CHAPTER 156

QUALITY AND DURABILITY OF CONCRETE ARMOUR UNITS

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1. INTRODUCTION

The reliability of rubble mound breakwaters not only depends on the hydraulic stability but to a large extent on the strength of the armour units as well. In the debate on the shape of armour units, which turns out quite often to be merely academic in nature, generally too little attention is paid to the question of structural strength. On the occasion of the realization of the new outer harbour at Zeebrugge (Belgium) a serious effort has been made to arrive at a better understanding in the behaviour of concrete as construction material for armour units. This contribution gives an overview of the routine tests and of some particular investigations, carried out with respect to quality and durability of concrete armour units.

2. GENERAL CHARACTERISTICS OF THE ARMOUR UNITS

2.1. Types of armour units

In the Zeebrugge harbour extension works two types of armour units have been used : the Antifer cube (±60.000 units) and the HARO® (±13.000 units) (fig.1).

During the design of the main breakwaters the Antifer cube was chosen as armour unit. Consequently it has been used on the breakwaters protecting the LNG-terminal, which were built first.

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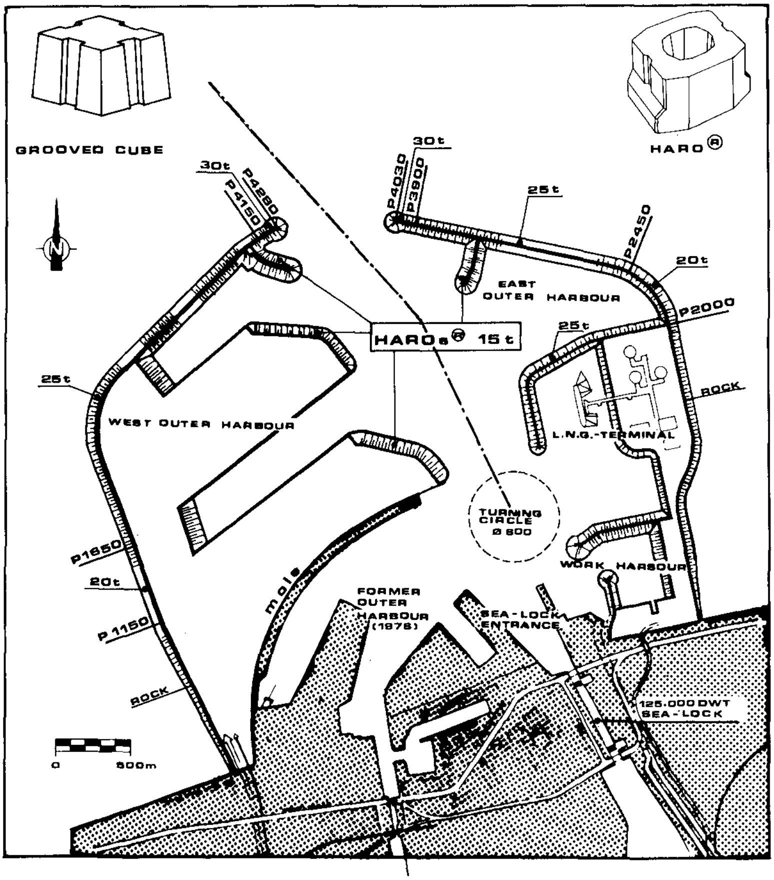

Figure 1 : Zeebrugge outer harbour, with indication of the types of armour unit

On the outer-harbuor breakwaters, a slightly adapted grooved "cube" (the height is somewhat smaller than the bottom side) has been used. During the same optimization one has looked for concrete with higher density : a mean density of 2,47 t/m³ (1434 test results) has been achieved by adding lead slag. Depending on the location the weight of the units equals 20 or 25 tonnes. The main-breakwater heads have been armoured with 30t-grooved cubes.

Fig. 1 shows the areas, where the different units have been used.

During the design of the inner-harbour breakwaters the HARO® has been developed. The HARO® is a flat (height is less than the short side in plan view) concrete block with a large central opening. Both short sides are made wider at the base, thus constituting an alternative type of block profile by weight. The corners of the block are asymmetrically tapered in plan. The general form of the block in plan is rectangular.

