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7th Trans-national Workshop

Lisboa • LNEC • 30th May 2012

Maintenance and Repair of Transport Infrastructure TECHNICAL GUIDE

PART IV – CONCRETE STRUCTURES

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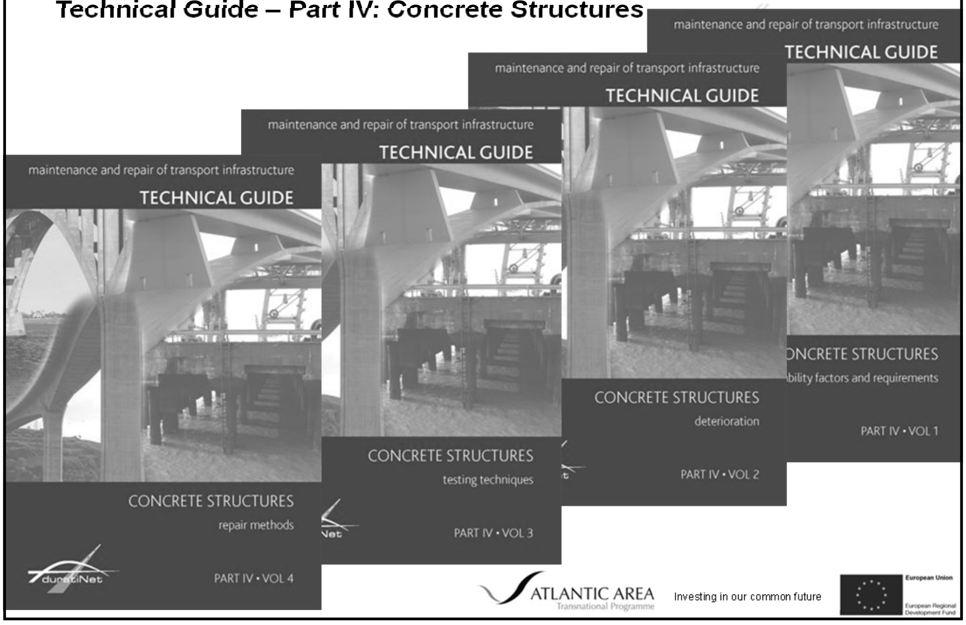
Technical Guide – Part IV: Concrete Structures



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Part IV: Concrete Structures - Vol 1 - Durability factors and requirements

1 General considerations

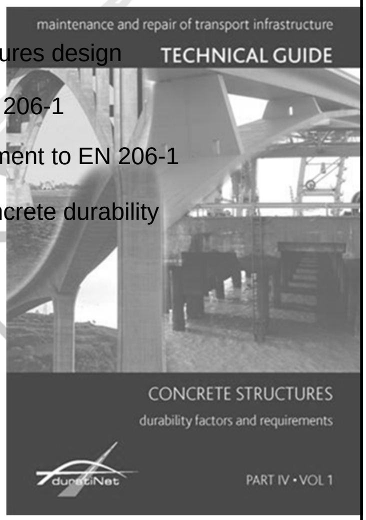
2 Overview of European standards for concrete structures design

3 National standards or guidelines to complement EN 206-1

4 Comparison of the national requirements in complement to EN 206-1

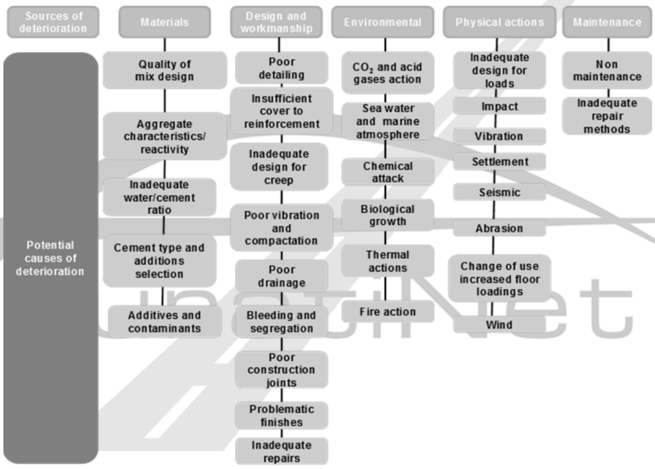
5 Examples of projects with performance limits for concrete durability

6 Conclusions



Part IV: Concrete Structures - Vol 1 - Durability factors and requirements

1. General considerations



Part IV: Concrete Structures - Vol 1 - Durability factors and requirements

1. General considerations

Causes of the problem	Results
Poor reinforcement details, for example congested or inadequate cover to environment action, and voids around the steel reinforcement	Cracking, poor compaction, insufficient reinforcement or inadequate reinforcement distribution
Poor detailing of fixings, window frames, handrails, supports, and expansion joints defects	Water penetration, localized cracking and balcony
Long, slender components	Excessive deformation and cracking
Inadequate design for creep	Deflection due to strain under continued stress
Decorative finishes, such as acid etching, bush hammering, and fluting	Varying depth of cover around the steel and localised corrosion
Poor drainage	Water ponding and localised corrosion/degradation
Incorrect concrete grade for purpose	Concrete with too low or too high strength for the application
Concrete mixes with high drying shrinkage	Possible cracking
Concrete mixes that are highly permeable to chloride ions	Chloride induced reinforcement corrosion

Table 1. Concrete deterioration caused by adequate or wrong design

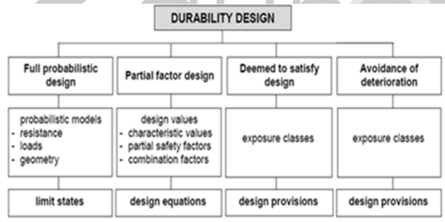


Fig. 2. Different levels of durability based design approach

Causes of the problem	Results
Inadequate mixing proportions facing casting conditions	Inhomogeneous concrete, localised weakness, and reinforcement corrosion
Inadequate water/cement ratio	Variable strength, inadequate durability, increased drying shrinkage, excessive permeability
Inadequate compaction/vibration	Honeycombing, voids, excessively permeable concrete, localised reinforcement corrosion
Scattering or inadequate cover depths of reinforcements	Localised reinforcement corrosion, penetration of damaging substances
Poor curing techniques	Shrinkage cracks, increased permeability
Premature stripping of formwork	Cracking and deformation
Control of maximum temperature during setting and hardening	Possible thermal cracks and Delayed Ettringite Formation DEF

