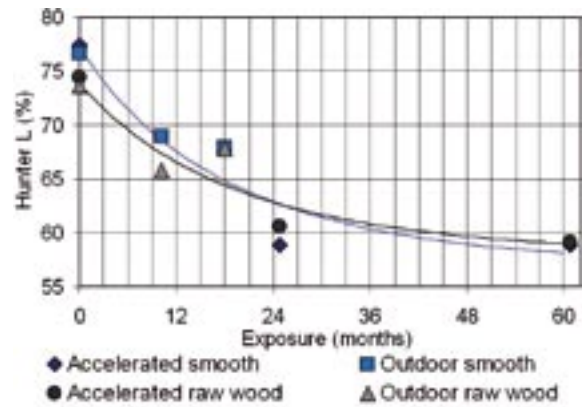
Untreated white concrete. Minor damages are less visible and only enhances the perception of the material as being truly white, as intended.



Design guidelines



Smooth (left) and rough (right) white concrete surface with dirt on the surface. The rough surface (concrete cast against raw wooden boards) is covered with approximately the same amount of dirt as the smooth, but it is more visible on the smooth surface



Hunter L (reflectance) as a function of exposure duration for the surfaces shown below. There is no significant difference in the colour change recorded.

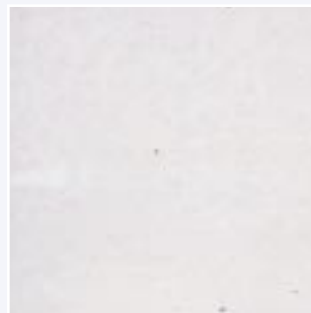
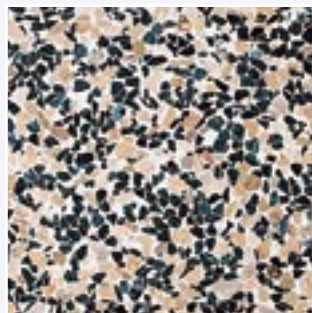
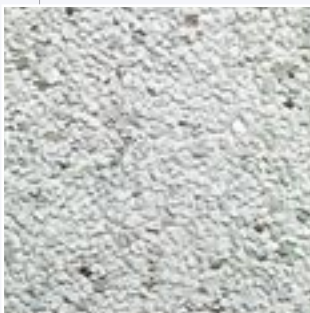


Two surfaces made with an identical concrete composition and casting procedure, but different formwork.

3

Guidelines for concrete composition

Concrete consists of aggregates (sand and stone), paste (consisting of powder in the form of cement, fillers and pigments additives, and water). All the constituents influence the colour of the concrete [3,10], and the dosages should therefore be kept constant, regardless of casting conditions such as differences in temperature or pumping distance [20,24].



Exposed aggregate surfaces, polished terrazzo, smooth as-cast surfaces and acid-etched surfaces impose different demands on the aggregates.

■ 3.1 Aggregates

The significance of the aggregates depends on the choice of surface texture.

Obviously, the expression of an exposed aggregate surface is totally dependent on the colour, colour consistency, grain size and grain shape of the exposed coarse aggregate material [2]. The grain size for exposed aggregate concrete should be considered in relation to the viewing distance [22].

For totally smooth as-cast surfaces the finest sand particles and powder materials play an important role in the consistency of the concrete's surface colour [2,23,24,34].

Over time the first millimetre or so of cement paste is worn away owing to freeze/thaw action, abrasion by airborne particles etc., revealing mainly the finer sand particles [13,26]. In order to maintain a certain colour over time, the colour of the fine sand should therefore be chosen to be close to the desired colour [2,25].

When designing for an exposed aggregate surface texture, there should be a gap in grain size distribution, so that the larger aggregate particles are not moved too far apart by intermediate-sized particles [3,11]. This can be achieved by only using medium-fine sand particles up to 2 mm in diameter and stone particles larger than 8 mm if a rough expression is desired.

Over an extended period (~50 years or more, depending on mortar resistance and erosive conditions) mortar erosion may lead to loosening of the larger exposed aggregates. This results in the fading of any design details [16].

All aggregate materials should be free from discolouring minerals (especially iron ferrite) and residue materials (such as clay). For a given structure it should be ensured that aggregates for the entire concrete volume are reserved in advance in order, to minimise colour variations [3,24].

Guidelines for concrete composition

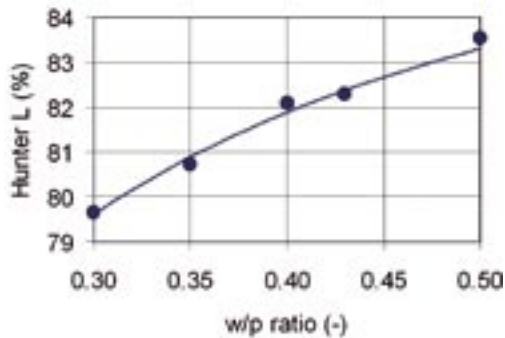


The intricate details of the Baha'i Temple, Chicago Illinois, USA, are slowly fading owing to erosion of the mortar, releasing the larger aggregate particles.