The criteria which have been taken into account during the development of the HARO® are :

- a high structural strength (given by its strong compact shape) ;
- hydraulic stability ($K_D > 15$) ;
- advantageous wave reflection and run-up characteristics ;
- simplicity of fabrication : no opening of the moulds and demolding in one single movement upwards ;
- simplicity in placement of the block on the breakwater slope ;
- economy : by using HAROs® the total volume of concrete needed in the armour layer decreases by more than 35% compared with grooved cubes. This has mainly been achieved by the reduced block weight ($K_D > 15$) and by the high porosity (P = 52 à 55%).

The inner-harbour breakwaters will be armoured with HAROs®. The specified characteristic density of the HARO®, is 2,3 t/m³.

More details on these types of armour units may be found in ref. (1) and (2).

2.2. Placement pattern

During the first construction phase (breakwaters surrounding the LNG terminal) the chosen placement pattern required very little re-positioning of the crane (fig. 2a). However hydraulic stability tests showed a rather high risk of jamming-up when tending towards the design conditions.

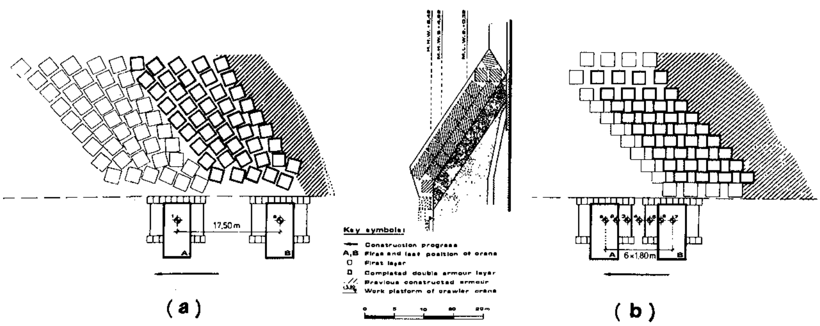

Figure 2 : Placement pattern of armour units.

A placement pattern to eliminate this phenomenon has been elaborated : Within the considered (upper or lower) layer each unit rests on the two adjacent blocks of the lower row. This placement pattern requires an almost continuous repositioning of the crane (fig. 2b). All units on the outer-harbour breakwaters and all HAROs® are placed according to this pattern.

2.3. Concrete composition

The concrete mix proportions to obtain a characteristic density of 2,3 t/m^3 are as follows :

- cement LK30 300 kg/m^3
- gravel (4/28) 1.300 kg/m^3
- sand (0/5) 700 kg/m^3

This concrete composition holds for a mean water content of aggregates of ca. 2,5 %. To obtain a characteristic density of 2,4 t/m^3, as stipulated for the grooved cubes, lead slag is added at a rate of ca. 100 l/m^3. The W/C ratio was lower than 0,4. A blast furnace cement (LK30), with no more than 15% Portland clinker, and low heat of hydration (200 kJ/kg at an age of 72 h) is used. The sand and gravel are marine aggregates with a sufficiently low chloride content and an acceptable shell content.

2.4. Concrete quality

A total of 2.313 compressive strength results are available over a period of 4 years. The test specimens are cubes with side length of 200 mm and cured under water until an age of 28 days. The following statistical characteristics were found :

mean	39.40	N/mm^2
standard deviation	4.59	N/mm^2
coefficient of variation	11.60	%
skewness	0.369	
curtosis	3.768	

On the basis of the values for skewness and curtosis, the normality hypothesis for the distribution function has to be rejected. This is due to the long term variation of the parameters which determine the strength characteristics of the concrete.

3. USE OF LEAD SLAG

3.1. Selection criteria

A higher density of concrete can be obtained by substituting heavy inert materials for part of the gravel. The selection of the most suitable aggregate requires the examination of several physical and mechanical concrete properties, such as : density, compressive and tensile strength, segregation during mixing, plasticity, porosity, shrinkage, creep, capillar absorption, permeability, workability, optimal compaction, resistance against aggressive agents.

The following aggregates have been considered : natural rock, basalt, hematite, lead slag and iron. A cost comparison showed the lead slag mix to be the most economic (table 1).