Table 2. Concrete deterioration caused by the lack of workmanship or quality control

Causes of the problem	Results
Low cement content	Inadequate concrete strength and low performance to environmental actions.
High cement content	Inadequate workability, shrinkage, and cracking
High water cement ratio	Inadequate concrete strength and increased permeability to gases and chloride
Calcium aluminate cement	Loss of concrete strength concrete especially in wet environment
Finely-ground cements or binders	Concrete shrinkage
Reactive aggregates	Expansive reactions AAR and loss of concrete strength and stiffness
Contaminated aggregates	Steel corrosion initiation
Poorly shaped and badly graded aggregates	Poor workability, requiring extra water or vibration and leading to segregation and bleeding

Table 3. Concrete deterioration caused by adequate concrete specifications by the user

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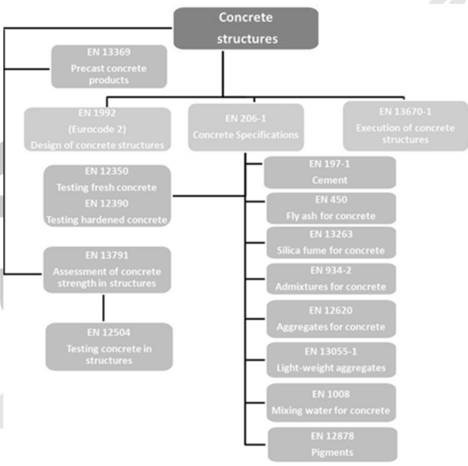
2. Overview of European standards for concrete structures design



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2. Overview of European standards for concrete structures design

2.1. Classification of the exposure environments

Table 4. Exposure classes related to environmental conditions in accordance with EN 206-1

Class designation	Description of the environment	Informative examples where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze/thaw, abrasion or chemical attack For concrete with reinforcement or embedded metal: very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
3 Corrosion induced by chlorides		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools Concrete components exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements Car park slabs
4 Corrosion induced by chlorides from sea water		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5. Freeze/Thaw Attack		
XF1	Moderate water saturation, without de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agents	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation with de-icing agents or sea water	Road and bridge decks exposed to de-icing agents Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zone of marine structures exposed to freezing
6. Chemical attack		
XA1	Slightly aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water
XA2	Moderately aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water
XA3	Highly aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water

2.2. Durability requirements for concrete

✓ **Prescriptive method for concrete properties specification**

- permitted types and classes of constituent materials;
- maximum water/cement ratio;
- minimum cement content;
- minimum concrete compressive strength class (optional);
- minimum air-content of the concrete (if relevant).

✓ **Performance-related concrete design methods**

✓ **Concrete cover depth specification**

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3. National standards or guidelines to complement EN 206-1

- ✓ United Kingdom (BS EN 206-1, BS 8500-1 and BS 8500-2)
- ✓ Ireland (IS EN 206-1)
- ✓ Portugal (NP EN 206-1, LNEC E 461, LNEC E 464 and LNEC E 465)
- ✓ France (NF EN 206-1:2004)
- ✓ Spain (EHE-08)

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4. Comparison of the national requirements in complement to EN 206-1

- ✓ National standards or regulations

Table 1. National standards or regulations

Country	Location of national requirements
France	1 standard National annex included in the NF EN 206
Ireland	National Annex; published with IS EN 206-1 as a single document.
Portugal	The Portuguese requirements are in the National Annex to NP EN 206-1 and to NP EN 13670-1 and in the following National Civil Engineering Laboratory (LNEC) specifications, referenced in the NA of NP EN 206-1. LNEC E 461:2007: Methodology for avoiding internal expansive reactions LNEC E 464:2005: Prescriptive methodology for a 50 and 100 years design working life under the environmental exposures. LNEC E 465:2005: Methodology for estimating the concrete performance properties allowing to comply with the design working life of the reinforced or prestressed concrete structures under the environmental exposures XC and XS.
Spain	Spain has not adopted yet EN 206-1 Erro! A origem da referência não foi encontrada.
United Kingdom	BS 8500: Concrete - Complementary British Standard to BS EN 206-1 - Part 1: Method of specifying and guidance for the specifier. - Part 2: Specification for constituent materials and concrete.

- ✓ Exposure classes

Table 1. Grouped exposure classes in each country

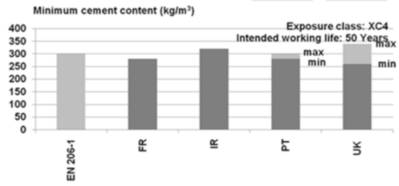
Country	Grouped exposure classes
France	(XC1, XC2) (XC3 XC4, XD1, XF1) (XS1, XS2)
Ireland	None
Portugal	(XS, XD)
United Kingdom	(XC3, XC4) In 2006 revision of BS 8500-1, the recommendations for resisting the XD and XS exposures are adequate for resisting the associated XC exposure

- ✓ Methods for minimising risk of damage by AAR

Table 1. National recommendations and standards for reduce the risk of AAR

Country	Location of national requirements
France	Guidelines: Recommendations for the prevention of damage by the alkali-aggregate reaction, LCPC, 1994.
Ireland	Alkali-Silica Reaction in Concrete, published by The Institution of Engineers of Ireland and The Irish Concrete Society, 2003. (IEI/ICS ASR Report).
Portugal	LNEC E 461:2007: Methodology for avoiding internal expansive reactions.
United Kingdom	BS 8500-2 (see Table 1). More detailed guidance is provided in BRE Digest 330: Alkali-silica reaction in concrete.

- ✓ Limiting values for concrete mixes



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5. Examples of projects with performance limits for concrete durability

Fig. 1. Vasco da Gama bridge in Lisbon, Portugal.

