Sika Concrete Handbook

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Foreword

This new Concrete Handbook is a Chapter by Chapter guide about the main methods and processes for the production of concrete to meet different requirements. Of course the growing demands for sustainability in concrete are also taken into consideration.
One of the main requirements for durable concrete is its impermeability to water. But watertight concrete alone is not all that is required to make a structure waterproof. A specific chapter 'White Box' on 'Watertight Concrete Construction' which considers the form and dimensions of the design, the watertight concrete mix design and the alternative solutions for watertight joint sealing has been added to this Concrete Handbook.

The book is divided into the following chapters:

1. Construction Material Concrete
2. The Five Concrete Components
3. Fresh Concrete Properties and Tests
4. Hardened Concrete Properties and Tests
5. Concrete Types
6. Recommended Measures

Modern concrete is produced from five components. This results in a complex matrix, control of which presents a constantly recurring challenge for everyone involved. For every structure the concrete components must be adapted to both the fresh and the hardened concrete performance requirements.

The authors of the Concrete Handbook have worked in Sika for many years as engineers in project and product management. This booklet is written both as an introduction to concrete and its application and for a deeper study of the most important building material concrete; it is intended as a reliable source of information for our partners.

May 2012

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1. Construction Material Concrete

1.1 Introduction

Sika – with Long Experience

Founded by Kaspar Winkler in 1910, the name Sika today stands for waterproof and durable solutions. Beginning with rendering mortar, used for the first time in the waterproofing of the old Gotthard Railway Tunnel, and extending to entire waterproofing systems for a wide number of applications, which also currently includes the Gotthard Base Tunnel, the longest high-speed railway tunnel in the world, Sika products contribute to building success. To seal durably against penetrating water, while in other instances to protect precious water and prevent its leakage; two sides of a comprehensive challenge present complex interfaces.

Designing an entire watertight building from the basement to the roof requires the development of solutions for the widest range of applications, solutions which can be installed practically and provide permanent protection. For a complete structure this means the sealing of surfaces such as roofs, underground walls or foundation plates. It also means assuring the watertightness of construction joints and of movement joints. Furthermore, waterproofing solutions in visible areas must meet high aesthetical requirements.
Alongside water, building structures are exposed to a broad range of forces and strains, starting with mechanical stresses resulting from the type of construction and extending to various external attacks. Extreme hot or cold temperature conditions, aggressive water or other chemicals, continually rolling, abrading or pulsating strains on surfaces, or in extreme cases the impact of fire, places enormous stresses on structures as a whole and on building materials.

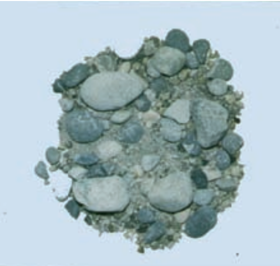
Concrete has shaped Sika's development sustainably, and since 1910 Sika has made a notable contribution to the development of concrete as a durable building material!

1.2 Terms

Three main constituents are actually enough to produce concrete:

- Binder (Cement)
- Aggregates
- Water

Due to continually increasing demands for the concrete quality (mainly durability) and huge advances in admixture and concrete technology, it is now possible to produce many different kinds of concrete.



The aggregates (sand and gravel) are the main constituents of concrete, at over 70% by volume. The type and quality of the aggregates are therefore vitally important for the properties of the concrete, both fresh and hardened.

■ Standard concrete	Concrete with a maximum particle diameter > 8 mm Density (kiln dried) > 2'000 kg/m³, maximum 2'600 kg/m³
■ Heavyweight concrete	Density (kiln dried) > 2'600 kg/m³
■ Lightweight concrete	Density (kiln dried) > 800 kg/m³ and < 2'000 kg/m³
■ Fresh concrete	Concrete, mixed, while it can still be worked and compacted
■ Hardened concrete	Concrete when set, with measurable strength
■ 'Green' concrete	Newly placed and compacted, stable, before the start of detectable setting (green concrete is a precasting industry term)

Other terms in use are shotcrete, pumped concrete, craned concrete etc. they define the placement into the formwork, working and/or handling to the point of installation (see Chapter 6).

1. Construction Material Concrete

In addition to the three main components of concrete, concrete admixtures and additives are also used in concretes with higher performance specifications again both fresh and hardened.

Sika began developing the first admixtures for cementitious mixes in 1910, the year in which it was founded. At that time the main aims were to shorten the setting time of mortar mixes, make them watertight or increase their strength. Some of these early, successful Sika products are still in use today.
Water is necessary in concrete for consistence and hydration of the cement, but too much water in the hardened concrete is a disadvantage, so Sika products were also developed to reduce the water content while maintaining or even improving the consistence (workability):

Date	Product base	Typical Sika product	Main effects
1910	Aqueous alkaline solution	**Sika®-1**	Waterproofing agent
1930	Lignosulfonate	**Plastocrete®**	Water reduction up to 10%
1940	Gluconate	**Plastiment®**	Water reduction up to 10% plus retardation
1960	Mix of carbohydrate and polyphosphates Mix of synthetic surfactants	**Sika Retarder®** **Sika-Aer®**	Retardation Air-entrainment
1970 1980 1990	Naphthalene Melamine Vinyl copolymers	**Sikament®**	Water reduction up to 20% Water reduction up to 25%
1990	Mixture of organic and inorganic salt solution	**SikaRapid®**	Hardening accelerator
2000	Modified Polycarboxylates (PCE)	**Sika® ViscoCrete®**	Water reduction up to 40%
2010	Modified Polycarboxylates (PCE)	**Sika® ViscoFlow®**	Slump rentention up to 7 hours

Ever since the company was founded, Sika has always been involved where cement, aggregates, sand and water are made into mortar or concrete – the reliable partner for economic construction of durable concrete structures.

1.3 Main Uses of Concrete

It makes sense to classify the uses of concrete on the basis of where and how it is produced, together with its method of application, since these have different requirements and properties. The sales of cement in four different countries in 2010 are given as an example of how the percentages vary for the different distribution and usage channels for the overall methods of use:

Germany	USA	China	India
■ Approx. 45% to ready-mix plants	■ Approx. 70% to ready-mix plants	■ Approx. 40% to ready-mix plants	■ Approx. 10% to ready-mix plants
■ Approx. 30% precast component and concrete product producers	■ Approx. 10% precast component and concrete product producers	■ Approx. 10% precast component and concrete product producers	■ Approx. 15% precast component and concrete product producers
■ Approx. 15% contractors	■ Approx. 10% contractors	■ Approx. 30% contractors	■ Approx. 20% contractors
■ Approx. 10% other outlets	■ Approx. 10% other outlets	■ Approx. 20% other outlets	■ Approx. 55% other outlets

The requirements for the concrete differ for each of these applications. The right planning and preparation of the concrete works are crucial for the successful use of this fantastic building material.

1. Construction Material Concrete

Preparation steps

When preparing the concrete design, the concrete performance must be defined by the specific project requirements. The following parameters should be defined:

- Strength requirements
- Durability requirements
- Aesthetic requirements
- Maximum aggregate diameter
- Method of placement
- Placing rate
- Concrete consistence
- General boundary conditions (temperature etc.)
- Delivery method and time
- Curing/waiting time
- Definition of test requirements
- Mix design and specification
- Preliminary testing
- Mix design adjustment if necessary

Production

Production of concrete is a critical factor for the resulting concrete and consists basically of dosing and mixing the components. The following parameters can affect the concrete properties during mixing:

- Concrete mix design
- Suitability of admixture
- Type and size of mixer
- Mixing intensity and mixing time
- Concrete mixer operator
- Cleaning/maintenance of mixer
- Addition of raw materials
- Plant quality control

Preparation on site

The preparation on site includes the following:

- Installation of the concrete handling/placing systems
- Preparation of the formwork (including release agent application)
- Reinforcement check
- Formwork check (fixing, integrity, form pressure)
- Supply of tools for compacting (vibrators etc.) and finishing (beams and trowels etc.)

Delivery

If the concrete is supplied, the following additional criteria must be considered:

- Delivery time (traffic conditions, potential hold-ups, etc.)
- Define the necessary drum revolutions during the journey
- Do not leave the ready-mix truck standing in the sun during waiting periods
- For a fluid consistence (SCC), define the maximum capacity to be carried
- Do not add water or extra doses of admixture (unless specified)
- Mix again thoroughly before unloading (one minute per m^3)

Placing the concrete

The concrete is generally placed within a limited and defined time period. The following factors contribute to the success of this operation, which is critical for the concrete quality:

- Delivery note check
- Use of the right equipment (vibrators, etc.)
- Avoid over handling the concrete
- Continuous placing and compacting
- Re-compaction on large pours
- Take the appropriate measures during interruptions
- Carry out the necessary finishing (final inspection)

Curing

To achieve constant and consistent concrete quality, appropriate and correct curing is essential. The following curing measures contribute to this:

- Generally protect from adverse climatic influences (direct sun, wind, rain, frost, etc.)
- Prevent vibration (after finishing)
- Use a curing agent
- Cover with sheets or frost blankets
- Keep damp/mist or spray if necessary
- Maintain the curing time relevant to the temperature

1. Construction Material Concrete

3. The Five Concrete Components

3.1 Cement and Binder

Cement is the hydraulic binder (hydraulic = hardening when combined with water) which is used to produce concrete. Cement paste (cement mixed with water) sets and hardens by hydration, both in air and under water. The main base materials, e.g. for Portland cement, are limestone, marl and clay, which are mixed in defined proportions. This raw mix is burned at about 1'450 °C to form clinker which is later ground to the well-known fineness of cement.

Cement to European standard

In Europe, cements are covered by the standard EN 197-1 (composition, specifications and conformity criteria). The standard divides the common cements into five main types, as follows:

CEM I	Portland cement
CEM II	Composite cements (mainly consisting of Portland cement)
CEM III	Blast furnace cement
CEM IV	Pozzolan cement
CEM V	Composite cement

3. The Five Concrete Components

The various types of cement may contain different components amongst Portland cement clinker (K):

Major components

Granulated slag	S
Silica fume	D
Natural and industrial pozzolans	P or Q
Silica-rich fly ashes	V
Lime-rich fly ashes	W
Burnt shales (e.g. oil shale)	T
Limestone	L or LL

Minor components

These are mainly selected inorganic natural mineral materials originating from clinker production, or components as described (unless they are already contained in the cement as a major constituent, see p. 24).

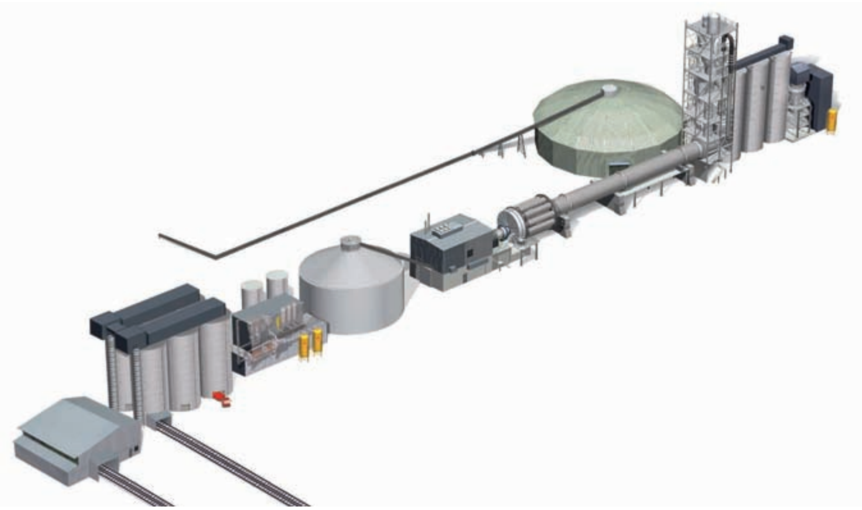


Table 3.1.1: Types of cement and their composition according to EN 197-1

Main cement type	Designation	Cement type	Composition (parts by weight in %)[1]										
			Main components										Minor components
			Portland cement clinker	Slag	Silica dust	Pozzolans		Fly ashes		Burnt shale	Limestone		
						Natural	Artificial	High silica	High lime				
			K	S	D[2]	P	Q	V	W	T	L[4]	LL[5]	
CEM I	Portland cement	CEM I	95–100	–	–	–	–	–	–	–	–	–	0–5
CEM II	Portland slag cement	CEM II/A-S	80–94	6–20	–	–	–	–	–	–	–	–	0–5
		CEM II/B-S	65–79	21–35	–	–	–	–	–	–	–	–	0–5
	Portland silica dust cement	CEM II/A-D	90–94	–	6–10	–	–	–	–	–	–	–	0–5
	Portland pozzolan cement	CEM II/A-P	80–94	–	–	6–20	–	–	–	–	–	–	0–5
		CEM II/B-P	65–79	–	–	21–35	–	–	–	–	–	–	0–5
		CEM II/A-Q	80–94	–	–	–	6–20	–	–	–	–	–	0–5
		CEM II/B-Q	65–79	–	–	–	21–35	–	–	–	–	–	0–5
	Portland fly ash cement	CEM II/A-V	80–94	–	–	–	–	6–20	–	–	–	–	0–5
		CEM II/B-V	65–79	–	–	–	–	21–35	–	–	–	–	0–5
		CEM II/A-W	80–94	–	–	–	–	–	6–20	–	–	–	0–5
		CEM II/B-W	65–79	–	–	–	–	–	21–35	–	–	–	0–5
	Portland shale cement	CEM II/A-T	80–94	–	–	–	–	–	–	6–20	–	–	0–5
		CEM II/B-T	65–79	–	–	–	–	–	–	21–35	–	–	0–5
	Portland limestone cement	CEM II/A-L	80–94	–	–	–	–	–	–	–	6–20	–	0–5
		CEM II/B-L	65–79	–	–	–	–	–	–	–	21–35	–	0–5
		CEM II/A-LL	80–94	–	–	–	–	–	–	–	–	6–20	0–5
		CEM II/B-LL	65–79	–	–	–	–	–	–	–	–	21–35	0–5
	Portland composite cement[3]	CEM II/A-M	80–94	6–20									0–5
		CEM II/B-M	65–79	21–35									0–5
CEM III	Blast furnace cement	CEM III/A	35–64	36–65	–	–	–	–	–	–	–	–	0–5
		CEM III/B	20–34	66–80	–	–	–	–	–	–	–	–	0–5
		CEM III/C	5–19	81–95	–	–	–	–	–	–	–	–	0–5
CEM VI	Pozzolan cement	CEM VI/A	65–89	–	11–35					–	–	–	0–5
		CEM VI/B	45–64	–	36–55					–	–	–	0–5
CEM V	Composite cement[3]	CEM V/A	40–64	18–30	–	18–30			–	–	–	–	0–5
		CEM V/B	20–39	31–50	–	31–50			–	–	–	–	0–5

[1] The numbers in the table refer to the total major and minor components.
[2] The silica dust content is limited to 10%.
[3] In the Portland composite cements CEM II/A-M and CEM II/B-M, the pozzolan cements CEM IV/A and CEM IV/B and the composite cements CEM V/A and CEM V/B, the major component type must be specified by the cement designation.
[4] Total organic carbon (TOC) must not exceed 0.2% by weight.
[5] Total organic carbon (TOC) must not exceed 0.5% by weight.

Cement according to ASTM standard

According to ASTM regulations cement is described as:

Portland Cement	ASTM C150
Blended Cement	ASTM C595

ASTM C150 ***Standard Specification for Portland Cement*** covers the following cement types:

Type I	For use when the special properties specified for any other type are not required
Type IA	Air-entraining cement for the same uses as Type I, where air-entrainment is desired
Type II	For general use, more especially when moderate sulfate resistance is desired
Type IIA	Air-entraining cement for the same uses as Type II, where air-entrainment is desired
Type II(MH)	For general use, more especially when moderate heat of hydration and moderate sulfate resistance are desired
Type II(MH)A	Air-entraining cement for the same uses as Type II(MH), where air-entrainment is desired
Type III	For use when high early strength is desired
Type IIIA	Air-entraining cement for the same use as Type III, where air-entrainment is desired
Type IV	For use when a low heat of hydration is desired
Type V	For use when high sulfate resistance is desired

ASTM C 595 ***Standard Specification for Blended Hydraulic Cement*** covers blended hydraulic cements for both general and special applications, using slag or pozzolan, or both, with Portland cement or Portland cement clinker or slag with lime.

These cements are classified as following:

Type IS	Portland blast-furnace slag cement
Type IP	Portland-pozzolan cement
Type IT	Ternary blended cement

They can also be described according to air-entraining, moderate sulfate resistance, moderate heat of hydration, high sulfate resistance, or low heat of hydration properties.

3.2 Concrete Aggregates

Concrete aggregates, consisting of sand and gravel, represent the grain skeleton of the concrete. All cavities within this skeleton have to be filled with binder paste as complete as possible. Concrete aggregates sum up to approximately 80% of the concrete weight and 70 – 75% of the concrete volume. Optimum use of the aggregate size and quality improves the concrete quality.

Aggregates can occur naturally (fluvial or glacial), industrially produced like lightweight aggregates as well as recycled aggregates. For high-quality concrete they are cleaned and graded in industrial facilities by mechanical processes such as crushing, screening, mixing together and washing.
Concrete aggregates should have a strong bond with the hardened cement paste, should not interfere with the cement hardening, and should not have negative effect on concrete durability.

Standard aggregates	Density 2.2 – 3.0 kg/dm³	From natural deposits, e.g. river gravel, moraine gravel etc. Material round or crushed (e.g. excavated tunnel)
Heavyweight aggregates	Density > 3.0 kg/dm³	Such as barytes, iron ore, steel granulate for the production of heavy concrete (e.g. radiation shielding concrete)
Lightweight aggregates	Density < 2.0 kg/dm³	Such as expanded clay, pumice, polystyrene for lightweight concrete, insulating concretes
Hard aggregates	Density > 2.0 kg/dm³	Such as quartz, carborundum; e.g. for the production of granolithic concrete surfacing
Recycled granulates	Density approx. 2.4 kg/dm³	From crushed old concrete etc.

Standard aggregates according to European standards

In Europe aggregates are defined in standard EN 12620. This standard is very comprehensive and to give more details than in the list below would be outside the scope of this document.

Important terms from the standard (with additional notes)**:**

- **Natural aggregate**
  Comes from mineral deposits; it only undergoes mechanical preparation and/or washing.
- **Aggregate Mix**
  Aggregate consisting of a mixture of coarse and fine aggregates (sand).
  An aggregate mix can be produced without prior separation into coarse and fine aggregates or by combining coarse and fine aggregates (sand).
- **Recycled aggregate**
  Aggregate made from mechanically processed inorganic material previously used as a building material (i.e. concrete).
- **Filler (rock flour)**
  Aggregate predominantly passing the 0.063 mm sieve, which is added to obtain specific properties.
- **Particle size group**
  Designation of an aggregate by lower (d) and upper (D) sieve size, expressed as d/D.
- **Fine aggregate (sand)**
  Designation for smaller size fractions with D not greater than 4 mm.
  Fine aggregates can be produced by natural breakdown of rock or gravel and/or crushing of rock or gravel, or by the processing of industrially produced minerals.
- **Coarse aggregate**
  Name (description) for larger size fractions with D not less than 4 mm and d not less than 2 mm.
- **Naturally formed aggregate 0/8 mm**
  Designation for natural aggregate of glacial or fluvial origin with D not greater than 8 mm (can also be produced by mixing processed aggregates).
- **Fines**
  Proportion of an aggregate passing the 0.063 mm sieve.
- **Granulometric composition**
  Particle size distribution, expressed as the passing fraction in percent by weight through a defined number of sieves.

Passing fraction, particle size distribution curves

The particle size is expressed by the hole size of the test sieves just passed by the particle concerned.
It is of high importance to design a reasonable combination of the different materials and their corresponding fractions in order to achieve a continuous combined grading curve.

Aggregates according to ASTM standards

According to ASTM specification three different principal aggregate types are described:

Normal weight:	
Coarse and fine normal weight aggregates	ASTM C33
Lightweight:	
Lightweight aggregates for structural concrete	ASTM C330
Lightweight aggregates for masonry concrete	ASTM C331
Lightweight aggregates for insulating concrete	ASTM C332
Heavyweight:	
Heavyweight aggregates (aggregates for radiation-shielding concrete)	ASTM C637

A**STM C33** ***Standard Specification for Concrete Aggregates*** defines the requirements for grading and quality of fine and coarse aggregate for use in concrete.

Fine aggregate shall consist of natural sand, manufactured sand, or a combination thereof. Fine aggregate shall be free of injurious amounts of organic impurities. Fine aggregate for use in concrete that will be subject to wetting, extended exposure to humid atmosphere, or contact with moist ground shall not contain any materials that are deleteriously reactive with the alkalis in the cement in amount sufficient to cause excessive expansion of mortar or concrete. Fine aggregate subjected to five cycles of the soundness test shall have a required weighted average loss.

Coarse aggregate shall consist of gravel, crushed gravel, crushed stone, air-cooled blast furnace slag, or crushed hydraulic-cement concrete, or a combination thereof.

ASTM C330/331/332 ***Standard Specification for Lightweight Aggregates for Concrete*** covers the requirements of lightweight aggregates intended for use in various types of concrete applications in which prime consideration is reduced density while maintaining the compressive strength of the concrete.

Two general types of lightweight aggregates are covered by this specification:
- Aggregates prepared by expanding, pelletizing, or sintering products such as blast-furnace slag, clay, diatomite, fly ash, shale, or slate; and
- Aggregates prepared by processing natural materials, such as pumice, scoria, or tuff

The aggregates shall be composed predominately of lightweight-cellular and granular inorganic material. Lightweight aggregates shall be tested, and should not contain excessive amounts of deleterious substances; and should conform to the specified values of organic impurities, aggregate staining, aggregate loss of ignition, clay lumps and friable particles, loose bulk density, compressive strength, drying shrinkage, popouts, and resistance to freezing and thawing.

ASTM C637 ***Standard Specification for Aggregates for Radiation-Sielding Concrete*** covers special aggregates for use in radiation-shielding concretes in which composition or high specific gravity, or both, are of prime consideration.

Aggregates covered by this specification include:
- Natural mineral aggregates of either high density or high fixed water content, or both. (These include aggregates that contain or consist predominately of materials such as barite, magnetite, hematite, ilmenite, and serpentine).
- Synthetic aggregates such as iron, steel, ferrophosphorus and boron frit or other boron compounds (see Descriptive Nomenclature C638).
- Fine aggregate consisting of natural or manufactured sand including high-density minerals.
- Coarse aggregate may consist of crushed ore, crushed stone, or synthetic products, or combinations or mixtures thereof.

3.3 Concrete Admixtures

Concrete admixtures are liquids or powders which are added to the concrete during mixing in small quantities. Dosage is usually defined based on the cement content.

Concrete admixtures have significant impact on the fresh and/or hardened concrete properties. Admixtures can act chemically and/or physically.

Concrete admixtures to European standard

According to EN 206-1, concrete admixtures are defined and the requirements are described in EN 934-2. The standard differentiates between different product groups, which are described with slight abbreviations in the table on page 31.

Table 3.3.1: Dosage of admixtures according to EN 206-1:

Permitted dosage	≤ 5% by weight of the cement (The effect of a higher dosage on the performance and durability of the concrete must be verified.)
Low dosages	Admixture quantities < 0.2% of the cement are only allowed if they are dissolved in part of the mixing water.

If the total quantity of liquid admixture is > 3 L/m³ of concrete, the water quantity contained in it must be included in the w/c-ratio calculation.
If more than one admixture is added, their compatibility must be verified by specific testing.

Table 3.3.2: Admixtures - according to EN 934-2:

Water reducing admixture
Admixture which permits a reduction in the water content of a given mix without affecting the consistence, or which increases the slump/flow without affecting the water content; or produces both effects simultaneously.
Superplasticizer (high range water reducing admixture)
Admixture which permits a high reduction in the water content of a given mix without affecting the consistence, or which increases the slump/flow considerably without affecting the water content; or produces both effects simultaneously.
Retarder/water reducing admixture
Combines effects of a water reducing admixture (primary effect) and a retarder (secondary effect).
Retarder/superplasticizer
Combines effects of a superplasticizer (primary effect) and a retarder (secondary effect).
Set accelerator/water reducing admixture
Combines effects of a water reducing admixture (primary effect) and a set accelerating admixture (secondary effect).

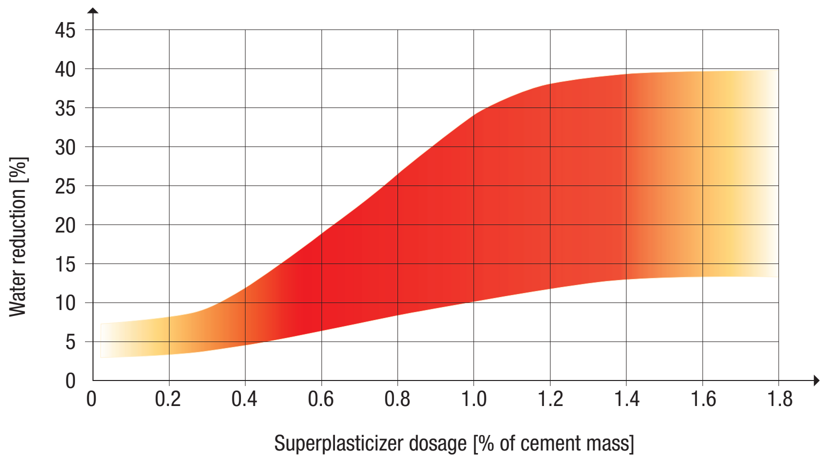


Fig. 3.3.1: Water reduction in % with Sika® ViscoCrete®/ SikaPlast®/ Sikament®

Table 3.3.3: Admixtures according to EN 934-2:

Viscosity modifying agent (stabilizer/water retaining admixture)
Reduces the loss of mixing water by reduction of bleeding of the fresh concrete.
Air-entraining agent
Provides evenly distributed air voids system by introducing a specific quantity of small air bubbles during the mixing process which remain in the concrete after it hardens.
Set accelerator
Reduces the time to initial set, with an increase in initial strength.
Hardening accelerator
Accelerates the early strength development of the concrete, with or without affecting the setting time and plastic properties of freshly mixed concrete.
Retarder
Extends the time to initial set, with an extended workability time and retardation of early strength development.
Water resisting admixture
Reduces the capillary water absorption of hardened concrete.

Table 3.3.4: Additional concrete admixtures not defined in European regulations:

Shrinkage reducing admixtures
Reduces early age drying shrinkage of the concrete in order to prevent drying shrinkage cracks.
Pumping aid
Admixture to improve the stability of the fresh concrete and easy pumping of concrete especially with application of difficult aggregates and unfavourable grading curves.
Corrosion inhibiting admixtures
Admixture producing a protective layer on the steel reinforcement in reinforced concrete. As a result start of corrosion is delayed and corrosion speed is decreased leading to extended durability.
Surface improving admixtures
Blowhole reducing admixture that significantly reduces the overall air void content in the fresh concrete- for production of high quality fair-faced concrete.
Admixtures to control alkali-silica reaction
Admixture allowing for control of alkali-silica reaction (ASR) in high-alkali concrete. Application minimizes deleterious expansions in concrete due to ASR and increases durability and life span of the concrete structure.

Concrete admixtures according to ASTM standard
According to ASTM regulations concrete admixtures are described as:

Chemical Admixtures	ASTM C494
Air-Entraining	ASTM C260
Corrosion Inhibiting Admixtures	ASTM C1582
Pigments	ASTM C979
Cold-Weather Admixture Systems	ASTM C1622
Shotcrete Admixtures	ASTM C1141

ASTM C494 *Standard Specification for Chemical Admixtures for Concrete* covers the materials and the test methods for use in chemical admixtures to be added to hydraulic-cement concrete mixtures in the field.
The standard states the following eight types:

Type A	Water-reducing admixtures
Type B	Retarding admixtures
Type C	Accelerating admixtures
Type D	Water-reducing and retarding admixtures
Type E	Water-reducing and accelerating admixtures
Type F	Water-reducing, high range admixtures
Type G	Water-reducing, high range, and retarding admixtures
Type S	Specific performance admixtures (e.g. slump retaining admixtures, used to improve and extend workability time of freshly mixed concrete without negative effect on setting times)

ASTM C979 ***Standard Specification for Pigments for Integrally Colored Concrete*** covers the basic requirement for colored and white pigments in powder form to be used as admixtures in concrete for the purpose of producing integrally colored concrete.