Unit weight w_c of concrete (t/m³)	Cost
Concrete :	
w_c = 2,30	1
Concrete with basalt (w_b = 3,10 t/m³)	
w_c = 2,41	1,02
w_c = 2,45	1,12
w_c = 2,51	1,25
w_c = 2,58	1,39
Cyclops concrete with natural rock (w_r = 2,65 t/m³)	
w_c = 2,40	1,10
Concrete with hematite (w_h = 5 t/m³)	
w_c = 2,40	1,16
w_c = 2,50	1,34
w_c = 2,65	1,61
Concrete with lead slag (w_l = 3,5 t/m³)	
w_c = 2,42	1,03
w_c = 2,54	1,07
w_c = 2,65	1,11
Concrete with iron cuttings (w_i = 7,85 t/m³)	
w_c = 2,40	1,16
w_c = 2,50	1,35
w_c = 2,65	1,63

Table 1 : Cost comparison of high-density concrete

3.2. Tests on lead slag

Concrete containing lead has a very bad reputation, as expansion of lead in a humid environment may give rise to splitting of concrete. However, lead slag as a residue from the lead production process has a negligible lead content.

A comprehensive analysis has been carried out in order to determine the behaviour of lead against cement and the behaviour of concrete containing lead slag against sea water.

The analysis has been conducted in the following way :

a) Mineral analysis of the slag

From slag samples, thin slices with a thickness of 30 to 40 microns have been taken. Examination of the slices showed the presence of various mineral components difficult to identify in an optical way. An analysis by electron microprobe was used to determine the composition of very small zones (1 micron). The components found are not likely to provoke serious damage for the intended utilization of the lead slag.

b) Reactivity of the slag with respect to cement

The reactivity of the slag with respect to cement has been analyzed by comparing the mechanical properties of two mortars realized with cement and two types of fine aggregates : an inert sand (quartz) and crushed slag. This part of the analysis revealed no significant difference of behaviour.

c) Simulation of sea-water attack

After three months of hardening in a humid chamber, mortar specimens were alternately immersed in and removed from sea-water. At an age of 4 1/2 months, mechanical resistance tests and microscopic examinations were carried out on specimens, subjected to sea-water attack and on reference specimens, one series being composed of normal sand and another series being composed of crushed slag.

The mechanical resistance showed higher values for both series exposed to sea-water. The corresponding results of sand and slag mortar were of the same magnitude (maximum deviation 8%). For both specimen types, no irregularities were noticed by microscopic examination, neither in the cement matrix nor at slag-cement or sand-cement interface.

d) Examination of core samples

At an age of about two years, core samples were taken from blocks on-site. The following characteristics were determined :

- density
- water absorption by immersion
- compressive strength.

The results of these tests correspond to values usually recorded for standard concrete and show no significant deviation from the reference values. The examination of ground-up slices taken from the cores showed that lead slag didn't instigate concrete disintegration.

The foregoing considerations show that the addition of lead slag, with a low lead content, to the concrete is not likely to alter the behaviour of this concrete over its design life.

4. THERMAL STRESSES

Different researchers have demonstrated the relationship between heat development due to hydration of cement and crack formation in young concrete. In order to verify the behaviour of concrete at early ages, a comprehensive investigation program was set up.

4.1. Temperature measurements in armour units

Two series of measurements on concrete blocks were carried out on the site, one in a winter period, the other during summertime.

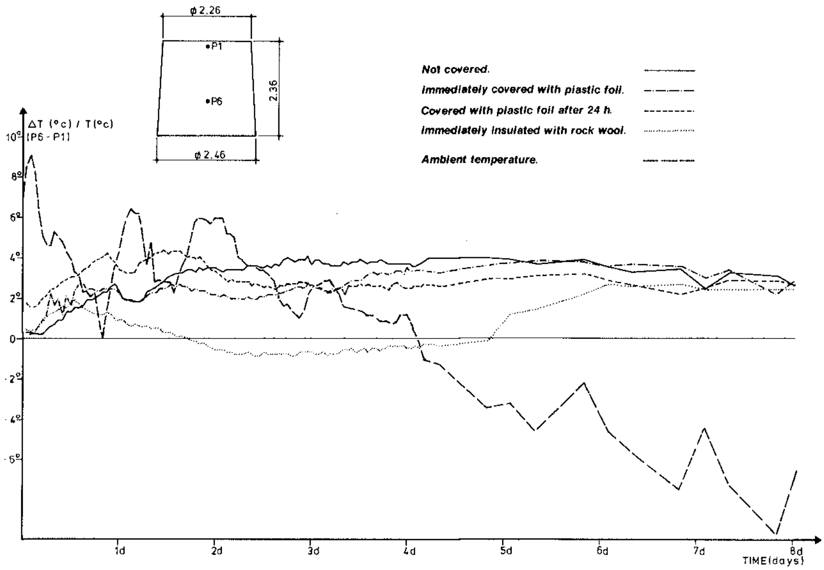

Figure 3 : Evolution of temperature difference between the core and the upper suface for 30 t cubes (winter time)