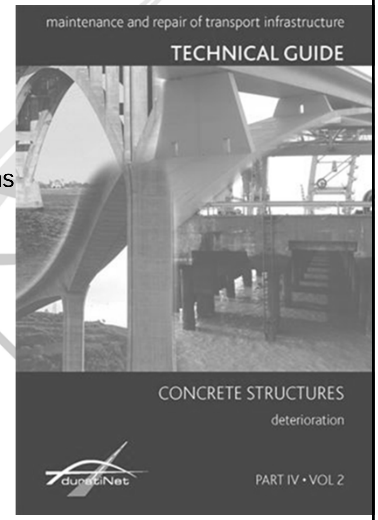
Fig. 1. Millau Bridge in France

Table 1. Description of tests used to assess if the performance limits shown in Table 41 were met

Project	Property	Specified durability property	Description of tests	Results
Channel Tunnel	Water permeability (m/sec)	$< 10^{-13}$	Water permeability tests measuring the depth of ingress of water	$0.6\text{-}0.7\times10^{-13}$ m/sec at 50-days. 1.4×10^{-13} m/sec at 8 months
Vasco da Gama Bridge	Gas Permeability (m^2)	$< 10^{-17}$ at 28 days	Cembureau method	$0.7\text{-}0.3\times10^{-6}$ m2 between 28 and 90days. $\leq 0.01\times10^{-17}$ m^2 at 18 months
	Apparent Chloride Diffusion Coeff.(m^2/sec)	$< 10^{-12}$ at 28-days	Migration test in non-steady state conditions	$1\text{-}4\times10^{-12}$ m^2/sec between 28 and 90 days. $0.2\text{-}0.8\times10^{-12}$ m^2/sec at 18 months
	Quantity of electricity (coulombs)	<1500 at 28-days < 1000 at 90-days	AASHTO test (ASTM Standard C1202.	
Extension of Condamine Port floating dyke	Water porosity	< 12 (B54) < 10 (B65)	Mercury Intrusion (water porosity). AFPC-AFREM procedure (mercuary porosity)	8.8 - 9.4 5.8 - 5.6
	Gas Permeability (m^2)	$< 10^{-16}$ to 10-^{17} (28-days 800C drying	AFPC-AFREM Test procedure	5.54×10^{-19} to 1.25×10^{-18}
	Apparent Chloride Diffusion Coeff.(m^2/sec)	$<5\times10^{-12}$ (B54) $<1\times10^{-12}$ (B65)	Non-steady state (Tang Method)	
	Quantity of electricity (coulombs)	100-1000 (B65), 1000-2000 (B54)	AASHTO test (ASTM Standard C1202.	377 - 401

Part IV: Concrete Structures - Vol 2 - Deterioration

1 General considerations
2 Physical /mechanical deterioration processes
3 Chemical deterioration processes
4 Classification of defects and deterioration symptoms
5 Final considerations



Part IV: Concrete Structures - Vol 2 - Deterioration

1. General considerations

Table 1. Deterioration processes for reinforced concrete structures

Concrete		
CHEMICAL	PHYSICAL/ MECHANICAL	BIOLOGICAL/ ORGANIC
Alkali aggregate reaction (AAR) Internal sulfate attack (ISA) External sulfate attack (ESA) and salt crystallisation Carbonation Chloride contamination Leaching Acid attack	Freeze-thaw Creep Shrinkage Thermal cracking Abrasion/Erosion Fire Overloading	Living organisms activity Accumulation of dirt or rubbish Oil and fat contamination
Reinforcement and prestressing steel		
Reinforcement steel uniform and pitting corrosion Stress corrosion of prestressing steel Stray current		

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2. Physical /mechanical deterioration processes

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	DETERIORATION PROCESS		
FREEZE AND THAW	 (Concrete –Microstructure, Properties, and Materials)		
Description	The main mechanism is a consequence of the expansiveness of water as it freezes within the concrete pores. It is possible identify two types of damage: - Internal damage is caused by water freezing inside the concrete. The freezing causes internal cracking either in the cement paste or the aggregate particles or both. - Surface scaling caused by freezing of the concrete surface in contact with water contaminated by chlorides. The cement matrix is gradually broken up by this process with the eventual loss of sand and aggregate particles. The extent is dependent of the severity of the environment, the rate of cooling and the chloride concentration. Frost damage only affects the concrete in the structure, but indirectly the reinforcement suffers a reduction in bond and reduction in the concrete cover.		
Critical factors	Environment: Exposed to water (concrete is especially vulnerable to areas of fluctuating water levels or under spraying conditions); Very low environmental temperatures. The use of de-icing chemicals on concrete surface (may accelerate the process).		
	Material: Nature of aggregates (high porous); concrete with low paste porosity (the resistance to this degradation phenomena is improved by the use of intentionally entrained air which creates an internal network of bubbles enabling the free expansion of ice)		
Defects classification/ Symptoms	Contamination ☐	Deformation ☐	Deterioration ☒
			Pop-Outs Concrete Strength Reduction
	Displacement ☐	Discontinuity ☒	Loss of material ☒
		Craks III (AAR/DEF/FREEZE AND THAW)	Pop-Outs Scaling
Testing techniques	Visual survey ☒	NDT ☒	DT ☒
	Is the simple solution and provides information about the extent of damage.	Ultrasonic velocity Rebound hammer	Compressive strength Tensile strength Static elastic modulus Apparent and effective diffusion content Permeability coefficient
Prevention	Use of a concrete with air entraining agent confers frost resistance		
Repair/Protection methods	Crack Injection; Surface Treatments; Patch Repair; Strengthening		
References	Newman J. and Choo B.S.; Advanced Concrete Technology – Concrete Properties; Chapter 11-Freeze/thaw resistance, by Michel Pigeon, Bruno Zuner and Jacques Marchand; Elsevier, 2003. Mehta, P.K.; Monteiro P.J.M.; Concrete – Microstructure, Properties, and Materials; McGraw-Hill, 2006. Richardson, M.; Fundamentals of durable reinforced concrete; Spoon Press, 2002.		

