ISSN 1330-3651
UDC/UDK 691.328:627.235

CONCRETE MIX DESIGN FOR RECONSTRUCTION OF NORTHWEST BREAKWATER IN THE TRIPOLI HARBOUR – LIBYA

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Professional paper

Reconstruction of Northwest breakwater in the Tripoli Harbour - Libya (about 4500 m long) required manufacture of various concrete elements (cubes and accropodes) in total amount of 550 000 m^3. Volumes of cubes were 6,3 m^3, 8,5 $m^3$and 12,7 m^3, volumes of accropodes were 6,3 m^3 and 9,0 m^3. After preliminary trials and trial production, an optimum mix proportion was chosen, in compliance with technical specification requirements. One of the main causes for concrete blocks cracking is the temperature difference between core and external surface of the blocks, so new blocks with new mix proportions were made (three variations in cement content). Temperature was measured at three characteristic points: in the middle of the cube, in the middle of vertical outer surface and in the middle of horizontal upper edge. Finally, optimal proportions of the constituent materials were adopted.

Keywords: *marine structure, mass concrete, temperature*

Projektiranje betonskih mješavina za rekonstrukciju sjeverozapadnog lukobrana u Tripoliju – Libija

Stručni članak

U svrhu rekonstrukcije sjeverozapadnog dijela lukobrana luke u Tripoliju – Libija, dužine 4500 m zahtijevala se izrada raznih betonskih elemenata (kocke i akropodi) u ukupnoj količini od 550 000 m^3. Obujam kocki bio je 6,3 m^3, 8,5 m^3 i 12,7 m^3, a akropoda 6,3 m^3 i 9,0 m^3. Nakon preliminarnih proba i probne proizvodnje određena je optimalna betonska mješavina, u skladu sa zahtjevima iz tehničke specifikacije. Jedan od glavnih razloga za pojavu pukotina kod betonskih blokova je temperaturna razlika između jezgri i vanjske površine blokova, pa su izrađeni novi blokovi s novim mješavinama (tri varijacije u sadržaju cementa). Temperatura je mjerena u tri karakteristične točke: u sredini kocke, u sredini vertikalne vanjske strane i u sredini gornjeg horizontalnog ruba. Na kraju je usvojena optimalna receptura.

Ključne riječi: *masivni beton, morski hidrotehnički objekti, temperatura*

1 Introduction
Uvod

Mass concrete in marine structures must comply with specific requirements which differ greatly from those for common applications of mass concrete. As with most mass concretes, compressive strength requirements for concrete in marine structures are often not as important as achieving durability. Therefore, design of concrete mixture, including concrete ingredients, must be done very carefully, taking into account many factors influencing behaviour and durability of marine structures concrete.

Thermal stress is one of the main causes for concrete damage in mass concrete structures. It causes cracks to occur in concrete at early age [1, 2, 3]. Temperature changes in concrete elements are influenced by external (environment) and internal (cement hydration) conditions [4].

Concrete crack occurrence due to thermal stress can be avoided by choosing a material composition that provides lower rates of hydration, reducing the placing temperature of concrete, controlling lift thickness and adjusting the time intervals between lifts to allow heat to dissipate [5, 6, 7].

Surface or internal cracking may occur at various stages of hydration:

- During the early stages of hydration, when the internal temperature of the immature concrete is increasing, the cooler surface zone is subjected to tensile stress. Thus surface cracking, usually fairly shallow, may occur within a few days after casting.
- At later stages, after the peak temperature has been reached and the internal concrete enters the cooling phase, the increased stiffness of surface zone now acts as a restraint to the thermal shrinkage of the internal concrete. Internal sections are, therefore, subjected to tensile stress and significant internal cracking is possible [8].

Appropriate concrete mixture design, including choice of ingredients, is influenced by cost; thus this paper offers solutions that also permit cost control.

The Tripoli Harbour Northwest breakwater, about 4,5 km long and built 30 years ago, was partly damaged by great storms during recent years. As damages occurred, it emerged that design assumptions for existing breakwater were inadequate, so the entire breakwater was redesigned, in order to provide adequate protection against future storms. Reconstruction of breakwater included the following phases: placement of new layers of stone blocks, concrete cubes and accropodes, and repairs of quay walls.

The total quantity of mass concrete for the armouring elements for entire breakwater was about 550 000 m^3. Only two types of concrete blocks were to be used: cubes of 6,3, 8,5 and 12,7 m^3 and accropodes of 6,3 and 9,0 m^3. The basic requirements for concrete (the same for cubes and accropodes) according to the original technical specifications (Designer: Nedeco Consulting Engineers, The Netherlands) were: minimum cement content: 300 kg/m^3; maximum w/c ratio: 0,42; maximum particle size: D_{max}= 75 mm; compressive strength at 28 days: 25 MPa and minimum unit weight: 2350 kg/m^3. The first project proposal suggested cubes and tetrapodes should be included in the breakwater, and different specifications were provided. The outcome of model testing led to some changes in the basic technical specification, and the cubes and accropodes mixture preparation was adopted according to the same specification.

All data presented in this paper were generated during the first stage of concrete works on Tripoli Harbour Breakwater Reconstruction. First stage of concrete works included preparation works on the site and equipment, preliminary investigations and trial tests on concrete ingredients and concrete, trial production of stone blocks, concrete cubes and accropodes and finally placing of produced elements into a first 100 m long section of breakwater. All tests were performed either at the on-site concrete laboratory, at IMS (Institute for testing of materials), Belgrade, Serbia, or the Industrial Research Center, Tripoli – Libya.

Admixtures were not used for the first iteration of the preliminary trials. However, concrete that met the maximum water to cement ratio criterion was not workable. The next iteration of concrete mixtures included superplasticizers.

Following the preliminary trials and trial production, the optimum mix proportion compliant with technical specifications, was chosen. As some cracks occurred in trial blocks, the next iteration of blocks included variations with new mix proportions (three cement content variations). As cracking of concrete blocks is caused by the temperature difference between the core and the external surface of the blocks, the temperature was measured at 3 specific points in order to estimate real block temperature, as well as its influence on crack occurrence. Finally, an optimum mix proportion was adopted.