In the first test trial, four cubic blocks (30 t) were instrumented with 11 thermocouples. After removal of the mould, two blocks were covered with a plastic foil, one block was insulated with rock wool and one block was left unprotected. Fig. 3 shows the evolution of temperature difference between the core and the upper surface for these four 30t-cubes.

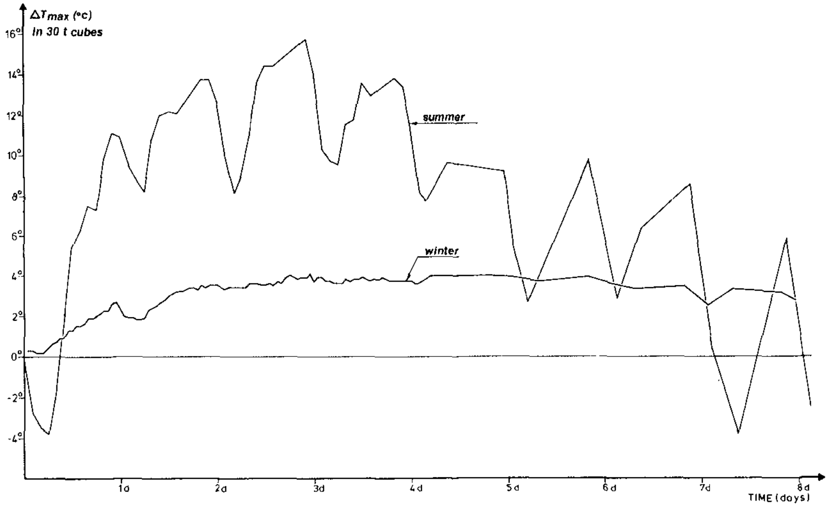

Figure 4 : Maximum measured temperature difference in the unprotected 30 t cubes

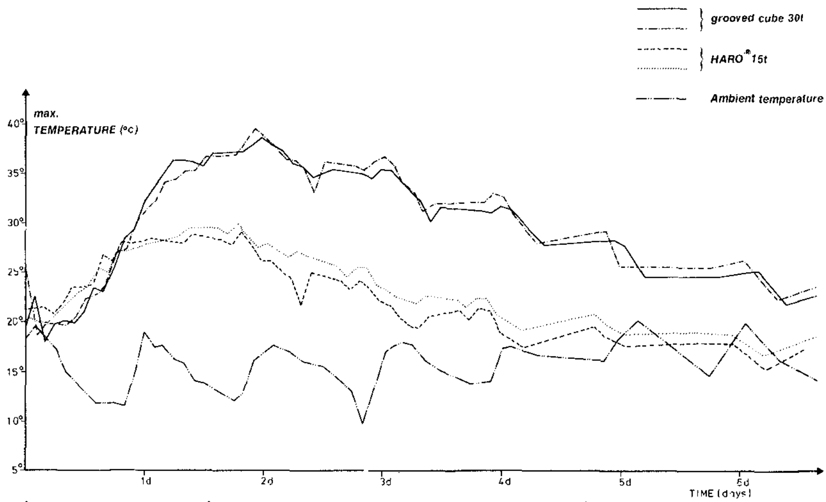

Figure 5 : Maximum temperature (measured in summer) for grooved cubes and HAROs®.

A second series of temperature measurements was carried out during a summer period on 2 cubic blocks (30t) and 2 HAROs® (15t). All blocks were left unprotected. Fig. 4 shows the maximum temperature difference between core and upper surface for the unprotected blocks i) in winter, ii) in summer. Fig. 5 also shows the maximum temperature, both in summertime, and for both grooved cube and the HARO®. Due to the central opening in the HARO® the temperature increase remains small.

4.2. Characteristics of cement and concrete

4.2.1. Properties of cement

The mechanical properties of cement type LK30 were determined on mortar prisms (40x40x160 mm). The compressive strength equals 17.4 N/mm^2 at 3 days, 28.8 N/mm^2 at 7 days and 41.8 N/mm^2 at 28 days.