3. Chemical deterioration processes

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	DETERIORATION PROCESS		
ACID ATTACK			
Description	Concrete is susceptible to acid attack due to its alkaline nature. The components of the cement paste break down during the contact with acids. The most important is the dissolution of calcium hydroxide but other cement paste compounds and also aggregates can be attacked. Acid attack occurs when concrete surface is exposed to the environments or atmospheres with pH < 6,5.		
Critical factors	Environment: Type, concentration and renewal of the acid source (e.g. sulphuric, nitric, hydrochloric and acetic acids are very aggressive). Pressure and velocity of flow of contaminated groundwater.		
	Material: High W/C, low cement content and limestone aggregates.		
Defects classification/ Symptoms	Contamination ☒	Deformation ☐	Deterioration ☒
	Efflorescence Discoloration Inorganic/organic and/or Biologic Contamination		Efflorescence Concrete Strength Reduction
	Displacement ☐	Discontinuity ☐	Loss of material ☐
Testing techniques	Visual survey ☒	NDT ☒	DT ☒
	Will show disintegration of the concrete mainly evidenced by loss of cement paste and aggregate from the matrix.	Visual inspection Corrosion rate Half-cell potential Electrical resistivity	Compressive strength Tensile strength Static elastic modulus Porosity Portlandit content Apparent and effective diffusion content Capillary absorption Permeability coefficient Chloride penetration depth by colorimetric Chloride profile Petrography test Chemical analysis of sulphat and alkalis content
Prevention			
Repair/Protection methods	Patch Repair; Surface Treatments; Strengthening		
References	CO Sen, Lee How, Yuen, George C.S.; Building Maintenance Technology; First published, 1993. Young J.F., Scrivener K.L.; Mechanisms of Chemical Degradation of Cement-based Systems Vol 1; First published, 1995. Mehta, P.K.; Monteiro P.J.M.; Concrete – Microstructure, Properties, and Materials; McGraw-Hill, 2006. Richardson, M.; Fundamentals of durable reinforced concrete; Spoon Press, 2002.		

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4. Classification of defects and deterioration symptoms

Classification	Defects & Symptoms
Contamination (1)	Discoloration or staining (leakage, oxides, deposit of oils), incrustation, exudation, deposits of dirt or rubbish, vegetation growth, fouling.
Deformation (2)	Deflection, tilting, buckling, settling, volume change.
Deterioration (3)	Concrete delamination with loss of steel bond, concrete compressive strength reduction, internal concrete disintegration due to different processes, steel strength reduction and all concrete properties change due to environmental impact (carbonation, chloride contamination and leaching with formation of efflorescence).
Discontinuity (4)	Defects due construction faults (bug holes, honeycombing and construction joints). Defects due to deterioration processes (concrete cracking, fracture of steel reinforcement, fracture of prestressing).
Displacement (5)	Vertical and horizontal movement with translation of element or structure, bearing distortion or element rotation.
Loss of material (6)	Concrete spalling, pop-outs, scaling and other forms of concrete disintegration with significant loss of concrete and/or joint sealants. Complete fracture or loss of reinforced concrete elements.

Table 2. Defects and symptoms due to deterioration processes and construction faults in concrete structures

Deterioration Processes	Symptoms and Defects classification type					
	(1)	(2)	(3)	(4)	(5)	(6)
CHEMICAL AND BIOLOGICAL PROCESSES						
Corrosion in reinforcement: Chloride, Carbonation, Stray currents	▪		▪	▪		▪
Corrosion in prestressing steel (stress corrosion cracking)				▪		▪
Alkali aggregate reaction (AAR)		▪	▪	▪	▪	▪
Internal Sulfate Attack (Delayed Ettringite Formation - DEF; Thaumasite sulfate attack- TSA)		▪	▪	▪		▪
External Sulfate Attack (seawater, soils,salts...)			▪	▪		▪
Acid attack			▪	▪		▪
Leaching	▪		▪			
Living organisms activity (fouling) and plant growing	▪		▪	▪		▪
Oils, dirt, other types of deposition	▪					

Table 3. Relationship between the deterioration processes and the classification of symptoms and defects observed in reinforced concrete structures

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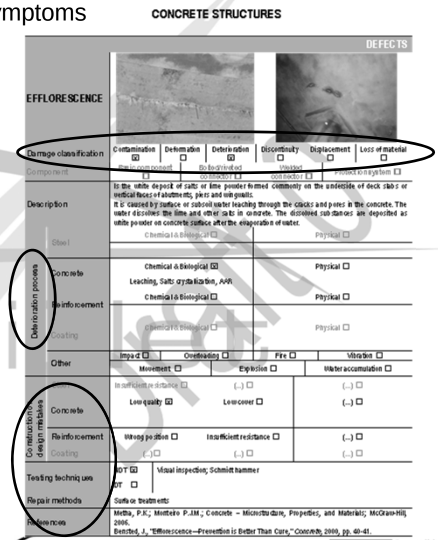
5. Classification of defects and deterioration symptoms

- ✓ Contamination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DEFECTS

EFFLORESCENCE

Damage classification: Contamination ☒ Deformation ☐ Deterioration ☒ Discontinuity ☐ Displacement ☐ Loss of material ☐

Component: Basic component ☐ Bolted/riveted connector ☐ Welded connector ☐ Protection system ☐

Description: Is the white deposit of salts or lime powder formed commonly on the underside of deck slabs or vertical faces of abutments, piers and wingwalls.
It is caused by surface or subsoil water leaching through the cracks and pores in the concrete. The water dissolves the lime and other salts in concrete. The dissolved substances are deposited as white powder on concrete surface after the evaporation of water.