2 Choice of concrete ingredients
Izbor komponentnih materijala za beton

The selection of concrete ingredients and mix proportion was carried out after overall testing of available materials and preliminary trials on fresh and hardened concrete taking into account all relevant conditions (technical specifications, market availability of materials including unit price and transportation distance, actual site conditions, equipment requested for manufacturing, transportation, placing, consolidation and curing of concrete etc.). All chosen materials complied with Technical Specifications and relevant BS and ASTM standards.

2.1 Aggregate
Agregat

Two types of available area-specific materials were used for the concrete works, both of them commonly used in the Tripoli area:

- Dune sand from massive deposits in the Tarhuna area, located 40 km away from the site. Samples of sand taken from different neighbouring areas were very uniform in grain size distribution. Sulfates and chlorides were present only occasionally and in traces. Although designated as fraction 0 – 2 mm, this sand was actually 0 – 0,6 mm. In search for sand with greater maximum size, some more distant neighbouring areas were investigated (in the Zliten area, located more than 150 km away) but tests performed at the on-site concrete laboratory did not show any significant differences.
- Crushed limestone aggregate was separated into fractions 2-5, 5-10, 10-20, 20-40 and 40-75 mm. The quarry where triassic limestone was excavated, crushed and separated is located about 70 km south from the site, 10-15 km north of Gharyan mountain range, near Spea Raas Qadih village.

Both materials were confirmed to comply with the quality requirements of the technical specifications:

- Sand used for preliminary trials was a blended sand (BS 882: 1992, item 2.3.4), produced from natural dune sand 0-2 mm and crushed fraction 2-5 mm (mixing of mentioned fractions was performed directly in concrete mixer), in the proportion 56 : 44 %,
- Grading of fraction 2-5 mm was satisfactory (acc. to BS 882: 1992, Tab. 3),
- Grading of fraction 0-2 mm did not meet requirements of BS 882 concerning content of undersize particles (see Fig. 1, particles passing 0,15 mm sieve exceed permissible 15 %).
- Grading of blended sand 0-5 mm, although not satisfying requirements of table 2.5.3 of ACI 207.1R (concerning percentage retained individual by weight on certain sieves), satisfied overall grading limits for sand acc. to BS 882:1992, Tab. 4.
  Content of material finer than 0,075 mm satisfied requirements of Specifications, (according to cl. 10.3.2.2 of specifications particles passing 0,075 mm sieve shall not exceed the following:
  - coarse aggregate 1 % by weight
  - natural sand 2 % by weight
  - crushed stone sand 5 % by weight).
- Behaviour of above mentioned blended sand in concrete, which is of greatest importance in estimating the suitability of ingredients for concrete, (in both fresh and hardened state) was quite satisfactory (see item 2.5.3 of ACI 207.1R). Concrete in fresh state was homogenous, relatively easily workable (by means of vibration) and not prone to segregation. Distribution of aggregate in hardened concrete (observed on specimens after compressive strength testing) was uniform, no excess or lack of sand was observed.
- In order to avoid "gap" (relative small amount of particles between 0,60 and 2,36 mm), it would be desirable to find and to use the sand 0-2 mm with a higher content of mentioned particles (it would decrease the need for water in concrete mixture but, in our opinion, not substantially). Such sand could not be found. That is the reason why 0-0,6 mm sand was used, instead of 0-2 mm.

Some test results are given in Tab. 1, Tab. 2 and Tab. 3. Aggregate particle size distribution and aggregate mixture are given in Fig. 1.

2.2 Cement
Cement

The choice of cement for the concrete works was the most complex part in providing all the concrete ingredients. According to Technical specifications, cement with minimum 65 % of blast furnace slag was required. The nearest sources of such type of cement were in Spain, Italy and Greece. There were several cement factories in Libya but not one of them produced this type of cement. Sulfate-resistant portland cement (type V ASTM C-150) was produced by a cement factory in Benghazi that was located more than 1000 km away. Usage of cement from the local factories was considered. Cements that were produced in the Tripoli region (Zliten, Lebda, Al Khoms and Suq al Khamis factories) were tested for properties and chemical composition. Cement from Suq al Khamis factory had the

Table 1 *Aggregate particle size distribution*
Tablica 1. *Granulometrijski sastav frakcija agregata*

Aggregate:	0-2 mm, dune sand												
	2-75 mm, crushed from Spea Raas Qadih quarry												
Fraction 0 - 2 mm							**Fraction 2 - 5 mm**						
Sieve mm	Ret. (g) on the sieve			Total		Pass. %	Sieve mm	Ret. (g) on the sieve			Total		Pass. %
	I	II	III	g	%			I	II	III	g	%	
2,36							10	0	0	0	0	0	100
1,18						100	5	18	18	21	57	4	96
0,6	1	0	2	3	1	99	2,36	346	330	337	1013	68	29
0,3	45,5	41	39,5	126	40	59	1,18	118	132	122	372	25	4
0,15	41,5	38,5	40	120	38	22	0,60					0	
Pan	22,5	20,5	25,5	68,5	22		Pan	18	20	20	58	4	
Total	110,5	100	107	317,5			Total	500	500	500	1500		
Fraction 5 - 10 mm							**Fraction 10 - 20 mm**						
Sieve mm	Ret. (g) on the sieve			Total		Pass. %	Sieve mm	Ret. (g) on the sieve			Total		Pass. %
	I	II	III	g	%			I	II	III	g	%	
20							28						100
14	0	0	0	0	0	100	20	112	55	148	315	7	93
10	45	52	37	134	6	94	14	545	642	589	1776	38	55
5	610	596	608	1814	79	15	10	710	633	604	1947	42	13
2,36	90	102	108	300	13	2	5	150	185	168	503	11	2
Pan	10	16	17	43	2		Pan	32	45	26	103	2	
Total	755	766	770	2291			Total	1549	1560	1535	4644		
Fraction 20 - 40 mm							**Fraction 40 - 75 mm**						
Sieve mm	Ret. (g) on the sieve			Total		Pass. %	Sieve mm	Ret. (g) on the sieve			Total		Pass. %
	I	II	III	g	%			I	II	III	g	%	
50						100	90						100
37,5	410	550	321	1281	6	94	75	0	0	0	0	0	100
28	2650	2418	2872	7940	39	55	63	7455	7612	8455	23522	47	53
20	2815	3088	2947	8850	43	12	50	3155	3080	3985	10220	20	33
14	822	512	610	1944	9	3	37,5	3080	3710	2814	9604	19	13
Pan	205	155	172	532	3		28	2020	1455	1610	5085	10	3
Total	6902	6723	6922	20547			Pan	402	710	552	1664	3	
							Total	16112	16567	17416	50095		
Material finer than 0,075 mm													
Fraction / mm		**0-2**		**2-5**		**5-10**		**10-20**		**20-40**		**40-75**	
Dry mass / g		A - before washing						B - after washing					
A		1520,0		3414,0		4020,0		8000,0		9510,0		12245,0	
B		1508,0		3362,0		4002,0		7962,0		9494,0		12211,0	
((A-B)/A)·100 %		**0,8**		**1,5**		**0,4**		**0,5**		**0,2**		**0,3**	