A single aggregate grain containing iron pyrite significantly affects the aesthetic appearance of a concrete surface [13].

Guidelines for concrete composition



Relationship between water/powder ratio and Hunter L value (reflectance) of the concrete surface after 28 days of conditioning [12].

■ 3.2 Paste

The paste consists of powder (cement and filler materials such as micro silica, slag or pigments), additives and water.

Both the composition of the paste and the amount of paste present in the concrete are of significance.

The colour of fine powder materials, especially cement and pigments, will obviously affect the resulting concrete colour. Therefore the content and colour consistency of all filler materials should be controlled very carefully, and a single supplier used for a given concrete production [3,24,25].

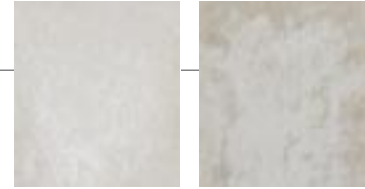
Using white cement increases the colour intensity for coloured concretes [13,18,32].

The water/powder ratio is also significant, as it determines both the immediate brightness and the porosity of the surface paste layer [3,12,13,23].

The higher the water/cement ratio, the lighter the concrete colour at later stages - and the higher the surface layer porosity [17,20,23,24,25].

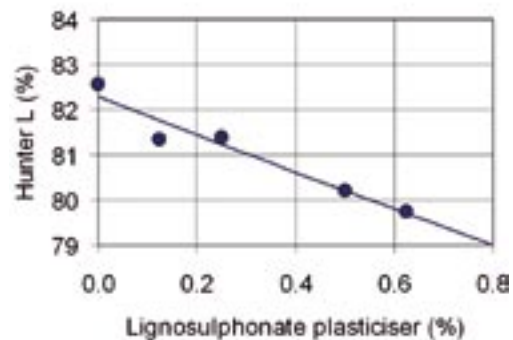
A high porosity means that the surface layer of the concrete absorbs water faster [17] and can contain more dirt and moisture, promoting organic growth [6,7]. Also, the surface layer is more vulnerable to freeze/thaw damage, abrasion and chemical attack [7,17].

Water cement ratio 0.36 and 0.45. Otherwise identical concrete composition and curing conditions.



The water should be clean and free from significant amounts of salts, organic materials and other potentially staining impurities [34].

Ideally, additives (plasticisers, air entrainment agents, viscosity-modifying agents, accelerators, retarding agents, hydrophobic agents, etc.) should not directly influence the colour, colour uniformity and consistency of a concrete mix [3,34]. However, some additives are dark brown, black, red or other potentially contrasting colours. Therefore the colour of the additive should always be considered in relation to the desired concrete colour before a selection is made.

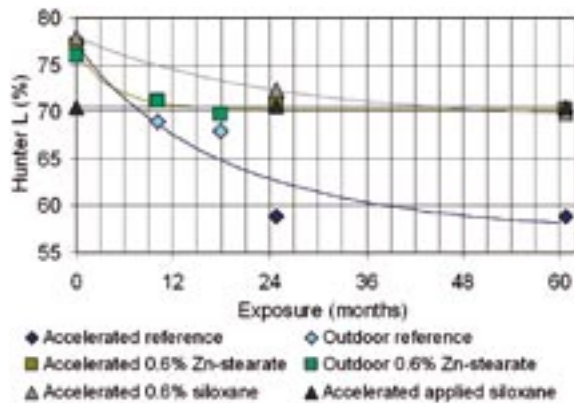


Relationship between content of dark brown lignosulphonate plasticiser and Hunter L value (reflectance) of the concrete surface [12].

Additives also affect how well pigments and fine fillers are dispersed in the mix during production, and this must also be considered carefully.

Some additives react in sunlight (UV radiation) and alkaline environments [3], and additives resistant to UV radiation and the alkaline environment in concrete should be chosen.

Guidelines for concrete composition



Hunter L (reflectance) as a function of exposure duration for surfaces with different types of hydrophobic treatments. All tested hydrophobic agents decrease the rate of ageing, the most effective being a treatment applied externally.

3.3 Other considerations

When all the above-mentioned factors have been considered, it is advisable to produce a mock-up to test the combination of concrete composition, form-work and execution to ensure that the combined solution results in the desired surface expression [3,10,15, 24,26,27,29,32,33] before a final decision is made.

It should be large enough to permit evaluation of all details and may be used to test and approve proposed repair techniques and coatings as well [29,32,33].