Setting starts at 6h40 min. and ends at 9h20 min. (Vicat test).

A chemical analysis reveals the following composition :

calcium oxide	44,9 %	magnesium oxide	1,6 %
silicon oxide	30,1 %	loss on ignition	0 %
aluminium oxide	12,3 %	insoluble residue	1,5 %
ferric oxide	1,7 %	other components	0,2 %
sulphur trioxide	7,3 %		

The heat of hydration, determined by means of the conduction method, is found to be 53.7 kJ/kg at 24 h, 146.2 kJ/kg at 48 h and 198.4 kJ/kg at 72 h. It is clear that the heat of hydration of the cement used is rather low which is favourable in order to limit internal thermal stresses.

4.2.2. Mechanical properties of the hardening concrete

During the measuring trial, the compressive and the splitting tensile strength of cubes (side length 200 mm) is determined at several ages, both for on-site and laboratory cured specimens. The laboratory cured specimens are left in a humid chamber at 10°C and a relative humidity of at least 90%. Prisms for the determination of the secant modulus of elasticity are also cured in these environmental conditions.

The results for the concrete of the 30 ton cubes cast in summer are mentioned in table 2.

Age (days)	Curing	Compressive strength (N/mm²)	Splitting tensile strength (N/mm²)	Secant Modulus of Elasticity (N/mm²)
1	site laboratory	2.63 2.64	0.19 0.18	4.300 -
2	site laboratory	- -	0.99 1.08	31.000 -
3	site laboratory	18.0 23.2	1.59 1.93	36.200 -
7	site laboratory	- -	1.98 2.87	35.400 -
28	site laboratory	32.0 40.8	2.76 3.24	42.500 -

Table 2 : Mechanical properties of the concrete used for the 30-ton cubes (summertime)

The results for the HAROs® also cast in summer are of the same order.

4.3. Thermal stresses in young concrete

The measured temperature and the secant modulus of elasticity, determined on the specimens were used to calculate the thermal stresses that develop in concrete blocks by means of a finite element program.

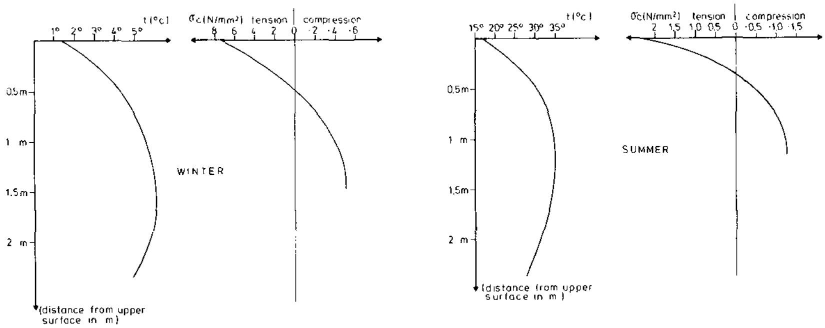

Figure 6 : Measured temperature distribution and calculated horizontal stress distribution along the vertical axis in 30 t cubes.

Fig. 6 gives the measured temperature distribution and calculated horizontal stress distribution along the vertical axis in a cubic block (30t).

The maximum tensile stress at the block's upper surface is obtained after 4 days in the winter and after 3 days in the summer.

It appears that the calculated tensile stresses due to hydration heat are comparable in magnitude with the tensile strength of the concrete at that time as shown in table 3. Consequently, cracks may arise at the block's surface.

	WINTER (4 days after casting)	SUMMER (3 days after casting)
calculated maximum tensile stress	0.75 N/mm^2	2.3 N/mm^2
tensile strength	0.4 N/mm^2	1.6 N/mm^2

Table 3 : Calculated maximum tensile stress versus available tensile strength of the young concrete

5. FROST RESISTANCE

After two severe winters, some blocks on the site showed a surface with exposed coarse aggregates due to the alternating action of freezing and thawing.

One could fear that with a repetition of that process the units could loose an important fraction of their weight or that an accelerated deterioration long before the presumed lifetime could take place and consequently cause stability problems.

In order to investigate the problem in detail, freezing and accelarated ageing tests were executed on specimens taken from the damaged blocks.