Table 2 *Some properties of aggregate*
Tablica 2. *Neka svojstva agregata*

Test method: BS 812: Part 107							
Fraction		**0-2 mm**			**2-5 mm**		
Weight of pycnometer+aggregate+water / g	(B)	2095,0	2101,0		2451,0	2451,5	
Weight of pycnometer filled with water / g	(C)	1780,0	1783,0		1826,0	1826,0	
Weight of SSD aggregate / g	(A)	510,0	512,0		1005,5	1006,0	
Weight of OD aggregate / g	(D)	508,0	509,5		988,0	987,0	
Particle density (Oven Dry) / kg/m^3	D/(A-(B-C))	2605	2626		2597	2594	
Particle density (SSD) / kg/m^3	A/(A-(B-C))	2615	2639	**2630**	2643	2644	**2655**
Apparent particle density / kg/m^3	D/(D-(B-C))	2632	2661		2722	2730	
Water absorption /%	100·(A-D)/D	0,39	0,49	**0,44**	1,77	1,93	**1,85**
Fraction		**5-10 mm**			**10-20 mm**		
Weight of pycnometer+aggregate+water / g	(B)	2453,0	2455.5		2448,0	2454,0	
Weight of pycnometer filled with water / g	(C)	1826,0	1826.0		1826,0	1825,0	
Weight of SSD aggregate / g	(A)	1008,5	1011.0		1000,0	1009,7	
Weight of oven dry aggregate / g	(D)	991,0	993.0		984,0	994,0	
Particle density (Oven Dry) / kg/m^3	D/(A-(B-C))	2598	2603		2603	2611	
Particle density (SSD) /kg/m^3	A/(A-(B-C))	2644	2650	**2658**	2646	2652	**2659**
Apparent particle density / kg/m^3	D/(D-(B-C))	2723	2732		2718	2723	
Water absorption /%	100·(A-D)/D	1,77	1,81	**1,79**	1,63	1,58	**1,60**
Fraction		**20-40 mm**			**40-75 mm**		
Weight of pycnometer+aggregate+water / g	(B)	2462,0	2475,0		12581,0	12584,0	
Weight of pycnometer filled with water / g	(C)	1827,0	1827,0		9424,0	9424,0	
Weight of SSD aggregate / g	(A)	1018,0	1040,0		5074,0	5059,0	
Weigth of oven dry aggregate / g	(D)	999,0	1022,0		4981,0	4976,0	
Particle density (Oven Dry) / kg/m^3	D/(A-(B-C))	2608	2607		2598	2620	
Particle density (SSD) / kg/m^3	A/(A-(B-C))	2658	2653	**2667**	2647	2664	**2667**
Apparent particle density / kg/m^3	D/(D-(B-C))	2745	2733		2731	2740	
Water absorption / %	100·(A-D)/D	1,90	1,76	**1,83**	1,87	1,67	**1,77**

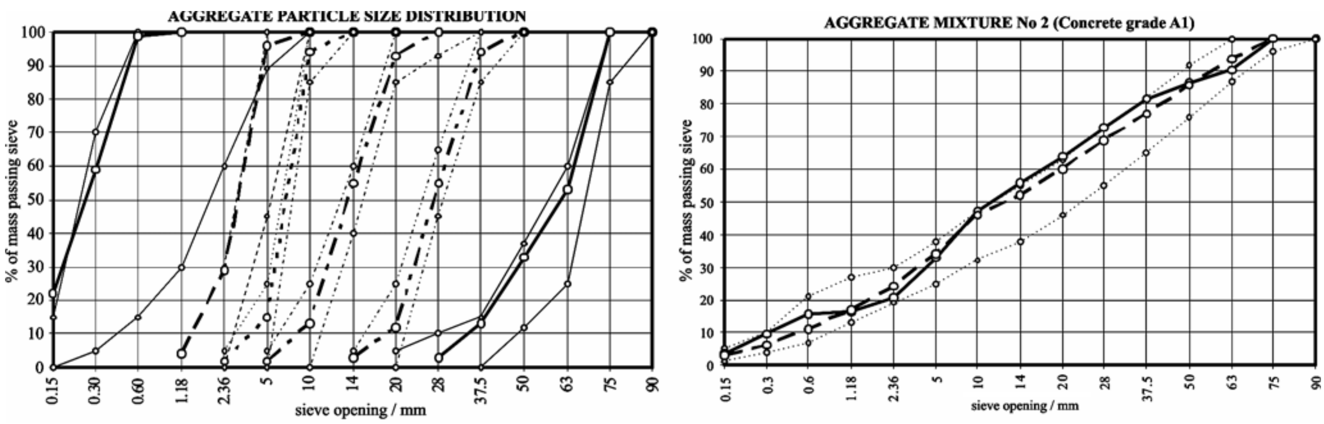
***Table 3** Water absorption and density of aggregate*
***Tablica 3.** Upijanje vode i zapreminska masa agregata*