In addition finished constructions may be selected as references in respect of standards for the finished work [26].

It is also advisable to produce additional test mixes in which the limits for anticipated variation in constituent dosages and colours are tested in order to obtain an indication of the colour robustness of the mix.

The choice of concrete composition should always be balanced against the desired surface texture, the location of the given surface (more or less protected from washing, dirt, etc.) and the intervals at which maintenance is expected to be carried out.



4

Execution guidelines

The execution phase covers all aspects of actual production of the concrete structure:

- Mixing (dosage of constituents, mixing time and mixer type)
- Placing (transporting, pouring, vibrating, etc.)
- Curing (time, conditions)
- Post casting treatment (grinding, sandblasting, bush hammering, acid washing, exposed aggregates, anti-graffiti treatment, hydrophobic agents, etc.)
- Placing (handling of pre-cast elements, assembly, etc.)

It is very important that the concrete composition is uniform, especially with regard to water/cement ratio, paste content and air content, since these variables influence the surface porosity.

Increased surface porosity results in visible colour differences that become more pronounced when the surface is wet. High porosity also increases the accumulation of dirt and promotes the growth of algae, lichen, etc. Variations in wetting and dirtying of the surface owing to the design of the building will accentuate these differences, as well as being accentuated themselves [5,7,27],

■ 4.1 Mixing

Ensuring a consistent ratio between the different constituents in relation to each other is very important, and dosage should therefore be carried out consistently and accurately [3,24]. This also applies to the order in which the constituents are added, and the mixing sequence should be the same each time [25].

The mixer and other equipment that comes into contact with the concrete during production should be clean, particularly with regard to oil and grease [3,10,11,20,24].

The mixer should not leave material unmixed - e.g. by not scraping the bottom closely enough.

Mixing should be continued long enough to ensure uniform composition within each batch, and variation should be minimised [3]. Coloured concrete (incorporating pigment) should be mixed longer than usual to avoid streaking [18,20].



Mixing white concrete.

Execution guidelines

■ 4.2 Placing

The method of transporting the concrete from the mixer to the formwork should be the same each time, and the transporting devices should be kept clean.

Pumping, long drops and other handling methods involving large pressure fluctuations affect the air content and flowability of the concrete, as well as creating a risk of segregation [3,8] and producing air pockets inside the air concrete [2]. These methods should be used as gently as possible or avoided.



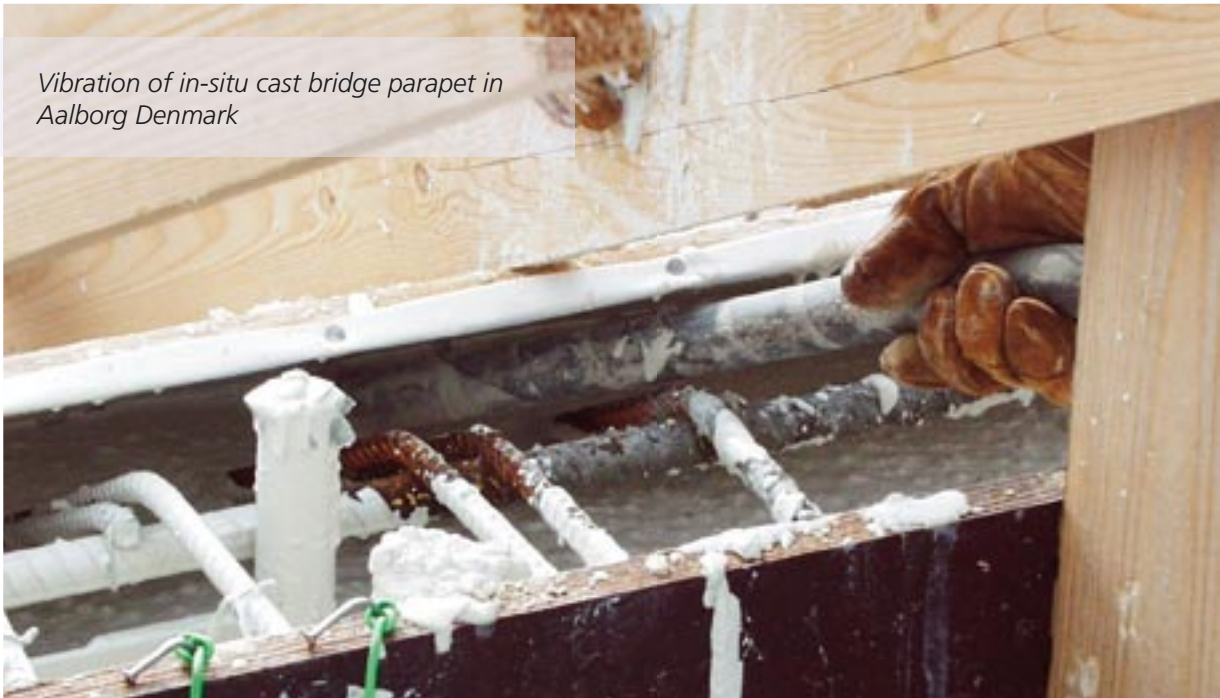
Placing concrete with feeder belt for in-situ cast bridge parapet in Aalborg Denmark.