Deterioration process:
Steel: Chemical & Biological ☐ Physical ☐
Concrete: Chemical & Biological ☒ Physical ☐
Leaching, Salts crystallization, AAR
Reinforcement: Chemical & Biological ☐ Physical ☐
Coating: Chemical & Biological ☐ Physical ☐
Other: Impact ☐ Overloading ☐ Fire ☐ Vibration ☐ Movement ☐ Explosion ☐ Water accumulation ☐

Construction or design mistakes:
Steel: Insufficient resistance ☐ (...) ☐ (...) ☐
Concrete: Low quality ☒ Low cover ☐ (...) ☐
Reinforcement: Wrong position ☐ Insufficient resistance ☐ (...) ☐
Coating: (...) ☐ (...) ☐ (...) ☐

Testing techniques: NDT ☒ DT ☐ Visual inspection; Schmidt hammer

Repair methods: Surface treatments

References: Metha, P.K.; Monteiro P.J.M.; Concrete – Microstructure, Properties, and Materials; McGraw-Hill, 2006.
Bensted, J., "Efflorescence—Prevention is Better Than Cure," Concrete, 2000, pp. 40-41.

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6. Final considerations

- ✓ Concrete durability characterises its resistance to weathering action, chemical attack and other deterioration processes;

- ✓ Many of the factors which lead to the initiation and development of most defects in concrete are common;

- ✓ The need to identify the value of material parameters and influential parameters (material or environmental) required for a quantified diagnostic;

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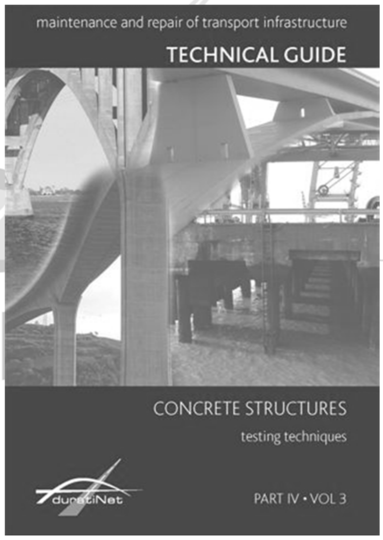
1 General considerations

2 Non-destructive testing methods (NDT)

3 Destructive testing methods (DT)

4 Consideration on testing selection



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Part IV: Concrete Structures - Vol 3 – Inspection Techniques

1. General considerations

- ➢ Determination of the performance of the structure by
  - ✓ **investigating the current condition of the structure**
  - ✓ **diagnose the causes of defects or deterioration**
  - ✓ **select an appropriate solution to the problem**
  - ✓ **check the quality and the efficiency of the solution**

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2. Non-destructive testing methods

CONCRETE STRUCTURES

TESTING TECHNIQUES

REBOUND HAMMER

Principle		With a defined energy, a striker strikes the concrete and rebounds according to the hardness of the concrete. Tables of conversion (calibration curves), make it possible to deduce the compressive strength from the value of rebound called rebound number/index.			
Objectives and Applicability		Objectives	Assessment of the concrete compressive strength on new or existing structures.		
		Deterioration process(es)	Defect(s)	Control of repair	
			Concrete strength		
Equipment and availability		Several commercial systems available: a new generation of the device is available (digital measurement and display with a direct estimation of the concrete compressive strength). The existing devices are summarized in the following website: http://www.abbeyspares.co.uk/pdfs/SchmidtHammerAbbey.pdf. Can be combined with ultrasound measurements (SonReb technique)			
Destructive feature		NDT ☒	DT ☐	SD ☐	
Key aspects		Advantages / Disadvantages	Quick and easy to use, low cost, the results are instantaneously available, makes possible the investigation of large areas and the location of weaker zones / Need calibration, low accuracy, the measurement is affected by numerous factors such as (carbonation, concrete mixture, smoothness of test surface, moisture content…).		
		Accuracy	The local value of rebound is the average of at least 9 measurements in the same vicinity. Deducing the strength requires a calibration. If a standard calibration curve is used, the error can be very large. The correct calibration requires some cores from the same structures. After calibration, the standard error is about +/- 5MPa. European standard EN13791 provides two variants for calibration(building appropriate calibration curve or drifting a prior curve)		
		Limits	Evaluation of 'internal' concrete (not close to the surface) is impossible.		
		Maturity	> 10 years ☒	< 5 years ☐	Under development ☐
		Qualification & interpretation	Inspector ☒	Inspector+Specialist ☐	Specialised lab ☐
Sustainability	Social	Service disruption	Yes ☐	No ☒	
	Environment and health	Health	Yes ☐	No ☐	
		Ecology	Yes ☒	No ☐	
	Economical	Preliminary works	Yes ☒	No ☐	Checking calibration requires at least 9 cores and this take some more time. Verification of the device calibration before and after measurements using standard anvil, localisation of the measured surfaces, surface preparation.
		Time consumption	low (less 1 hour) ☒	medium (a day) ☐	high(> one day) ☐
		Cost	Low ☒	Medium ☐	High ☐
Application	In situ	Access to the element	1 face ☒	2 faces ☐	
	Sampling	Type of samples			
		Dimension			
		Extraction			
		Transport			

Fig. 2.Sclerometric test on concrete structure

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3. Destructive testing methods