Place of sampling: Stock piles at concrete factory			
Aggregate: crushed, SPEA RAAS QADIH quarry			
Aggregate impact value (AIV)		**Test method: BS 812: Part 112**	
Sample No	Mass of sample / g	Pass through sieve 2,36 mm / g	Aggregate impact value (AIV)
1	303,0	76,0	25,1
2	303,0	71,0	23,4
3	303,0	81,0	26,7
		Average:	**25,1**

Aggregate ten percent fines value (TFV)				**Test method: BS 812: Part 111**		
Sample No	Mass of sample / g	Pass through sieve 2,36 mm / g	Retained on the sieve 2,36 mm / g	Pass through the sieve 2,36 mm / %	Applied force / kN	Force for 10 % of fines / kN
1	2645,0	270,0	2387,0	10,2	161,0	157,7
2	2645,0	251,0	2413,0	9,5	166,0	174,9
3	2645,0	282,0	2405,0	10,7	153,0	143,5
			Ten percent fines value:			**158,7**

Aggregate ten percent fines value (TFV)				**Test method: BS 812: Part 111**		
Sample No	Mass of sample, / g	Pass through sieve 2,36 mm / g	Retained on the sieve 2,36 mm / g	Pass through the sieve 2,36 mm / %	Applied force / kN	Force for 10 % of fines / kN
1	2645,0	270,0	2387,0	10,2	161,0	157,7
2	2645,0	251,0	2413,0	9,5	166,0	174,9
3	2645,0	282,0	2405,0	10,7	153,0	143,5
			Ten percent fines value:			**158,7**

Aggregate flakiness index		**Test method: BS 812: Section 105.1**		
Fraction / mm	Size-fraction /mm	Mass of sample / g	Mass passing gauge / g	Flakiness index / %
5 - 10	6,3 - 10	500	55	**11.0**
	10 - 14	1003	132	
10 - 20	14 - 20	2001	204	
		3004	336	**11.2**
	20 - 28	5072	390	
20 - 40	28 - 37,5	15056	1370	
		20128	1760	**8,7**
	37,5 - 50	35095	2380	
40 - 75	50 - 63	50125	4575	
		85220	6955	**8,2**
Overall		108352	9051	**8,4**



---------	Recommended limits after J. D. Mc Intosh: The use in mass concrete of aggregate of large maximum size - Civil Engineering, 52, No 615, pp 101-15 (London, sept. 1957)
– – – –	Talsperre - 1955 curve (Clause 10.3.2.7 of Specifications)
———	Current aggregate mixture

***Figure 1** Aggregate size distribution and aggregate mixture*
***Slika 1.** Granulometrijaki sastav frakcija agregata i mješavine*

least amount of C_3A and C_4AF and it was proposed by the Contractor (and approved by the Engineer) as an alternative cement instead of the specified type. According to chemical composition, this type of cement was moderately sulphate resistant, type II ASTM C-150.

Given that blast furnace slag cement was not available, one of the technical procedures that improved concrete durability in aggressive environments (in this case saline water from the sea – considered "highly ranked aggressive" according to [9]) was the provision of an appropriate level of water penetration resistance [10].

In order to get concrete with higher level of water penetration resistance for structures exposed to saline sea water action, the technical requirement is a minimum cement content of 350 kg/m^3 [10].

It is important to appreciate that the price of this locally obtained cement was about 2,5 times lower than the price of any of imported cements, so the final choice of cement was more a financial than a technical question.

Table 4 *Portland cement from Factory "Suq Al Khamis"*
Tablica 4 *Portland cement iz fabrike "Suq Al Khamis"*

	C_3A	C_4AF	C_4AF+2C_3A
Number of results	266	266	266
Maximal value / %	7,65	14,30	26,90
Mean value / %	5,28	11,86	22,41
Minimal value / %	2,03	10,20	16,54
Standard deviation	0,86	0,67	1,44

The sample of cement from Souq Al Khamis (Tab. 4) was sent to the IMS laboratories (Institute for testing of materials) Belgrade, Serbia, for testing of physical and mechanical properties, as well as for testing of its potential expansion as a mortar when exposed to sulfates (test method ASTM C 452-89). Test results were in compliance with requirements for sulfate-resisting portland cement.

The samples of the chosen cement and aggregate were sent to IMS (Institute for testing of materials), Belgrade, Serbia, for potential alkali reactivity testing (ASTM C 227 and 289) and the test results showed that there was no danger of such reactivity.

2.3 Admixtures
Kemijski dodaci

As w/c ratio is limited by the Technical specifications to 0,42 maximum (for durability), and as the first part of preliminary trials proved that this low w/c ratio could be obtained only by using very high cement content, usage of certain admixtures (superplasticizers) was considered. A total of 12 admixtures were obtained from 3 manufacturers: Sika – Egypt, MBT – Egypt and Handy Chemicals – Canada. Comparative testing was performed in order to obtain relevant data for the appropriate choice of admixture. The testing methodology included estimation of the appropriate admixture amount; this is the amount of each admixture that is required in order to obtain the same consistency as in the basic concrete mixture (without admixture) with w/c ratio decreased by 20 %. Consistency was expressed as slump and it was measured at 2 points: immediately after mixing of concrete and 30 minutes later. The concrete mixture used for comparative testing had a cement content of 350 kg/m^3, as required by the Engineer. Target consistency of fresh concrete was expressed as slump 9 ± 2 cm.

The final choice of admixture was based on the following data:

- required consumption for the same effect,
- behaviour of admixture in fresh concrete, especially maintenance of consistency in hot weather, and
- unit price of admixture.

Finally three superplasticizers were chosen, two of which had already been used successfully: Sikament 163 – Naphtalene Formaldehyde Sulphonate (Sika – Egypt), Sikament NN – Polymer Type Dispersion (Sika – Egypt, not yet in use) and Rheobuild 1100 – Synthetic Polymer (MBT – Egypt).

3 Design of concrete mixtures
Projektiranje betonskih mješavina

In order to establish the appropriate proportions of the different ingredients in the fresh concrete mixture, several preliminary trials were performed. Design of aggregate mixtures was carried out according to recommended limits for aggregate mixture with large size aggregates [11, 12] and Talsperre – 1955 curve (Fig. 1).