The formwork determines whether the finished surface in general is smooth, profiled or patterned, and for as-cast surfaces yields the final surface texture [19,27]. It is therefore essential to consider the choice of formwork material and release agent thoroughly. In particular, the following issues should be taken into consideration:

- ▶ Formwork material (porosity, consistency of porosity, texture and variation of texture, staining ability, retarding ability) [2,24].
- ▶ Workmanship of mould building (joints must be sealed to avoid water seepage [3,15,24], edges should be crisp, plane areas free from minor holes and extrusions in the formwork surface, details, inserts, etc., correctly and uniformly placed, etc.).
- ▶ Release agent should be evenly applied in the minimum layer thickness possible to obtain sufficient release effect and a uniform saturation of any aggressive or slightly porous mould material surfaces [2,3,11,13,34]. Excess release agent should be removed from the mould using clean cloth [11]. The release agent should be non-staining and not affect the bond of any later coatings [30].
- ▶ The form should be rigid enough to support the form pressure without deformation so that the intended shape of the finished structure is obtained [3,29].

Execution guidelines

Vibration of in-situ cast bridge parapet in Aalborg Denmark

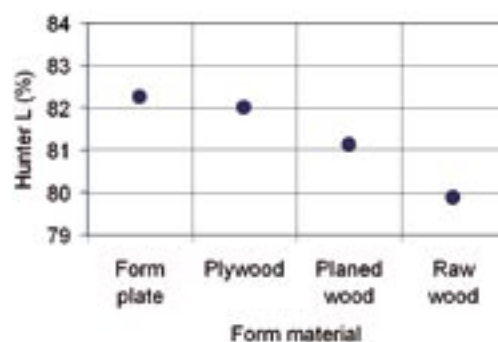


Special considerations for wooden forms: the structure of raw wood can be enhanced by acid washing or sandblasting the wooden surface. If a smooth surface is desired, the wood must be polished and impregnated with lacquer or wax. If boards are used, the joints between them should be glued or otherwise sealed to prevent water or paste from escaping [11].

Raw wood contains resin and sugar compounds that retard and colour the concrete surface [31]. Raw wood also varies in porosity, which some believe leads to variations in the w/c ratio and therefore variations in reflectance [11], while others consider this to be a secondary effect [31]. Differences in moisture content in the wood will result in varying absorption and therefore colour differences in the finished concrete surface [14,31].

To counter the retardation and discoloration owing to the resin content, raw wooden formwork should be washed with lye or cement paste [11,31].

Exposure to warm weather and sunlight may draw the extracts (especially resins and sugar compounds) to the surface from the interior of the wood and increase the problems [31]. Wood that has been used previously is normally neutralised and will cause few problems [31]. The type and amount of release agents only affects discoloration slightly [12,31].



Relationship between formwork material and Hunter L value (reflectance) of the concrete surface [12].

Execution guidelines

Special considerations for steel and plastic forms: these forms are well suited for producing large smooth surfaces. They are also impermeable, which increases the risk of air bubbles forming in the surface [11].

If an exposed aggregate surface is desired, one method is to apply a retarding agent to the mould surface prior to placing, which allows the mortar layer to be washed off after the concrete is demoulded [30]. Alternative methods for post casting procedures are described in section 4.4, Post casting treatment.

Vibration of the concrete via the formwork during placing should be avoided, as this creates a porous layer of cement paste on the surface [2].

Poker vibrators should be used uniformly throughout the entire concrete mass [2], and only when the concrete is evenly distributed in the mould [11].

For pre-cast elements cast in vibrated moulds, the vibration must be uniform for the entire mould [11].

Trowelling should be carried out at the appropriate time. Over-working the surface should be avoided as it creates so-called »burn marks« on the surface - areas of varying porosity.

Alternatives to trowelling includes brushing or impressing patterns in the fresh concrete surface. Concrete consistency, brush type and time from casting to final surface treatment all influence the final expression. The appropriate procedure for achieving the desired expression should be determined in advance by means of trial castings [13].

Finishing top surface of in-situ cast bridge parapet in Aalborg Denmark.