Where the pigments are a constituent of a multi component admixture, this specification applies to the pigment constituent of the admixture. This specification does not include the determination of pigment stability when elevated temperature using low-pressure (atmospheric) or high-pressure (autoclave) steam is used to accelerate the curing process. Cement (either Type I or Type II), aggregates, and admixtures materials shall be subjected to the following test methods: water wettability; alkali resistance; percentage of sulfates; water solubility; atmospheric curing stability; light resistance; effects on concrete, which include preparation of mixtures, making and curing, time of setting, air content, and compressive strength; and color match of shipment.

ASTM C1622 ***Standard Specification for Cold-Weather Admixtures Systems*** covers cold-weather admixture systems to be added to hydraulic-cement concrete when the temperature of the concrete immediately after placement will be low.

This specification stipulates tests of the cold-weather admixture system with suitable materials specified or with materials proposed for specific work, and provides three levels of testing. The apparatus used shall be suitable for low temperature environment. The concrete, cementitious materials, aggregates, and air-entraining admixture shall be tested and shall conform to the values of chemical and performance requirements such as initial setting time, compressive strength, shrinkage, durability.

3.3.1 Sika Products

Product name	Product type
Sika-Aer®	Air-entrainer
Sika® Antisol®	Curing agent
Sika® Antifreeze	Cold weather concretingadmixture
Sika® ColorFlo®	Concrete colors
Sika® Control	Shrinkage reducer
Sika® Control ASR	Admixture to control Alkali-Silica-Reaction in concrete
Sika® Ferrogard®	Corrosion inhibitor
SikaFiber®	Micro, macro or steel fiber
SikaFume®	Silica fume
Sika® Lightcrete	Foaming admixture
Sikament®	Plasticizer
SikaPaver®	Compaction aid / anti-efflorescence admixture
Sika® PerFin	Concrete surface improver
SikaPlast®	Superplasticizer
Sika® Plastiment®	Plasticizer / water reducer
Sika® Plastocrete®	Plasticizer / water reducer
SikaPoro®	Foam formers
SikaPump®	Pumping agent
SikaRapid®	Concrete accelerator
Sika® Retarder	Retarder
Sika® Rugasol®	Surface retarder
Sika® Separol®	Mold release agent
Sika® Sigunit®	Accelerator
Sika® Stabilizer	Viscosity modifying agent
SikaTard®	Retarder
Sika® ViscoCrete®	Superplasticizer
Sika ViscoFlow®	Workability enhancing admixture
Sika® WT	Water resisting admixtures

3.4 Concrete Additions and Supplementary Cementious Materials (SCM)

Concrete additions are defined as finely divided materials used in concrete in order to improve or to obtain desired fresh and hardened concrete properties. EN 206-1 lists two types of inorganic additions:

- Nearly inert additions (type I)
- Pozzolanic or latent hydraulic additions (type II)

Type I

Virtually inactive materials such as lime fillers, quartz dust and color pigments.

- Rock flours (quartz dust, powdered limestone)
  Low fines mixes can be improved by adding rock flours. These inert materials are used to improve the grading curve. The water requirement is higher, particularly with powdered limestone.
- Pigments
  Pigmented metal oxides (mainly iron oxides) are used to color concrete. They are added at levels of 0.5 – 5% of the cement weight; they must remain color-fast and stable in the alkaline cement environment. With some types of pigment the water requirement of the mix can increase.

Type II

Pozzolanic or latent hydraulic materials such as natural pozzolans (trass), fly ash and silica dust as well as ground granulated blast furnace slag.
Fly ash is a fine ash from coal-fired power stations which is used as an additive for both cement and concrete. Its composition depends mainly on the type of coal and its origin and the burning conditions (EN 450).
Silica dust (Silica fume) consists of mainly spherical particles of amorphous silicon dioxide from the production of silicon and silicon alloys. It has a specific surface of 18 – 25 m² per gram and is a highly reactive pozzolan (EN 13263).
Standard dosages of silica dust are 5% to 10% max. of the cement weight.
Specifications and conformity criteria for ground granulated blast-furnace slag for use in concrete, mortar and grout are regulated in EN 15167-1.

According to ASTM regulations supplementary cementitious materials (SCM) are defined as:

Fly ash and raw or calcined natural pozzolan	ASTM C618
Ground granulated blast-furnace slag	ASTM C989
Silica Fume	ASTM C1240

ASTM C618 ***Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*** covers coal fly ash and raw or calcined natural pozzolan for use in concrete where cementitious or pozzolanic action, or both, is desired, or where other properties normally attributed to fly ash or pozzolans may be desired, or where both objectives are to be achieved.

Fly ash and natural pozzolans shall conform to the prescribed chemical composition requirements and physical requirements. The materials shall be tested for fineness, strength activity index, water requirement, soundness, and autoclave expansion or contraction.

ASTM C989 ***Standard Specification for Slag Cement for Use in Concrete and Mortars*** covers three strength grades of finely ground granulated blast-furnace slag (Grades 80, 100, and 120) for use as a cementitious material in concrete and mortars.

The slag shall contain no additions and shall conform to the sulfide sulfur and sulfate chemical composition requirement. Physical properties of the slag shall be in accordance with the requirements for fineness as determined by air permeability and air content, slag activity index, and compressive strength.

ASTM C1240 ***Standard Specification for Silica Fume Used in Cementitious Mixtures*** covers silica fume for use in concrete and other systems containing hydraulic cement.

The material shall be composed of silica fume, mostly of amorphous silica. Test methods for chemical analysis, moisture content and loss on ignition, bulk density, specific surface, air entrainment of mortar, strength activity index, reactivity with cement alkalis, and sulfate resistance of silica fume shall conform to this specification. Physical tests shall include determining the specimen's density and the specific surface by utilizing the BET, nitrogen adsorption method. Silica fume shall be stored in such a manner as to permit easy access for the proper inspection and identification of each shipment.

3.5 Water

The suitability of water for concrete production depends on its origin.

EN 1008 lists the following types:

- **Drinking water**
  Suitable for concrete. Does not need to be tested.
- **Water recovered from processes in the concrete industry** (e.g. wash water)
  Generally suitable for concrete but the requirements in Annex A of the standard must be met (e.g. that the additional weight of solids in the concrete occurring when water recovered from processes in the concrete industry is used must be less than 1% of the total weight of the aggregate contained in the mix).
- **Ground water**
  May be suitable for concrete but must be checked.
- **Natural surface water and industrial process water**
  May be suitable for concrete but must be checked.
- **Sea water or brackish water**
  May be used for non-reinforced concrete but is not suitable for reinforced or prestressed concrete. The maximum permitted chloride content in the concrete must be observed for concrete with steel reinforcement or embedded metal parts.
- **Waste water**
  Not suitable for concrete.

Combined water is a mixture of water recovered from processes in the concrete industry and water from a different source. The requirements for the combined water types apply.

Preliminary tests (EN 1008, Table 1)
The water must first be analyzed for traces of oil and grease, foaming agents (detergents), suspended substances, odor (e.g. no odor of hydrogen sulphide after adding hydrochloric acid), acid content (pH $\geq$ 4) and humic substances.
Water which does not meet one or more of the requirements in Table 1 may only be used if it meets the following chemical specifications and its use does not have negative consequences for the setting time and strength development (see EN 1008 for test methods).

ASTM C1602 ***Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete*** covers mixing water used in the production of hydraulic cement concrete.

It defines sources of water and provides requirements and testing frequencies for qualifying individual or combined water sources. Mixing water shall consist of: batch water, ice, water added by truck operator, free moisture on the aggregates and water introduced in the form of admixtures.

Potable and non-potable water is permitted to be used as mixing water in concrete. The following are concrete performance requirements for mixing water: compressive strength and time of set.
Density of water shall be tested or monitored with a hydrometer. Optional chemical limits for combined mixing water are given for: chloride, sulfate, alkalis and total solids.

5. Fresh Concrete Properties and Tests

5.1 Water/Cement - Ratio

The water/cement-ratio (w/c) is the water : cement weight ratio of the fresh concrete.
It is calculated by dividing the weight of the total water (w) by the weight of the added cement (c).
The equation for the w/c-ratio is therefore:

$$w/c = \frac{w}{c} \text{ or } \frac{w}{c_{eq}} = \frac{w}{c + (K \times \text{type II addition})} \qquad [5.1.1]$$

The effective water content w_{eff} of a mix is calculated from the difference between the added water quantity w_0 in the fresh concrete and the water quantity absorbed of the aggregates (w_G, determined according to EN 1097-6) or the humidity of the aggregates w_h respectivly.

$$w_{eff} = \frac{w_0 - w_G + w_h}{c} \qquad [5.1.2]$$

The water content required is influenced by the aggregates used, round or crushed materials and their composition.
The choice of the w/c-ratio is determined principally by the environmental influences (exposure classes) according to EN 206-1.

Two methods to evaluate the water content in a concrete are used. The basic principle is to evaporate the water by kiln drying. The test can be done either by a gasburner or a microwave.

5.1.1 Pan testing method

The weight of the pan for water content testing has to be measured in the first step (a). A mass of approx. 10 kg of concrete (b) has to be placed in the pan. After 20 minutes of heating the pan, the weight of the pan with the dried concrete (c) has to be measured. The difference between a+b and c is the water content in the concrete.

To make sure that the concrete is dry weight it after 20 minutes, dry it again for 5 minutes and weight again. If the difference is below 5 g the concrete is dry by definition.

Calculation:

Water content of the sample:

$$w_0 = (m_0 - m_1) \times p_0 / m_0 \quad [kg/m^3] \qquad [5.1.3]$$

w/c-ratio:

$$(w_0 - w_G) / c \qquad [5.1.4]$$

p_0	density [kg/m³]	m_0	sample wet [kg]	w_G	absorbed water [kg/m³]
c	cement content [kg/m³]	m_1	sample dry [kg]	w_0	water content [kg/m³]

5.1.2 Microwave testing method

The microwave testing method for water content of fresh concrete is based on an Austrian norm. The maximal grain size for this test is 32 mm. The time between the mixing and the testing of the concrete shall not exceed 90 minutes.

For this test an amount of approx. 2'000 ± 100 g of fresh concrete is needed and has to be evenly distributed on the testing plate. The weight (m_f) of the concrete and the plate has to be measured with a scale with an accuracy of Δ ± 1g. Figure 5.1.1 shows the minimal kiln drying time according to the power of the microwave. After that time the weight of the plate with the dried concrete shall be measured and after that kiln drying in the microwave for another two minutes. The current weight and the measured weight shall not exceed a difference of 5 g. Else the sample has to be dried again.

$$w_0 = \frac{m_f - m_{dry}}{m_f} * 100\% \qquad [5.1.5]$$

w_0 water content [%]
m_f weight of sample of fresh concrete inclusive testing plate
m_{dry} weight of sample of dried concrete inclusive testing plate

The density of water is set at p_{water} = 1'000 kg/m³

Based on the calculated water content in % and the density of the fresh concrete the water content in kg/m³ can be calculated according to equation 5.1.6:

$$w_{(kg/m^3)} = w_0 * p_{fc} / 100 \qquad [5.1.6]$$

$w_{(kg/m^3)}$ water content [kg/m³]
w_0 water content [%]
p_{fc} fresh concrete denstity [kg/m³]

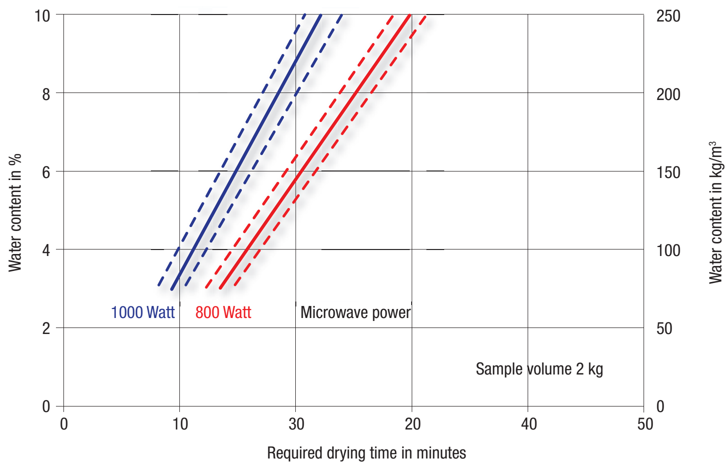


Fig. 5.1.1: Water content/drying time

5.2 Workability and Consistence

The consistence defines the behavior of the fresh concrete during mixing, handling, delivery and placing on site and also during compaction and surface smoothing. Workability is therefore a relative parameter and is basically defined by the consistence.

Workability requirements

- Cost effective handling, pouring/placing and finishing of the fresh concrete
- Maximum plasticity ('flowability'), with the use of superplasticizers
- Good cohesion
- Low risk of segregation, good surface smoothening ('finishing properties')
- Extended workability → Retardation/hot weather concrete
- Accelerated set and hardening process → Set and hardening acceleration / cold weather concrete

Unlike 'workability', the consistence – or deformability – of the fresh concrete can be measured. Standard EN 206-1 differentiates between 4 and 6 consistence classes dependent on the test method and defines fresh concretes from stiff to fluid.
The consistence tests are generally among the concrete control parameters which are established in preliminary tests for the applications involved.

Factors influencing consistence

- Aggregate shape and composition
- Cement content and type
- Water content
- Use of additives
- Use of concrete admixtures
- Temperature conditions
- Mixing time and intensity
- Time of measurement

Time and place of tests

The consistence of the concrete should be determined at the time of delivery, i.e. on site before placing (monitoring of workability).
If the consistence is recorded both after the mixing process (production consistency check) and before installation on site, a direct comparison of the change in consistence as a factor of the fresh concrete age is possible.
If the concrete is delivered in a ready-mix truck, the consistence may be measured on a random sample taken after about 0.3 m³ of material has been discharged.

Testing the consistence

'Workability' means the behavior of the fresh concrete during mixing, handling, delivery and placement at the point of placing and then during compaction and finishing of the surface. It is a measure of the deformability of the fresh concrete. It is defined by measurable numbers. Standard EN 206-1 divides consistence into 4 to 6 classes depending on the testing method. They can be used to specify and test a stiff to almost liquid consistence.
Testing the consistence by
- Slump test (see p. 57)
- Degree of compactability (see p. 58)
- Flow table spread (see p. 59)

Consistence tests are used for regular monitoring of the fresh concrete. The test frequency should be based on the importance of the structure and arranged so that a given concrete quality can be obtained consistently.

Chapters 8 – 10 of EN 206-1 give detailed information on these conformity controls.

Table 5.2.1: Tolerances for target consistence values according to EN 206-1

Test method	Degree of compactability			Flow table spread (FTS)	Slump		
Target value range	≥1.26	1.25 ... 1.11	≤1.10	All values	≤40 mm	50 ... 90 mm	≥100 mm
Tolerance	±0.10	±0.08	±0.05	±30 mm	±10 mm	±20 mm	±30 mm

Testing the consistence by the slump test

Principle:
The fresh concrete is placed in a hollow cone-shaped form and compacted. When the form is raised, the slump gives a measure of the concrete consistence. The slump is the difference in mm between the height of the form and the height of the fresh concrete cone out of the form.

EN 12350-2
The whole process from the start of pouring to rising of the form must be carried out within 150 seconds. The test is only valid if it gives a residual slump in which the concrete remains largely intact and symmetrical after removal of the form, i.e. the concrete remains standing in the form of a cone (or body resembling a cone). If the concrete collapses, another sample must be taken. If the specimens collapse in two consecutive tests, the concrete does not have the plasticity and cohesion required for the slump test.

Measurement of slump

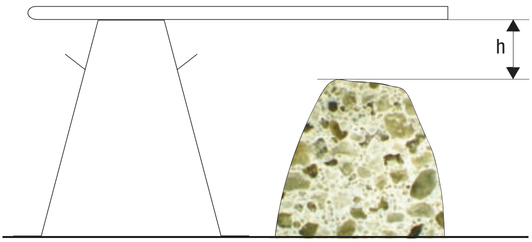


Fig. 5.2.1: Measurement of slump

Forms of slump

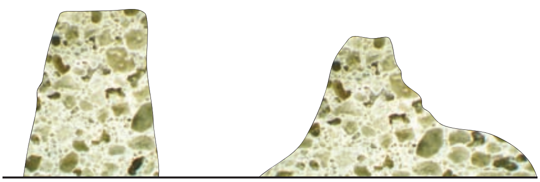


Fig. 5.2.2: Forms of slump

Slump classes: see chapter 11.1.3, Classification by consistence, page 227

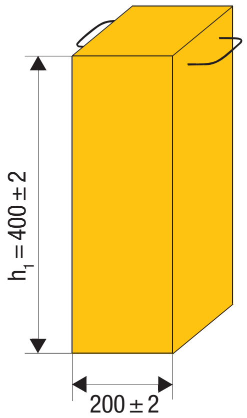
Testing the consistence by degree of compactability

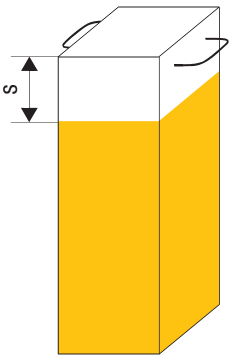
Principle:

The fresh concrete is placed carefully in the steel test container. Compaction must be avoided. When the container is full, the concrete is smoothed flush towards the edge without vibration. The concrete is then compacted, e.g. with a poker vibrator (max. bottle diameter 50 mm). After compaction the distance between the concrete surface and the top of the container is measured at the center of all 4 sides. The mean figure (s) measured is used to calculate the degree of compactability.

EN 12350-4

Container dimensions	*Base plate*	*200 x 200 mm*	*(±2 mm)*
	Height	*400 mm*	*(±2 mm)*





Dimensions in millimeters

Fig. 5.2.3: Concrete in container before compaction

Fig. 5.2.4: Concrete in container after compaction

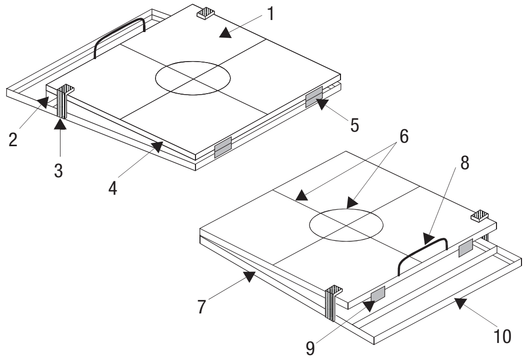
Degree of compactability: $c = \frac{h_1}{h_1 - s}$ (non-dimensional) [5.2.1]

Degree of compactibility classes: see chapter 11.1.3, Classification by consistence, page 227.

Testing the consistence by flow table test

Principle:
This test determines the consistence of fresh concrete by measuring the flow of concrete on a horizontal flat plate. The fresh concrete is first poured into a cone-shaped form (in 2 layers), compacted and smoothed flush with the top of the form. The form is then carefully removed vertically upwards. At the end of any concrete collapse, the plate is raised manually or mechanically 15 times up to the top stop and then dropped to the bottom stop. The concrete flow is measured parallel to the side edges, through the central cross.

EN 12350-5
Flow diameter classes: see see chapter 11.1.3, Classifictaion of consistence, page 227.



1 Metal plate
2 Lift height (limited to 40 ± 1)
3 Topstop
4 Impact place
5 Hinges (outside)
6 Marking
7 Frame
8 Handle
9 Bottom stop
10 Foot rest

Fig. 5.2.5: Flow table

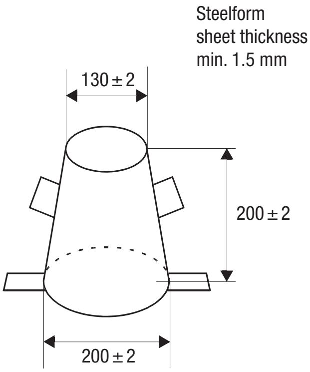


Fig. 5.2.6: Slump cone

Testing the consistence by slump-flow test and t_{500}

Principle:
This test determines the consistence of fresh concrete (SCC) by measuring the flow of concrete on a horizontal flat plate. The fresh concrete is first poured into a cone-shaped form. The form is then carefully removed vertically upwards. The concrete flow is measured parallel to the side edges, through the central cross. On the plate a ring with 500 mm diameter from the center is marked. The time measured from lifting the cone until the first contact of the flowing concrete and that ring is the so call t_{500} time.

EN 12350-8

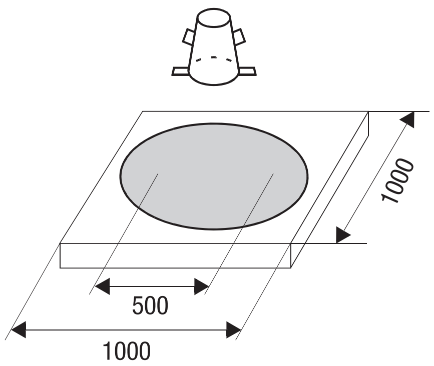


Fig. 5.2.7: Slump-flow test

An alternative method which can be found sometimes is to invert the slump cone. This makes the work easier, as the form does not have to be held while pouring.

This method is suitable for both site and laboratory use.

Further obstacles can be added by placing a ring of steel (J-ring) with serrated steel in the centre, to simulate the flow behavior around reinforcement.

Testing the consistence by L-Box test

Principle:
This test determines the consistence of fresh self-compacting concrete by measuring the flow of concrete in a L-box. The fresh concrete is first poured in the box. After lifting the barrier the concrete flows into the box. The height at the vertical section and the height at the end of the horizontal section is measured. The ratio of these heights is a measure of the passing or blocking behavior of the self-compacting concrete.
Two variations of this test are usually used: the two bar test and the three bar test. The three bar test simulates more congested reinforcement.

EN 12350-10

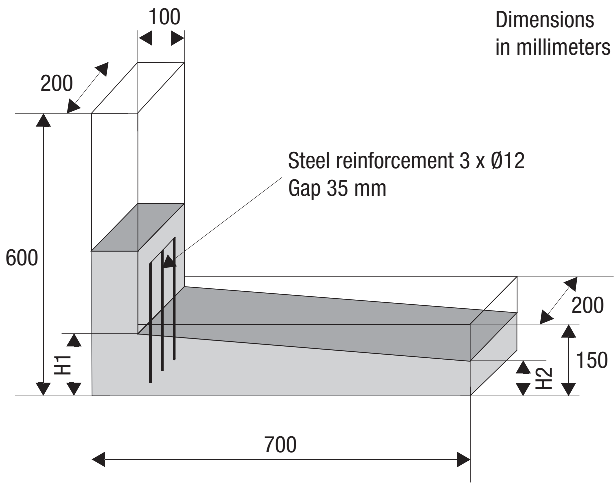


Fig. 5.2.8: L-Box

Testing the consistence by V-Funnel test

Principle:
This test determines the consistence of fresh self-compacting concrete by measuring the flow of concrete in a V-funnel. The fresh concrete is first poured in the V-funnel. After opening the barrier the concrete flows out of the V-funnel. The time measured from opening the barrier until the V-funnel is empty is recorded as V-funnel time. This test gives an indication about the viscosity and filling ability of self compacting concrete.

EN 12350-9

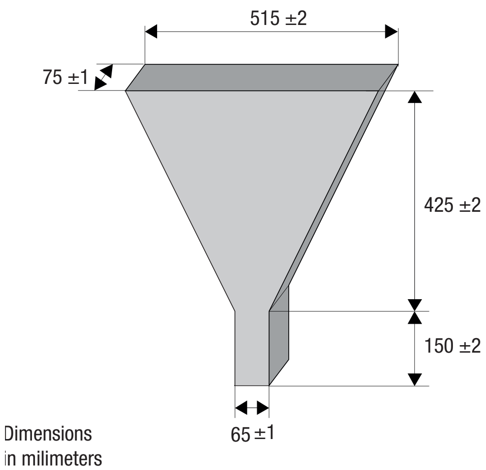
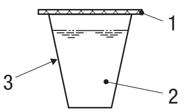


Fig. 5.2.9: V-Funnel

Testing the consistence by sieve segregation test

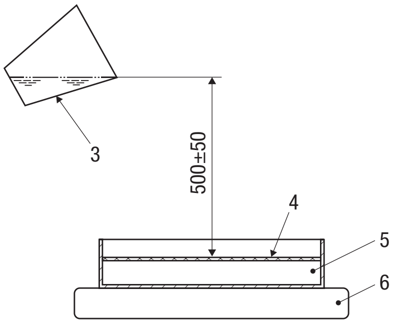
Principle:
This test determines the resistance of fresh self-compacting concrete against segregation. A sample of approx. 10 L has to be taken and allow the sample to stand for 15 minutes. After that waiting time the SCC is poured from a height of around 50 cm on the sieve set. Approx 4.8 kg has to be poured on the sieve set in one operation.

EN 12350-11



Key
1 Cover
2 Concrete
3 Sample container

Fig. 5.2.10: Sample container and cover



Key
3 Sample container
4 Sieve
5 Sieve receiver
6 Balance

Fig. 5.2.11: Measurement of segregated portion

The segregated portion SR is calculated from the following equation and reported to the nearest 1 %.

$$SR = \frac{(m_{ps} - m_p) \times 100}{m_c} \qquad [5.2.2]$$

where:

SR segregated portion [%]
m_{ps} mass of sieve receiver plus passed material [g]
m_p mass of the sieve receiver [g]
m_c initial mass of concrete placed onto the sieve [g]

5.3 Hot Weather Concrete

Concreting is only possible at high temperatures if special protective measures are provided. These must be in place from the start of concrete production to the end of curing. It is dependent on the outside temperature, air humidity, wind conditions, fresh concrete temperature, heat development and dissipation and the dimensions of the element. For example the concrete should be protected from drying out during transport.

The fresh concrete must not be hotter than +30 °C during placing and installation without protective measures.

Possible problems

Working with non-retarded concrete can become a problem at air temperatures higher than 25°C.

- Hydration is the chemical reaction of the cement with the water. It begins immediately on contact, continues through stiffening to setting (initial setting) and finally to hardening of the cement paste.
- All chemical reactions are accelerated at elevated temperatures.

As a result of early stiffening placing the concrete is no longer possible.
The normal countermeasures are the use of retarded superplasticizers or superplasticizers combined with a set retarder.

Retardation terms and dosing tables

Purpose of retardation: To extend the working time at a specific temperature.
Working time: The time after mixing during which the concrete can be correctly vibrated.
Free retardation: The initial setting is certain to start only after a specific time.
Targeted retardation: The initial setting starts at a specific time.

Certainty comes only from specific preliminary testing!

Table 5.3.1: Decisive temperature for structual elements

Structural element and retardation	Decisive temperature
Voluminous concrete cross sections	Fresh concrete temperature
Small concrete cross sections	Air temperature at placement point
The higher temperature (fresh concrete or air temperature) is the decisive one for voluminous concrete cross sections with long retardation, and for small concrete cross sections with short retardation.	

Dosing table for concrete with free retardation

The retardation depends largely on the type of cement.