Frost resistance is related to the water-cement ratio and the air content of the concrete. Although the W/C ratio is below 0.40, the porosity at the surface, especially the upper surface, might be higher than in the core of the units. Tests on cores drilled near the surface showed water absorption ranging from 6 to more than 8 percent.

5.1. Freezing tests

A freezing test was executed on a large sample with a mass of 950 kg.

In the first stage the following environmental conditions were used :
- freezing chamber at -15°C
- laboratory conditions at 20°C
- salty water at 20°C.

A complete cycle has a duration of 24 hours. No breakage or deterioration of the blocks was observed after 3 cycles.

In the second stage, 15 cycles of two days each are performed. The first day at -15°C in the freezing chamber, the second day it is brought into salty water at 20°C. After the third cycle cracking of the block started and finally several branched cracks extending over the complete block were observed.

After the freezing test concrete quality was measured on cores drilled from the uncracked areas of the block. In comparison with reference values, a reduction of compressive and tensile strength is observed but the values are still acceptable taking into account the very severe conditions. The water absorption also decreased.

5.2. Accelerated ageing test

From several blocks, two cores are drilled. One as a reference specimen and the other one is used for the tests.

The test specimens are subjected to 12 ageing cycles over a total period of 24 hours, each consisting of consecutive periods of variations in temperature, ultraviolet and infrared radiation, artificial rain and freezing. After 12 cycles no breaking or deterioration was observed. Here too the concrete quality remains acceptable and the water absorption percentage is decreasing.

6. REMOVAL OF THE FORMWORK

Apart from thermal influences cracking may also occur while removing the formwork and as a result of drying-out of the surface.

About 16 hours after casting, demoulding takes place. To detach the mould from the young concrete, a hydraulic jack is used which pushes on a steel plate placed on top of the block. After the complete mould has slightly been lifted, it is further struck upwards in one single movement. During the whole operation, the mould is not opened.

Particularly attention is paid to avoid cracking of the young concrete, given its low resistance at the moment of striking. The steel plate is therefore as large as possible in order to distribute the load.

Special attention was paid to the curing of the concrete. A heavy duty membrane compound was used in order to keep concrete surfaces permanently wet for the whole of the curing period. Nevertheless, where cracks were noticed they were treated with a synthetic resin.

7. ALKALI SILICA REACTION

Another possible cause of crack formation is internal damage of the concrete.

As the first blocks were placed almost 10 years ago, it was found useful to make a petrographic analysis of the concrete in order to investigate whether or not internal damage occured due to the exposure to the marine environment. More particularly, alkali silica reaction (ASR) and ettringite formation are examined.

The ASR in concrete is a reaction which takes place in humid environment between aggregates (SiO_2 minerals) and the alkalis (Na, K) present in the cement in a humid atmosphere. The reaction results in a very expansive gel which causes the formation of cracks, which is accelerated when ettringite is formed in the cracks.

That aggregates that have been noticed for their sensitivity to alkalis belong to the granulometric fraction of sand and fine gravel. Some types of coarse aggregates also take an active part in the ASR e.g. flint stones, which generally have a white external layer. Also volcanic rock is known as a reacting aggregate.

The concrete, affected by ASR, is manufactured with a cement of the ordinary portland cement type.

As in many regions there is only a limited choice in aggregates and cement, this petrographic examination can provide useful information with respect to the durability of the concrete units.

8. RECOMMENDATIONS

The experience gained during the construction of the breakwaters at Zeebrugge has led to the development of the following proposals for obtaining high-quality concrete :

- A minimum cement content of 300 kg/m^3.
- Use of low heat cement.
- A low water-cement ratio (<0.4).
- Good compaction of concrete, not only in the core of the unit but also close enough to the mould.
- Careful curing (use of curing compound).
- A rigid formwork, which is easy to remove.

- Removal of the formwork at an appropriate time depending on the setting-time of the cement and on the ambient temperature.
- Dense and impermeable aggregates approved for use by prior testing.
- Limitation of the initial temperature of fresh concrete.
- Insulation of the young concrete may be envisaged in order to limit the temperature gradient.

Although the application of these proposals in practice could be limited by local technical or economic constraints, it generally does not increase production costs.

In spite of the application of these guidelines and the extra care taken, about 1% of the concrete cubes placed in Zeebrugge present significant cracking. Although these cracks are note expected to cause stability problems, they are carefully followed.

No cracks are noticed in the HARO®-units.

9. ACKNOWLEDGMENT

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