Execution guidelines

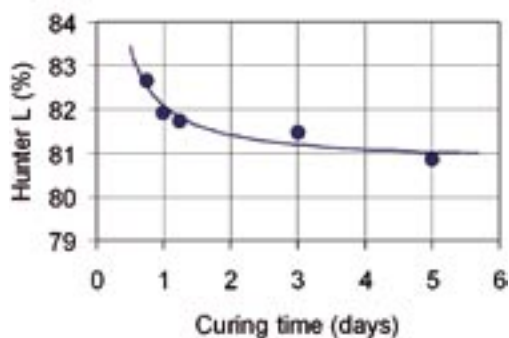
4.3 Curing

A varying water/powder ratio influences both visible colour and surface porosity. A uniform loss of moisture during hardening is therefore essential in order to obtain uniform colour and porosity of concrete surfaces [7,11,13,27,32].

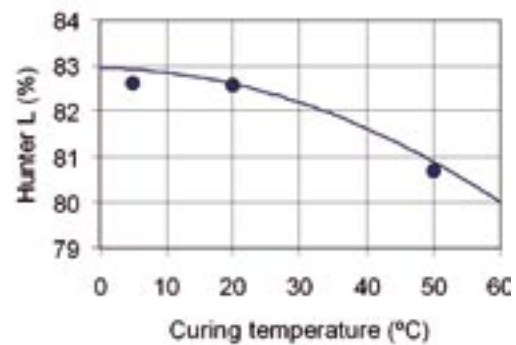
The first 24-48 maturity hours (typically the first 2-7 actual days of curing, depending on temperature and wind conditions) are the most important - after that the differences in colour and porosity from varying moisture loss become less pronounced [2,12].

There are several ways of controlling water loss from the surface [2,8]:

- Sprinkling water on the surface
- Curing compound sprayed on the surface (an emulsion that forms a thin impermeable coating).
- Plastic sheets, impervious paper or other coverings - be aware of the risk of condensation producing patterns on the surface [3,10].
- Keeping the formwork on



Hunter L value (reflectance) of concrete surfaces as a function of the duration of curing (days in the mould at 20°C) [12].



Hunter L value (reflectance) of concrete surfaces as a function of curing temperature (adjusted to the same equivalent maturity) [12].



Surface covered with plastic during curing, resulting in areas of varying porosity.

Execution guidelines

Very damp, sunny and windy weather influences the drying rate of the concrete surface [14].

Clear-coloured curing compounds may be used without much risk of changing the appearance of the concrete surface [3], if applied in normal dosages.

To produce a uniform, evenly porous concrete surface, it is advisable to protect the surface for equal durations of maturity, that is the temperature-adjusted hardening time of the concrete [12].

Spraying with water or damp coverings may increase the risk of lime efflorescence [28,32].

Curing temperature also influences the colour: lowering the temperature darkens the surface colour [13,14].

■ 4.4 Post casting treatment

Even when everything has been done to prevent faults or discolorations, no concrete surface is completely free from surface blemishes [27,30].

Depending on the post casting treatment and the viewing distance, these blemishes may be more or less detrimental to the expression of the final structure [27].

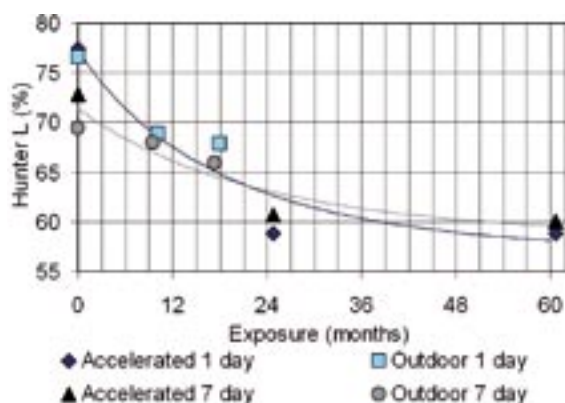
When assessing the significance of the blemishes, a viewing distance similar to the actual viewing distance of the users should be employed, and only blemishes visible from this distance treated. In addition, it should be considered, that some blemishes lessen over time owing to ageing over a short period [27].

The post casting treatment produces the final surface texture and appearance of the concrete, and should be chosen carefully

The different methods include grinding or polishing, sand- or water-blasting, bush hammering, acid washing and surface coatings (incl. painting) [2,3,11,22,30].

To create a uniform expression, it is important that the post casting treatment is carried out by skilled craftsmen [15] - and preferably the same person for an entire structure, since minor variations in the way sandblasting, bush hammering or acid washing is carried out can result in distinct colour variations [11].

Also, the treatment should be applied on all surfaces at a consistent concrete age, in order to minimise differences in colour and texture [34].



Hunter L (reflectance) as a function of exposure duration for surfaces cured in the mould for different durations. Increased curing time decreases the rate of ageing.