Table 5.3.2: Dosage of Sika Retarder® in % of cement mass

Retardation time	Decisive temperature					
[h]	10 °C	15 °C	20 °C	25 °C	30 °C	35 °C
3	0.1	0.1	0.2	0.3	0.3	0.5
4	0.2	0.2	0.3	0.4	0.4	0.6
6	0.2	0.3	0.4	0.5	0.6	0.8
8	0.3	0.4	0.5	0.6	0.8	1.0
10	0.4	0.5	0.6	0.8	1.0	1.3
12	0.4	0.6	0.8	0.9	1.2	1.5
14	0.5	0.7	0.9	1.1	1.3	1.8
16	0.5	0.8	1.0	1.2	1.5	
18	0.6	0.9	1.1	1.4	1.7	
20	0.7	1.0	1.2	1.6		
24	0.8	1.1	1.5	1.8		
28	1.0	1.3	1.8			
32	1.2	1.5				
36	1.5	1.8				
40	1.8					

The dosages relate to concrete with 300 kg CEM I 42.5 N and w/c = 0.50. The dosage should be increased by about 20% for semi-dry concrete.
The figures in this table are laboratory results and relate to one specific cement type and special formulation of retarder which might not be available everywhere.
Preliminary suitability tests are always necessary.

Influencing factors
Various factors affect the retardation:

Influence of temperature
- Temperature increases shorten, and temperature reductions extend the retardation

Rule of thumb
- Each degree under 20 °C extends the retardation time by about 1 hour.
- Each degree over 20 °C shortens the retardation time by 0.5 hours.

For safety: **Preliminary testing!**

Influence of w/c-ratio
A cement content of 300 kg/m³ and a **Sika Retarder**® dosage of 1% show that:
- An increase in the w/c-ratio of 0.01 causes additional retardation of about half an hour

Combination with plasticizer/superplasticizer
- With a non-retarded superplasticizer, **Sika Retarder**® extends the retardation slightly.
- With a retarded superplasticizer, **Sika Retarder**® further extends (cumulative) the retardation.
- **Sika ViscoFlow**® can be used as a high performance retarder without any strong retardation of the initial setting of the concrete.

Preliminary testing should always be carried out on major projects.

Influence of cement
The hydration process of different cements can vary due to the different raw materials and grinding fineness. The retardation effect is also susceptible to these variations, which can be considerable at dosages of over 1%.
The tendency:
- Pure, fine Portland cements: retardation effect reduced
- Coarser cements and some mixed cements: retardation effect extended

For safety
- Preliminary tests!
- Always preliminary test at dosages over 1%!

Influence of concrete volume
If the whole of a concrete pour is retarded, the volume has no influence on the retardation effect. During the initial set of an adjacent pour (e.g. night retardation in a deck slab), the 'decisive temperature' changes in the contact zone with the retarded next section (it increases), and this will cause the retardation effect to decrease.

Characteristics of the retarded concrete

■ Hardening

If hardening is initiated after the retardation has stopped, it is quicker than in non-retarded concrete.

■ Shrinkage/creep

The final shrinkage or creep is less than in non-retarded concrete.

■ Early shrinkage

Contraction cracks resulting from early shrinkage can form due to dehydration during the retardation period (surface evaporation).

Protection from dehydration is extremely important for retarded concrete!

Correct curing is essential!

Examples of concreting stages with retardation

1. Night retardation

■ Foundation slabs

■ Decks, beams etc.

Towards the end of the normal day's concreting, 3 strips about 1.20 m wide with increasing retardation are laid.

1st strip: 1/3 of main dosage

2nd strip: 2/3 of main dosage

3rd strip: main dosage from table or preliminary testing results

Suspension of the works overnight.

Resumption of the works next morning:

1st strip (adjacent to the 3rd from the previous day) is retarded at 1/3 of the main dosage

2. Retardation with simultaneous initial setting

This happens with large bridge decks, basement slabs etc.

Important preparations are:

■ Define a precise concreting program with the engineer and contractor

■ On that basis, divide into sections and produce a time schedule

■ Target: all the sections set together

■ When the times are determined, the dosages for the individual sections can be specified on the basis of preliminary tests and precise temperature information.

Preliminary tests

Preliminary tests relate only to the concrete composition specified for the retarded stage:

- Same w/c-ratio and same cement type at the same dosage

The vibration limitations should be tested on site with several concrete samples per dosage (in minimum 20 liter vessels), in temperature conditions as similar as possible to the conditions during placing.

Procedure:

- Determine the retarder dosage from the table
- Fill at least 5 vessels with that concrete mix
- Vibrate the contents of the first vessel 2 hours before the assumed initial setting
- After every further hour vibrate the next vessel (the contents of each vessel are only vibrated once)
- When the contents of a vessel cannot be vibrated anymore, the concrete has begun to set
- Note the times obtained and check whether they correspond with the predictions (in the table)
- If the differences are too great, repeat the tests with an adjusted dosage.

Measures for retarded concrete

The formwork

Timber formwork used for the first time can cause unsightly staining, surface dusting etc., particularly around knots, due to wood sugars on the surface.

Timber formwork which is highly absorbent insufficiently wetted and not properly treated with release agent, draws far too much water from the concrete surface. Loose or friable particles and dusting are the result. This damage is greater in retarded concrete because the negative effects continue for longer.

Timber formwork which is properly prepared and correctly treated with **Sika® Separol®** will produce good, clean surfaces also with retarded concrete.

Compaction and curing

Retarded concrete must be compacted. The following stage (e.g. next morning) is vibrated together with the 'old pour'. Retarded areas are compacted and finished together.

Curing is enormously important, so that the retarded, compacted and now resting concrete loses as little moisture as possible.

The best methods for retarded surfaces (floors etc.) are:

- Cover with plastic sheeting or insulating blankets.

On retarded areas to be vibrated again later:

- Full covering with plastic sheets or damp hessian. Protect from draughts. Additional surface watering (i.e. misting) can cause washout.

5.4 Cold-Weather Concrete

Set Acceleration/Cold Concrete

The concrete should be protected from rain and frost during handling.
Concreting is only permissible in freezing temperatures if special protective measures are taken. They must be in place from the start of concrete production to the end of curing.
They depend on the outside temperature, air humidity, wind conditions, fresh concrete temperature, heat development and dissipation and the dimensions of the concrete pour.
The fresh concrete must not be colder than +5 °C during placement and installation without additional protective measures. The mixing water and aggregates should be preheated if necessary.

Problem

Low temperatures retard the cement setting. At temperatures below -10 °C the chemical processes of the cement stop (but continue after warming). Dangerous situations arise if concrete freezes during setting, i.e. without having a certain minimum strength. Structural loosening occurs, with a corresponding loss of strength and quality. The minimum strength at which concrete can survive one freezing process without damage is the so-called freeze resistance strength of 10 N/mm². The main objective must be to reach this freeze resistance strength as quickly as possible.

The temperature T of fresh concrete can be estimated by the following equation:

$$T_{mix} = \frac{c \cdot c_c \cdot T_c + a \cdot c_a \cdot T_a + w \cdot c_w \cdot T_w + w_a \cdot c_w \cdot T_a}{c \cdot c_c + a \cdot c_a + (w + w_a) \cdot c_w} \quad [°C] \qquad [5.4.1]$$

c	cement content [kg/m³]	c_c	specific heat content of cement 0.72 bis 0.92 kJ/(kg·K)		
a	aggregates [kg/m³]				
w	water [kg/m³]	c_a	specific heat of the aggregates		
w_a	water in aggregates as surface - and core moisture [kg/m³]		Quartz	0.80	kJ/(kg·K)
			Limestone	0.85 bis 0.92	kJ/(kg·K)
T_c	cement temperature [°C]		Granite	0.75 bis 0.85	kJ/(kg·K)
T_a	aggregates temperature [°C]		Basalt	0.71 bis 1.05	kJ/(kg·K)
T_w	water temperature [°C]	c_w	specific heat of water	4.19	kJ/(kg·K)

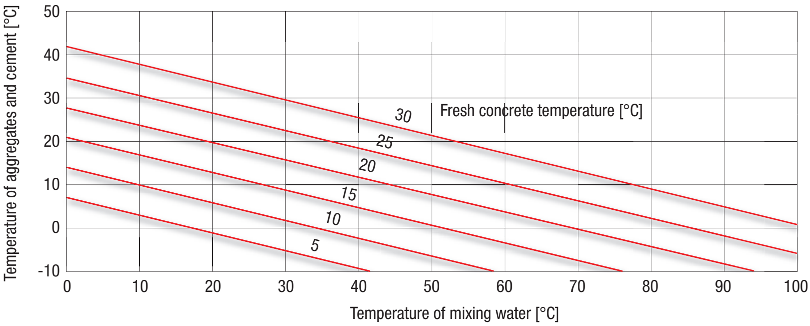


Fig. 5.4.1: Fresh concrete temperature

Measures

1. Minimum temperature

According to EN 206-1, the fresh concrete temperature on delivery must not be below +5 °C. (For thin, fine structured elements and ambient temperatures of -3 °C or below, EN requires a fresh concrete temperature of +10 °C, which must be maintained for 3 days!) These minimum temperatures are important for setting to take place at all. The concrete should be protected from heat loss during handling and after placing (see protective measures on site).

2. Reduction of w/c-ratio

The lowest possible water content leads to a rapid increase in initial strength. In addition, there is also less moisture available which could freeze. Superplasticizers allow a low w/c-ratio while retaining good workability.

3. Hardening acceleration

The use of **SikaRapid®-1** gives maximum hardening acceleration when there are high initial strength requirements.

Table 5.4.1: Time to reach 10 N/mm² at 0 °C in days [d]

	Time in days	
Concrete	**Control mix**	**With 1% SikaRapid®-1**
CEM I 300 kg/m³ w/c = 0.40	4 d	1 d
CEM I 300 kg/m³ w/c = 0.50	8 d	2 d

(Sika MPL)

4. Use of CEM I 52.5

The more finely ground, top grade cements are known to produce a more rapid increase in initial strength. Superplasticizers guarantee the best workability with a low w/c-ratio.

Protective measures on site

1. No concreting against or on frozen existing concrete.
2. The steel reinforcement temperature must be more than 0 °C.
3. Install the concrete quickly and immediately protect it from heat loss and evaporation (as important as in summer!). Thermal insulation blankets are best for this.

Example

for an outside temperature of -5 °C and a fresh concrete temperature of 11 °C.

Structural element	Decrease of concrete temperature down to +5 °C within	
Concrete deck d = 12 cm on timber formwork	~ 4 hours **without** insulation blankets	~ 16 hours **with** insulation blankets

4. For slabs: Heat the formwork from below if necessary.
5. Check air/ambient and concrete temperatures and the strength development regularly (e.g. with a rebound hammer).
6. Extend the formwork dismantling and striking times!

Conclusion: Winter measures must be planned and organized at an early stage by all parties.

Sika Product use

Product name	Product type	Fresh concrete property
Sikament® **SikaPlast®** **Sika® ViscoCrete®**	Superplasticizer	Freeze resistance strength reached rapidly due to water reduction
Sika® ViscoCrete®-HE	Superplasticizer	High initial strength in a short time
SikaRapid®-1	Hardening accelerator	Very high initial strength in a very short time
Sika® Antifreeze	Cold weather concreting admixture	Early concrete temperature increase

5.5 Fresh Concrete Air Content

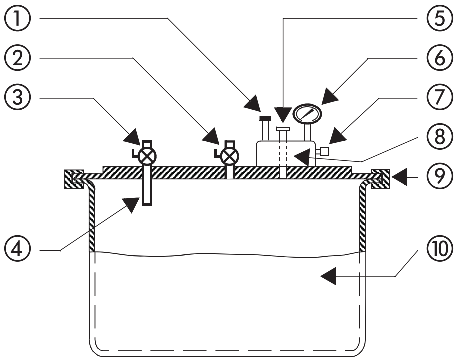
Determination of Air Content

There are two test methods using equipment operating on the same principle (Boyle-Mariotte's Law): these are the water column method, and the pressure equalization method. The description below is for the pressure equalization method, as this is more commonly used.

Principle:
A known volume of air at a known pressure is equalized with the unknown volume of air in the concrete sample in a tightly sealed chamber. The scale graduation of the pressure gauge for the resultant pressure is calibrated to the percentage of air content in the concrete sample.

EN 12350-7

1 Pump
2 Valve B
3 Valve A
4 Expansion tubes for checks during calibration
5 Main air valve
6 Pressure gauge
7 Air outlet valve
8 Air chamber
9 Clamp seal
10 Container



Air void test containers for standard concrete normally have a capacity of 8 liters. Compaction can be carried out with a poker or table vibrator. If using poker vibrators, ensure that entrained air is not expelled by excessive vibration.

Neither method is suitable for concrete produced with lightweight aggregates, air-cooled blast furnace slags or highly porous aggregates.

5.6 Fresh Concrete Density

Determination of Fresh Concrete Density

Principle:
The fresh concrete is compacted in a rigid, watertight container and then weighed.

EN 12350-6
The minimum dimensions of the container must be at least four times the maximum nominal size of the coarse aggregate in the concrete, but must not be less than 150 mm. The capacity of the container must be at least 5 liters. The top edge and base must be parallel.

(Air void test pots with a capacity of 8 liters have also proved very suitable.)

The concrete is compacted mechanically with a poker or table vibrator or manually with a bar or tamper.

$$p = \frac{m_t - m_{Pot}}{v_{Pot}} \cdot 1'000 \quad [kg/m^3] \qquad [5.6.1]$$

where:
p density [kg/m³]
m_t total weight [kg]
m_{Pot} weight air void test pot [kg]
v_{Pot} volume air void test pot [L]

5.7 Fresh Concrete Temperature

The fresh concrete temperature should not be too low, so that the concrete gains sufficient strength fast enough and does not suffer damage from frost at an early age.

- The fresh concrete temperature should not drop below +5 °C during placement and installation.
- The freshly placed concrete should be protected from frost. Freezing resistance is reached at a compressive strength of approximately 10 N/mm².
- On the other hand too high concrete temperatures can result in (cause) placement problems and decline of certain hardened concrete properties. To avoid this, the fresh concrete temperature should not go above 30 °C during placement and installation.

Precautions at low temperatures

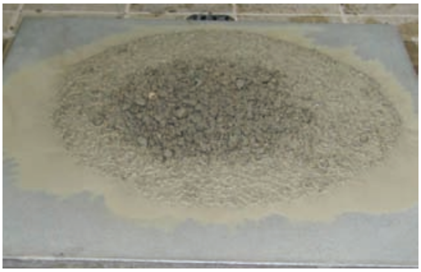
→ see cold weather concrete in cold ambient temperature conditions

Precautions at high temperatures

→ see hot weather concrete in warm temperature ambient conditions

5.8 Cohesion and Bleeding

The homogeneity and the internal cohesion of the concrete are the determining factors for an easy to handle and durable concrete. If the internal cohesion is bad and/or the homogeneity is insufficient, separation, bleeding and structure disturbances can occur and the structure of the concrete is damaged.



Cohesion

Ways to improve cohesion

- Increase the fines (powder + fine sand)
- Reduce the water content → use of a superplasticizer
  → **Sika® ViscoCrete®/SikaPlast®/Sikament®/Sika ViscoFlow®**
- Use a stabilizer → **Sika® Stabilizer**
- Use an air-entrainer → **Sika-Aer®**

Insufficient internal cohesion and/or homogeneity lead to

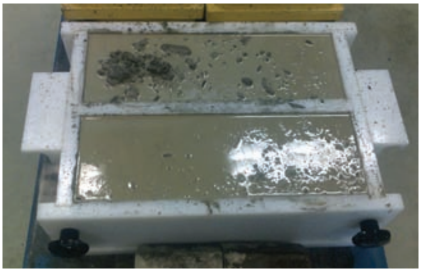
- Separation of the concrete
- Segregation of the concrete
- Structure disturbances can occur and the structure of the concrete is damaged
- Concrete placing can be hindered

How to improve cohesion/homogeneity?

- Adapt the grading curve of the aggregates
- Check the mix design concerning cement paste and fines content
- Target low w/c-ratios with simultaneous soft/fluid consistence
  → **Sika® ViscoCrete®** technology
- Use a water retaining/viscosity modifying admixture (VMA)
  → **SikaPump®/Sika® Stabilizer**

Bleeding

Bleeding is the leakage of water on the surface caused by separation of the concrete. It often occurs as a result lack of fines in the aggregate and in low cement or high water containing mixes.



Causes for bleeding

- Lack in fines in the aggregates
- Low cement containing mixes
- High water containing mixes
- Low fines containing mixes
- Variations in raw material dosage due to improper batching
- Overdosing of superplasticizer

Consequences

- Irregular, dusting, porous concrete surface
- Inadequate resistance to environmental actions and mechanical wear of concrete surface
- Efflorescence on the concrete surface

Possibility to reduce bleeding

- Optimize grading curve
- Reduce water content
- Use a viscocity modifying admixture (VMA)
- Increase the cement content

5. Fresh Concrete Properties and Tests

7. Hardened Concrete Properties and Tests

7.1 Requirements for Specimens and Molds

EN 12390-1

Terms from this standard:

- Nominal size:
  The common specimen size.
- Specified size:
  The specimen size in mm is selected from the permitted range of nominal sizes in the standard and used as the basis for the analysis.

Permitted nominal sizes available for use (in mm)							
Cubes [1]	Edge length	100		150	200	250	300
Cylinders [2]	Diameter	100	113 [3]	150	200	250	300
Prisms [1] [4]	Edge length of face	100		150	200	250	300

1 The specified sizes must not differ from the nominal sizes.
2 The specified sizes must be within 10% of the nominal size.
3 This gives a load transfer area of 10'000 mm².
4 The length of the prisms must be ≥ 3.5 d.

Permitted tolerances for specimens

Permitted tolerances	Cubes	Cylinders	Prisms
Specified size	± 0.5%	± 0.5%	± 0.5%
Specified size between top area and bottom (base) area	± 1.0%		± 1.0%
Evenness of load transfer areas	± 0.0006 d in mm	± 0.0005 d in mm	
Squareness of sides in relation to the base area	± 0.5 mm	± 0.5 mm	± 0.5 mm
Height		± 5%	
Permitted straightness tolerance for the barrel line of cylinders used for splitting tests		± 0.2 mm	
Straightness of the area on the supports, for flexural tests			± 0.2 mm
Straightness of load transfer area, for tensile splitting strength tests			± 0.2 mm

Molds

Molds must be waterproof and non-absorbent. Joints may be sealed with suitable material.

Calibrated molds

These should be made of steel or cast iron as the reference material. If other materials are used, their long term comparability with steel or cast iron molds must be proven.
The permitted dimensional tolerances for calibrated molds are stricter than as defined above for standard molds.

Making and Curing Specimens *

* **Note**: It is recommended that this standard should also be applied to all comparative concrete tests other than just the strength tests.

EN 12390-2

Notes on making specimens

- Stacking frame
  Pouring into the molds can be easier with an extension frame, *but its use is optional*.
- Compaction
  Poker vibrator with a minimum frequency of 120 Hz (7'200 oscillations per minute).
  (Bottle diameter ≤ ¼ of the smallest dimension of the specimen.)
  or
  Table vibrator with a minimum frequency of 40 Hz (2'400 oscillations per minute).
  or
  Circular steel tamper x 16 mm, length approx. 600 mm, with rounded corners.
  or
  Steel compacting rod, square or circular, approx. 25 × 25 mm, length approx. 380 mm.
- Release agents
  These should be used to prevent the concrete from sticking to the mold.

Notes on pouring

The specimens should be poured and compacted in at least 2 layers, but layers should be no thicker than 100 mm.

Notes on compaction

When compacting by vibration, full compaction is achieved if no more large air bubbles appear on the surface and the surface has a shiny and quite smooth appearance. Avoid excessive vibration (release of air voids!).
Manual compaction with a rod or tamper: The number of impacts per layer depends on the consistence, but there should be at least 25 impacts per layer.

Identification of specimens

Clear and durable labelling of the demolded specimens is important, particularly if they will then be conditioned for some time.

Conditioning of specimens

The specimens must remain in the mold at a temperature of 20 (± 2) °C, or at 25 (± 5) °C in countries with a hot climate, for at least 16 hours but no longer than 3 days. They must be protected from physical and climatic shock and drying.

After demolding, the specimens should be conditioned until the test begins at a temperature of 20 (± 2) °C, either in water or in a moisture chamber, at relative air humidity ≥ 95%.

(In the event of dispute, water conditioning is the reference method.)

Specifications for Testing Machines

EN 12390-4

This standard consists mainly of mechanical data: Pressure plates/force measurement/force regulation/force transmission.

For detailed information see the standard.

Principle

The test specimen is placed between an upper movable pressure plate (spherical) and a lower pressure plate and an axial compressive force is applied until break occurs.

Important notes

The test specimens must be correctly aligned in relation to the stress plane. The lower pressure plate must therefore be equipped with centering grooves, for example.

The compression testing machine should be **calibrated** after initial assembly (or after dismantling and reassembly), as part of the test equipment monitoring (under the quality assurance system) or at least once a year. It may also be necessary after replacement of a machine part which affects the testing characteristics.

Making and Curing Concrete Test Specimens in the Field

ASTM C31

This practice covers procedures for making and curing cylinder and beam specimens from representative samples of fresh concrete for a construction project. The concrete used to make the molded specimens shall be sampled after all on-site adjustments have been made to the mixture proportions, including the addition of mix water and admixtures. This practice is not satisfactory for making specimens from concrete not having measurable slump or requiring other sizes or shapes of specimens.
Molds for casting concrete test specimens shall conform to the requirements of Specification ASTM C470.

Report the following information:
- Identification number
- Location of concrete represented by the samples
- Date, time and name of individual molding specimens
- Slump, air content, and concrete temperature, test results and results of any other tests on the fresh concrete and any deviations from referenced standard test methods
- Curing method. For standard curing method, report the initial curing method with maximum and minimum temperatures and final curing method. For field curing method, report the location where stored, manner of protection from the elements, temperature and moisture environment, and time of removal from molds.

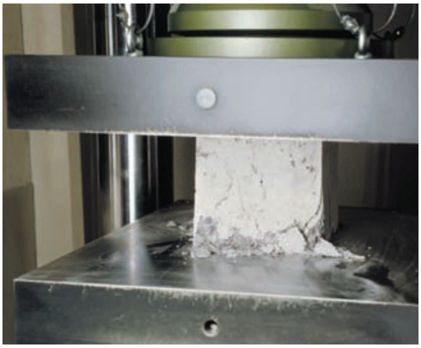
7. Hardened Concrete Properties and Tests

7.2 Compressive Strength

Copmpressive strength classes according to EN 206-1

An important property of hardened concrete is the compressive strength. It is determined by a compression test on specially produced specimens (cubes or cylinders) or cores from the structure.

The main factors influencing compressive strength are the type of cement, the w/c-ratio and the degree of hydration, which is affected mainly by the curing time and method.

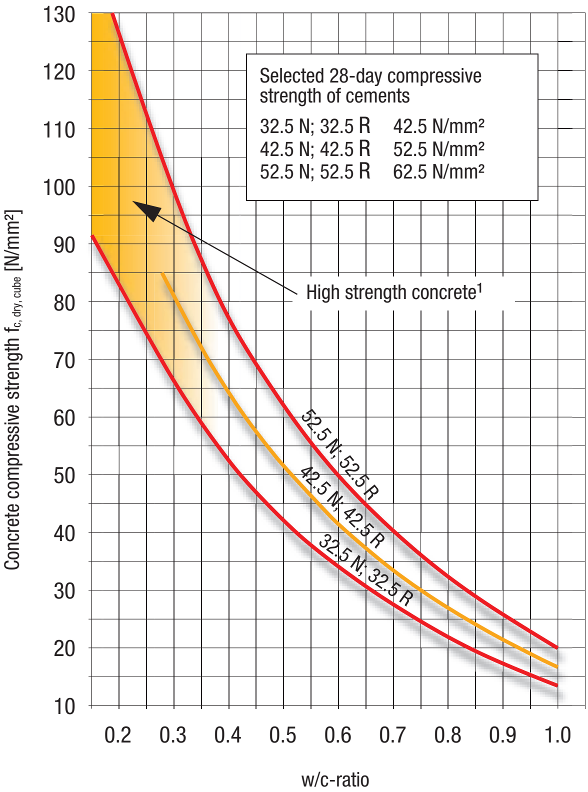


The concrete strength therefore results from the strength of the hydrated cement, the strength of the aggregate, the bond between the two components and the curing. Guide values for the development of compressive strength are given in the table below.

Table 7.2.1: Strength development of concrete (guide values[1])

Cement strength class	Continous storage at	3 days [%]	7 days [%]	28 days [%]	90 days [%]	180 days [%]
32.5 N	+ 20 °C + 5 °C	30 ... 40 15 ... 30	50 ... 65 40 ... 60	100 90 ... 105	100 ... 125	115 ... 130
32.5 R; 42.5 N	+ 20 °C + 5 °C	50 ... 60 20 ... 35	65 ... 80 40 ... 60	100 75 ... 90	105 ... 115	110 ... 120
42.5 R; 52.5 N	+ 20 °C + 5 °C	70 ... 80 20 ... 35	80 ... 90 35 ... 50	100 60 ... 75	100 ... 105	105 ... 110
52.5 R	+ 20 °C + 5 °C	80 ... 90 15 ... 25	90 ... 95 25 ... 45	100 45 ... 60	100 ... 103	103 ... 105

[1] The 28-day compressive strength at continuous 20 °C storage corresponds to 100%.



[1] In high strength concrete the influence of the standard compressive strength of the cement becomes less important.

Notes on the diagram:

$f_{c, dry, cube}$: – Average 28-day concrete compressive strength of 150 mm sample cubes.
– Storage according to DIN 1048; 7 days in water, 21 days in air.

Fig. 7.2.1: Correlation between concrete compressive strength, standard strength of the cement and w/c-ratio (according to Cement Handbook 2000, p.274)

High early strength

High early strength is the needed compressive strength after a predefined amount of time. This time needed is defined by the application. In general it is within the first 24 hours after production.

Parameters influencing high early strength concrete

Table 7.2.2: The strength development depend on the following parameters:

Parameter	Influence factor
CEM type	+++
CEM content	++
Additives (SF/Slag/FA)	+/-
Water content	+
Plasticizer/Superplasticizer	+/-
Accelerator	+++
Temperature (ambient, concrete, substrate)	+++
Curing	+/-
Aggregates	+

Final strength

By definition a concrete reaches its final strength after 28 days even though the compressive strength may increase in time (see *Table 7.2.1: Strength development of concrete*).

Parameters influencing final compressive strength

Table 7.2.3: The strength development depend on the following parameters:

Parameter	Influence factor
w/c-ratio	+++
CEM type	++
Additives (SF/Slag/FA)	++
Aggregates	+

The w/c-ratio is the decisive factor to influence the strength development/final strength and impermeability/durability of a concrete.

Compressive Strength of Test Specimens

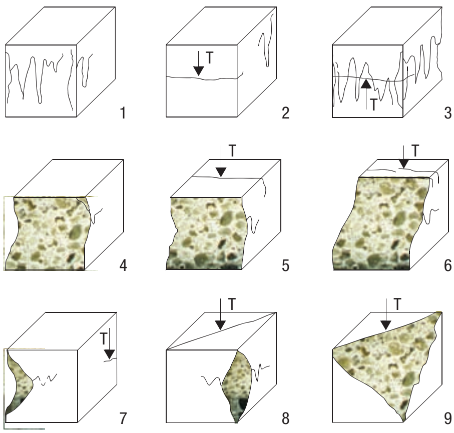
EN 12390-3 / ASTM C39

Test equipment: Compressive testing machine according to EN 12390-4.

Specimen requirements
The specimens must be cubes or prisms. They must meet the dimensional accuracy requirements in EN 12390-1. If the tolerances are exceeded, the samples must be separated out, adapted or screened according to Annex B (normative). Annex B gives details of how to determine the geometric dimensions.
One of the methods described in Annex A (normative) is used for adaptation (cutting, grinding or applying a filler material).
Cube samples should be tested perpendicular to the direction of pouring (when the cubes were made).
At the end of the test, the type of break should be assessed. If it is unusual, it must be recorded with the type number.