The grading of the aggregates shall comply with the Talsperre – 1955 curve (1) or shall approximate to this curve, all to the approval of the Engineer. The equation of the Talsperre – 1955 curve is as follows:

$$P = \frac{10}{9} \cdot \left[100 \cdot \left(\frac{d}{D} \right)^{\frac{1}{3}} - 10 \right], \tag{1}$$

where in :
P – percentage retained on a sieve with a nominal aperture d
d – nominal aperture of the sieve
D – maximum nominal aggregate size.

First estimation of the proportion for concrete mixture was made using American standard ACI 211.1. Two pilot trials were carried out in order to obtain data for fine adjustments of the proportion of aggregate fractions and for final design of concrete mixtures. The most important factors taken into considerations for final proportions determination were:

1. specified limits for cement content,
2. w/c ratio and
3. specified compressive strength.

The first part of investigations was designed to provide concretes without admixtures, these samples were made at the Site concrete laboratory. Cement content was in the range 300 – 400 kg/m^3 with 25 kg increment. Test results showed that maximum permissible water/cement ratio (0,42 according to Specifications) was reached at cement content of about 375 kg/m^3. This can be considered to be a relatively "rich" concrete mixture (mixture with high content of cement) for mass concrete. The high cement content has certain negative effects, especially when the concrete is in a fresh state and in the early stages of hardening (higher possibility of plastic shrinkage, higher amount of heat of hydration and consequently higher thermal gradient in concrete element). As a consequence

Table 5 *Concrete mixture in first iteration with admixture*
Tablica 5. *Betonske mješavine u prvoj iteraciji s aditivima*

Trial N°	Ingredients for 1m^3 of concrete				Fresh concrete		
	Cement	Aggregate*	Admixture	Water	w/c	Slump	Unit weight
	kg	kg	Type, content %	kg		cm	kg/m^3
1	350	1967	Sikament –NN, 0,9 %	140	0,4	8,0	2460
2	325	2002	Sikament –NN, 0,9 %	130	0,4	7,5	2462
3	350	1967	Sikament –NN, 0,9 %	140	0,4	8,5	2462
4	325	2001	Sikament –NN, 0,9 %	130	0,4	8,0	2462
5	325	2001	Rheobuild 1100, 1,25 %	130	0,4	8,0	2462
6	350	1966	Rheobuild 1100, 1,0 %	140	0,4	8,5	2459
SSD – saturated surface dry							

of these effects, the likelihood of cracks forming in the concrete element increases.

In fact, the cement content mentioned above would have needed to have been even higher, as proved by the subsequent trial production runs which obtained consistencies (slump of about 4 cm) which were not appropriate for the proposed transportation (truck mixers and conveyor belt).

Concrete mixtures with the properties listed below were chosen using the test results from the first part of investigations (concrete without admixtures):

- Same aggregate mixture with maximum particle size D_{max}= 75 mm,
- Cement content 325 and 350 kg/m^3,
- Water/cement ratio 0,40 in order to ensure that the w/c ratio in actual production does not exceed maximum permissible value of 0,42,
- Increased workability (target slump 8 ± 2,5 cm), to ensure quick and efficient discharge, transportation, placing and compacting.

Six preliminary concrete mixtures (Tab. 5) were then made (following pilot trials, that were carried out to establish proper amount of admixture and unit weight) varying cement content from 325 to 350 kg/m^3. Each concrete mixture had about the same consistency (expressed by slump of 8,0 ± 2,5 cm) that provided adequate transportation and placing characteristics.

Due to the occurrence of cracks, the next block samples were made with three new mix proportions (300, 320 and 350 kg/m^3 cement content) as shown in Tab. 6.

4 Test results and comments
Rezultati ispitivanja i komentari

4.1 Concrete compressive strength
Tlačna čvrstoća betona

According to the test results, all kinds of concrete (Tab. 5) with cement content of 325 and 350 kg/m^3 had 7 day compressive strengths in the range of 36 – 40 MPa and 28 day compressive strengths in the range of 45 – 50 MPa. Unit weight of all concretes was about the same (about 2460 kg/m^3) and although no measurement of entrained air was carried out, it was inferred, based on a comparison with unit weight of concretes without admixture, that none of the selected admixtures entrained significant amounts of air in the concrete. A cross section of one cube is given in Fig. 2, showing homogeneity of concrete and uniform distribution of coarse aggregate across element (required by and performed according to Specifications).

4.2 Cracks
Pukotine

Observations of concrete cubes in the early ages after production showed that cracks were occurring in the very moment of demoulding or shortly after demoulding, always on the upper edges of element and never more than one crack on one particular edge. Cracks were positioned somewhere in the middle third of the edge. In a total of 12 blocks, there were two blocks with two cracks, five blocks with three cracks and five blocks with four cracks. No tendency for widening and lengthening of cracks was observed. Cracking occurred even in the blocks with the lowest w/c ratio.

A first possible cause of crack occurrence in concrete might have been drying shrinkage. However, this was discounted because cracks were occurring at the very moment of demoulding, before the drying shrinkage could take place (moisture loss is not possible through the metal mould except on upper horizontal surfaces where a little moisture loss is possible even through the curing compound). To eliminate this possible cause, in the trial production the upper surface of the cube was covered with plastic sheet immediately after finishing and kept in place to the moment of demoulding. After demoulding, all free surfaces were sprayed with liquid curing compound.

A second possible cause of crack occurrence might have been tensile stresses produced by temperature differences between the core and external surfaces of the block induced by internal thermal processes in the concrete during hardening and heat dissipation through external surfaces. The early-age heat evolution of clinker cement depends on its microstructure and composition [8]. A brief analysis and calculation showed that cubic shape of element was the worst case regarding generated heat dissipation. The ratio of total outer surface vs volume of the element is much greater in the case of accropodes when compared to that of cubes. So, the ability of for natural cooling of element to take place during the early stage of hardening is greater for accropodes (cracks on accropode like those on cubes were not observed at all, no matter under what conditions they had been produced). Consequently, the peak internal temperature, temperature difference between the core and outer surface and temperature of outer surface for accropodes are significantly lower than for cubes under the same conditions.