Execution guidelines

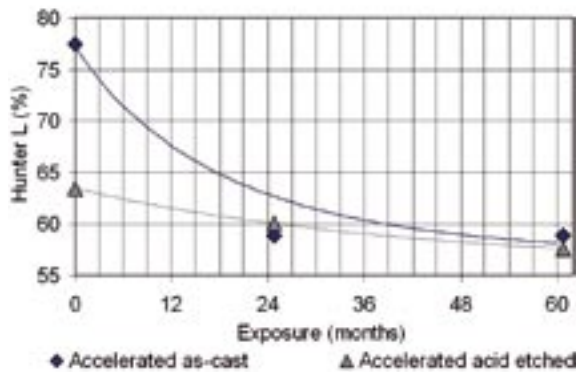


White polished concrete surface in dry conditions.

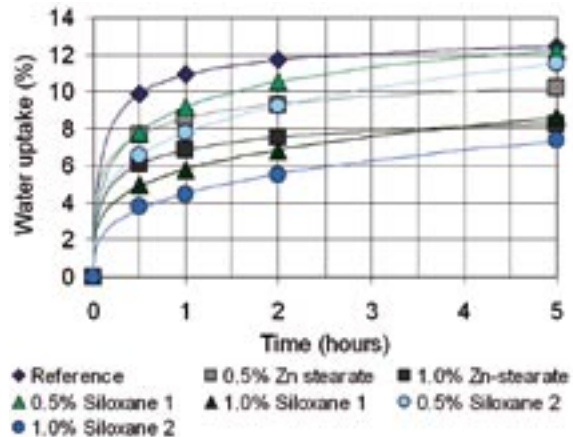


Yellow exposed aggregate and acid-etched surfaces made from one concrete composition, in wet conditions.

Execution guidelines



Hunter L (reflectance) as a function of exposure duration for acid-etched surface compared to as-cast. The acid-etched surface is initially darker owing to the exposed aggregate grains, but the surface ages slowly compared with the as cast surface.



Water uptake for mortar prisms added different amounts and types of hydrophobic agents. Surface water uptake rates are significantly reduced.

Except for surface coatings, all the above-mentioned techniques remove the thin layer of cement paste and a varying amount of aggregate from the concrete surface, exposing the bulk concrete to a varying degree (exposed aggregate surface). The deeper the abrasion, the more significant to colour the larger aggregates become [22].

The treatments therefore result in a more porous surface [29] with the detrimental consequences this has for the resistance of the surface to dirtying, algae growth etc., but also the benefits regarding reduced visibility of variations.

An anti-graffiti-coating (either a sacrificial layer - typically a wax, or a lacquer-like coating that facilitates cleaning) can be applied to the surface if considered relevant [2].

Water repellent coatings may reduce the potential of the concrete for staining [26,30] or efflorescence formation [28].

Before applying coatings it is advisable to carry out a trial application in a inconspicuous area, to ensure that the coating does not change the appearance of the concrete in an unacceptable manner, especially with regard to gloss and hue [1,30,34].

Coatings should not be applied before 28 days of curing, and the surface must be clean and free from precipitations [26].

For pre-cast elements it is important that they are stored in uniform temperature and humidity conditions, and that the placement of necessary support blocks and spacers, or contact with other elements, is considered carefully, as it often results in permanent discolorations [2].

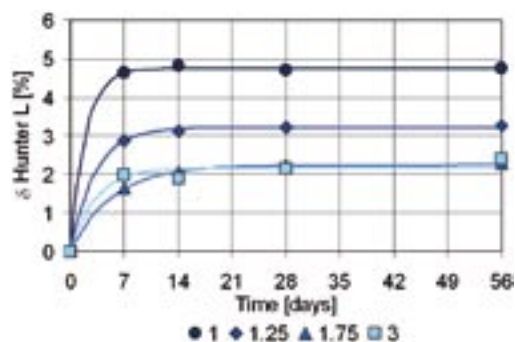
Execution guidelines

■ 4.5 Placing (for pre-cast elements)

For pre-cast elements placing without damaging and dirtying the elements is essential.

Damage during placing cannot be avoided completely - accidents do happen. However, precautions such as protecting corners and outcroppings on the elements should be taken. To avoid dirtying, wooden support beams in direct contact with the visible surfaces during transport should be avoided [2,11], as should dirty gloves and straps during placing

Prior to comparing the colour of elements it is advisable to store the elements for at least 7-14 days in uniform conditions to ensure that they have reasonably uniform moisture contents [12].



Development of Hunter L value (reflectance) of concrete surfaces over time in a uniform environment (20°C, 55% relative humidity) for samples cured for different durations (days in the mould) [12].

Staining with splashes of water containing dirt, cement, oil, grease, paint or other colouring contaminants during cleaning must be avoided by protecting the elements throughout the assembly and cleaning phase of construction (e.g. with plastic sheets) [2,11].