Fig. 7.2.2: Standard break patterns (illustrations from the standard)

Fig. 7.2.3: Unusual break patterns on cubes (illustrations from the standard)



T = Tension crack

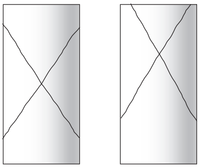
Schematic of typical fracture patterns according to ASTM C39

This test method covers determination of compressive strength of cylindrical concrete specimens such as molded cylinders and drilled cores. It is limited to concrete having a density in excess of 800 kg/m³ [50 lb/ft³].

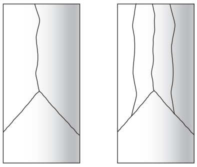
This test method consists of applying a compressive axial load to molded cylinders or cores at a rate which is within a prescribed range until failure occurs. The compressive strength of the specimen is calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen.

Molds and specimen have to be in accordance to ASTM C470 and ASTM C31.

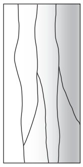
The compressive load has to be applied until the load indicator shows that the load is decreasing steadily and the specimen displays a well-defined fracture pattern (s. Fig. 7.2.4).



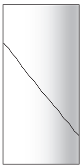
Type 1
Reasonably well-formed cones on both ends, less than 1 in. (25 mm) of cracking through caps



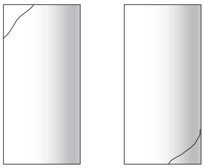
Type 2
Well-formed cone on one end, vertical cracks running through caps, no well-defined cone on other end



Type 3
Columnar vertical cracking through both ends, no well-formed cones



Type 4
Digital fracture with no cracking trough ends; tap with hammer to distinguish from Type 1



Type 5
Side fractures at top or bottom (occur commonly with unbonded caps)

Type 6
Similar to Type 5 but end of cylinder is pointed

Fig. 7.2.4: Fracture patterns according to ASTM C39

For Lightweight Insulating Concrete ASTM C495 applies.

Non destructive testing of compressive strength

ASTM C805

This test method covers the determination of a rebound number of hardened concrete using a spring-driven steel hammer.
It is applicable to assess the in-place uniformity of concrete, to delineate regions in a structure of poorer quality or deteriorated concrete, and to estimate in-place strength.
Relationships between rebound number and concrete strength that are provided by instrument manufacturers shall be used only to provide indications of relative concrete strength at different locations in a structure. To use this test method to estimate strength, it is necessary to establish a relationship between strength and rebound number for a given concrete mixture and given apparatus. Establish the relationship by correlating rebound numbers measured on the structure with the strengths of cores taken from corresponding locations. At least two replicate cores shall be taken from at least six locations with different rebound numbers. Select test locations so that a wide range of rebound numbers in the structure is obtained. Obtain, moisture condition, and test cores in accordance with Test Method C42/C42M.
For a given concrete mixture, the rebound number is affected by factors such as moisture content of the test surface, the method used to obtain the test surface (type of form material or type of finishing), vertical distance from the bottom of a concrete placement, and the depth of carbonation. These factors need to be considered in interpreting rebound numbers.
Different hammers of the same nominal design may give rebound numbers differing from 1 to 3 units. Therefore, tests should be made with the same hammer in order to compare results. If more than one hammer is to be used, perform tests on a range of typical concrete surfaces so as to determine the magnitude of the differences to be expected.
This test method is not suitable as the basis for acceptance or rejection of concrete.

EN 12504-2

Methodology similar as ASTM C805

7.3 Watertightness

The watertightness defines the resistance of the concrete structure against the penetration of water. The watertightness of concrete is determined by the impermeability (capillary porosity) of the hydrated cement.

Definition of watertightness

- Max. penetration depth has to be agreed by the involved parties (Sika recommendation < 30 mm)
- Requirement: Good concrete quality and the right solution for joint design!

In the US there is no ASTM standard for watertightness instead following methods are used:
- CRD-C 48-92 Standard Test Method for Water Permeability of Concrete.
- ASTM C 1585 Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes.

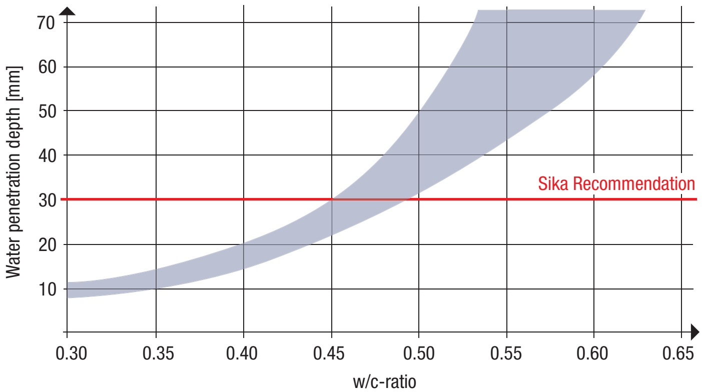


Fig. 7.3.1: Water penetration depth

Definition of water impermeability

- Water conductivity q_w < evaporable water volume q_d
  →The higher wall thickness d is, the better the watertightness

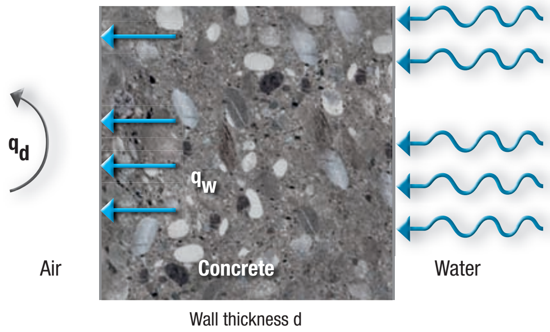


Fig. 7.3.2: Principle of water conductivity

- Recommended range for watertight structures: $q_w \leq 6$ g/m² ×h

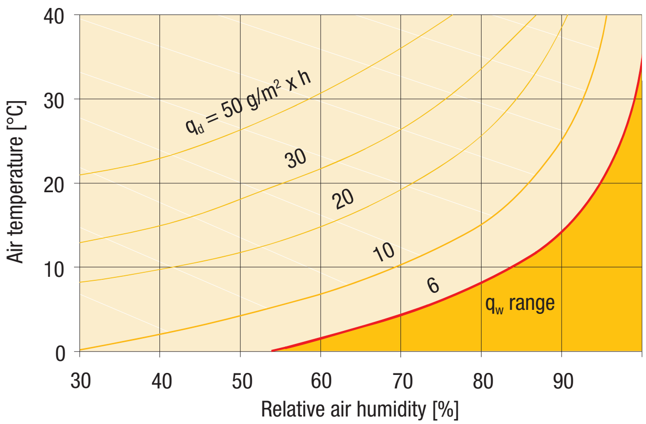


Fig. 7.3.3: Water conductivity

- **Load**
  Variable saturation due to continuous water contact
- **Test**
  Measurement of water conductivity q_w

Reduction of capillary voids and cavities by water reduction

High w/c-ratio > 0.60
Large voids due to absence of fine sand and fines

Low w/c-ratio > 0.40
Very dense cement matrix

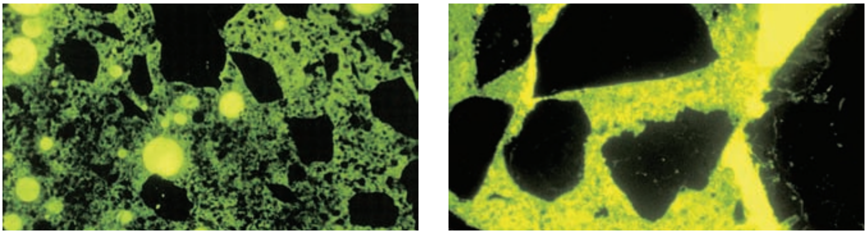


Fig. 7.3.4: Porosity of concrete at different w/c-ratios

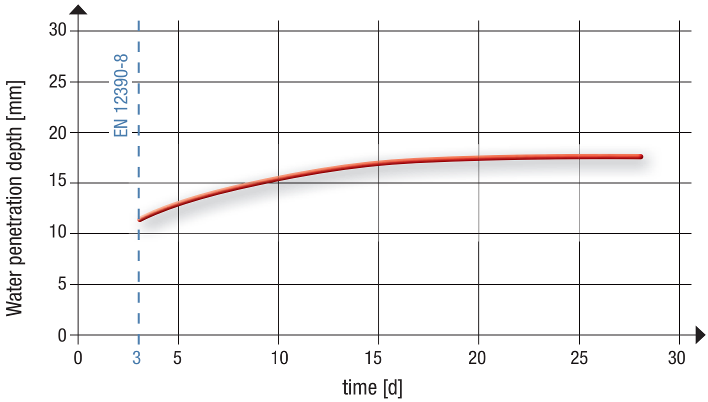


Fig. 7.3.5: Water penetration depth under 5 bar pressure over time

Proper hydration is of primary importance for watertight concrete. Therefore correct curing of the concrete is essential.

Test methods e.g. EN 12390-8 ASTM C1012 CRD-C 48-92

EN 12390-8: Depth of penetration of water under pressure

Principle
Water is applied under pressure to the surface of hardened concrete. At the end of the test period the test specimen is split and the maximum depth of penetration of water is measured.

Test specimens
The specimens are cubes, cylinders or prisms with a minimum edge length or diameter of 150 mm. The test area on the specimen is a circle with a 75 mm diameter (the water pressure may be applied from above or below).

Conditions during the test
- The water pressure must not be applied on a smoothed/finished surface of the specimen (preferably take a shuttered lateral area for the test). The report must specify the direction of the water pressure in relation to the pouring direction when the specimens were made (at right angles or parallel).
- The concrete surface exposed to the water pressure must be roughened with a wire brush (preferably immediately after striking of the specimen).
- The specimens must be at least 28 days old at the time of the test.

Test
During 72 hours, a constant water pressure of 500 (± 50) kPa (5 bar) must be applied. The specimens must be regularly inspected for damp areas and measurable water loss. After the test the specimens must be immediately removed and split in the direction of pressure. When splitting, the area exposed to the water pressure must be underneath. If the split faces are slightly dry, the directional path of penetration of water should be marked on the specimen. The maximum penetration under the test area should be measured and stated to the nearest 1 mm.

ASTM C1585: Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes

This test method is used to determine the rate of absorption (sorptivity) of water by hydraulic cement concrete by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time when only one surface of the specimen is exposed to water.
The exposed surface of the specimen is immersed in water and water ingress of unsaturated concrete dominated by capillary suction during initial contact with water.

7.4 Frost and Freeze/Thaw Resistance

Frost stress

Damage to concrete structures due to frost can generally be expected when those have been penetrated by moisture and are exposed to frequent freeze/thaw cycles in that condition. The damage to the concrete occurs due to the cyclic freezing and thawing of the water which has been absorbed due to capillary suction. Destruction follows due to the increase in volume of the water [ice] in the outer concrete layers.

Essentials for high frost resistance

- Frost-proof aggregates
- Impermeable concrete structure and/or
- Concrete enriched with micropores
- Thorough and careful curing
- Degree of hydration of the concrete as high as possible (i.e. it is not a good idea to place concrete immediately before periods of frost)

Freeze/thaw resistance

Given the extensive use of de-icing salts (generally sodium chloride NaCl, intended to lower the freezing point of the water on roads and prevent ice formation etc.), the concrete surface cools abruptly due to heat extraction from the concrete. These interactions between frozen and unfrozen layers cause structural breakdown in the concrete.

Conditions for freeze/thaw resistance

- Frost-proof aggregates
- Concrete with a dense structure enriched with micropores
- Thorough and careful curing
- Avoid too much fine mortar deposits on the surface area
- Concreting as long as possible before the first freeze/thaw stress so that the concrete can dry out.

Test methods e.g. Pre Standard CEN/TS 12390-9 ASTM 666

EN 12390-9 (2006: Pre-standard)

The standard describes how to test the frost resistance of concrete with water and the freeze/thaw resistance with NaCl solution ('salt water'). The amount of concrete which has separated from the surface after a defined number and frequency of freeze/thaw cycles is measured.

Principle
Specimens are repeatedly cooled to temperatures partly below – 20 °C and reheated to + 20 °C or over (in water or a common salt solution). The resultant amount of material separation indicates the available frost or freeze/thaw resistance of the concrete.

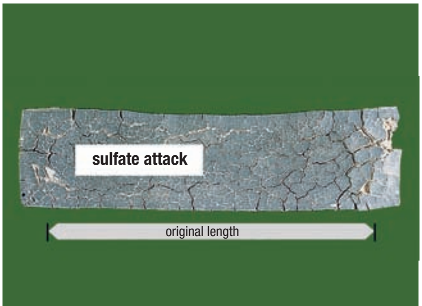
Three methods are described:
- Slab test method
- Cube test method
- CD/CDF test method

The slab test method is the reference method.

Terms from the pre-standard
- Frost resistance:
  Resistance to repeated freeze/thaw cycles in contact with water
- Freeze/thaw resistance:
  Resistance to repeated freeze/thaw cycles in contact with de-icing agents
- Weathering:
  Material loss on the concrete surface due to the action of freeze/thaw cycles
- Internal structure breakdown:
  Cracks within the concrete which are not visible on the surface but which produce a change in the concrete characteristics such as a reduction in the dynamic E-modulus

7.5 Sulfate

Water containing sulfate sometimes occurs in soil or dissolved in ground water and can attack the hardened concrete.



Picture: BetonSuisse Merkblatt 01

Process
Water containing sulfate combines with the tricalcium aluminate (C_3A) in the cement to form ettringite (also thaumasite under certain conditions), which leads to increases in volume and to high internal pressure in the concrete structure and therefore cracking and spalling occurs.

Measures
- Concrete structure as impermeable as possible i.e. low porosity → use of the Sika Silica fume technology → **SikaFume®**
- Low w/c-ratio aim for ≤ 0.45 → **Sika® ViscoCrete®/SikaPlast®/Sikament®**
- Use cement with a low amount of tricalcium aluminate (C_3A) content
- Curing suited to the structure

Note: Clarification of specific requirements is essential for every project.
Limiting values for exposure classification of chemical attack from natural soil and ground water (see p. 225).

Test methods e.g. ASTM C1012 SIA 262/1

ASTM C1012

This test method provides a means of assessing the sulfate resistance of mortars made using portland cement, blends of portland cement with pozzolans or slags, and blended hydraulic cements.
The standard exposure solution used in this test method, unless otherwise directed, contains 352 moles of Na_2SO_4 per m^3 (50 g/L). Other sulfate concentrations or other sulfates such as $MgSO_4$ may be used to simulate the environmental exposure of interest. This test method covers the determination of length change of mortar bars immersed in a sulfate solution.

SIA 262/1

This test method provides a means of assessing the sulfate resistance of a concrete sample. Concrete samples have to be prepared according to EN 206-1. For four cycles samples have to be dried and stored in a sulfate containing solution (5% sodium sulfate solution). The sulfate might react with parts of the samples and causes a volumetric change of the sample.

7.6 Fire Resistance

The danger of fire is present always and everywhere. The imminent danger depends upon actual exposure, and naturally differs if the threatened construction is a pedestrian subway, a roadway tunnel or a subterranean garage in a skyscraper. Concrete is the load-bearing material in nearly all built structures and is therefore at high risk, since the entire structure would collapse upon its material failure. Concrete must therefore, independent of the danger scenario, be properly formulated or protected by external measures, in order to hinder failure at high temperature in case of fire.

Measures

- Aggregates of the carbonate type – limestone, dolomite, limerock, tend to perform better in a fire as they calcine. Types containing silica perform less well.
- Polymer or polypropylene monofilament fibers significantly reduce the explosive spalling effect of concrete under fire load
  → common dosage 2-3 kg/m^3
- Sprayed applied lightweight mortars such as **Sikacrete®-F** act as a passive protection of the concrete

Test methods e.g. ASTM E119 ACI 216 DIN 4102 DIN 1991-1-2

ASTM E119

The test exposes a test specimen to a standard fire controlled to achieve specified temperatures throughout a specified time period. The test provides a relative measure of the fire-test-response of comparable building elements under these fire exposure conditions. The exposure is not representative of all fire conditions because conditions vary with changes in the amount, nature and distribution of fire loading, ventilation, compartment size and configuration, and heat sink characteristics of the compartment. Variation from the test conditions or test specimen construction, such as size, materials, method of assembly, also affects the fire-test-response. For these reasons, evaluation of the variation is required for application to construction in the field.

Testing with design fires (temperature-time curves)

These fire exposure rating curves all simulate the temperature profile of a tunnel fire. The example of the Dutch RWS curve defines the maximum exposure which can be expected in the worst case scenario: This is defined as a fire of a road tanker truck with a load capacity of 50 m^3 that is 90% full of liquid hydrocarbon fuel (petrol). After 120 minutes the temperature on the reinforcement of the concrete shall not exceed 250 °C in order to pass the test procedure.

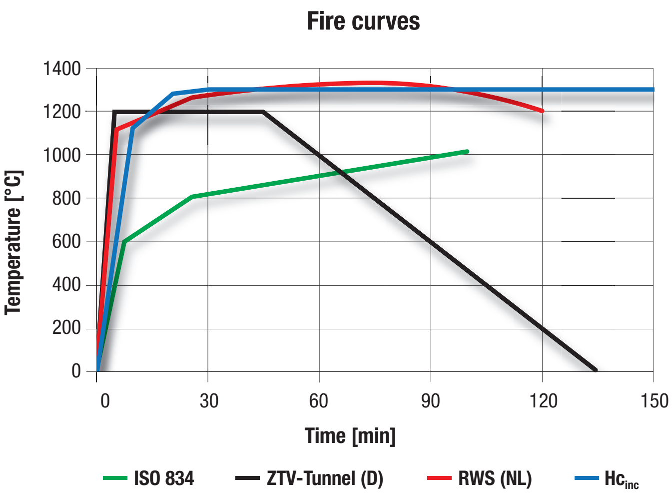
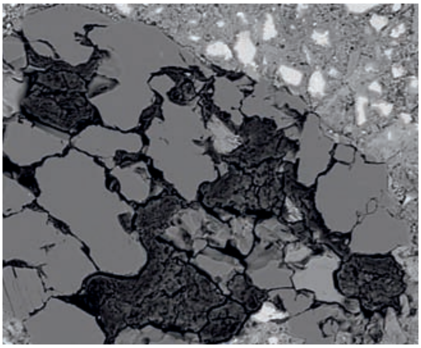


Fig. 7.6.1: Temperature-time curves of various design fires based on different regulations

7.7 AAR Resistance



Alkali-Aggregate Reaction (AAR) means reactions of the pore solution of the concrete with the aggregates. They produce a silica gel which swells due to water absorption and causes cracking or spalling in the concrete.
The form and rate of the reaction vary according to the type of aggregate.

- Alkali-Silica Reaction (ASR) with volcanic aggregates
- Alkali-Carbonate Reaction (ACR) with limestone
- Alkali-Silicate Reaction (ASR) with crystalline aggregates

Alkali-Aggregate Reaction
There is a risk of this reaction when using alkali-sensitive aggregates. The problem can obviously be overcome by not using these aggregates – but this is often impractical for economic and ecological reasons. By using suitable cements and high performance concrete technology, this reaction can be prevented or at least reduced.
The precise mechanisms involved continue to be intensively analyzed in great detail. Roughly speaking, alkali ions penetrate the aggregates with water absorption, and generate an internal pressure which causes cracks and bursting in the aggregate, and later the cement matrix, destroying the concrete. This can be described in simple terms as a pressure or expansion effect. Its duration and intensity depend on the reactivity of the cement, type and porosity of the aggregate, the porosity of the concrete and the preventative measures adopted.

The measure are:

- Partial replacement of the Portland cement by slag or other additions (silica fume/fly ash) with low equivalent Na_2O
- Analysis of the AAR/ASR potential of the aggregate and its classification (petrographic analyses/microbar test/performance testing etc.)
- Replacement or partial replacement of the aggregates (blending of available aggregates)
- Keep moisture access to the concrete low or prevent it (seal/divert)
- Reinforcement design for good crack distribution in the concrete (i.e. very fine cracks only)
- Impermeable concrete design to minimize the penetration of moisture

Test methods e.g. ASTM C1260 AFNOR P 18-454 AFNOR XPP 18-594

ASTM C1260 Test method for potential alkali reactivity of aggregates (Mortar-Bar method)

This test method provides a means of detecting the potential of an aggregate intended for use in concrete for undergoing alkali-silica reaction resulting in potentially deleterious internal expansion. It is based on the NBRI Accelerated Test Method (1-4). It is especially useful for aggregates that react slowly or produce expansion late in the reaction. However, it does not evaluate combinations of aggregates with cementitious materials nor are the test conditions representative of those encountered by concrete in service.
Because the specimens are exposed to a NaOH solution, the alkali content of the cement is not a significant factor in affecting expansions.
When excessive expansions (see Appendix X1) are observed, it is recommended that supplementary information be developed to confirm that the expansion is actually due to alkali-silica reaction. Sources of such supplementary information include:

- Petrographic examination of the aggregate (Guide C295) to determine if known reactive constituents are present
- Examination of the specimens after tests (Practice C856) to identify the products of alkali reaction
- Field service records can be used in the assessment of performance (where available)

When it has been concluded from the results of tests performed using this test method and supplementary information that a given aggregate should be considered potentially deleteriously reactive, the use of mitigative measures such as low-alkali portland cement, mineral admixtures, or ground granulated blast-furnace slag should be evaluated.
This test method permits detection, within 16 days, of the potential for deleterious alkali-silica reaction of aggregate in mortar bars.

7.8 Abrasion Resistance

Concrete surfaces are exposed to rolling stress (wheels/traffic), grinding stress (skids/tyres) and/or impact stress (bulk materials/liquids). The cement matrix, aggregates and their bond are all stressed together. This attack is therefore primarily mechanical.

Conditions for better abrasion resistance

The abrasion resistance of the hydrated cement is lower than that of the aggregate, particularly with a porous cement matrix (high water content). However, as the w/c-ratio decreases, the porosity of the hydrated cement decreases as well and the bond with the aggregate improves.

- Ideal: w/c-ratio equal or lower than 0.45
- Improvement in the density of the hydrated cement matrix, the bond of the aggregate and the hydrated cement (**SikaFume**®)
- Selection of a good grading curve, using special sizes if necessary, thorough curing
- To increase the abrasion resistance still further, special aggregates should also be used

If the layer thickness exceeds 50 mm, a light reinforcement mesh should normally be incorporated (min. 100×100×4×4 mm).

Adhesion to the substrate and finishing

- Before installation, a ‘bond coat’ is brushed into the slightly damp substrate (pre-wetted!).

Curing

Curing has to start as early as possible and should be maintained for sufficient period of time, by spraying **Antisol**® (Attention! Take any subsequent coating into consideration!) or by covering with sheets.

Test methods e.g. ASTM C779 ASTM C418 ASTM C944 DIN 52108

ASTM C779 Standard test method for abrasion resistance of horizontal concrete surfaces

The three test methods provide simulated abrasion conditions, which can be used to evaluate the effects on abrasion resistance of concrete, concrete materials, and curing or finishing procedures. They may also be used for quality acceptance of products and surface exposed to wear. They are not intended to provide a quantitative measurement of length of service.
The equipment used by each of these procedures is portable and thus suitable for either laboratory or field testing.

This test method covers three procedures for determining the relative abrasion resistance of horizontal concrete surfaces. The procedures differ in the type and degree of abrasive force they impart, and are intended for use in determining variations in surface properties of concrete affected by mixture proportions, finishing, and surface treatment. They are not intended to provide a quantitative measurement of the length of service that may be expected from a specific surface.

DIN 52108 Testing of inorganic non-metallic materials – wear test using the grinding wheel according to Böhme – Grinding wheel method

This test method provides simulated abrasions conditions using a grinding wheel. Cubes or plates are tested under norm conditions according to the procedure described in DIN 52108. The result is either a loss in thickness or loss in volume of the specimen.

7.9 Chemical Resistance

Concrete can be attacked by contaminants in water, soil or gases (e.g. air). Hazards also occur in service (i.e. in tanks, industrial floors, wastewater treatment facilities etc.).

- Surface and ground water, harmful soil contaminants, air pollutants, vegetable and animal substances can attack the concrete chemically
- Chemical attack can be divided into two types:
  - Disolvent attack: caused by the action of soft water, acids, salts, bases, oils and greases etc.
  - Swelling attack: caused mainly by the action of water soluble sulfates (sulfate swelling)

Picture: BetonSuisse Merkblatt 01

Measures

- Concrete matrix as dense as possible, i.e. low porosity → use of the Sika Silica fume technology → **SikaFume®**
- Low w/c-ratio aim for ≤ 0.45 → **Sika® ViscoCrete®/SikaPlast®/Sikament®**
- Increase the concrete cover by 10 mm minimum

Concrete only has adequate resistance against very weak acids. Medium strength acids degrade the concrete. Therefore extra protection of the concrete with a coating must always be specified for moderate to highly aggressive acid attack.

Test methods e.g.

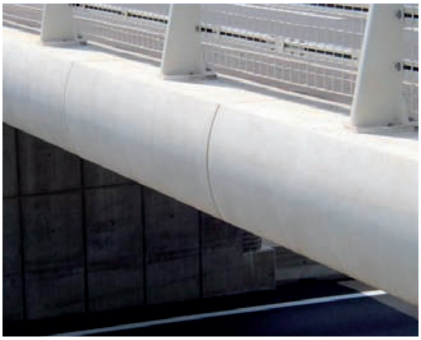
There is no standard covering all kind of chemical attack.

EN 13529 AASHTO T 259 ASTM C1202

7. Hardened Concrete Properties and Tests

7.10 Flexural Strength

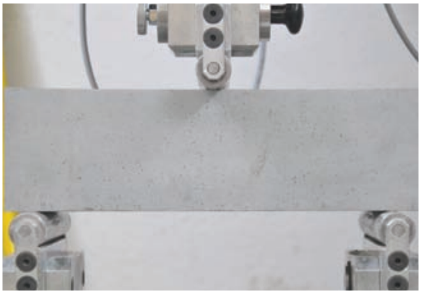
Concrete is basically used under compressive stress and the tensile forces are absorbed by reinforcement bars. Concrete itself has some tensile and flexural strength, which is strongly dependent on the mix. The critical factor is the bond between aggregate and hydrated cement. Concrete has a flexural strength of approximately 2 N/mm² to 7 N/mm².

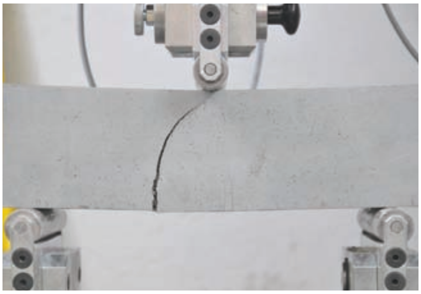


Influences on flexural strength

Flexural strength increases
- As the standard cement compressive strength increases (CEM 32.5; CEM 42.5; CEM 52.5)
- As the w/c-ratio decreases
- By the use of angular and crushed aggregate

Applications
- Steel fiber reinforced concrete
- Runway concrete
- Shell structure concrete





Test methods e.g. EN 12390-5 ASTM C78

EN 12390-5 or ASTM C78 (Using Simple Beam with Third-Point Loading)

Principle

A bending moment is exerted on prism test specimens by load transmission through upper and lower rollers.

- Prism dimensions:

Width = height = d
Length $\geq$ 3.5 d

Two test methods are used:

- 2-point load application

Load transfer **above through 2 rollers** at a distance d (each one ½ d from center of prism).
The reference method is 2-point load application.

- 1-point load application (central)

Load transfer **above through 1 roller**, in center of prism.

In both methods the lower rollers are at a distance of 3 d (each one 1½ d from center of prism).

Analyses have shown that 1-point load transfer gives results about 13 % higher than 2-point load transfer.