The third possible cause of crack occurrence is thermal shock at the moment of demoulding (cracking occurred shortly after demoulding). It was observed that in cubes produced in months with higher ambient temperature (during the summer) there were significantly less

Table 6 *Concrete mixture in second iteration with admixture*
Table 6. *Betonske mješavine u drugoj iteraciji sa aditivima*

Trial N°	Ingredients for 1m3 of concrete				Fresh concrete		
	Cement	Aggregate*	Admixture	Water	w/c	Slump	Unit weight
	kg	kg	Type, content %	kg		cm	kg/m^3
1	350	1966	Rheobuild 1100, 1,4 % or Sikament-163, 1,4 %	140	0,40	8,5	2460
2	320	2023	Rheobuild 1100, 1,3 % or Sikament-163, 1,3 %	128	0,40	8,0	2475
3	300	2050	Rheobuild 1100, 1,4 % or Sikament-163, 1,4 %	120	0,40	8,0	2475
**SSD – saturated surface dry*							

Figure 2 *Cross-section of armour cube*
Slika 2. *Poprečni presjek kocke*

observable cracks than in cubes produced in autumn. In summer months the night ambient temperature is high and thus the difference between ambient temperature and that of the concrete surfaces is significantly lower.

4.3 Temperature and cracks measuring with new mixtures
Mjerenje temperature i prslina s novim recepturama

In order to avoid or at least minimize crack occurrence in concrete cubes, the contractor carried out a trial production of total of nine cubes type B and C (8,5 m^3 and 12,7 m^3) with changes in the mix proportions (results related to concrete mixture in the second iteration, Tab. 6) of the fresh concrete and in the procedures for concreting and curing. For guidance, recommendations regarding concrete specification from the American Concrete Institute (ACI) [13,14,15] and other standards were used.

In order to decrease the total heat generated (and hence the maximum internal and surface temperature and temperature gradient), the cement content was decreased to 320 and 300 kg/m^3, according to cl. 2.8.2 of ACI 207.1R - Mass concrete (Specifications require 300 kg/m^3 as minimum cement content). The actual admixture content for proper workability of fresh concrete was also established.

Another improvement in curing of the relatively large upper surfaces of cubes prior demoulding was made by covering with plastic sheets immediately after finishing [15]. In this way, water loss from the upper layer of concrete was completely avoided (even with proper curing compound some small water loss which can be dangerous, was observed during early stages of setting and hardening). Plastic sheet covering proved to be a good measure. No cracks of plastic shrinkage of fresh concrete were observed, concrete surface in the moment of plastic sheet removal was entirely wet.

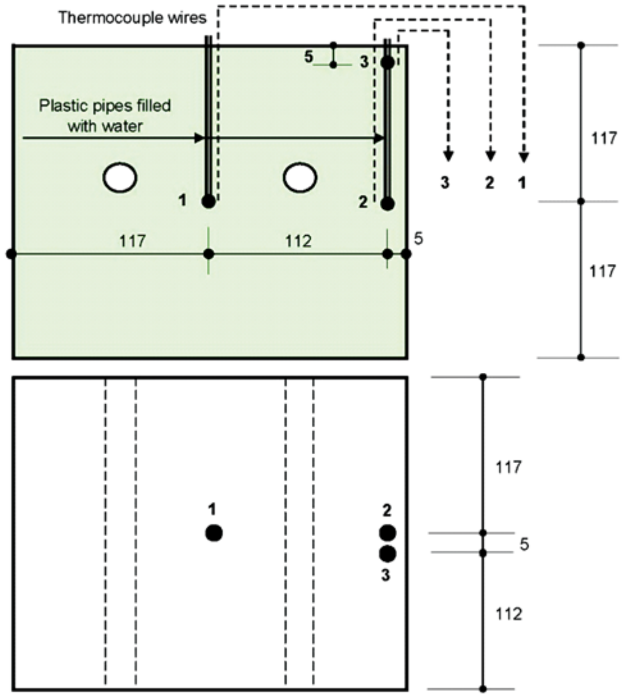


Figure 3 *Location of measuring points*
Slika 3. *Položaj mjernih mjesta*

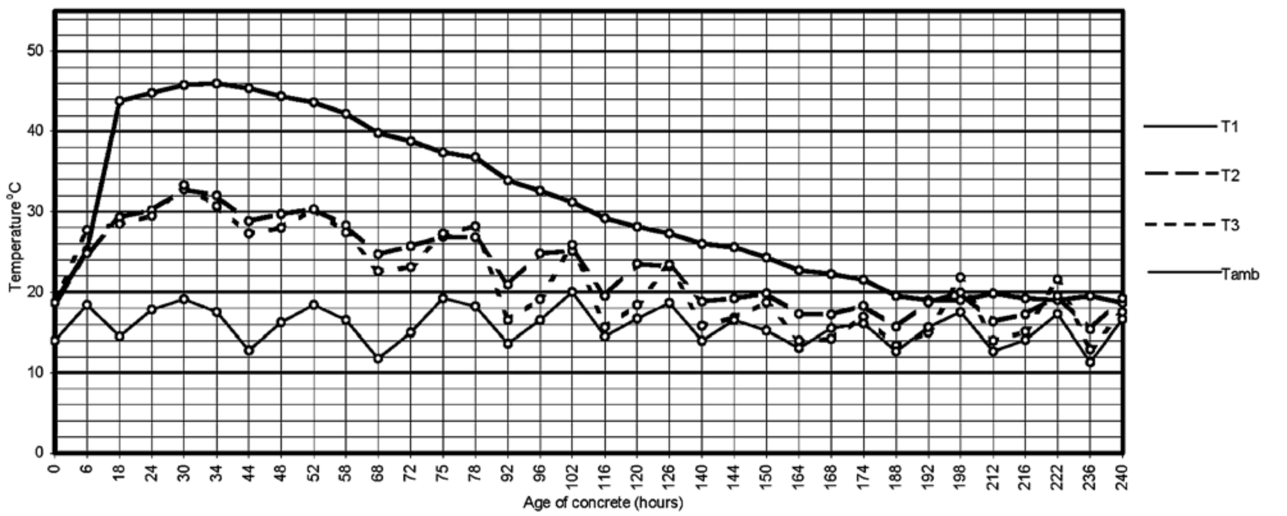
Early rate heat evolution depends on concrete mixture, time and position in the concrete elements [4,8,16].