Joints between elements should be filled with a colourmatched sealant to prevent water penetrating the structure [22].



Placing pre-fabricated facade elements for the Arlanda Control Tower, Stockholm, Sweden.



Execution guidelines



The finished control tower in Arlanda.

■ 4.6 Other considerations

Lime blooming – or efflorescence – or other surface discolorations may appear up to a year after completion [28].

Lime efflorescence is formed when dissolved calcium hydroxide dissipates to the surface, where it combines with atmospheric carbon dioxide and precipitates as the low solubility product calcium carbonate [21,28].

Lime efflorescence may be lessened by reducing the amount of alkali in the concrete materials, and by ensuring a dense impermeable surface [21,28].

Lime efflorescence may be removed. Light precipitations may be removed by cleaning the surface with a stiff brush, more resilient precipitations by washing once or more with a weak acidic solution [26,28]. Before the acid is applied, the surface should be wetted to avoid the acid being drawn into the pores of the concrete [28].

5

Maintenance guidelines

Maintenance of structures aims to preserve a desired state, in this case a certain aesthetic expression. Therefore, maintenance may include promoting ageing mechanisms if the aesthetic effect created by these mechanisms is a deliberate and necessary element in the appearance of the structure. This, of course, provided the process does not lead to physical deterioration.

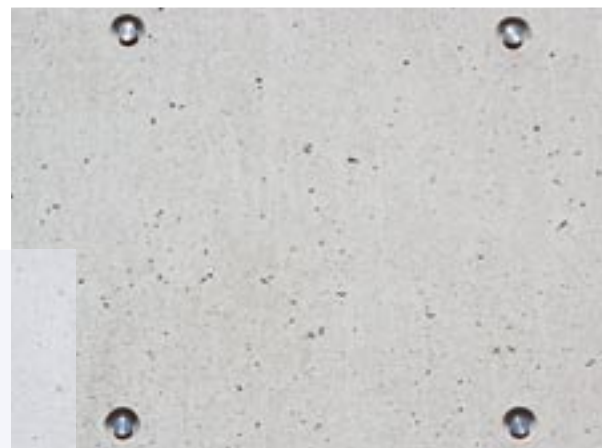
However, most maintenance of structures is carried out for three different reasons:

- ▀ Cleaning
- ▀ Repairs
- ▀ Preventive maintenance

When a structure is cleaned or repaired, care is in some cases also taken to prevent future damage or discoloration, but not always - hence the distinction.

Before maintenance is started, an assessment should be made of the condition of the surfaces.

Specifically it should be determined where the surface is clean, dirty, eroded or damaged [2].



Surface before and after exposure to a high pressure water jet. The Courthouse in Holstebro, Denmark

Maintenance guidelines

■ 5.1 Cleaning

A more or less evenly distributed layer of dirt normally covers aged concrete surfaces. Removing the dirt by cleaning part of the surface will create a clean spot that contrasts with the remaining surfaces. This clean spot cannot be removed, so the only option is to clean whole segments or sides of a structure [2]. It should therefore be considered if cleaning is actually desirable in the given situation [2].

Most cleaning methods damage the surface to some extent by removing part of the skin layer of paste and/or changing the texture [2].

The method least likely to alter the surface expression is hand washing with lukewarm water and possibly a mild detergent [2,13,26], but cleaning can also be done using high-pressure water, chemicals, sandblasting, steam or flame [2].

When cleaning with chemicals to dissolve stains, it is advisable to use an absorbent paste together with the chemical agent, or to use the chemical in the form of a foamed paste. This prevents the dissolved dirt from being absorbed by the pores in the concrete surface, thereby transporting the dirt further into the concrete surface instead of removing it [2,8].



The Baha'i Temple in Chicago, Illinois, USA, is 50 years old, but still looks bright white because it has been cleaned on a regular basis.

Maintenance guidelines

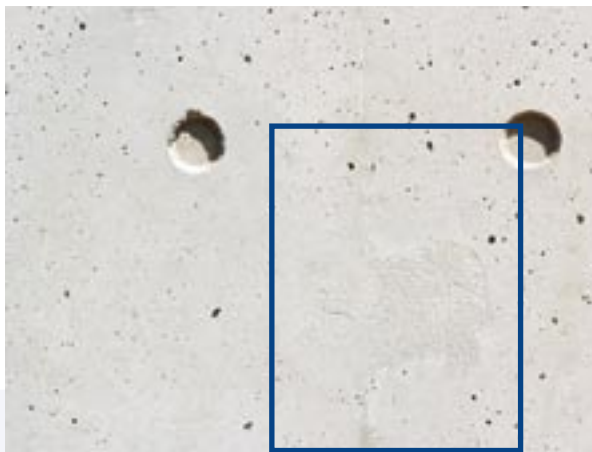
■ 5.2 Repairs

The objectives of repairs are usually both to:

- Prevent further structural damage
- Improve the visual impression.