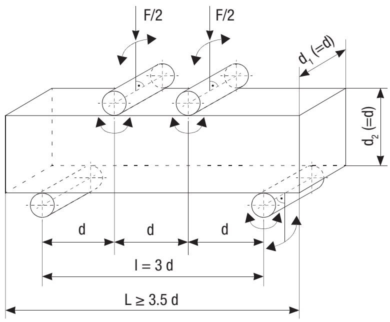


Fig. 7.10.1: Two-point load transfer

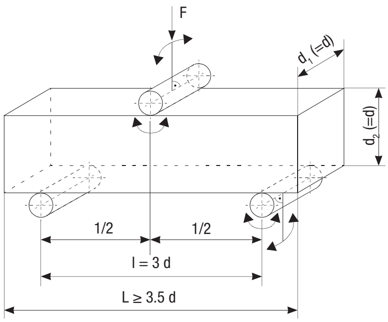


Fig. 7.10.2: Central load transfer

7.11 Shrinkage

Shrinkage means the contraction or decrease in volume of the concrete.
The time sequence and shrinkage deformation level are influenced mainly by the start of drying, ambient conditions and the concrete composition.

The time sequence breaks down as follows:

- Chemical shrinkage of the new concrete is due only to the difference in volume between the reaction products and the base materials. Shrinkage affects only the cement matrix, not the aggregate.
- Plastic shrinkage of the new concrete in the initial stage of setting and hardening. Water is drawn out of the concrete after the initial set by evaporation, which reduces the volume and results in contraction of the concrete in every direction. The deformation usually stops when the concrete reaches a compressive strength of 1 N/mm².
- Drying shrinkage → shrinkage caused by the slow drying of the hardened concrete, i.e. the quicker the quantity of free water in the structure decreases, the more the concrete shrinks.

Influences on the degree of shrinkage

- Planning and detailed specification of construction joints and concreting stages
- Optimized mix design
- Lowest possible total water content → use of **Sika® ViscoCrete®/SikaPlast®/Sikament®**
- Shrinkage reduction admixture **Sika® Control-40** → reduction in shrinkage after the start of hydration
- Prevention of water extraction by pre-wetting the formwork and substrate
- Thorough curing: by covering with plastic sheets or insulating blankets, water-retaining covers (hessian, geotextile matting) or spraying with a liquid curing agent → **Sika® Antisol®**

Test methods e.g. ASTM C157 SIA 262/1

Phase I	Phase II	Phase III
Chemical shrinkage	**Plastic shrinkage**	**Drying shrinkage**
Recompaction	Prevent water loss	Curing shrinkage reduction
approx. 4 - 6 hours	approx. 1 N/mm^2	

ASTM C157 Standard test method for length change of hardened hydraulic-cement mortar and concrete

Measurement of length change permits assessment of the potential for volumetric expansion or contraction of mortar or concrete due to various causes other than applied force or temperature change. This test method is particularly useful for comparative evaluation of this potential in different hydraulic-cement mortar or concrete mixtures.
This test method provides useful information for experimental purposes or for products that require testing under nonstandard mixing, placing, handling, or curing conditions, such as high product workability or different demolding times.
If conditions for mixing, curing, sampling, and storage other than specified in this test method are required, they shall be reported but are not to be considered as standard conditions of this test method. Nonstandard conditions and the reasons for departure from standard conditions shall be reported clearly and prominently with comparator values.

SIA 262/1

This test method provides a means of assessing the change of length over time caused by the drying process of a concrete sample. Size of the prism is 120 x 120 x 360 mm. For a test at least two prisms have to be measured. After 24 h (± 1h) of concrete production the length of every dimension of the concrete sample has to be measured and is used as the reference value. Further measurements have to be taken after 3, 7, 14, 28, 91, 182 and 364 days after concrete production. The result will be expressed in ‰ shrinkage.

7.12 Tensile Strength

Tensile splitting strength of test specimens

Principle

A cylindrical test specimen is subjected to a compressive force applied immediately adjacent along its longitudinal axis. The resultant tensile force causes the test specimen to break under tensile stress.

Test specimens

Cylinders according to EN 12390-1, but a diameter to length ratio of 1 is permissible.
If the tests are carried out on cube or prism specimens, convex steel spacers may be used for load application (instead of conventional flat plates).
The broken specimen should be examined and the concrete appearance and type of break recorded if they are unusual.

Test methods e.g. EN 12390-6 ASTM C496

7.13 Density

Density of hardened concete

Principle

The standard describes a method to determine the density of hardened concrete.
The density is calculated from the mass (weight) and volume, which are obtained from a hardened concrete test specimen.

Test specimens

Test specimens with a minimum volume of 1 liter are required. If the nominal size of the maximum aggregate particle is over 25 mm, the minimum volume of the specimen must be over 50 D^3, when D is the maximum aggregate particle size.
(Example: Maximum particle size of 32 mm requires a minimum volume of 1.64 liters.)

Determining the mass

The standard specifies three conditions under which the mass of the specimen can be determined:

- As a delivered sample
- Water saturated sample
- Sample dried in warming cupboard (to constant mass)

Determining the volume

The standard specifies three methods to determine the volume of the specimen:

- By displacement of water (reference method)
- By calculation from the actual measured masses
- By calculation from checked specified masses (for cubes)

Determining the volume by displacement of water is the most accurate method and the only one suitable for specimens of irregular design.

Test methods e.g. EN 12390-7 ASTM C157

8. Concrete Types

8.1 Waterproof Concrete

Design and construction of a watertight concrete structure is a system approach. The water impermeability of a construction is determined by fulfilment of the decisive requirements regarding limitation of water permeability through the concrete, the joints, installation parts as well as cracks.
Long lasting, durable watertight constructions are achieved by application of a well defined, engineered system. All involved parties have to closely interact in order to minimize the probability of mistakes.

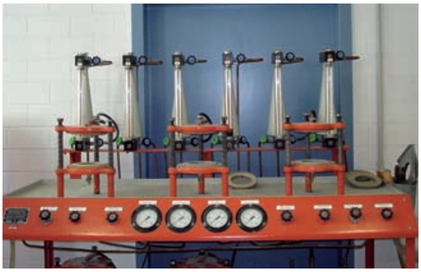


Fig. 8.1.1: Water absorption of concrete under pressure measures the maximum water penetration in mm after a defined time with a specified pressure. (72 hours with 5 bar according EN12390-8)

Waterproof concrete is normally an impermeable concrete. To obtain an impermeable concrete, a suitable particle-size distribution curve must be generated and the capillary porosity has to be reduced.

Measures to reduce the capillary porosity are as follows:
- Reduction of w/b-ratio
- Pore blocker to further reduce the water transport
- Shrinkage reduction (dry and plastic) to minimize crack formation
- Additional sealing of the voids with pozzolanic reactive material
- The concrete curing process is the final parameter affecting the water resistance

Concrete Composition

Aggregate
- Well graded particle-size distribution curve
- Fines content of the aggregate kept low
- Adjustment to the binder content is usually necessary to obtain a satisfactory fines content

Cement
- Conformity with the minimum cement content according to EN 206
- Minimize paste volume as for the recommended application

Additions

- Use of pozzolanic or latent hydraulic additions

Water content (w/b-ratio)

- Low w/b-ratio to reduce the capillary porosity

Placing

- A plastic to soft concrete is recommended to produce waterproof concrete
- Careful and correct compaction of the concrete is important

Curing

- Immediate and thorough curing is essential

Impermeability of concrete against water is determined by the impermeability of the binder matrix, i.e. capillary porosity. Decisive factors for the capillary porosity are the w/b-ratio as well as the content and type of pozzolanic or latent hydraulic materials. A powerful superplasticizer is used to lower the w/b-ratio. This in turn decreases the volume of capillary pores within the concrete matrix, while lending the concrete high workability. These pores are the potential migratory paths for water through the concrete. With application of a second admixture the calcium in the cement paste produce a hydrophobic layer within the capillary pores. This consequently blocks the pores and provides effective protection even at 10 bar (100 meters head of water). The concrete should be placed, compacted and cured in accordance with good concrete practice. The correct system for jointing (movement joints, construction joints) is the key to achieving a watertight structure. Concrete pour sequences and bay sizes need to be considered in order to reduce the risk of plastic shrinkage cracking. As a guide, an aspect ratio not exceeding 3:1 is suggested for wall pours in particular.

Fig. 8.1.2: Sika waterbars are flexible preformed PVC waterstops for the waterproofing of both movement and construction joints which can be subjected to low and high water pressure.

Correct design of any joints is essential on the one hand. On the other hand proper and careful installation of the jointing system is decisive for achieving watertightness of constructions. If watertight concrete leaks, then most often this is due to poor joint construction. In addition other details such as tie bar holes and service entries need to be considered. Depending on the level of protection against water, i.e. outside water pressure as well as intended utilization of the construction, different joint systems are available. Non-movement joints are usually sealed using hydrophilic strips which come in various shapes and sizes and swell on contact with water. Where a structure requires a higher level of protection, more advanced joint systems are available which may offer a combination of hydrophilic elements built into a resin injected hose. This provides an excellent secondary line of defense. Where movement joints are necessary, these can be sealed using hypalon strips secured internally or externally using special epoxy adhesives, or traditional PVC water bars.

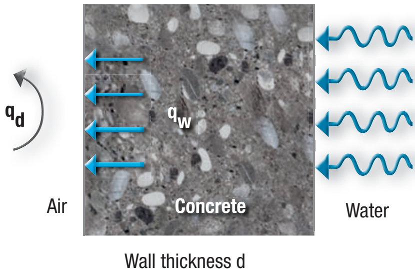


Fig. 8.1.3: Immersion and permanent water contact. The water permeability limit for watertightness is defined as 10 g/m² x hours (according to SIA 262/1), where water permeability is smaller than vaporizable volume of water without pressure over a defined period.

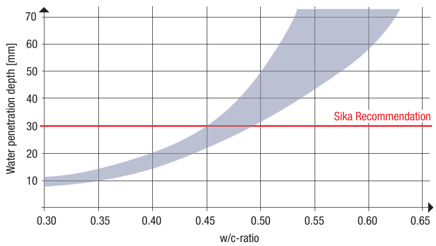


Fig. 8.1.4: Water penetration under hydrostatic pressure. The water permeability limit for watertightness is defined as a maximum water penetration into the concrete under a specific pressure over a defined period.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Any quality aggregates possible	All aggregate sizes are possible	
Cement	Any cement meeting local standards	350 kg/m³	
Powder additives	Fly ash or ground granulated blast furnace slag	Sufficient fines content by adjustment of the binder content	
Water content	Fresh water and recycling water with requirements regarding fines content	w/c-ratio according to standards with regard to exposure class	< 0.45
Concrete admixtures	Superplasticizer Type dependent on placement and workability time	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.60 – 1.50%
	Water resisting admixture	**Sika® WT**	1.00 – 2.00%
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	
Joint sealing	Sealing of movement joints, construction joints, penetrations and construction damage	**Sika®-Waterbars** **Sikadur®-Combiflex®** **Sika® Injectoflex-System** **SikaSwell®**	
Waterproofing systems	Flexible Waterproofing membrane systems, if required with single or double compartment	**Sikaplan®** **SikaProof®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®** **Sikament®**	Superplasticizer	Increased strength and impermeability Substantial water reduction Reduction in capillary porosity
Sika® WT-100	Water resisting admixture	Reduced water conductivity and improved water impermeability
Sika® WT-200	Water resisting and crystalline waterproofing concrete admixture	Reduced water conductivity and improved water impermeability Enhances the self-healing properties of the concrete
Sika® Antisol®	Curing agent	Protection from premature drying

8.2 Corrosion Resistant Concrete

Concrete is an ingenious building material, also because in combination with reinforcing steel it exhibits tremendous load-bearing capacity. The combination of steel and concrete has the advantage that under normal conditions the high pH value of concrete creates a passivating layer of iron hydroxides on the steel surface which protects it from corrosion. Particularly steel, however, can be compromised in its durability of performance by the presence of moisture and salt.

Fig. 8.2.1: Damage to concrete structure due to insufficient concrete cover and low concrete quality.

Working mechanism of Sika® FerroGard® corrosion inhibitors

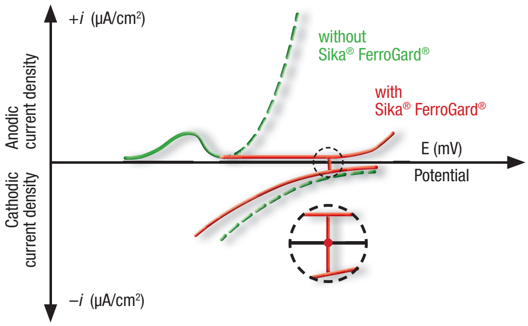


Fig. 8.2.2: Steel in the chloride-containing concrete; with and without Sika® FerroGard®.

Chlorides are displaced at the steel surface by **Sika® FerroGard®**. It forms a protective film which moves the corrosion potential and reduces the current densities to a very low level.

Standard construction practices ensure that corrosion of steel reinforcements is limited. These practices include observance of minimum concrete quality (w/b-ratio, cement content, minimum strength) and minimum concrete cover of rebars. However, in many cases, especially in environments with high levels of chlorides (de-icing salts, seawater or even contaminated concrete mix components), these basic protection procedures prove insufficient. In order to prevent corrosion or delay its start and thereby extend the life of a structure, three additional steps can be taken to protect the steel from corrosion: increase concrete quality, utilize corrosion inhibitors, and application of protective coatings. Increasing concrete quality means reduction of the number and size of capillary pores. This increases the density in the concrete matrix and as a result hinders the transport of chlorides or CO_2 into the concrete. Reduction of the w/c-ratio through application of high range water reducers or use of supplementary cementitious materials like fly ash, silica fume or natural pozzolans represent opportunities in concrete technology to improve better the mix design.

When choosing improved concrete quality for protection against corrosion, extra attention must be given to proper placement, curing of concrete and shrinkage potential of the concrete mix, as small cracks can allow chlorides or CO_2 to penetrate to the reinforcing steel regardless of the density of the concrete mix. Corrosion inhibitors are added to the concrete mix during the batching process. Inhibitors do not significantly influence the density of concrete or impact the ingress of chlorides or CO_2, but act directly on the corrosion process. Corrosion inhibitors are defined in a number of ways. On one hand either as an admixture which will extend the time before corrosion initiates, or as one which reduces the corrosion rate of the embedded steel, or both, in concrete containing chlorides.
By another definition a corrosion inhibitor must reduce the corrosion rate and the corroded area of rebars in concrete containing chlorides. The main products used as corrosion inhibitors today are either calcium nitrite based products or aminoester organic corrosion inhibitors.
Protective coatings are used to reduce the ingress of chlorides or carbon dioxide. Coatings can be applied according to two basic options, either to the surface of the concrete or to the steel rebars themselves beforethey are embedded in the concrete.

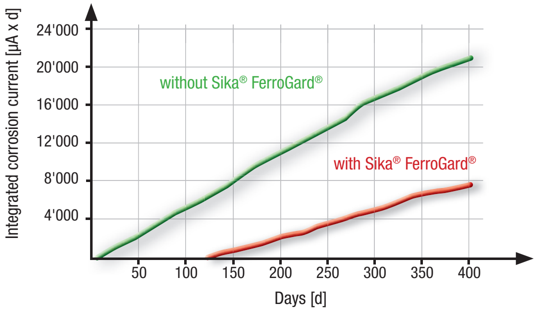


Fig. 8.2.3: The Sika Research Department in Zurich tested the anticorrosive effect of Sika® FerroGard® on cracked concrete beams.
The specimens were produced in accordance with ASTM G 109 and were cyclically treated with road salts. Periodic measurement of the corrosion current confirms the protective effect of Sika® FerroGard®.

-5	-75	0	-145	15	-105	10	-25	0
-125	-180	-160	-150	-140	-175	-175	-150	-135
-150	-245	-170	-145	-190	-205	-155	-185	-170
-155	-230	-145	-195	-185	-185	-185	-205	-205
-175	-240	-210	-165	-215	-215	-210	-220	-190
-215	-250	-175	-200	-200	-230	-215	-220	-190
-210	-250	-210	-210	-205	-185	-235	-260	-210
-255	-270	-310	-220	-225	-255	-280	-285	-235
-260	-280	-295	-300	-330	-240	-230	-285	-235
-220	-280	-315	-245	-320	-295	-290	-275	-290
-260	-320	-325	-305	-325	-335	-270	-310	-330

Color scale

<-300	>-300	>-250	>-200	>-150	>-100	>-50	>0

Fig. 8.2.4: Potential measurement on a retaining wall along a road with heavy traffic with high use of de-icing salt, after less than 10 years of exposure. The darker the coloration, the higher the potential for corrosion.

Surface Applied Corrosion Inhibitor for Reinforced Concrete

Sika® FerroGard® can also be applied on the surface, designed for use as an impregnation on hardened reinforced concrete.
Sika® FerroGard®-903 is a multifunctional inhibitor which controls the cathodic and anodic reactions. This dual action effect significantly retards both the onset and the rate of corrosion and increases the time to future maintenance. **Sika® FerroGard®-903** is normally applied as part of a corrosion management strategy. It is compatible and a component of all the Sika concrete repair and protection systems.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Any quality aggregates possible	All aggregate sizes are possible	
Cement	Any cement meeting local standards	Target cement paste volume as low as possible for the respective placing method	
Powder additives	Fly ash, ground granulated blast furnace slag, silica fume, natural pozzolanes		
Water content	Fresh water and recycling water with requirements regarding fines content	w/c-ratio according to standards with regard to exposure class	< 0.46
Concrete admixtures	Superplasticizer Type dependent on placement and early strength requirements Corrosion inhibitor	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®** **Sika® FerroGard® -901** **Sika® CNI**	0.60 – 1.50% 10 – 12 kg/m³ 13 – 40 kg/m³
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	
Protective system	Surface protection against ingress of chlorides and calcium carbonate	Sika offers a wide range of rigid and flexible solutions to prevent the penetration of water. Sika Solution: **Sikagard®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®** **Sikament®**	Superplasticizer	Water reduction, increased strength and impermeability with guaranteed consistence (workability) and pumpability
Sika® Ferrogard® **Sika® CNI**	Corrosion inhibitor	Protects the surface of steel reinforcement and reduces the rate of corrosion
SikaFume®	Silica fume	High strength, increased impermeability improved sulfate resistance
Sika-Aer®	Air-entrainer	Air-entrainment Interruption of capillary voids Reduction in water absorption
Sika® Antisol®	Curing agent	Protection from premature drying

8.3 Frost and Freeze/Thaw Resistant Concrete

De-icing salt attacks concrete surfaces, one of the most damaging strains for concrete structures, though underestimated for decades also due to the periodically extreme quantities of de-icing salt applied. Through appropriate structural technique and observance of basic technological measures pertinent to concrete, the building material can demonstrate permanently high resistance to frost and to the strain which de-icing salt represent.
Frost and freeze/thaw resistant concrete must always be used when concrete surfaces are exposed to weather (wet) and the surface temperature can fall freezing.

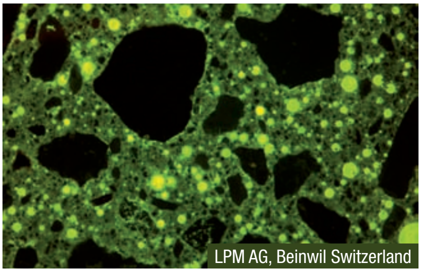


Fig. 8.3.1: Artificially introduced air voids, caused by an air-entrainer, generate space for expansion in the concrete structure to allow for the roughly 10% increase in volume when water freezes to become ice.

By adding air-entrainers, small spherical air voids are generated during the mixing process in the ultra-fine mortar aera (cement, fines, water) of the concrete. The aim is to ensure that the hardened concrete is frost and freeze/thaw resistant (by creating room for expansion of any water during freezing conditions).

Design of air-entrained concrete
Detailed specifications for strength, air content and test methods must be given. For major projects, preliminary test should be carried out under actual conditions. During the concreting works check the air content at the concrete plant and before placing.

Characteristics of air voids	Shape: spherical Size: 0.02 to 0.30 mm Spacing factors: ≤ 0.20 mm frost resistant ≤ 0.15 mm freeze/thaw resistant
Positive secondary effects	Improvement in workability Disrupting of capillary pores (water resistant) Better cohesion of the fresh concrete
Negative effects	Reduction in mechanical strengths (compressive strength)

The factors influencing air-eintrainment

■ **Granulometry**

The air voids are mainly formed around the 0.25 – 0.50 mm sand fraction. Larger particles have no effect on the air-entrainment. Ultrafines from the sand constituents or the cement and some admixtures can inhibit air-entrainment.

■ **Consistence**

Optimum air-entrainment is achived in the plastic to soft plastic range. A concrete that is softened by the addition of extra water might not retain the air voids as well or as long as the original concrete.

■ **Temperature**

The air-entrainment capability decreases as fresh concrete temperatures rise and vice versa.

■ **Delivery**

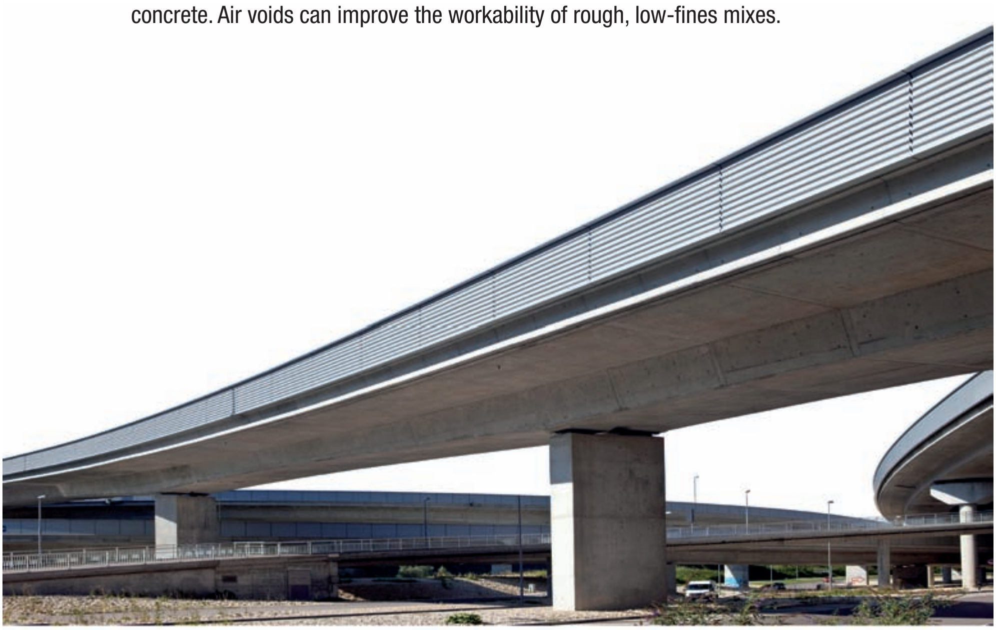
A change in the air content can be expected during delivery. Dependent on the method of delivery and the vibration during the journey, mixing or demixing processes take place in the concrete. Air-entrainment concrete must be mixed again before installation and the air content is only then determined.

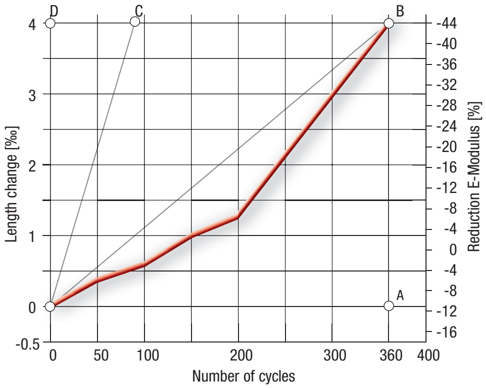
■ **Compaction of air-entrainment concrete**

Concrete vibration mainly removes the air 'entrapped' during placing, including the coarse voids in the concrete. Pronounced overvibration can also reduce the 'entrained' air by 10 to 30%. Concrete susceptible to segregation can then lose almost all of the air voids or exhibit foaming on the surface.

■ **Fines replacement**

1% of entrained air can replace approximately 10 kg of ultra-fine material (< 0.2 mm) per m^3 of concrete. Air voids can improve the workability of rough, low-fines mixes.





Resistance range	AOB = high (WF-L > 80 %)
	BOC = middle (WF-L = 80-25 %)
	COD = low (WF-L < 25 %)
Rating	**High WF-L = 94 %**

Fig. 8.3.2: In test BE II according to D-R 400, the test prisms are subject to alternating loads between +20°C and -20°C, the change in length is measured and judged between three ranges of durability (low / middle / high). Calculation according to ASTM C666.

Type, size and distribution of air voids

Air voids contained in a standard concrete are generally too large (> 0.3 mm) to increase the frost and freeze/thaw resistance. Effective air voids are introduced through special air-entrainers. The air voids are generated physically during the mixing period. To develop their full effect, they must not be too far from each other. The ‘effective spacing’ is defined by the so-called **spacing factor SF.**

Production/mixing time

To ensure high frost and freeze/thaw resistance, the wet mixing time must be longer than for a standard concrete and continue after the air-entrainer is added. Increasing the mixing time from 60 to 90 seconds improves the content of quality air voids by up to 100%.

Quality of air voids required

To obtain high frost resistance, the cement matrix must contain about 15% of suitable air voids. Long experience confirms that there are enough effective air voids in a concrete if the result of the test (air pot) show the following air contents:

- Concrete with 32 mm maximum particle size 3% to 5%
- Concrete with 16 mm maximum particle size 4% to 6%

Fresh concrete with an air void content of 7% or over should only be installed after detailed investigation and testing.

Fig. 8.3.3: Scattered de-icing agent considerably intensifies the reaction upon freezing of water and leads to substantially greater damage in areas of concrete close to the surface.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Aggregates employed must be frost-resistant	All aggregate sizes are possible	
Cement	Any cement meeting local standards Pure Portland cement for highest resistance	Target cement paste volume as low as possible for the respective placing method	
Powder additives	For increased density	**SikaFume®**	up to max. 4%
Water content	Clean mixing water, free of fines	w/c-ratio according to standards with regard to exposure class	< 0.46
Concrete Admixtures	Superplasticizer Dosing dependent on formula superplasticizer and air-entrainer must be adapted to each other	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.60 – 1.40%
	Air-entrainer (mixing time approx. 90 sec.) Required quantity of air entrainer is highly dependent on cement and the fines portion in sand	**Sika-Aer®** dosing: Air void content with - max. particle diam. 32 mm - max. particle diam. 16 mm	0.10 – 0.80% approx. 3 – 5% approx. 4 – 6%
Installation requirements and curing	Curing compound Frost resistant concrete should only be transported in ready-mix trucks, and should be mixed again thoroughly (approx. 30 sec./m³) before unloading. Standard air void measurement should follow.	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®/Sikament®**	Superplasticizer	To reduce the capillary porostity and therefore introduce less water
Sika-Aer®	Air-entrainer	Air-entrainment to ensure frost and freeze/thaw resistance
SikaFume®	Silica fume	For further compaction of the hardened cement paste and improvement of the bond between aggregate and hardened cement paste
Sika® Antisol®	Curing agent	Protection from premature drying

8.4 Sulfate Resistant Concrete

Particularly in underground construction, concrete structures are exposed alongside loads and wear of decade-long use to influences emerging from the sub grade such as permanent mechanical stresses and aggressive water. Concrete is nevertheless characterized by its outstanding durability. Solutions containing sulfates, such as in natural or polluted groundwater, represent a considerable deteriorating impact on concrete. This can eventually lead to loss of strength, expansion, spalling of surface layers and ultimately to disintegration.

Fig. 8.4.1: Concrete deterioration due to sulfate attack before and after the load shows a strong increase in length because of the spalling attack. First cracks have appeared in sample.