Temperature was measured at three characteristic points [16]: in the middle of the cube, in the middle of vertical outer surface and in the middle of horizontal upper edge (Fig 3). According to ACI, the range of temperature variation depending on distance from the surface can be computed [14] from the equation (2).

$$\frac{R_x}{R_0} = \mathrm{e}^{-x\sqrt{\pi / h^2\gamma}}, \tag{2}$$

where:
R_x – temperature range at distance x from surface
R_0 – temperature range at the surface (x=0)
e – base of natural logarithms, ft (m)
x – distance from surface
h^2 – diffusivity, ft^2/h (m^2/h)
γ – period of the cycle of temperature variation in day.

In order to establish concrete block thermal data (necessary for problem analyzing, followed by adequate procedures to avoid cracks occurrence), concrete temperature was measured at three characteristic points in the concrete blocks (12,7 m^3) over a period of ten days



Time (h)	0	6	18	24	30	34	44	48	52	58	68	72	75	78	92	96	102
T1	19	25	44	45	46	46	45	44	44	42	40	39	37	37	34	33	31
T2	19	25	29	30	33	32	29	30	30	28	25	26	27	27	21	25	25
T3	19	28	29	30	33	31	27	28	30	27	23	23	27	28	17	19	26
Tamb	14	18	15	18	19	18	13	16	18	17	12	15	19	18	14	17	20
T1 - T3		-3	15	15	13	15	18	16	13	15	17	16	10	9	17	14	5

Time (h)	116	120	126	140	144	150	164	168	174	188	192	198	212	216	222	236	240
T1	29	28	27	26	26	24	23	22	22	20	19	19	20	19	19	20	19
T2	20	24	23	19	19	20	17	17	18	16	19	20	16	17	20	15	19
T3	16	18	23	16	17	19	14	14	17	13	15	22	14	15	22	13	18
Tamb	15	17	19	14	17	15	13	16	16	13	16	18	13	14	17	11	17
T1 - T3	14	10	4	10	9	6	9	8	5	6	4	-3	6	4	-3	7	1

Figure 4 *Results of temperature measurements at three characteristic points and air*
Slika 4. *Rezultati mjerenja temperature betona u tri karakteristične točke i ambijenta*

(Fig. 4, T1 is temperature at point 1 as shown in Fig. 3 etc.). Blocks were made with three new mix proportions (300, 320 and 350 kg/m^3 cement content – Tab. 6).

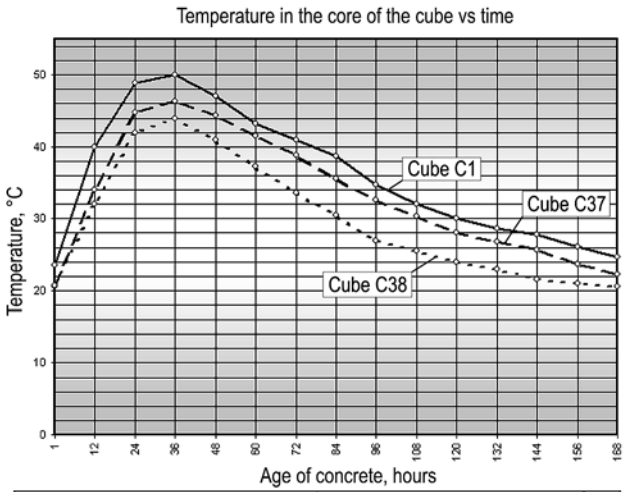
Two methods of measuring temperature were used simultaneously: thermocouples embedded into concrete and plastic pipes embedded into concrete filled with water. Temperature readings were performed using the same measuring digital thermometer (HANNA HI 9043):

1. By attaching thermocouple wires directly to measuring instrument and
2. By immersing T-bar probe 600 mm long, attached to measuring instrument into water in embedded pipe.

By doing so, a comparison between the two methods could be made (second method is widely used in mass concrete structures as it is simple, inexpensive and no special equipment is needed). Preliminary control by simultaneous immersion of thermocouples and T-bar probes into water (20 °C and 60 °C) showed difference not greater than 0,2 °C.

Three characteristic points for temperature measuring were chosen: point 1 in the geometrical middle of the block (maximum expected temperature), point 2 in the geometrical middle of the vertical outer surface and point 3 in the middle of the horizontal upper edge (minimum expected temperature, where cracks were occurring).

The concrete blocks were not made on the same day, but they were made under almost identical conditions (concreting schedule, equipment, workers, ambient conditions and temperatures). Temperature in the core of the cubes with three different cement contents is shown in Fig. 5.



Element:	Cement content* / kg/m^3
Cube C1	350
Cube C37	320
Cube C38	300
* Concrete mixtures are given in the Tab. 6	

Figure 5 *Temperature in the core of the cubes with three different cement contents*
Slika 5. *Temperatura u sredini kocke za tri različite količine cementa*

4.4 Discussion
Diskusija

The obtained results for concrete blocks with three new mix proportions can be discussed and compared, as listed below:

- The maximum temperature occurs 30 – 36 hours after casting.
- As shown in Fig.5, decrease of cement content decreases maximum temperature rise by about 1,2 °C for each 10 kg/m^3 reduction.
- After reaching its maximum, the temperature in the core is sustained at that level for a relatively short period of time after which slow natural cooling takes place.
- Cooling of the core of element is relatively uniform, average rates of cooling being 0,15, 0,17 and 0,20 °C per hour for cement contents of 300, 320 and 350 kg/m^3 respectively. Temperature measurements were

performed over a 10 day period, and showed that thermal equilibrium in the core of element was reached after approximately seven days; by that time most of the potential heat had already been generated and dissipated into the atmosphere.