Achieving both objectives requires the repair to be both physically and visually comparable to the original surface, with regard to texture, colour and porosity.

To achieve these objectives, it is necessary to use a concrete or mortar composition as close to the original mix as possible, as well as form materials that match the existing texture as closely as possible [6,9,30]. Even so, it is very difficult to obtain a good match between the repair and the original concrete [27].



Repair patch matching the original concrete colour, but not the surface texture. Distance approx 0.5 metres. The Bunker Museum, Hanstholm, Denmark.

Repair patch made with a different material, neither, matching the colour nor the texture, but only visible from less than 1 metre away. Viewing distance should also be taken into account. The Baha'i Temple, Chicago, Illinois USA.

It is more important that the surface characteristics of the repaired patches match those of the surrounding surfaces as closely as possible than to achieve an immediate colour match between the patch and the original surface, in order to ensure good long-term visual compatibility [6]. Even so, some sources recommend adjusting the repair material composition to match the colour [9,30]. Surface porosity and roughness in particular should be similar to ensure a comparable uptake of moisture and dirt between the repair patch and the surrounding surfaces [6].

Ready-mixed repair mortars or other materials can be used for minor defects that will not be viewed from within 5 metres.

If it proves impossible to create repair patches with comparable surface properties and the long-term visual appearance is important, it may be necessary to treat an entire section of the surface – both repair and original surface – to ensure an acceptable appearance for the structure [6].



Maintenance guidelines

■ 5.3 Preventive maintenance

The objective of preventive maintenance can be one or both of:

- Delaying visual degradation
- Delaying physical deterioration

The focus here will be on delaying visual degradation, but in most cases this will also to some extent result in delayed physical deterioration of the concrete.

A special area of preventive maintenance is that of anti-graffiti coatings. Anti-graffiti coatings can be either a clear coating or a visible finish [6], and vary from lacquer-like layers, through sacrificial coatings (typically wax), to drying-retardant coatings, which slow down the drying time of paint [2]

Hydrophobic agents can be used by way of impregnation to reduce the permeability of the surface, see section 4.3. This will to some extent prevent water from being absorbed by the surface, and therefore reduce the amount of dirt being deposited, see section 4.4. Most of these agents require repeated treatments at differing intervals.

Before coatings are applied, it is advisable to carry out a trial application in an inconspicuous area to ensure that the coating does not change the appearance of the concrete in an unacceptable way, especially with regard to gloss and hue [1,30].



Repair matching both colour and texture of original surface. Distance approx 5 metres. The Bunker Museum, Hanstholm, Denmark.



Acid-etched washed surface without coating, after removal of graffiti. Parken, Copenhagen, Denmark.

6

Summary

The ageing of concrete surfaces is in principle no different from other organic, natural, porous building materials such as brick or wood, and is therefore no less attractive from a material point of view.

One of the reasons for a difference in perception of aesthetic performance existing between structures made from brick or wood and concrete structures is that many of the design elements developed for brick and wood buildings over the centuries to cope with the weathering of the structure, such as window sills, eaves with gutters, subdivision of larger facade areas etc., have been discarded in the design of concrete buildings [7].

Considering and applying alternative design features to counter the same basic mechanisms should therefore reduce the problems with less than acceptable ageing of concrete structures.

However, it will also have to be understood and accepted by the *users* of concrete buildings that a concrete building ages and requires maintenance just like other materials if concrete is to be accepted as an aesthetically pleasing material by the general public.

This understanding is best disseminated by designing, building and maintaining buildings where aesthetically pleasing ageing is part of the deliberate plan for the entire life cycle of the structure: by embracing concrete as a living material, using the naturally occurring ageing mechanisms actively and constructively as part of the design, rather than trying to prevent or remove the effects of ageing, an even wider palette of varied concrete expressions presents itself to the architect and building owner.

Therefore, for any concrete structure, design, concrete composition, execution and maintenance should be regarded as an integral whole from the outset. The companies and individuals involved should co-operate to ensure that all aspects of the design, construction and service life take aesthetic durability into account, to their mutual benefit [15,24].



Drawing visualising the effects of ageing on a building prior to construction.

The drawing, which shows discolorations beneath windows and at other exposed sites in particular, indicates that ageing was a deliberate part of the plan for the architectural expression - and that this was communicated to the building owner in advance. C.F. Hansen, architect, 1805.

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Aalborg Portland A/S

Rørdalsvej 44
Postbox 165
9100 Aalborg
Denmark

Phone +45 98 16 77 77
Fax +45 98 10 11 86
E-mail: white@AalborgWhite.dk
Internet: www.AalborgWhite.com