The intended life cycle of a concrete structure is ensured by a suitable concrete mix design that is adapted to the expected exposition to various impacts. Sulfate contained in water reacts with the tricalcium aluminate (C_3A) in the cement to form ettringite (also thaumasite under certain conditions), which leads to increases in volume. This volume increase results in high internal pressure in the concrete structure which induces cracking and spalling. Such attack is classified among types of chemical attack under which standard concrete designed without dedicated measures can experience significant damages. Field experience demonstrates that loss of adhesion and strength are usually more severe than concrete damage resulting from expansion and cracking.
Sulfate resistance of concrete is determined by the sulfate resistance of the cement matrix as well as its ability to withstand diffusion of sulfate ions through the matrix. Concrete intended to be sulfate-resistant should therefore be characterized by high impermeability as well as higher compressive strength on the one hand. Furthermore cements with low C_3A and Al_2O_3 content should be used. Doing so reduces the potential for any deteriorating reactions. In addition the inclusion of silica fume is favorable, since this contributes to higher density of the cement matrix in conjunction with enhanced bonding between the cement matrix and aggregates, and thus leading to higher compressive strength.

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8. Concrete Types

Sulfate attack is designated as exposure class chemical attack according to EN 206-1. Therefore the exposure class is determined by the expected sulfate content in the water contacting the concrete. Depending on the exposure class, a minimum cement content in combination with a maximum w/c-ratio is required, as well as a mandatory utilization of cement with high sulfate resistance.
In tunneling, durability is of decisive importance and sulfate attack is a constantly occurring and challenging phenomenon. This is especially true in the case of production of precast tunnel lining segments for TBM and rock support applied by sprayed concrete. In excavations in which high sulfate attack is anticipated, it is difficult to fulfill all technical requirements unless appropriate measures regarding the concrete mix design are also taken.

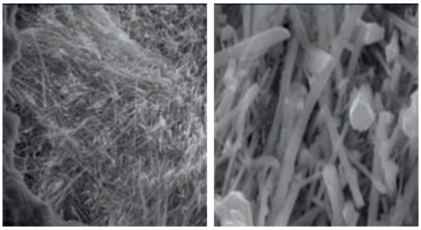


Fig. 8.4.2: Classic form of sulfate attack associated with ettringite or gypsum formation. Flurry of ettringite rods grown in mature cement pastes subjected to external sulfate solutions.

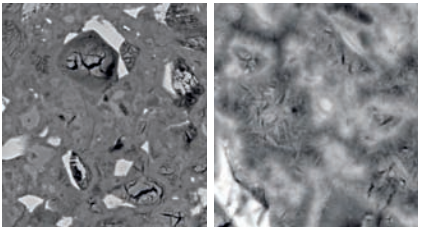


Fig. 8.4.3: Ettringite cores forming into aged cement pastes. Right picture is a 2 years old paste subjected to sulfate attack. One clearly sees the ettringite cores forming within the C-S-H.

For sprayed concrete the use of alkali free accelerators is mandatory to achieve adequate sulfate resistance. The industrialized, swift production of tunnel lining segments requires production cycles of only a few hours, with a maximum temperature development of 60 °C in the concrete. This is very difficult with conventional sulfate resistant cements, due to the fact that these cements exhibit slow strength development. A concrete mix containing silica fume and a superplasticizer fulfills both criteria, productivity and sulfate resistance, but this system is very sensitive to proper curing due to crack formation. With the application of a water-based epoxy emulsion immediately after formwork release of the segments, micro-crack free concrete can be produced.

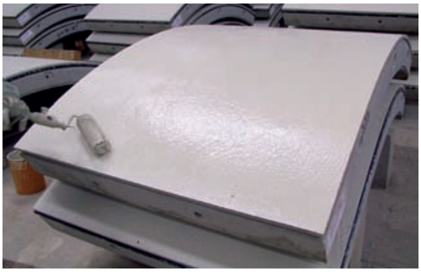


Fig. 8.4.4: Immediately following curing in a steam channel, the concrete surface of tunnel lining segments is coated with water-based epoxy emulsion that is absorbed even into the smallest pores, thereby generating a sealed, protective coating.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Any quality aggregates possible	All aggregate sizes are possible	
Cement	Compliance with EN 206 with moderate to high sulfate resistance ASTM C150 sulfate resistant cements	Target cement paste volume as low as possible for the respective placing method	
Powder additives	Fly ash, ground granulated blast furnace slag, silica fume, natural pozzolanes	**SikaFume®**	4 – 8%
Water content	Compliance with EN 206, depending on exposure class Compliance with ASTM, depending on exposure class	Exposure class XA 1 XA 2 XA 3 Moderate Typ 2 Severe Typ 5 Very severe Typ 5	w/c-ratio < 0.55 < 0.50 < 0.45 < 0.50 < 0.45 < 0.40
Concrete Admixtures	Superplasticizer Type dependent on placement and early strength requirements	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.60 – 1.50%
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	
Protective system / Special curing system	Concrete resistance to chemicals is highly limited. Appropriate coatings can durable protect the concrete surface against sulfate exposure	Special curing of precast tunnel segments immediately after demolding with **Sikagard®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®/Sikament®**	Superplasticizer	Substantial water reduction Improvement in placing (workability and compaction)
SikaFume®	Silica fume	Reduced permeability
Sika® Antisol®	Curing agent	Protection from premature drying

8.5 Fire Resistant Concrete

The danger of fire is present always and everywhere. The imminent danger depends upon actual exposure, and naturally differs if the threatened construction is a pedestrian subway, a roadway tunnel or a subterranean garage in a skyscraper. Concrete is the load-bearing material in nearly all built structures and is therefore at high risk, since the entire structure would collapse upon its material failure. Concrete must therefore, independent of the danger scenario, be properly formulated or protected by external measures, in order to hinder failure at high temperature in case of fire.

Fig. 8.5.1: In special furnace chambers fire trajectories can be replicated, panels tested and subsequently evaluated. Temperature development is measured and recorded at various depths.

Concrete with high fire resistance is used for
- Emergency areas in enclosed structures (tunnel emergency exits)
- General improved fire resistance for infrastructure
- Fire resistant cladding for structural members

Production of concrete with high fire resistance
- The concrete production does not differ from standard concrete
- The mixing process must be monitored due to the fibers normally included
- It is beneficial to the future fire resistance of this concrete if it can dry out as much as possible

Constituents for the production of concrete with high fire resistance
- Achievement of maximum fire resistance is based on the composition of the aggregates used
- The resistance can be greatly increased by using special aggregates
- The use of special plastic fibers (PP) increases the resistance considerably
- The use of selected sands improves the resistance of the cement matrix

Behaviour of concrete under fire load

The capillary and interstitial water begins to evaporate at temperatures around the boiling point of water (100 ºC). Steam needs more space and therefore exerts expansion pressure on the concrete structure. The cement matrix begins to change at temperatures of about 700 °C. The effect of the aggregates is mainly dependent on their origin and begins at about 600 °C.

Fire resistance is defined as the ability of a structure to fulfill its required functions (load bearing function and/or separating function) for a specified fire exposure and a specified period (integrity).

Fire resistance applies to building elements and not the material itself, but the properties of the material affect the performance of the element of which it forms a part. In most cases fire temperature increases rapidly in minutes, leading to the onset of explosive spalling as the moisture inherent in the concrete converts to steam and expands. The most severe fire scenario modeled is the RWS fire curve from the Netherlands and represents a very large hydrocarbon fire inside a tunnel.

There are various options available to improve the fire resistance of concrete. Most concretes contain either Portland cement or Portland blended cement which begins degrading in important properties above 300 °C and starts to lose structural performance above 600 °C.

Of course the depth of the weakened concrete zone can range from a few millimeters to many centimeters depending on the duration of the fire and the peak temperatures experienced. High alumina cement used to protect refractory linings reaching temperatures of 1'600 °C has the best possible performance in a fire and provides excellent performance above 1'000 °C.

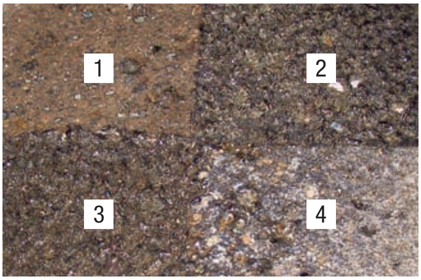


Fig. 8.5.2: Fire exposure trials for concrete containing various aggregates. Surface spalling and sintering, and a range of temperature developments at differing depths can thereby be compared.
1 No spalling, fused surface
2 Limestone; spalling 17 mm, disintegration after cooling + humidity absorption
3 Limestone; spalling 14 mm, disintegration after cooling + humidity absorption
4 Granite; spalling 25 mm, fused surface

The choice of aggregate will influence the thermal stresses that develop during the heating of a concrete structure to a large extent. Aggregates of the carbonate type such as limestone, dolomite or limerock tend to perform better in a fire as they calcine when heated, liberating CO_2. This process requires heat, so the reaction absorbs some of the fire's exothermic energy. Aggregates containing silica tend to behave less well in a fire. Finally as the heat performance is related to the thermal conductivity of the concrete, the use of lightweight aggregates can under certain conditions enhance the fire performance of the concrete.

Polymer or polypropylene monofilament fibers can significantly contribute to the reduction of explosive spalling and thus improve the 'fire resistance' of the concrete. In a fire, these fibers melt at around 160 °C, creating channels which allow the resulting water vapor to escape, minimizing pore pressures and the risk of spalling.

Under conditions in which the risk of structural collapse is unacceptable, designers examine other ways to protect the concrete from the effects of fire. Alternatives range from local thickening of the concrete, cladding using heat shields coated with intumescent paint, use of protective board systems and spray-applied lightweight mortars. The purpose of these passive fire protection systems depends on the type of tunnel as well as the form being protected.

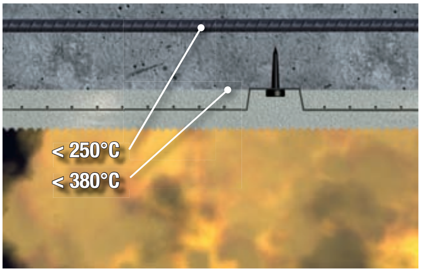


Fig. 6.5.3: Passive fire protection systems should meet the following requirements: The concrete temperature during the fire exposure shall not exceed 380 °C and the steel reinforcement temperatures shall remain under 250 °C while fire exposure.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Aggregates of the carbonate type – limestone, dolomite, limerock, tend to perform better in a fire as calcine. Types containing silica perform less well.	All aggregate sizes are possible	
Cement	Any cement meeting local standards	Target cement paste volume as low as possible for the respective placing method	
Water content	Fresh water and recycling water with requirements regarding fines content	w/c-ratio according to standards with regard to exposure class	< 0.48
Concrete admixtures	Superplasticizer Type dependent on placement and early strength requirements	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.60 – 1.20%
	Polymer or polypropylene monofilament fibers Steel fibers	**SikaFiber®** **SikaFiber® FE**	2 – 3 kg/m³ 10 – 30 kg/m³
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	
Passive protection of the concrete	Sprayed-applied lightweight mortars	**Sikacrete®-F**	25 – 40 mm

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®/Sikament®**	Superplasticizer	Due to the substantial water reduction, there is less excess water in the concrete
SikaFiber®	Polypropylene fibers	To strongly increase fire resistance of cementitious material
SikaFiber® FE	Steel fibers	To increase mechanical properties of concrete by increasing impact strength and flexural strength

8.6 Alkali-Silica-Reaction Resistant Concrete

Aggregates constitute a major portion of concrete. Their influence on the fresh and hardened concrete is considerable. Sources of high quality aggregates are gradually dwindling in number, as a result of which the building and construction materials industry and builders of major infrastructure projects seek solutions for the use of aggregates with lower quality. The Alkali-Silica-Reaction (ASR), which can occur with aggregates, presents a particular challenge and can affect the durability of concrete.

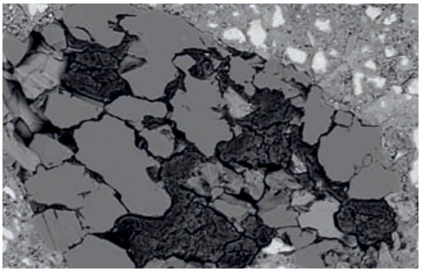


Fig. 8.6.1: Amorphous silica spots within the aggregate have reacted with alkali ions and formed a gel that expanded upon ingress of water. The aggregate has subsequently swelled and cracked while the amorphous region (black cracked masses) expanded.

Major infrastructure projects such as dams, roadways or airport runways require enormous quantities of aggregates, sought in closest proximity to construction sites. Some aggregates can exhibit an increased or high risk of ASR. Alkali-Silica-Reaction is a chemical reaction which occurs between the amorphous silica in the aggregate and the pore solution (alkalis) of the cement matrix. The reaction results in an increase in concrete volume, causing cracking and spalling when the generated forces exceed the tensile strength of the concrete. Essential conditions for occurrence of ASR are moisture within the concrete, a high alkaline content in the pore solution and reactive aggregates. Selection of the correct concrete mix design is critical for avoidance of ASR. Choice of the right solutions can prevent damages resulting from ASR even if highly reactive aggregates are used. Cement clinker contributes the greatest proportion of alkaline material. The higher the cement content is, the more alkaline the mix will be. Blended cements introduce a lower alkaline content. A low w/c-ratio is considered the central factor for achievement of dense, watertight concrete. Dense concrete slows the diffusion of free alkalines and the migration of water to aggregates. For ASR to occur it requires aggregates particularly sensitive to alkalines, such as siliceous limestone, sandy limestone, limestone, gneisses and strongly deformed quartzite. Porous, cracked, weathered or crushed aggregates are more reactive than those with dense structure and rounded surfaces.

Pozzolanic additives such as fly ash, granulated blast furnace slag or silica fume react with and consume hydroxyl (alkaline) ions during hydration. This reaction lowers the pH value of the pore solution, suppressing the occurrence of ASR. Pozzolanic additives differ in shape and reactivity depending on their source, but generally their effect is more homogeneous if added to the cement grinding process as opposed to the concrete mix. There remains however some dispute regarding the efficiency of additives in lowering the speed of ASR.
Admixtures such as traditional accelerators for shotcrete may introduce considerable quantities of alkalines and greatly increase the reactivity of the pore solution. In case of aggregates considered sensitive, alkalinefree accelerator should be used.
Experience has shown that inclusion of special admixtures can hem the ASR reaction, thus preventing expansion. A further possible solution is proposed with the addition of an air-entrainment agent to create artificial expansion room (air voids) for the reaction products. If the possible occurrence of ASR represents a major concern, reaction trials are suggested to define the ASR potential.

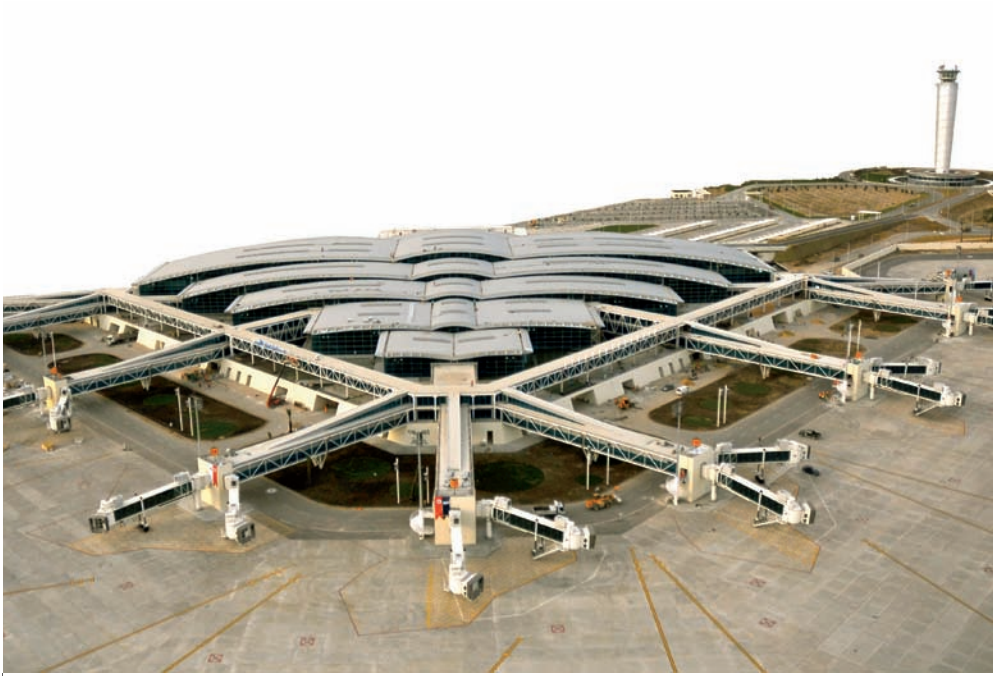


Fig. 8.6.2: The increase in volume due to the strain resulting from ASR becomes perceptible by measurement of a change in length of test specimens. Ordinarily the specimens are stored under intensified conditions (temperature, humidity, applied load) in order to accelerate the reaction.

Fig. 8.6.3: The appearance of ASR damage can be assessed very well on the drying concrete surface of this bridge pylon. Damage can appear within years or only after decades.

The measures are:

- Partial replacement of the Portland cement by slag or other additions (Silica fume/fly ash) with low equivalent Na_2O
- Analysis of the AAR/ASR potential of the aggregate and its classification (petrographic analyses/microbar test/performance testing etc.)
- Replacement or partial replacement of the aggregates (blending of available aggregates)
- Keep moisture access to the concrete low or prevent it (seal/divert)
- Reinforcement design for good crack distribution in the concrete (i.e. very fine cracks only)
- Impermeable concrete design to minimize the penetration of moisture

Fig. 8.6.4: Damage is often only visible after decades. Precise clarification of risk is therefore necessary in order to estimate the potential of aggregates for ASR damage reliably.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	The ASR potential of aggregates should be previously determined	All aggregate sizes are possible	
Cement	Preferably cements with ground granulated blast furnace slag or fly ash content	Target cement paste volume as low as possible for the respective placing method	
Powder additives	Silica fume, fly ash or ground granulated blast furnace slag	**SikaFume®**	3% – 6%
Water content	Clean mixing water, free of fines	w/c-ratio according to standards with regard to exposure class	< 0.48
Concrete admixtures	Superplasticizer Type dependent on placement and early strength requirements	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.60% – 1.20%
	Special admixtures limiting ASR	**Sika® Control ASR**	2 – 10 kg/m³
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	
Protective system	Beside free alkalines and reactive aggregates, the concrete must contain moisture for ASR to occur. If a structure is exposed to water the concrete surface needs to be protected.	Sika offers a wide range of rigid and flexible solutions to prevent the penetration of water. Sika Solution: **Sikagard®**, **SikaPlan®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®/Sikament®**	Superplasticizer	Substantial water reduction Improvement in placing (workability and compaction)
SikaFume®	Silica fume	Reduced permeability
Sika® Control ASR	Admixture to control Alkali-Silica-Reaction in concrete	Minimizes deleterious expansions in concrete due to ASR
Sika® Antisol®	Curing agent	Protection from premature drying

Types

8.7 Abrasion Resistant Concrete

Awe-inspiring gorges and valleys are nature's testimony to the undeniable strength of water. Primarily in technical hydraulic engineering, but also in traffic zones with high loads or hard rolling bodies, concrete surfaces experience considerable and at times extremely abrasive pressure. The mechanisms of damage thereby depend centrally on the type of burden. Whether the surface is exposed to rolling, rubbing or percussive influences differentiates the possible patterns of damage as well as any preventive measures substantially.

Fig. 8.7.1: Particularly in whitewater, concrete surfaces are subject to massive additional strains by rubble, sharp edges and abrasion, as well as possible temperature stresses due to frost exposure.

Over the course of decades and even centuries, exposure to abrasion can yield the most varied experiences with damage patterns. Above all the difference between rolling loads in roadway traffic, heavy traffic including steel wheels or exposure to water, with or without the additional transport of sediment, must be considered. In traffic zones the intensity, weight and the type of wheels are decisive for the overall load. In the case of abrasion by water, it is the velocity of flow, the quantity and type of sediment that are crucial.

In order to boost concrete's abrasion resistance, in most cases provision for hard surfaces is the proper dimensioning approach. If, however, handling the exposure involves percussive or bumping assault, then in addition the adsorptive capacity of the surface plays a role, which can stand in contradiction to surface hardness. The most critical basic principle in the concept is the expert installation of the concrete (prevention of a rising up of fines to the surface due to excessive vibration) and excellent curing, so that the desired concrete properties can emerge above all in areas close to the surface. Furthermore, the surface should offer the lowest resistance possible to abrasive attack. Surfaces that are as level as possible provide the smallest potential for attack. Ascertaining damage patterns is rather straightforward, and is carried out by assessing the abrasion of the surface, the condition of the cement laitance skin and of aggregates near to the surface.

8. Concrete Types

Concrete with enhanced or high abrasion resistance should demonstrate a target compressive strength of roughly 50 MPa. The surface can be considerably enhanced against grinding abrasion through the use of micro silica and/or surface hardener scattered on the surface. In order to boost resistance against percussive or striking attack, the toughness and flexural strength of the concrete must be improved. This can be achieved with the use of fiber reinforcements in the mix. Improving the general working capacity of concrete can be accomplished by mixing in synthetic polymers to strengthen the hardened cement paste matrix, which furthermore enhances adhesion (entanglement) with aggregates. Finally there must be additional differentiation between transport distances and areas that are built to facilitate the dissipation of energy. In these areas, the use of high strength, steel-fiber-reinforced concrete with a strength above 80 MPa and corresponding flexural strength is recommended.
In construction the design of edges must be given particular attention. Whether this concerns dilatation joints in roadway surfaces or tearing edges in hydraulic construction, these must usually be handled specially; construction in concrete alone is normally insufficient. Special joint profiles must be incorporated, often made of steel.

Fig. 8.7.3: Concrete roadways and other publicly accessible areas, especially those experiencing high volumes of traffic or concentrated loads, are subject alongside high mechanical burdens also to strong abrasion, often presenting the risk of a smooth, slick surface.

Fig. 8.7.4: Industrial flooring surfaces also experience strong abrasion due to constantly rolling and striking loads in the same places. Hard concrete coatings and special dispersants can enhance the flooring grip and minimize wear.

Conditions for better abrasion resistance

The abrasion resistance of the hydrated cement is lower than that of the aggregate, particularly with a porous cement matrix (high water content). However, as the w/c-ratio decreases, the porosity of the hydrated cement decreases as well and the bond with the aggregate improves.

Curing

- With **Antisol**® (remove mechanically afterwards, i.e. by wire brushing or blast cleaning if a coating is to follow), cover with sheeting to cure, preferably for several days.

Fig. 8.7.5: Due to continuous exposure, the cement film is eroded in an initial step, and thereafter larger and larger aggregates are rubbed, knocked or washed out of the hardened cement paste.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Aggregates employed must be as hard as possible	All aggregate sizes are possible	
Cement	Any cement meeting local standards	Target cement paste volume as low as possible for the respective placing method	
Powder additives	Silica fume for enhanced compactness	**SikaFume®**	up to max. 8%
Water content	Clean mixing water, free of fines	w/c-ratio according to standards with regard to exposure class	< 0.45
Concrete admixtures	Superplasticizer Type dependent on placement and early strength requirements	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.80 – 1.60%
	Steel fibers	**SikaFiber®**	10 – 30 kg/m³
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	
Surface coating	Scattering material for surface hardening Protective coating	**Sikafloor®**	0.3 – 1.5 mm

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®/Sikament®**	Superplasticizer	Substantial water reduction Improvement in placing (workability and compaction)
SikaFume®	Silica fume	Reduced permeability
SikaFiber®	Steel fibers	Increase impact and abrasion resistance
Sika® Antisol®	Curing agent	Protection from premature drying

8.8 Chemical Resistant Concrete

Water is the source of all life as well as a scarce commodity. Clean drinking water should therefore be protected against contamination, while waste water must be treated before being released into a discharge system. The waste water itself as well as the treatment measures undertaken represents an exposure to chemicals for concrete surfaces. Through sensible planning and proper concrete design concepts, the surfaces can be designed for durability. Concrete's resistance to chemical attack is nevertheless limited, so that surface protection systems must be foreseen in case of heavy exposure.

Fig. 8.8.1: Heavy leaching and damage to the structural concrete are observed particularly in the water splash zone of biological treatment basins.

Chemical resistance in this case signifies resistance to corrosion and erosion of concrete. Alongside known types of spalling attack such as frost (with and without de-icing agents), ASR (Alkali-Silicate-Reaction), sulfate exposure and mechanical surface abrasion, in wastewater treatment facilities particularly, chemical and solvent aggression is also prevalent. The water treated in such facilities, however, varies too greatly to describe the attack on concrete surfaces as uniform. Decisive in addition to the general quality of the water is also its hardness (°fh or °dH).
On one hand the surface of the concrete is attacked by a cocktail of chemicals, while on the other mechanical stress (e.g. high pressure cleaning) also occurs at the surface. Thereby fines are washed out that have already been dissolved but remained adhered within the concrete structure. This entire process is additionally accelerated by softened water (hardness < 15°fh or 8.4°dH) and the reduction of the pH value on the surface of the concrete (e.g. in biofilm). The concrete design, curing and foremost the cleaning of the surface must be adapted to the respective exposure.
While for resistance to mechanical cleaning a hard and compact concrete surface is considered optimal, chemical cleansing is best tolerated by concrete with a high calcite content. Concrete's chemical resistance is limited. If exposure limits are exceeded, concrete surfaces can only be durably protected with appropriate coatings.

Fig. 8.8.2: As resistance of concrete against chemical attack is limited, protective coatings are a often used external protection. Epoxy resin-based protective coatings are applied over the entire surface following reprofiling of the concrete surface with sulfate-resistant repair mortar enhanced with synthetic material.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Aggregates employed must be of high quality and frost-resistant	All aggregate sizes are possible	
Cement	Sulfate resistant cements Cements with high proportion of calcium carbonate; cements containing silica fume	Target cement paste volume as low as possible for the respective placing method	
Powder additives	Silica fume, fly ash or ground granulated blast furnace slag	**SikaFume®**	3 – 6%
Water content	Clean mixing water, free of fines	w/c-ratio according to standards with regard to exposure class	< 0.45
Concrete admixtures	Superplasticizer Type dependent on placement and early strenght requirements	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.80 – 1.60%
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	
Protective system	The chemical resistance of concrete is highly limited. If exposure limits are exceeded, concrete surfaces can be durably protected with coatings.	Sika offers a wide range of solutions to prevent the penetration of chemicals. Sika Solution: **Sikagard®**, **Sikafloor®** and **Sikalastic®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete®/SikaPlast® Sikament®/Plastiment®	Superplasticizer	Improves the consistence
SikaFume®	Silica fume	Reduced permeability
Sika® Separol®	Mold release agent	Easier striking and cleaning
Sika® PerFin®	Concrete surface improver	Improves finished concrete surfaces by the reduction of pores and blowholes
Sika® Antisol®	Curing agent	Protection from premature drying

8.9 High Strength Concrete

High strength and ultra high performance concrete are not just cutting edge technologies for scientific research, but also continue to find new applications in practice. Whether in dealing with the slenderness of building components (e.g. design) or dimensioning under extreme conditions (e.g. earthquake stresses), high and highest material properties (compressive and flexural strength, elasticity and ductility) are finding entry in concrete technology. Durability and high strength of concrete are thereby interdependent.

Fig. 8.9.1: High strength and above all ultra high performance concrete (UHPC) are usually fiber-reinforced. Depending on the requirements, synthetic and/or steel fibers are thereby employed in large quantity.

High strength concrete (HSC)

Concretes with high compressive strength (> 60 MPa) after 28 days are classified in the high performance concretes group and are used in many different structures due to their versatile technical characteristics. They are often used in the construction of high load bearing columns and for many products in precast plants. High strength concrete is suitable for application in high rise buildings, especially in earthquake areas. In addition prestressed bridge constructions require high compressive strength leading to wider spans and slender bridge dimensions. Furthermore the outstanding mechanical characteristics of high strength concrete is utilized in structures exposed to high mechanical and chemical loading like industrial floors, traffic areas, offshore structures, sewage treatment plants and engineering structures like hydropower plants or cooling towers.