- Daily changes of ambient temperature had negligible influence on changes of concrete temperature in the core of element during the first ten days (because of relatively large element dimensions). However, once the cooling had begun, the influence of ambient temperature on temperature changes at the surface was fairly significant, outer surface temperatures "following" daily temperature changes very closely (Fig. 4).
- The maximum temperature difference between the core and outer surface did not exceed 20 °C (maximum permissible value according to cl 10.14.2 of Specifications, [15,17,18]). The maximum temperature difference was 18 – 19 °C.
- Observations on extracted cores (chosen from the cubes where cracks occurred, with 320 and 350 kg/m^3 cement content) showed crack depths of about 2 – 3 cm, crack widths about 0,2 mm, and 40 cm crack lengths. These measurements were performed on concrete cubes by using mm graded measuring tape and magnifying glass.
- Samples with cement content reduced to 300 kg/m^3 did not show any cracks.
- Simultaneously performed temperature measurements by two methods showed no significant difference (mean measuring difference between two methods was 0,4 °C). The method with embedded pipes filled with water or oil can be recommended as the method with acceptable accuracy for practical purposes.
- Observations showed that there was no tendency for lengthening and widening of any crack. If there was enough moisture in the crack zone (mostly by artificial wetting), cracks would be subjected to autogenous healing to certain depth so it was necessary to keep them wet as long as possible.

Figure 6 *Slump test*
Slika 6. *Ispitivanje mjere slijeganja*

Following the results and conclusions obtained in the site laboratory and at testing houses, the following mix proportion for the start of works on concrete armour accropodes and cubes was adopted:

- Cement: Souq Al Khamis 350 kg/m^3
- Aggregate: dune sand 0-2 mm; crushed from Spea Raas Qadih quarry, fractions 2-5, 5-10, 10-20, 20-40 and 40-75 mm
- Superplasticizer, chosen by principle of minimum cost per m^3 of concrete: Rheobuild 1100 and Sikament 163
- Water: from Bin Ghasheer well, water to cement ratio not greater than 0,42
- Consistency of fresh concrete: 8,0 ± 2,5 cm measured by slump test (Fig. 6). Consistency by slump test performed by using "minus fourty" portion of concrete sample, obtained by sifting original concrete sample through 40 mm sieve, according to BS 1881, ASTM C143M-03 and Technical Specifications.
- Unit weight of fresh concrete: 2460 kg/m^3.

Note: Contractor's proposal for cement content was 300 kg/m^3, the Engineer demand was strictly at least 350 kg/m^3 for two main reasons:

- Breakwater has to be durable at least 100 years,
- Cement that will be used is from local source, without addition of slag.

Figure 7 *Armour cubes*
Slika 7. *Kocke*

Figure 8 *Armour accropode*
Slika 8. *Akropodi*

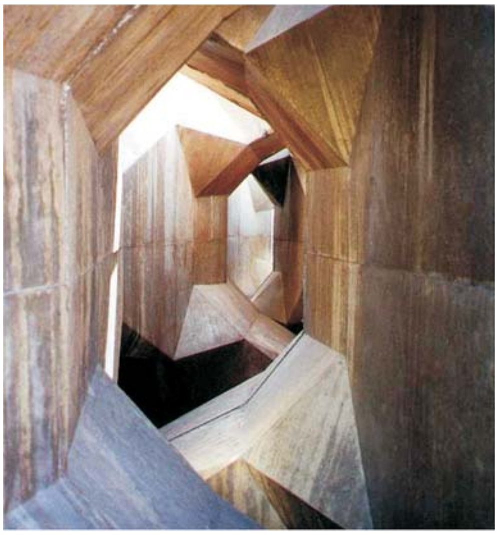


Figure 9 *Armour accropode units at stock*
Slika 9. *Akropodi na skladištu*

Accropodes, due to their irregular shape, have significantly higher surface vs volume ratio than cubes of the same volume (Fig. 7, 8). Ratios of total outer surface vs volume for particular elements are as follows:

- Cube A, 15 t, V = 6,3 m^3, Ratio = 3,22 m^2/m^3
- Cube B, 20 t, V = 8,5 m^3, Ratio = 2,93 m^2/m^3
- Cube C, 30 t, V = 12,7 m^3, Ratio = 2,57 m^2/m^3
- Accropode D, V = 6,3 m^3, Ratio = 4,59 m^2/m^3
- Accropode E, V = 9,0 m^3, Ratio = 4,09 m^2/m^3.

Accropodes in stock are shown in Fig. 9.

5 Conclusions
Zaključci

This paper presents different phases of suggested concrete mixture optimization – Project: Reconstruction of northwest breakwater in Tripoli Harbour-Libya, in compliance with Technical Specifications, considering that construction cost should be minimized without influencing concrete and construction quality.

On the basis of the tests of concrete ingredients, overall tests of fresh and hardened concrete and requirements of Specifications, the following can be concluded:

- all concretes in fresh state were uniform, not prone to segregation (thanks to a well composed aggregate mixture) and capable for efficient compaction by vibration;
- cement content was not a limiting factor for obtaining the prescribed compressive strengths;
- water to cement ratio was below the prescribed maximum value when super plasticizers were used;
- all concretes specimens had "opposite cones" type of failure.

Early age cracking is a predominant design constrain of massive structures. There are various means for limiting temperature rise in mass concrete structures in order to avoid or at least minimize the possibility of cracks occurrence. Detailed analysis of those means is more a financial than a technical question.

As cracks in concrete, depending on their number and physical dimensions (length and depth), can jeopardize durability of concrete, it was necessary to establish causes and take adequate measures to avoid or at least minimize future cracks occurrence.

On the basis of analysis of cracks, all factors which influence their occurrence, availability and feasibility of other materials and construction procedures and actual site conditions, the following can be concluded:

- Cracks occur mainly from a combination of two factors: temperature difference between the core of the cubes and their surfaces that induces tensile stresses exceeding tensile strength of young concrete and thermal shock in the very moment of demoulding (cracks occurred mainly on the blocks produced in cold seasons). It is very hard to tell which of these factors has greater influence but it seems that temperature difference prevails.
- Placing of concrete should be done during times of lower daily temperatures.
- Demoulding of cubes should be done during higher daily temperatures in order to minimize thermal shock.
- Regarding the fact there were no observed cracks on accropodes, the existing mix proportion with cement content 350 kg/m^3, is recommended for future accropodes concreting.

Precooling of concrete ingredients, optimal time for concreting and demoulding and protecting concrete ingredients from direct sunlight and wind will be a subject of further research.

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