CONCRETE STRUCTURES

TESTING TECHNIQUES

CHLORIDE PENETRATION DEPTH BY COLOURIMETRY

Principle		This test is based on the reaction of unbound or free chlorides in concrete with $AgNO_3$ aqueous solution. The reaction between silver ion (Ag^+) and chloride ion (Cl^-) produces a white precipitate of silver chloride. If silver ion (Ag^+) reacts with hydroxide ions (OH^-) in a non chloride contaminated concrete, a brown precipitate of silver hydroxide ($AgOH$) is also produced. The chloride penetration depth would be the distance between the concrete exposed surface and the border line given by the transition of color from white to brown.			
Objectives and Applicability		Objectives	To measure the depth of penetration of free chloride ions in concrete, by spraying silver nitrate ($AgNO_3$) aqueous solution on the cross-section of the freshly split chloride contaminated concrete. To evaluate in a quick way the penetration of chloride ions. To understand the influence of weak zones in concrete, for more easy chloride transport		
		Deterioration process(es)	Defect(s)	Control of repair	
		Chloride Penetration Corrosion reinforcement	Cracks type III - Corrosion	Chloride Extraction	
Equipment and availability		Drilling machine for sampling the cores. 0,1M $AgNO_3$ solution.			
Destructive feature		NDT ☐	DT ☒	SD ☐	
Key aspects		Advantages / Disadvantages	Test execution is cheap, quick and easy to perform on site. Can be widely applicable in both laboratory and site conditions. Not applicable to concrete mixed with chlorides. The test can be applicable for main types of concrete except in the case of concrete with fly ash or slag high content. In carbonated concrete the previous re-alkalinization of concrete is necessary. The depth of bound chlorides cannot be measured whereas they are also participating to corrosion initiation.		
		Accuracy	Free chloride penetration front is normally measured with the help of slide caliper and a suitable ruler at 10mm interval on the cross-section surface in order to obtain 5-7 valid depth readings. The average of the measurements would provide the chloride penetration depth.		
		Limits	The limit value of free chloride content detected by this test is variable with the type of binder. As no chloride content could be measured with this method it is very safe and costly for maintenance decision		
		Maturity	> 10 years ☒	< 5 years ☐	Under development ☐
		Qualification & interpretation	Inspector ☐	Inspector+Specialist ☒	Specialised lab ☐
Sustainability	Social	Service disruption	Yes ☐	No ☒	
	Environmental and health	Health	Yes ☐	No ☒	
		Ecology	Yes ☐	No ☒	
	Economical	Preliminary works	Yes ☒	No ☐	Sampling cores from concrete.
		Time consumption	low(less 1hour) ☒	medium (a day) ☐	high(> one day) ☐
		Cost	Low ☒	Medium ☐	High ☐
Application	In situ	Access to the element	1 face ☒	2 faces ☐	
	Sampling	Type of samples	The core specimen is split axially into two pieces and the piece having more perpendicular split is chosen for chloride penetration depth analysis.		
		Dimension	It depends from aggregate size but in general cores must have Φ / 100mm.		
		Extraction	Testing technique: Sampling		
		Transport	After extraction, the core must be dried with a cloth and closed in a plastic bag to avoid transfer of moisture (and chloride) during transport to lab.		

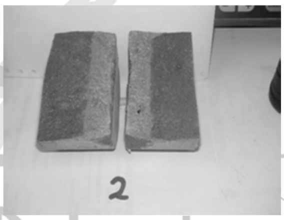

Fig. 59. Chloride penetration depth by colourimetry - Typical test result

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Part IV: Concrete Structures - Vol 3 – Inspection Techniques

4. Consideration on testing selection

Phases of structure	Level of inspection	Frequency	Purpose	Skills (Duration)	Possible actions
Acceptance	General	Once, before "in-use" condition	- Calibration of parameters in service life models (durability design models); - Certification of performance.	Engineer (hours to days)	If performance according to service life calculations are not met, additional protective measures are required.
In-use	Routine and General	1 to 3 years	Detection of obvious defects; especially important for the detection of unexpected defects due to irregularities during fabrication, unreported accidents or misuse of a structure.	Technician (hours)	- Short term repair on non-structural defects; - Call for general inspection
	Principal	Flexible, according to development of condition state	-Determination of condition state; - Calibration of parameters in service life models.	Engineer (days)	- Set date for next Inspection; - Call for repair action; - Call for structural Assessment.
	Special/ Structural assessment	On demand	Assessment of structural safety (static calculations, FEM analysis)	Engineer (days to weeks)	- Call for strengthening and repair - Temporary load restriction
Repair	General	During and after repair action	- Adaptation of MR&R extent; - Calibration of service life models; - Certification of Performance.	Engineer (days)	- Call for additional actions, if performance requirements are not fulfilled.

Table 17.Summary and inspections types

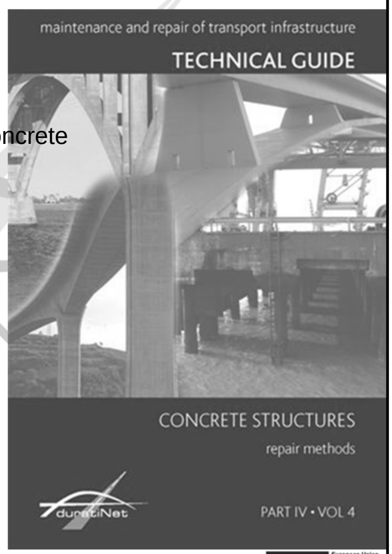
Part IV: Concrete Structures - Vol 4 – Repair Methods

1 General considerations

2 Concrete surface preparation prior to repair

3 Methods for protection and repair of reinforced concrete

4 Selection of repair methods



Part IV: Concrete Structures - Vol 4 - Repair Methods

1. General Considerations

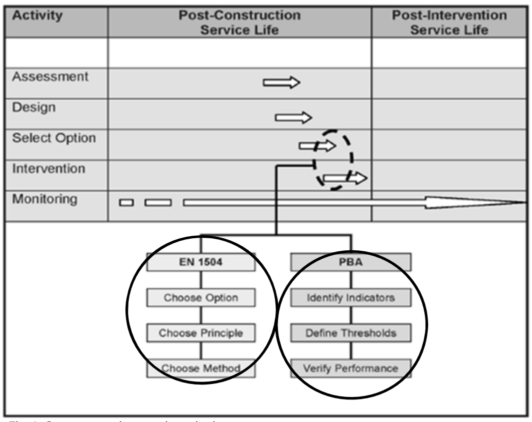


Fig. 1. Strategy to select repair method.