High strength concrete is characterized as following:
- 28 days compressive strength between 60 and 120 MPa
- Increased tensile and flexural strength
- Low permeable binder matrix leading to high durability
- Reduced creep and enhanced resistance to pollutants

Increased overall binder content does not necessarily lead to higher concrete strength, as the w/b-ratio represents the driving factor for final strength. The workability of the fresh concrete determines the minimum cement content and optimum binder combination.

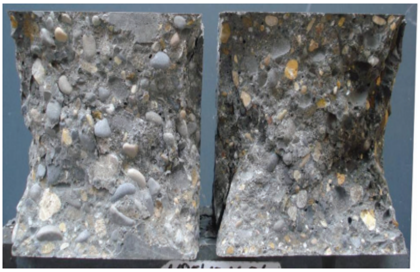


Fig. 8.9.2: Differences in the fractured surface occur in case of used components. The picture shows a reduction of the w/c-ratio from 0.32 (left) down to 0.28 (right).

Furthermore attention has to be drawn to the aggregates selection. High quality aggregates which are clean and free from inside cracks are mandatory. In addition the aggregate grading curve can be designed regarding high strength concrete with the following measures:

- Reduced overall sand content
- Reduced amount of fraction 2 to 4 mm
- Reduced fines from aggregates smaller than 0.125 mm
- Increased amount of fraction 0.25 to 1 mm

Note in particular that:

- High strength concrete is always highly impermeable
- Curing of high strength concrete is even more important than usual (inadequate supply of moisture from inside the concrete)
- High strength concrete is also brittle because of its strength and increased stiffness (impact on shear properties)
- Apart from Portland cement, high strength concrete uses large quantities of latent hydraulic and pozzolanic materials which have excellent long term strength development properties

Exemplary mix designs and influence of cement and binder content

The table below shows three different concrete mix designs, all representing high strength concrete. It can be derived, that the total binder content has no influence on the final compressive strength. The determining factor is the w/b-ratio. But it has to be pointed out that mixtures having water content below 120 L/m³ water face extreme workability challenges. Therefore minimum binder content is necessary for ensuring minimum water content in the mixture. An important mechanical characteristic, the E-Modulus, can be increased by reducing the binder content to a minimum.

Total binder	600 kg/m³	500 kg/m³	400 kg/m³
CEM I 42.5	570 kg/m³	475 kg/m³	380 kg/m³
Silica fume	30 kg/m³	25 kg/m³	20 kg/m³
Aggregates (round siliceous limestone 0 – 16 mm)	1'696 kg/m³	1'849 kg/m³	2'001 kg/m³
w/b-ratio	**0.25**	**0.25**	**0.25**
Water	150 kg/m³	125 kg/m³	100 kg/m³
Strength after 7 days	87 MPa	85 MPa	88 MPa
Strength after 28 days	93 MPa	98 MPa	96 MPa
E-Modulus	43'800 MPa	47'200 MPa	48'800 MPa

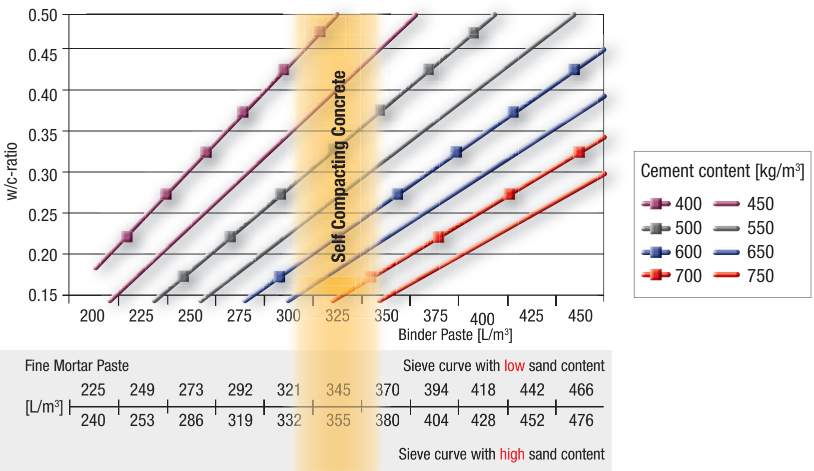


Fig. 8.9.3: Of central significance for achievement of high mechanical material properties is the targeted determination of a concept of fines and the cement paste volume. The highest possible packing density can only be achieved this way.

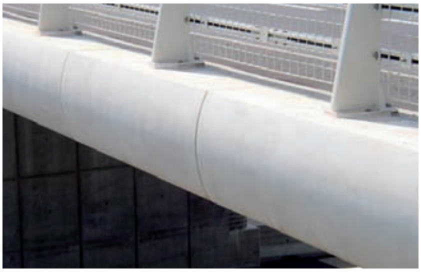


Fig. 8.9.4: Highly stressed building components such as columns and beams are made of high strength concrete. High resistance to external influences also makes high strength concrete an ideal protective coating for exposed construction elements.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Exceptional concrete strength can be achieved using high strength, crushed aggregates	Well distributed grading curve with low amount of fines	
Cement	Utilization of higher cement content and high grade	Target cement paste volume as low as possible for the respective placing method	
Power additives	Increased bond between aggregates and cement matrix silica fume	**SikaFume®**	5 – 10%
Water content	Clean mixing water, free of fines	w/c-ratio according to standards with regard to exposure class	< 0.38
Concrete admixtures	Superplasticizer Type according to target flowability and slump life	**Sika® ViscoCrete®**	1 – 4%
	Steel Fibers	**SikaFiber®**	30 – 40 kg/m³
Installation requirements and curing	Curing compound Thorough curing which starts as early as possible and is extended to two days for interior elements or three days for exterior elements, especially when silica fume is used	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete®	Superplasticizer	For maximum reduction of the water content and therefore strengthening of the hardened cement paste
SikaFume®	Silica fume	For further compaction and strengthening of the hardened cement paste and to improve the bond between aggregate and hardened cement paste
SikaFiber®	Steel fibers	Increase impact and abrasion resistance
Sika® Antisol®	Curing agent	Protection from premature drying

8.10 Shrinkage Controlled Concrete

Prevention of cracks contributes to the durability of concrete structures, because cracks promote the ingress of water and pollutants. Current construction codes specify limits for the width of cracks depending on environmental conditions in which a structure is built and its intended service life.

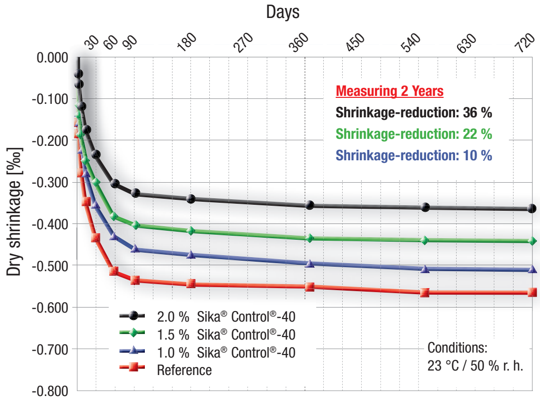


Fig. 8.10.1: Shrinkage behaviour of concrete containing shrinkage-reducing admixtures, measured 2 years to complete abatement of shrinkage due to drying.

Concrete shrinkage types

The most important types with the most severe impact are chemical shrinkage, plastic shrinkage, drying shrinkage, autogenous shrinkage and carbonation shrinkage.

In the case of **chemical shrinkage**, hydration products built up during the hydration process occupy lower volume than the total volume of individual raw materials. This results in a decrease of overall concrete element dimensions as long as the concrete is still soft.

Plastic shrinkage exhibits itself through a decrease in volume caused by evaporation of water, leading to concrete contraction in all directions. The major portion of shrinkage at early ages is in the horizontal plane, mainly in the surface in contact with the air. This is one of the most common and important types of shrinkage. Influencing factors are relative humidity, temperature and ambient wind. More severe drying conditions increase the shrinkage value.

Autogenous shrinkage is a change of volume that occurs after the initial setting of concrete due to hydration, since this process requires water and therefore reduces the internal free water.

Drying shrinkage in hardened concrete is usually caused by evaporation of water through existing capillary pores in the hydrated cement paste. The loss of water is a progressive process that tends to stabilize with time, depending on the dimensions of the structural element.

Possible measures include a reduction of cement paste volume and application of shrinkage reducing admixture.

Fig. 8.10.2: Immediate coverage or curing of concrete surfaces exposed to the elements is the most crucial step for protection of such surfaces.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Large volume of aggregates can reduce drying shrinkage	All aggregate sizes are possible	
Cement	Drying shrinkage can be reduced with low pure cement paste volume	Target cement paste volume as low as possible for the respective placing method	
Water content	Low water content is favorable to reduce plastic shrinkage and drying shrinkage At w/c-ratios lower than 0.4 autogenous shrinkage can occur	w/c-ratio according to standards with regard to exposure class	< 0.45
Concrete admixtures	Superplasticizer Type dependent on placement and early strength requirements	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.80 – 1.50%
	Shrinkage reducing agent	**Sika® Control**	0.5 – 1.5 %
	Polypropylene short fibers can reduce effects of plastic shrinkage	**SikaFiber®**	1 – 3 kg/m³
	Structural fibers to ensure even distribution of cracking	**SikaFiber® FE** **SikaFiber® Force**	20 – 40 kg/m³ 4 – 6 kg/m³
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast® / Sikament®**	Superplasticizer	Substantial water reduction Improvement in placing (workability and compaction)
Sika® Control	Shrinkage reducing agent	Reduction of shrinkage
SikaFiber®	Polypropylene fibers Steel fibers	Reduction of plastic shrinkage Even distribution of cracks
Sika® Antisol®	Curing agent	Protection from premature drying

8.11 Fiber Reinforced Concrete

With the addition of fibers made of various materials and different geometries the ductility and the tensile strength of concrete can be increased. Based on the idea of distributing the reinforcement evenly throughout the concrete, fiber reinforced concrete was developed by adding the reinforcement directly during the mixing process. Beside of the well known steel fibers nowadays plastic fibers and hybrid fibers (a mix of different fibers) will be used for additional applications.
The choice of fiber type and fiber geometry depends mainly on the application field. Therefore the geometry, quality and physical properties of the fibers are matched to each application.

Fig. 8.11.1: Fibers for use in concrete are produced from different materials and qualities of these materials, plus they can have different geometric dimensions and form, according to the required performance of the fresh or hardened concrete.

Many different properties of the fresh and hardened concrete can be effectively influenced by adding fibers. There are innumerable different types of fibers with different material characteristics and shapes. Correct selection for different uses is important. As well as the actual material, the shape of the fibers is also a critical factor.

To improve fire protection of concrete is only one application where micro PP fibers are used successfully. Another example micro PP fibers can be used is to improve the resistance of early age cracks in concrete where macro and steel fibers are mainly used to improve the strength, resistance and energy absorption of the hardened concrete and to substitute at least parts of the ordinary steel reinforcement.

Fiber reinforced concrete is used for:

- Industrial flooring
- Sprayed concrete
- Slender structures (usually in precast plants)
- Fire resistant structures
- Mortar applications (rehabilitation)

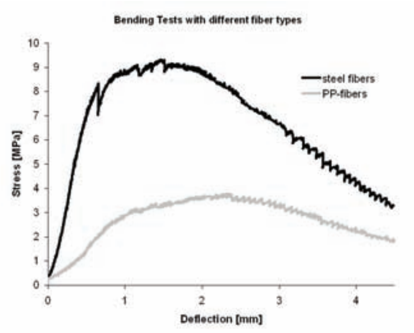


Fig. 8.11.2: The stress-deflection diagram of a bedding test shows the influence of different fiber types on the material properties of the concrete, like improved tensile strength and a well controlled post cracking behavior.

Concrete production

The fiber manufacturers' instructions must be followed when producing fiber reinforced concretes. Adding the fiber at the wrong time or mixing incorrectly can cause great problems and even make the fibers useless.

- Comply with the manufacturer's adding time and method (i.e. at the concrete plant or in the ready-mix truck)
- Comply with the mixing times (balling/destruction of fibers)
- Do not exceed the maximum recommended fiber content (considerable reduction in workability)
- Fibers generally increase the water requirement of the mix (compensate for this with superplasticizer)

Table 8.11.1: At which state of concrete hardening do which fibers operate the best?

Fresh concrete/ mortar	The homogeneity, especially with mortars, is improved by the addition of micro fibers
Until about 10 hours	Early age cracking, formed by plastic shrinkage, can be reduced with micro fibers
1-2 days	Cracks induced by restraint stresses or temperature stresses can be reduced by the use of micro and macro fibers
From 28 days	Forces coming from external loads can be transmitted to macro and steel fibers and the fire resistance can be improved by micro PP fibers with a melting point at 160 °C

Table 8.11.2: Parameters of different fiber types

Steel fibers	Density: ~7'800 kg/m^3 Tensile strength: 400 – 1'500 N/mm^2 E-modulus: ~200'000 N/mm^2	Steel is by far the most commonly used type of fiber. This is due to their availability, good mechanical properties and durability.
Polypropylen fibers	Density: ~900 kg/m^3 Tensile strength: 600 – 700 N/mm^2 E-modulus: 5'000 – 15'000 N/mm^2	Polypropylene gives very good alkali resistance and continuous E-modulus improvement offer a broad spectrum of uses.
Polyvinyl alcohol Fasern	Density: ~900 kg/m^3 Tensile strength: 600 – 700 N/mm^2 E-modulus: 10'000 – 64'000 N/mm^2	Special manufacturing processes enable high-modulus PVA fibers to be produced.
Vegetable fibers	Density: ~1'500 kg/m^3 Tensile strength: 0 – 1'000 N/mm^2 E-modulus: 5'000 – 40'000 N/mm^2	Vast natural resources but wide variations in the characteristics, which presents design difficulties.
Glass fibers	Density: ~2'700 kg/m^3 Tensile strength: 2'500 N/mm^2 E-modulus: ~80'000 N/mm^2	Due to continuous improvements in the alkali resistance (durability), the applications for glass fibers are extending all the time.
Carbon fibers	Density: ~1'700 kg/m^3 Tensile strength: 450 – 4'000 N/mm^2 E-modulus: up to 300'000 N/mm^2	Very good mechanical properties and high durability on the one hand but high costs on the other.
Polyester fibers	Density: ~900 kg/m^3 Tensile strength: 600 – 700 N/mm^2 E-modulus: 5'000 – 10'000 N/mm^2	Were developed for the textile industry but can also be found in the construction materials industry.
Ceramic fibers	Density: ~2'500 – 3'000 kg/m^3 Tensile strength: 1'700 – 3'400 N/mm^2 E-modulus: 150'000– 400'000 N/mm^2	Are used for heat insulators and lagging, but also for fiber-reinforced ceramics. High strength and E-modulus, but friable.

Effects of fiber reinforced concretes:

- Improved durability of the structure
- Increased tensile and flexural strengths
- Higher resistance to later cracking
- Improved crack distribution
- Reduced shrinkage of early age concrete
- Increased fire resistance of concrete
- Negative influence on workability
- Improved homogeneity of fresh concrete

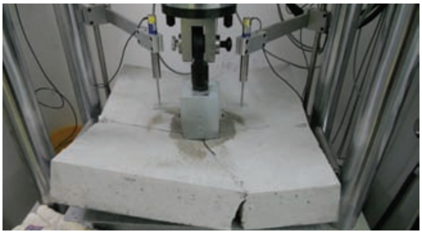


Fig. 8.11.3: Special testing for sprayed concrete: Energy absorption testing of fiber reinforced sprayed concrete to EN 14488-5.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Any quality aggregates possible	All aggregate sizes are possible	
Cement	Any cement meeting local standards	Target cement paste volume according pumping concrete recommendations	< 320 kg/m³
Powder additives	Limestone, fly ash, silica fume or ground granulated blast furnace slag	Sufficient fines content by adjustment of the binder content	Fines including cement > 375 kg/m³
Water content	Fresh water and recycling water without requirements regarding fines content	w/c-ratio according to standards with regard to exposure class	< 0.48
Concrete admixtures	Superplasticizer Type dependent on placement and early strength requirements Steel fibers Structural macro fibers Polypropylene micro fibers	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®** **SikaFiber®-FE** **SikaFiber®-Force** **SikaFiber®**	0.80 – 1.60% 20 – 60 kg/m³ 4 – 8 kg/m³ 0.6 – 3 kg/m³
Installation requirements	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast® / Sikament®**	Superplasticizer	Due to the substantial water reduction, there is less excess water in the concrete
SikaFiber®	Polypropylene micro fibers Structural macro fibers Steel fibers	To strongly increase fire resistance of cementitious material To increase mechanical properties of concrete by increasing impact restistance and flexural strength To increase mechanical properties of concrete by increasing impact restistance and flexural strength
Sika® Antisol®	Curing agent	Protection from premature drying

8.12 Fair-faced Concrete

Modern architecture is unimaginable without fair-faced concrete. For decades priority was given to the unique load-bearing properties and unequaled cost/performance ratio as a structural building material. It is only in recent years that the incredible design versatility and the creation of many different finishes have also come to the fore.

Fig. 8.12.1: Due to the development of SCC (self-compacting concrete), design and construction potential is now almost unlimited, and with special formwork technology and/or specific concrete admixtures, high quality finishes can be achieved even in the most difficult areas.

Concrete with high aesthetical requirements

In modern architecture concrete is increasingly used as a design feature as well as for its mechanical properties. This means higher specifications for the finish (exposed surfaces). There are many ways to produce special effects on these exposed surfaces:

- Select a suitable concrete mix
- Specify the formwork material and type (the formwork must be absolutely impervious!)
- Use the right quantity of a suitable mold release agent
- Select a suitable placing method
- Use form liners if necessary
- Color using pigments
- Install correctly (compaction, placing etc.)
- Thorough curing

In addition to all of these factors listed, the following are important for the concrete mix:

Aggregate/Cement/Water

- Use minimum fines content and a balanced grading curve as used for pumped concrete
- Cement generally > 300 kg/m³
- Allow for the effect of the cement on the color of the exposed surface
- The water content in a fair-faced concrete requires great care and consistency (avoid fluctuations) and prevent bleeding

Fig. 8.12.2: With a wide variety of formwork and treatments available, almost any concrete finish can be created, included mirror smooth, plain timber board or other patterns, bush hammered or exposed aggregate etc..

Placing and Curing

- Place the concrete in even layers of 300 to 500 mm. Each layer should be vibrated into the one below (mark the vibrator)
- Use a suitable size of vibrator (example: Wall thickness up to 20 cm → Poker Ø ≤ 40 mm)
- Plastic to soft installation consistence
- Specify thorough curing and allow for the climatic conditions

Precautions

- Considerable retardation can occur with new, untreated timber formwork due to the pressure of wood 'sugar' on the surface leading to discoloration and dusting
- If the concrete is too 'wet' when placed, water pores with a thin or non-existent cement laitance skin can occur (blowholes)
- Inadequate concrete vibration can result in vibration pores with a hard, thick cement laitance skin
- Excessive mold release agent application prevents the air bubbles (created by vibration) from escaping

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®** **Sikament®**	Superplasticizer	Increased strength and impermeability Substantial water reduction Reduction in capillary porosity
Sika® Separol®	Mold release agent	Easier striking and cleaning
Sika® Rugasol®	Surface retarder	Production of exposed aggregate concrete surfaces
Sika® PerFin®	Concrete surface improver	Improves finished concrete surfaces by the reduction of pores and blowholes
Sika® ColorFlo®	Concrete color (liquid or powder)	Creates even and intensive colored concrete
Sika® Antisol®	Curing agent	Protection from premature drying

Types

8.13 Colored Concrete

The manufacture and processing of colored concrete is not only a current trend, but also a sustainable and attractive way to design concrete structures or building components. Alongside the shape and surface structure, color is a central design element for concrete as a building material.
The effect thereby must reflect the desires of the building owner and the architect, being as uniformly as possible over the whole building component.

Fig. 8.13.1: Concrete, traditionally a solid, reliable, durable building material can be raised to new levels of architectural performance.

Colored concrete is produced by adding pigmented metal oxides (mainly iron oxide). The pigments are in the form of powder, fine, low dust granulates or liquid.
The dosage is normally 0.5 – 5.0% of the cement weight. Higher dosages do not enhance the color intensity but may adversely affect the concrete quality.

Typical primary colors are:
- Synthetic Iron oxide yellow and red
- Synthetic Iron oxide black (note: carbon black may adversely affect the creation of air voids)
- White (titanium dioxide; general brightener)

Out of the major primary colors a wide range of concrete colors could be created and there are almost not limits of creativity. In addition special colors are available.

The coloring can be heightened or structured:
- By using light colored aggregate and or by using white cement
- By using special types of forms (shuttering)

The main factors for the successful colored concrete construction and finishes include:
- Preliminary trials and agreed finishes, with the results visible for all parties
- A constant workflow throughout the concreting works from the mix design, trials, production, transport, formwork, placing, curing and protection of the concrete surfaces. The parameters must be maintained in accordance with the preliminary trials.
- Consistent water content in the concrete mix is one of the most important variables.

Fig. 8.13.2: Colored concrete demands far more than just adding the pigments. From planning to installation, essential decisions must be made for the application to succeed and the most diverse production steps must be checked and executed expertly. All participants are challenged. Exclusive Color Select® PC Liquid Dispensing System.

Especially the formwork, influencing the aesthetical aspect of colored fair-faced concrete significantly, has to be clarified with the project owner during the pre test application:
- Material of the formwork (steel, wood, plastic, …)
- Structure of the surface (smooth or rough)
- Tightness and cleanness of the fromwork (especially joints, new or used forms)
- Robustness of the formwork construction
- Mold release agent (type, application thickness & consistency)
- Placing and compaction of concrete in the formwork

When use Liquid Pigments:
- Faster more efficient loading (higher volumes)
- Clean and easy use of liquid color
- Greater technological accuracy - less chance of mistakes

When use Powder Pigments:
- Smaller applications (lower volumes)
- No need to store powders frost protected
- Automation not explicit necessary

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®** **Sikament®**	Superplasticizer	Increased strength and impermeability Substantial water reduction Reduction in capillary porosity
Sika® ColorFlo® Liquid	Liquid concrete colors	High concentrated liquid iron oxide pigments
Sika® ColorFlo® Powder	Powdered concrete colors	Iron oxide pigments in powder form
Sika® ColorSelect	Dispensing systems	Specific dosing and dispensing system for all type of applications

8.14 Underwater Concrete

As the name suggests, underwater concrete is installed below the water line, e.g. for:
- Port and harbour installations
- Bridge piers in rivers
- Water industry structures
- Metro systems
- Deep shafts in unstable ground

Fig. 8.14.1: When using underwater concrete, the placing and working conditions are very often complex, which is why these concretes often also need an extended working time.

Composition (Example 0 – 32 mm):
- Aggregate
  - Use an aggregate suitable for pumped mixes
  - Fines including cement > 400 kg/m³
- Cement and Powder Additives
  - Minimum cement content 350 kg/m³
  - Limestone can add to the fines content in the mix design
- Admixtures
  - Superplasticizer for the reduction of free water in the mix
  - Mix stabilizer to minimize washout effect of fines and cement (especially in running water conditions)

Special requirements

Standard method is pumping a suitably modified mix through a standard concrete pump. The end of the delivery pipe must be kept deep enough in the fresh concrete.
Another method of placing underwater concrete with minimum loss is the tremie process (Contractor method). The concrete is placed directly through a 20 – 40 cm diameter pipe into and through the concrete already installed. The pipe is raised continuously, but the bottom end must always remain sufficiently submerged in the concrete to prevent the water going back into the pipe.
Other important considerations:
- As the flow rate of water increases, more leaching can occur
- Avoid pressure differences on the pipe (such as water level differences in shafts)

Special underwater concrete

Previously installed rough stone bags or "gabions" can be infilled later with modified cement slurries (the bag method).

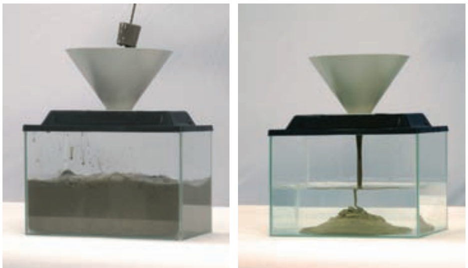


Fig. 8.14.2: Concrete poured underwater without (left) and with Sika UCS (right).

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Any quality aggregates possible	All aggregate sizes are possible	
Cement	Any cement meeting local standards	Target cement paste volume according pumping concrete recommendations	> 350 kg/m³
Powder additives	Limestone, fly ash or ground granulated blast furnace slag	Sufficient fines content by adjustment of the binder content	Fines including cement > 400 kg/m³
Water content	Fresh water and recycling water with requirements regarding fines content	w/c-ratio according to standards with regard to exposure class	< 0.48
Concrete admixtures	Superplasticizer Type dependent on placement and early strength requirements	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.60 – 1.50%
	Stabilizer for stagnant water Stabilizer for running water	**Sika® Stabilizer** **Sika® UCS**	0.20 – 2.00% 0.30 – 1.50%
Installation requirements	Most often used today is pumping a suitably modified mix through a standard concrete pump. The end of the delivery pipe must be kept deep enough in the fresh concrete.		

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®/Sikament®**	Superplasticizer	Substantial water reduction Improvement in placing (workability and compaction)
Sika® Stabilizer	Viscosity modifying agent	Improved cohesion of the concrete
Sika® UCS	Cohesion improver	Strong improvement of cohesion for underwater concrete
SikaPump®	Pumping aid	Improves pumpability and support cohesion
Sika® Retarder	Setting retarder	Extended workability by retarding setting point
SikaFume®	Silica fume	Reduced permeability and increased compactness

8.15 Lightweight Concrete

Lightweight means concrete and mortar with a low density. Either aggregates with a lower density are used or artificial voids are created to reduce the weight. The method used depends mainly on the lightweight concrete application and its desired properties.

Fig. 8.15.1: The compressive strengths obtainable are always linked to the existing density of the materials. The level of this correlation can be altered through the quality of the aggregates. As can be expected, voids result in very low strength and so-called expanded clays can also give very good strength development at low densities of around 1'500 kg/m^3.

Lightweight concrete is used for:

- Lightweight construction (ceilings, walls, bridge decks, slabs)
- Levelling concrete
- Infill concretes
- Thermal insulation

Characteristics of lightweight concretes:

- Reduction in fresh concrete density and in hardened concrete density
- If lightweight concrete is used as an infill concrete with low load bearing requirements i.e. for dimensional stability, highly porous concretes and mortars are generally produced (aerated lightweight concrete)
- If lightweight concrete with good mechanical properties (i.e. compressive strength) is required, special aggregates are used (naturally very porous but also dimensionally stable)

Production of lightweight concrete:

- Porous lightweight materials such as expanded clays must be pre wetted to prevent too much water being drawn out of the concrete during mixing
- Due to the risk of segregation do not use too fluid consistence
- Correct handling of vibrators is particularly important (quick immersion, slow lifting) to prevent air entrapment
- Cure immediately and thoroughly
- Foamed concretes often shrink considerably and have low dimensional stability

Fig. 8.15.2: Expansion causing additives (e.g. powdered aluminium) are mixed with the mortar for porous concrete. Porous concrete is generally produced industrially. Porous concrete is not really a concrete, it is really a porous mortar.