Table 17.Summary and inspections types

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Part IV: Concrete Structures - Vol 4 – Repair Methods

1. General Considerations

Principle	Repair methods	Standard
P1. Protection against ingress	1.1 Hydrophobic impregnation	EN 1504-2
	1.2 Impregnation	
	1.3 Coating	
	1.4 Surface bandaging of cracks	N/A
	1.5 Filling of cracks	EN 1504-5
	1.6 Transferring cracks into joints	N/A
	1.7 Erecting external panels	EN 1992-1-1 Erro! A origem da referência não foi encontrada.
	1.8 Applying membranes	N/A
P2. Moisture control	2.1 Hydrophobic impregnation	EN 1504-2
	2.2 Impregnation	
	2.3 Coating	
	2.4 Erecting external panels	EN 1992-1-1 Erro! A origem da referência não foi encontrada.
	2.5 Electrochemical treatment	N/A
P3. Concrete restoration	3.1 Hand-applied mortar	EN 1504-3
	3.2 Recasting with concrete or mortar	
	3.3 Spraying concrete or mortar	
	3.4 Replacing elements	EN 1992-1-1 Erro! A origem da referência não foi encontrada.
P4. Structural strengthening	4.1 Adding or replacing embedded or external reinforcing bars	
	4.2 Adding reinforcement anchored in pre-formed or drilled holes	EN 1504-6
	4.3 Bonding plate reinforcement	EN 1504-4
	4.4 Adding mortar or concrete	EN 1504-3/4
	4.5 Injecting cracks, voids or interstices	EN 1504-5
	4.6 Filling cracks, voids or interstices	
	4.7 Prestressing - (post tensioning)	EN 1992-1-1 Erro! A origem da referência não foi encontrada.
P5. Increasing physical resistance	5.1 Coating	EN 1504-2
	5.2 Impregnation	

Table 1. Principles and methods for protection and repair related to defects in concrete structures according EN 1504 -9:2008

Principle	Repair methods	Standard
P7. Preserving or restoring passivity	7.1 Increasing cover with additional mortar or concrete	EN 1504-3
	7.2 Replacing contaminated or carbonated concrete	EN 1504-3
	7.3 Electrochemical re-alkalization of carbonated concrete	CEN/TS 14038-1 **Erro! A origem da referência não foi encontrada.**
	7.4 Re-alkalization of carbonated concrete by diffusion	
	7.5 Electrochemical chloride extraction	CEN/TS 14038-2 **Erro! A origem da referência não foi encontrada.**
P8. Increasing resistivity	8.1 Hydrophobic impregnation	EN 1504-2
	8.2 Impregnation	
	8.3 Coating	
P9. Cathodic control	9.1 Limiting oxygen content (at the cathode) by saturation or surface coating	
P10. Cathodic protection	10.1 Applying an electrical potential	ISO/DIS 12696 **Erro! A origem da referência não foi encontrada.**
P11. Control of anodic areas	11.1 Active coating of the reinforcement	EN 1504-7
	11.2 Barrier coating of the reinforcement	
	11.3 Applying corrosion inhibitors in or to the concrete	N/A

Table 2. Principles and methods for protection and repair related to damage due to reinforcement corrosion according EN 1504 -9

Part IV: Concrete Structures - Vol 4 – Repair Methods

3. Methods for protection and repair of reinforced concrete

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CONCRETE STRUCTURES

REPAIR METHODS

SURFACE TREATMENTS


Hydrophobic Impregnation


Surface Impregnation

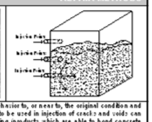

Surface Coatings

Description	This is a concrete treatment to prevent the ingress in concrete of water and aggressive substances associated with water transport. This treatment involves the application of low viscosity liquid products, creams and gels with active components: silanes and siloxanes, water or solvent based. The treatment by hydrophobic impregnation does not fill the pores and capillaries but produces a water-repellent surface, preventing the ingress of liquids that occurs by capillary suction. The appearance of the concrete surface does not change.				
Applicability	Defect(s): The treatment can prevent the ingress of water, air and substances carried in water or air. The treatment does not address deterioration which has already taken place.				
	Generic: It is a concrete treatment adequate to prevent or mitigate deterioration processes including concrete carbonation and concrete chloride penetration. They can be applied to new structures, ie before the initiation of the deterioration processes, or included as part of a repair system. This method respects the principles of protection and repair of EN 1504-9: P1 – protection against ingress of water and aqueous solutions; P2 – Moisture control; P8 – increasing resistivity of concrete by limiting moisture content.				
Key aspects	Advantages/ Disadvantages	Durability	High ☐	Medium ☒	Low ☐
	Limits	The penetration must be uniform and at least 2 mm all over the surface. Penetration is affected by moisture condition of the concrete cover. In new structures it is advisable to wait 2 or 3 months before applying the products. Inadequate for high water pressure conditions. In the case of previous patch repair, attention must be paid to the visual aspect. Carbonation rate can be increased due to decreasing of moisture content.			
	Control of repair	EN 1504-2 specifies the properties for surface protection systems for concrete. The execution of repairs should comply with certain minimum requirements to fulfil the requirements of EN 1504-10. Penetration depth can be directly assessed by core drilling or indirectly by consumption calculation.			
Specific equipment	Readily available equipment for roller or spray application.				
Sustainability – Social	Service disruption	Yes ☐	No ☒		
Sustainability – Environmental and health impacts	Health	Yes ☒	No ☐	EC legislation health and safety must be followed. Handing of products must follow the safety data sheet of each product.	
	Ecology	Yes ☒	No ☐	Depends of the composition of the product and the presence of organic solvents.	
Sustainability – Economical	Preliminary works	Yes ☒	No ☐	When concrete defects are present	
	Specialized labour	Yes ☐	No ☒		
	Time consumption	Low ☒		Medium ☐	High ☐
	Posterior works	Yes ☒	No ☐	Periodic Maintenance	
	Cost	Low ☒		Medium ☐	High ☐
Sustainability – Monitoring	Yes ☒	No ☐	Periodic visual observation and DT tests. Embedded sensors can be installed for automatic data		
Standards	EN 1504 "Products and systems for protection and repair concrete structures. Definitions, requirements, quality control and evaluation of conformity". Parts 2, 9,10 REHABCON Manual, EC DG ENTR-C-2, Innovation and SME Programme, IPS-2000-0062, June 2004				