Constituents for the production of lightweight concretes:
- Expanded clays
- Expanded polystyrene balls
- Wood shavings, sawdust
- Special void producing admixtures to generate large quantities of defined stable air voids
- Foaming agents

Density
Based on the mix and the constituents used, the following density classes and properties are obtainable:

Aggregate	Density over 1'800 kg/m^3	High mechnical properties
Expanded clays	Density over 1'500 kg/m^3	Limited mechnical properties
Void producers	Density over 1'500 kg/m^3	Porous lightweight concrete with low mechanical properties
	Density over 1'200 kg/m^3	No mechnical properties (easy to produce porous lightweight concrete)
Expanded polystyrene	Density over 800 kg/m^3	Low mechnical properties
Foaming agents	Density over 800 kg/m^3	No mechanical properties such as infill mortar

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® SikaPlast®/Sikament®	Superplasticizer	To reduce the permeability and improve the workability of lightweight concrete
Sika® Lightcrete	Foaming admixture	To produce low density concrete
SikaPoro®	Foam formers	To generate foam with a special gun to produce lightweight mortar ≤1'000 kg/m^3
SikaPump®	Pumping aid	To improve the pumpability and cohesion of lightweight concrete

Types

8.16 Heavyweight Concrete

The main application for heavyweight concrete is for radiation shielding (medical or nuclear), for offshore, heavyweight concrete is used for ballasting of pipelines.
Heavyweight concrete uses heavy natural aggregates such as barites or magnetite or manufactured aggregates such as iron or lead shot. The density depends on the type of aggregate used and can achieve between 3'000 kg/m^3 and close to 6'000 kg/m^3.

Fig. 8.16.1: The floor, walls and ceiling of this medical building were constructed with heavyweight concrete using hematite metallic aggregates to ensure full and secure radiation protection.

Heavyweight concrete is mainly used for radiation protection. The critical properties of a heavyweight concrete are:
- Homogeneous density and spatial closeness of the concrete
- Free from cracks and honeycombing
- Compressive strength is often only a secondary criterion due to the large size of the structure
- As free from air voids as possible
- Observe heat of hydration
- Keep shrinkage low

Composition
- **Aggregate**
  - Use of barytes, iron ore, heavy metal slags, ferrosilicon, steel granules or shot
- **Cement**
  - Consider hydration heat development when selecting the cement type and content
- **Water content**
  - Aim for a low w/c-ratio

Workability
To ensure a completely closed concrete matrix, careful consideration should be given to the placing (compaction).

Curing
Allowance must be made in the curing method for the high heat development due to large mass of the structure.

Type	Density concrete	Density aggegate
Heavyweigth concrete	Higher than 2'800 kg/m³	Heavyweight aggregates > 3'200 kg/m³
Normal concrete	In the range of 2'000 to 2'800 kg/m³	Normal aggregates
Leightweight concrete	Up to 2'000 kg/m³	Leightweight aggregates < 2'200 kg/m³

Table 8.16.1: Using barites the density will be in the region of 3'500 kg/m³, while with magnetite the density will be 3'900 kg/m³. Very heavy concretes can be achieved with iron aggregates, the density will be above 6'000 kg/m³.

Concrete mix design advice and recommended measures:

Components	Description	Example formula	
Aggregates	Use of heavyweight aggregates	Barites Magnetites Iron aggregates	~ 3'500 kg/m³ ~ 3'900 kg/m³ ~ 7'000 kg/m³
Cement	Any cement meeting local standards	Target cement paste volume as low as possible for the respective placing method	
Powder additives	Ground granulated blast furnace slag	Sufficient fines content by adjustment of the binder content	
Water content	Fresh water and recycling water with requirements regarding fines content	w/c-ratio according to standards with regard to exposure class	< 0.48
Concrete admixtures	Superplasticizer Type dependent on placement and early strength requirements	**Sika® ViscoCrete®** or **SikaPlast®** or **Sikament®**	0.60 – 1.50%
	Shrinkage reducing agent Viscosity modifying agent	**Sika® Control-40** **Sika® Stabilizer**	0.50 – 1.50% 0.20 – 2.00%
Installation requirements and curing	Curing compound Curing that starts as early as possible and is maintained for a sufficient period of time has significant influence on plastic and drying shrinkage	Careful installation and compaction. Subsequent curing to ensure high quality (compactness) of surfaces **Sika® Antisol®**	

Sika product use

Product name	Product type	Product use
Sika® ViscoCrete® **SikaPlast®/Sikament®**	Superplasticizer	Substantial water reduction Improvement in placing (workability and compaction)
SikaFume®	Silica fume	Reduced permeability
Sika® Control-40	Shrinkage reducer	Reduced shrinkage
Sika® Stabilizer	Viscosity modifying agent	Improves the cohesion of the concrete
Sika® Antisol®	Curing agent	Protection from premature drying

10. Recommended Measures

10.1 Formwork Preparation

The quality of concrete is influenced by many factors, whereas formwork preparation plays a major role for the final appearance of the concrete surface. The challenge is to prevent adhesion of the hardened concrete on the formwork and ensure easy cleaning of it. This can be achieved with correct application of a suitable mold release agent, which additionally leads to smooth and dense concrete surfaces improving the durability as well as the aesthetical appearance of the concrete surface.

The following requirements are specified for the action of mold release agents, both in situ/cast in place situations, and for precast concrete applications:

- Easy and clean release of the concrete from the formwork (no concrete adhesion, no damage to the formwork)
- Visually perfect concrete surfaces (impermeable surface skin, uniform color, suppression of void formation)
- No adverse effect on the concrete quality on the surface (no excessive disruption of setting, no problems with subsequent application of coatings or paints – or clear instructions for additional preparation are required)
- Protection of the formwork from corrosion and premature ageing
- Easy application
- Lowest impact on the environment
- High level of Ecology, Health and Safety on the construction site and in the precast plant

Another important requirement specifically for precast work is high temperature resistance when heated formwork or warm concrete is used. Unpleasant odor development is also undesirable, particularly in a precast factory. For site use, an important requirement is adequate rain or UV resistance, and possible accessibility after the mold release agent has been applied.

Structure of mold release agents

Mold release agents can be formulated from up to three different material groups:

- **Release film formers**
  These are the materials which are the base substances mainly responsible for the release effect, e.g. various natural and synthetic oils and also paraffin waxes are used.
- **Additives**
  Additional or intensified effects are obtained with these materials. They include release boosters, 'wetting' agents, anti-corrosion additives, preservatives and the emulsifiers which are necessary for water based emulsions. Most of the mold release agents in use today also contain other additives, some of which react chemically with the concrete, causing targeted disruption of setting. It is then much easier to release the concrete from the formwork and the result is a more general purpose product.
- **Thinners**
  These products act as viscosity reducers for the release film formers and additives. Their purpose is to adjust the workability, layer thickness, drying time, etc.. Thinners are basically organic solvents or water for emulsions.

As a result there are three different general technologies employed on which mold release agents are based on:

- Full oils
- Solvent based
- Water based emulsions

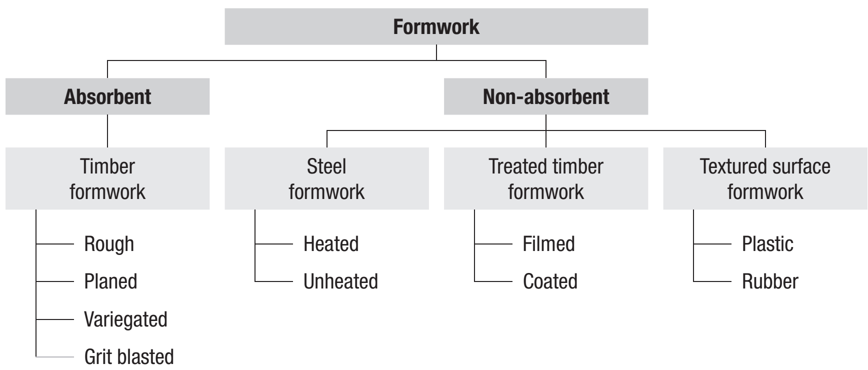
The thinner the mold release agent film the better the final concrete surface appearance. Solvent based mold release agents and water based emulsions were developed, because these technologies facilitate fast and easy application of thinnest mold release agent films.

Mold release agents for absorbent formwork

In previously unused new timber formwork, the absorbency of the timber is very high. If the formwork is not correctly prepared, the water will be drawn out of the concrete surface from the cement paste. The results seen will be concrete adhesion to the formwork, and future dusting of the hardened concrete surface due to a lack of cement hydration. The concrete layer near the surface can also be damaged by constituents in the formwork (e.g. wood sugars). This manifests itself as powdering, reduced strength or discolouration, and occurs particularly when timber formwork have been stored unprotected outdoors and are exposed to direct sunlight. The effects described can all be quite pronounced when formwork is used for the first time but gradually they decrease with each additional use.

A simple way of counteracting these problems with new formwork has been developed and it has proved effective in practice. Before being used for the first time, the timber form is treated with mold release agent and then coated with a cement paste or thick slurry. The hardened cement paste is then brushed off. After this artificial aging, a mold release agent with some sealing effect should be applied initially for a few concreting operations. A low solvent or solvent-free, weak chemically reactive release oil should generally be used for this.

When timber formwork has been used a few times, its absorbency gradually decreases due to increased surface sealing as the voids and interstices of the surface fill with cement paste and release agent residues. Therefore older timber formwork only needs a thin coat of mold release agent. It is also possible to use mold release agents containing solvents or release agent emulsions on this older formwork.



Mold release agents for non-absorbent formwork

Forms made from synthetic resin modified timber, plastic or steel are non-absorbent and therefore cannot absorb release agent, water or cement paste. With all these materials it is extremely important to apply the release agent sparingly, evenly and thinly. 'Puddles' should be avoided. They do not only result in increased void formation but can also cause discolouration and/or dusting of the concrete surface.

To obtain a thin and even release agent film on the form surface, low-viscosity oils with release additives are generally used, often also with solvents for fair-faced concrete. The release additives give improved release (e.g. with fatty acids or specific 'wetting' agents) and also better adhesion of the release film to smooth, vertical form surfaces.
This is particularly important where there are high formwork walls, considerable concrete pouring heights causing mechanical abrasion of the form surface, or the effects of weather and long waiting times between release agent application and concrete placing.

Heated steel forms represent a special application. The release film formed on the formwork must not evaporate due to heat and the release agent must be formulated so that a stronger chemical reaction (lime soap formation or saponification) cannot occur between the concrete and the release agent constituents during the heat treatment.

Textured forms made from special rubber or silicone rubber do not always require release agent, at least when new, because concrete does not stick to the smooth, hydrophobic form surface. If there is a need for release agent due to the form texture or increasing age, products containing solvents or special emulsions should be used dependent on the texture profile. A thin coat is necessary to prevent surplus release agent accumulating in lower lying parts of the form. A suitability test must be carried out to ensure that the release agents used do not cause the form to swell or partly dissolve.

The most favorable mold release agents for non absorbent formwork are water based emulsions, especially in precast concrete production. With this technology thinnest mold release agent films can be achieved, whereas fast and easy application is supported by its white dotted appearance, if correctly applied. Moreover water based emulsions are characterized by a high degree of efficiency and ecology. Raw material consumption is reduced and the working environment in precast concrete plants is improved.

Directions for use

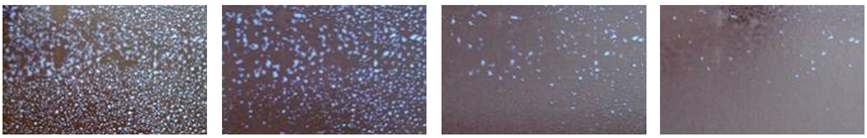
There are a few general directions for use in addition to the specific release agent product information.

Application of release agent

The most important rule is to apply the absolute minimum quantity as evenly as possible. The theoretic value to achieve optimum release performance in general would be a mold release agent thickness of 1/1'000 mm. The method of application for a release agent depends mainly on the consistence of the product. Low viscosity (liquid) products should preferably be applied with a high pressure spraying gun with an operating pressure of 3 to 6 bar. Use a flat spraying nozzle possibly combined with a control valve or filter to prevent excess application with runs and drips.

Application of a water based emulsion

Water based emulsion mold release agents should be applied in thin layers with a fine, white dotted appearance, covering the complete surface. After application one should allow for a water evaporation time of approximately 10 to 20 minutes, depending on ambient temperatures. During this evaporation time a thin uniform oil film is formed.



2 minutes | 4 minutes | 7 minutes | 9 minutes

On smooth formwork, the correct, uniform release agent thickness can be checked by the 'finger test'. No visible finger marks or release agent accumulations should be formed. Surplus release agent must be removed from horizontal formwork with a rubber or foam squeegee and the surface must be rubbed over. If too much material is applied on vertical or sloping formwork, runs on the surface or release agent accumulations at the base of the form will be visible. They must be removed with a cloth or sponge.

Very high viscosity release agents (e.g. wax pastes) are applied with a cloth, sponge, rubber squeegee, brush, etc.. Here again, only apply the absolute minimum quantity and as evenly as possible.

Checking the correct release agent application rate

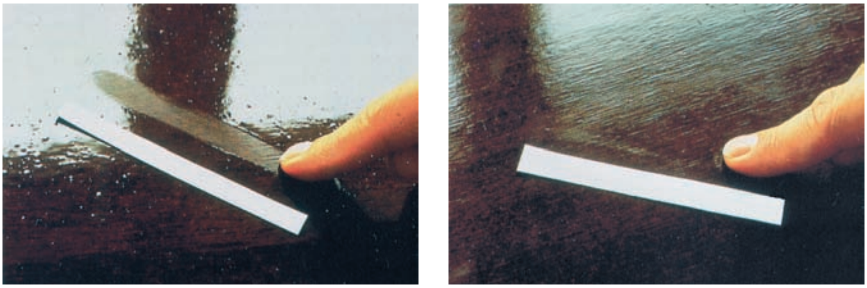


Fig. 10.1.1: Finger test of correct MRA application (left: too much MRA / right: good application of MRA)

The weather conditions play an important part in the use of release agents. It is not appropriate to apply a release agent in the rain due to potential inadequate adhesion and water on the form. Absorbent forms may have a higher release agent requirement in strong sunlight and drought. Release agent emulsions are at risk in frosty weather as the emulsion is destroyed once it is frozen.

Waiting time before concreting

A specific minimum waiting time between applying the release agent and concreting cannot generally be given, as it depends on many factors such as form type, temperature, weather and release agent type. The correct drying time of products containing solvents and water-based emulsions must always be maintained, otherwise the required release effect is not achieved. The quality of the concrete finish can also suffer because entrapped solvent residues can cause increased void formation.

The evaporation rate varies according to the type of solvent. The waiting times for each product should be taken from the Product Data Sheets.

Exposure or stress (foot traffic, weather etc.) on the release agent film and too long a time delay between application and concreting can reduce the release effect in some circumstances. With absorbent formwork this can happen after a period of a few days. Non-absorbent formwork is less critical and the effect of the release agent is generally maintained for a few weeks, dependent on the ambient conditions.

Summary

The concrete industry cannot do without release agents. When correctly selected and used with the right formwork and concrete quality, they contribute to visually uniform and durable concrete surfaces. Inappropriate or wrongly selected release agents, like unsuitable concrete raw materials and compositions, can cause defects and faults in and on the concrete surface.

The Sika® Separol® range offers ideal solutions for most form release requirements.

Sika product use

Product name	Product use
Sika® Separol® F	Suitable for all construction site applications and precast concrete applications where an immediate use of the formwork is essential.
Sika® Separol® S	Products offering enhanced concrete surface appearance in all kinds of concrete construction applications.
Sika® Separol® W	Improved release power, fast and easy application with the capability to produce fair-faced concrete surfaces fulfilling high aesthetical requirements.

10. Recommended Measures

10.2 Concrete Installation

Durable concrete constructions can only be built with correct installation of fresh concrete. Among the entire production chain the installation and vibration of concrete represent critical steps.
Correct placing of fresh concrete leads to
- Durable constructions
- Improved overall quality
- Ensured hardened concrete performance
- Functionality of mold release agents
- Enhanced surface appearance

Pouring
Several measures have to be considered when fresh concrete is placed.

First of all it is important to check if all concrete characteristics are on site as previously prescribed according to the relevant standards and additional requirements. Especially workability of the concrete should be sufficient in order to ensure easy and save placing as well as subsequent vibrating and finishing.

Regarding the applied mold release agent it is important to ensure that it suffers as little mechanical stress as possible. If possible the concrete should not be poured diagonally against vertical formwork to prevent localized abrasion of the release film. The pour should be kept away from the form as much as possible by using tremie pipes.

Avoid great falling heights especially with fair-faced and self-compacting concrete in order to avoid segregation and achieve uniform concrete surface appearance.

If a subsequent concrete pour is going to be installed after hardening of the previous pour, the joint between the two concrete parts has to have sufficient roughness in order ensure bonding between the hardened and the fresh concrete. This can be achieved by surface retardation of the first pour leading to an exposed aggregates surface in the joint. When concreting the subsequently fresh concrete against such rough joint required bond is ensured. Surface retardation can be achieved with **Sika® Rugasol®**.

Vibration

Correct compaction of the concrete is a vital step within concrete production, because only with correct execution it is possible to obtain the target air void content and as a consequence the required hardened concrete properties, like compressive strength.

Internal vibration with a vibration poker should be carried out in the way that the poker is immersed quickly to the bottom of the concrete layer and then reversed in one go slowly back over the entire concrete layer. Excessive vibration can have negative impact on the homogeneity of the fresh concrete. Especially with installation of frost and freeze/thaw resistant concrete the artificially introduced micro air voids should not be destroyed.

Make sure that the poker vibrators do not come too close to the formwork skin or touch it. If they do, they exert high mechanical stress on the form surface, which can result in abrasion of the release agent and later to localized adhesion (non-release) of the concrete.

Finishing

Depending on the casted element finishing characteristics of the concrete can play an important role.

Finishing characteristics of the fresh concrete can be influenced with the concrete mix design by fines content, utilized aggregates, w/b-ratio as well as the used admixtures in general and superplasticizer technology in particular. Especially application of suitable superplasticizers based on polycarboxylate-ether (PCE) can significantly influence the finishing characteristics of fresh concrete. In addition one can make use of finishing aids, like **SikaFilm**®.

Timing plays a critical factor regarding finishing, especially when finishing industrial floors with power floats. It is important to evaluate the correct timing for finishing.

10.3 Curing

Concrete quality and durability are determined by the density of the binder matrix. Therefore durable concrete should not only be characterized by high compressive strength. Even more important is its impermeability especially in the areas near the surface. The lower the porosity and the denser the hardened cement paste near the surface, the higher the resistance to external influences, stresses and attack.

To achieve this in hardened concrete, several measures have to be undertaken to protect the fresh concrete, particularly from:

- Premature drying due to wind, sun, low humidity, etc.
- Extreme temperatures (cold, heat) and damaging rapid temperature changes
- Rain
- Thermal and physical shock
- Chemical attack
- Mechanical stress

Protection from premature drying is necessary so that the strength development of the concrete is not affected by water removal. The consequences of too early water loss are:

- Low strength in the parts near the surface
- Tendency to dusting
- Higher water permeability
- Reduced weather resistance
- Low resistance to chemical attack
- Occurrence of early age shrinkage cracks
- Increased risk of all forms of shrinkage cracking

The diagram below gives an illustration of the amount of water evaporation per m² of concrete surface under different conditions. As can be seen from the figure (arrow marking), at air and concrete temperatures of 20 °C, relative air humidity of 50% and an average wind speed of 20 km/h, 0.6 liters of water per hour can evaporate from 1 m² of concrete surface. At concrete temperatures higher than air temperature and with widening temperature differences, the rate of water evaporation increases significantly. In equal conditions, a concrete temperature of 25 °C would result in 50% more evaporation, i.e. 0.9 liters per m² per hour.

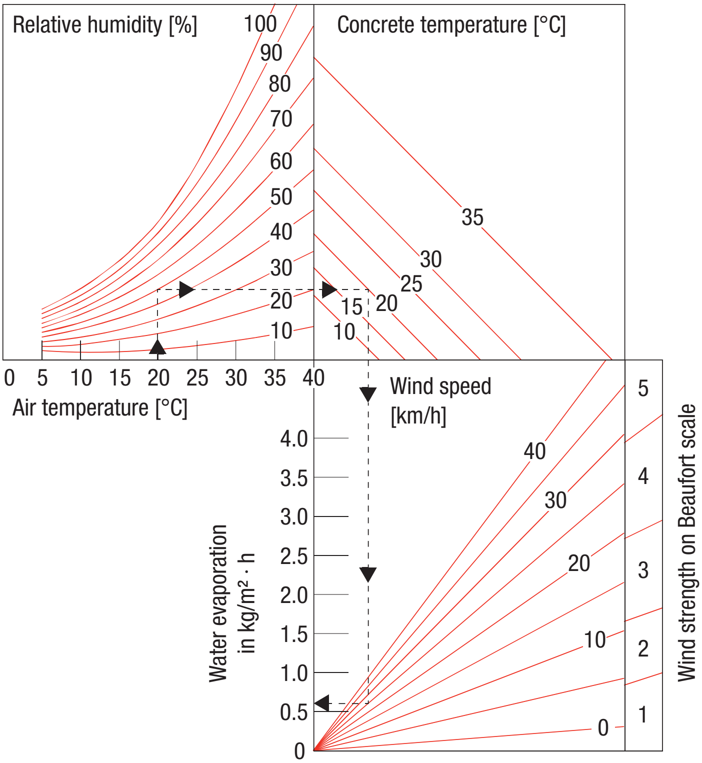


Fig. 10.3.1: Effect on evaporation of relative air humidity, air and concrete temperature as well as wind speed (according to VDZ [German Cement Manufacturers' Association])

Measures

An example to illustrate these figures:
Fresh concrete with a water content of 180 liters per m^3 contains 1.8 liters of water per m^2 in a 1 cm thick layer. The evaporation rate of 0.6 liters per m^2 per hour means that the concrete loses an amount of water equivalent to the total water content of concrete layers 1 cm thick within 3 hours and 3 cm thick after 9 hours. This thickness exceeds the minimum concrete cover required for external structures according to DIN 1045. A 'resupply' of the evaporated water from the deeper areas of the concrete only occurs to a limited extent. The negative impact on the strength, wear resistance and impermeability of the layers near the surface is considerable.

Extreme temperature effects cause the concrete to deform; it expands in heat and contracts in cold. This deformation causes stresses which can lead to cracks, as with shrinkage due to constraint. It is therefore important to prevent wide temperature differences (>15 K) between the core and the surface in fresh and new concrete and exposure to abrupt temperature changes in partially hardened concrete.

Mechanical stress such as violent oscillations and powerful shocks during setting and in the initial hardening phase can damage the concrete if its structure is loosened. Rainwater and running water often cause permanent damage to fresh or new concrete. Damage during subsequent works should be prevented by edge protection and protective covers for 'unformed' concrete surfaces and by leaving concrete longer in the formwork before striking.

Chemical attack by substances in ground water, soil or air can damage concrete or even make it unfit for its purpose, even given a suitable mix formulation and correct installation, if this stress occurs too early. These substances should be kept away from the concrete for as long as possible, e.g. by shielding, drainage or covering.

Curing Methods
Protective measures against premature drying are:
- Applying liquid curing agents (e.g. **Sika® Antisol® E-20**)
- Leaving in the forms
- Covering with sheets
- Laying water-retaining covers
- Spraying or 'misting' continuously with water, keeping it effectively submerged and
- A combination of all of these methods

Liquid curing agents such as **Sika® Antisol® E-20** can be sprayed onto the concrete surface with simple tools (e.g. low pressure, garden type sprayers). They must be applied over the whole surface as early as possible: on exposed concrete faces immediately when the initial 'shiny' surface of the fresh concrete becomes 'matt', and on formed faces immediately after striking. It is always important to form a dense membrane and to apply the correct quantity (in g/m²) as specified, and in accordance with the directions for use. Several applications may be necessary on vertical concrete faces.

Sika® Antisol® E-20 is milky white in color when fresh, making application defects or irregularities easy to detect. When it dries, it forms a transparent protective membrane.

Leaving in the form means that absorbent timber formwork must be kept moist and steel formwork must be protected from heating (i.e. by direct sunlight) and from rapid or over-cooling in low temperatures.

Careful covering with impervious plastic sheets is the most usual method for unformed surfaces and after striking of formwork components. The sheets must be laid together overlapping on the damp concrete and fixed at their joints (e.g. by weighing down with boards or stones) to prevent water evaporating from the concrete.
The use of plastic sheets is particularly recommended for fair-faced concrete, as they will largely prevent undesirable efflorescence. The sheets should not lie directly in the fresh concrete. A 'chimney effect' must also be avoided.

When enclosing concrete surfaces in water-retaining materials such as hessian, straw mats etc., the cover must be kept continuously moist or if necessary must also be given additional protection against rapid moisture loss with plastic sheets.

Premature drying can be prevented by keeping the surface continuously damp by wetting the concrete surfaces. Alternate wetting and drying can lead to stresses and therefore to cracks in the new concrete. Avoid direct spraying on the concrete surface with a water jet, as cracks can occur if the concrete surface cools due to the lower water temperature and the latent heat development of the concrete, particularly on mass concrete structures. Suitable equipment types are nozzles or perforated hoses of the type used for garden lawn sprinklers. Horizontal surfaces can be left to cure under water where possible.

Table 10.3.1: Curing measures for concrete

Method	Measures	Outside temperature in °C				
		Below -3 °C	-3 to +5 °C	5 to 10 °C	10 to 25 °C	over 25 °C
Sheet / curing membrane	Cover and/or spray with curing membrane and dampen. Wet timber formwork; protect steel formwork from sunlight					X
	Cover and/or spray with curing membrane			X	X	
	Cover and/or spray with curing membrane and heat insulation; advisable to use heat insulating formwork – e.g. timber		X*			
	Cover and heat insulation; enclose the working area (tent) or heat (e.g. radiant heater); also keep concrete temperature at +10 °C for at least 3 days	X*	X*			
Water	Keep moist by uninterrupted wetting				X	

* Curing and striking periods are extended by the number of frosty days; protect concrete from precipitation for at least 7 days

At low temperatures it is not enough just to prevent water loss on the concrete surface. To prevent excessive cooling, additional protective heat insulation measures must be prepared and applied in time. These depend mainly on the weather conditions, the type of components, their dimensions and the formwork.

Curing with water is not allowed in freezing temperatures. Thermal covers such as boards, dry straw and reed mats, lightweight building board and plastic mats are all suitable protection for brief periods of frost. The cover should preferably be protected on both sides from moisture with sheets. Foil-backed plastic mats are the most suitable and are easy to handle. In heavy frosts or long periods of freezing temperatures, the air surrounding the fresh concrete must be heated and the concrete surfaces must stay damp. Good sealing is important (e.g. by closing window and door openings and using enclosed working tents).

Curing period

The curing period must be designed so that the areas near the surface achieve the structural strength and impermeability required for durability of the concrete, and corrosion protection of the reinforcement.
Strength development is closely connected to the concrete composition, fresh concrete temperature, ambient conditions, concrete dimensions and the curing period required is influenced by the same factors.

As part of the European standardization process, standardized European rules are being prepared for concrete curing.

The principle of the European draft is incorporated in DIN 1045-3. Its basis is that curing must continue until 50% of the characteristic strength f_{ck} is obtained in the concrete component. To define the necessary curing period, the concrete producer is required to give information on the strength development of the concrete. The information is based on the ratio of the 2 to 28 day average compressive strength at 20 °C and leads to classification in the rapid, average, slow or very slow strength development range. The minimum curing period prescribed according to DIN 1045-3 is based on these strength development ranges.

Notes

Sika – a global Player in Specialty Chemicals for Construction and Industry

Sika AG, located in Baar, Switzerland, is a globally active specialty chemicals company. Sika supplies the building and construction industry as well as manufacturing industries (automotive, bus, truck, rail, alternative energies, building components).

Sika is a leader inprocessing materials used in sealing, bonding, damping, reinforcing and protecting load-bearing structures. Sika's product lines feature high-quality concrete admixtures, specialty mortars, sealants and adhesives, damping and reinforcing materials, structural strengthening systems, industrial flooring as well as roofing and waterproofing systems.

Worldwide local presence in 76 countries and some 15,300 employees link customers directly to Sika and guarantee the success of all partners.

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