CONCRETE STRUCTURES

REPAIR METHODS

CONCRETE INJECTION



Description	The purpose of injection is to restore the structural behavior to, or near to, the original condition and to protect from aggressive compounds. The products to be used in injection of cracks and voids can be classified in three categories: force transmitting filling (products which are able to bond concrete surfaces and transmit forces across them), ductile filling (flexible products which can accommodate subsequent movements) and swelling fitted filling (active products that are able to swell repeatedly by water absorption). Two main types of injection materials could be used: hydraulic (HIM) which is suited for the first category and polymeric (PIM) which, depending of the type of material, could be used for the three categories.				
Applicability	Defect(s): Efflorescence; Cracks type I, II and, in some special conditions, type III and IV, Honeycombing; Bug holes.				
	Generic: Crack wider than 0,2 mm. This method respects the principles of protection and repair of EN 1504-9: P1 – Protection against aggressive substances and P4 – Strengthening of building components.				
Key aspects	Advantages / Disadvantages	Durability	High ☐	Medium ☒	Low ☐
		Disadvantages: With corrosion deterioration already taking place or AAR and ESA deterioration processes this repair method in general is not efficient.			
	Limits	Injection of cracks due to corrosion always requires other additional protection methods (Cathodic Protection, Chloride Extraction, Re-alkalization or Coating application...). Injection of cracks of type IV is effective, only if no residual reactivity remains. the type of injection must be adapted to the active state of the cracks (active or dormant).			
	Control of repair	Before injecting the properties and characteristics of the injection materials must be fulfilled within the admissible tolerances. The control of workmanship must be performed by the supervisor monitoring the injection and approved using a NDT procedure.			
Techniques	SEALING - HIM			SEALING – PIM	
Specific equipment	Adequate equipment for mixing and pumping the injection materials				
Sustainability – Social	Service disruption	Yes ☐	No ☒		
Sustainability – Environmental and health impacts	Health	Yes ☐	No ☒	EC legislation health and safety must be followed. Handing of products must follow the safety data sheet of each product.	
	Ecology	Yes ☐	No ☒		
Sustainability – Economical	Preliminary works	Yes ☒	No ☐	Impurities in cracks, defects and interstices should be removed.	
	Specialized labour	Yes ☒	No ☐		
	Time consumption	Low ☒		Medium ☐	High ☐
	Posterior works	Yes ☒	No ☐	Restoration of surface concrete protection.	
	Cost	Low ☒		Medium ☐	High ☐
Sustainability – Monitoring	Yes ☒	No ☐	Impact echo or by petrography		
Standards	EN 1504 – 'Products and systems for protection and repair concrete structures. Definitions, requirements, quality control and evaluation of conformity" – part 5, 9 and 10				

Part IV: Concrete Structures - Vol 4 – Repair Methods

4. Selection of repair methods

Damage/Deterioration process	Defects	Repair method or system
Chloride contamination Carbonation Stress corrosion cracking	Cracks Spalling Lost section of ordinary reinforcement Corrosion of prestressed tendons Fracture of prestressing steel	Cathodic protection * Chloride extraction or re-alkalization * Concrete replacement ** Injection Surface protection systems Control of anodic areas using inhibitors Strengthening - External post-tensioning
Freeze-thaw attack Abrasion, erosion and cavitation Acid attack	Scaling Eroded surface	Concrete replacement Injection Surface protection systems
Alkali Aggregate Reaction (AAR) Delayed Ettringite Formation (DEF)	Internal expansion Cracks Loss of strength / cohesion Insufficient structural stability Internal expansion Concrete cracking. Loss of strength and cohesion Insufficient structural stability	Surface protection systems Strengthening - Steel plates bonding Strengthening - Externally bonded FRP Concrete replacement Demolishing / Replacement
Sulfate attack from sea water or soils	Pop-outs Cracks	Concrete replacement Surface protection systems
Leaching by pure or natural waters	Dissolution of paste in surface Dissolution in cracks	Concrete replacement and increasing cover Surface protection systems Injection
Drying and autogenous and thermal shrinkage	Cracks	Injection Surface protection systems
Anchorage rupture Bending fracture Shear fracture Fatigue fracture Compressive fracture	Crushing of concrete Cracking Yield reinforcements Fracture of concrete, loss of bond or reinforcements rupture	Concrete replacement with reinforcement addition Surface protection systems Strengthening - Steel plates bonding Strengthening - Externally bonded FRP Strengthening - External post-tensioning
Gels and solid deposition	Efflorescence, discoloration, vegetation growing and biologic deposition	Mechanical/chemical removal Surface protection systems
Concrete segregation and exposed steel	Honeycombing Defects on concrete joints	Injection Concrete replacement Surface protection systems

Table 22. Relationship between the repair methods, deterioration processes and the defects

5. Web Manual Example

http://durati.lnec.pt/techguide/index.html

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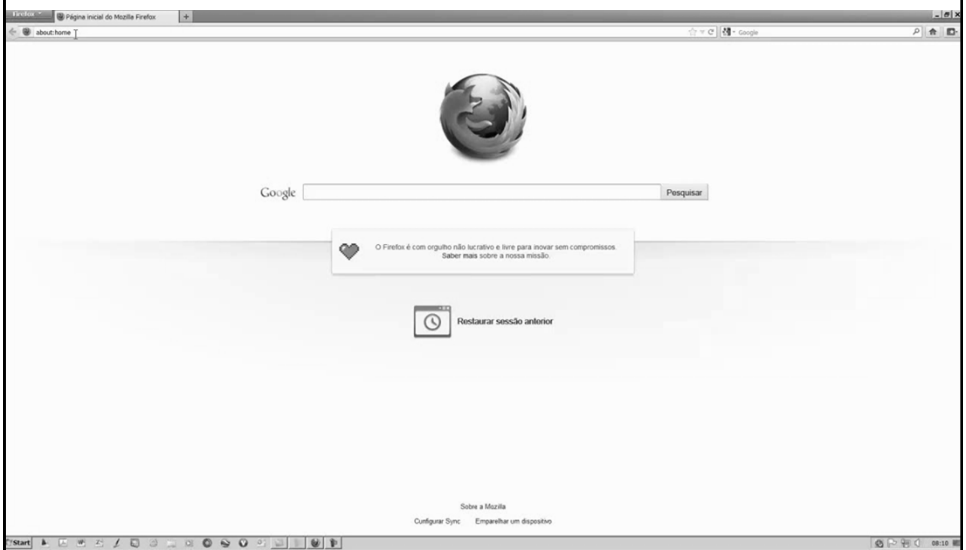

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