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Concrete mix design for wind power turbine foundations exposed to aggressive environment

Gajewski R.
CEMEX Polska, Quality Department of Concrete and Aggregate, Cracow, Poland
Gawlicki M.
AGH University of Science and Technology, Faculty of Material Science and Ceramics, Cracow, Poland
Glinicki M.A.*
Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland

Abstract
This paper presents concrete mix design as well as the results of testing of concrete during production of precast foundations for wind power turbines which are to be located in the Baltic Sea. From 2002 to 2010 approximately 120 000 m^3 of concrete was cast to form 210 foundation blocks. Concrete production and casting was performed in Poland and the manufactured concrete blocks were transported to wind farms in Denmark and Sweden. Massive reinforced concrete blocks were designed to be laid at the sea bottom about 7.5-12.5 m below the water level. For concrete mix design the following exposition classes were assumed: XC4, XF4, XS3 and XM3 according to EN 206-1. Exposure to exceptionally severe environmental conditions was assumed: chemical aggression and mechanical wear by seawater, freezing and thawing in saltwater. Because of the large size of blocks the danger of thermally induced cracking of concrete was carefully considered and computer simulation of stress build-up was used to select the optimal solution. Concrete mix C45/55 was designed using cement CEM III/A 32.5N HSR NA (containing about 60% GGBFS), silica fume, crushed aggregates up to 32 mm and water-reducing and air-entraining additives. High durability of concrete in the aggressive environment was predicted on the basis of microscopic testing of cement hydration products and quantitative evaluation of microstructure. The challenging issue was to maintain a stable air void system in concrete during the whole production process: air void characteristic was regularly monitored in fresh concrete using AVA and in hardened concrete using computer image analysis. Heat of hydration data and monitoring of temperature during concrete hardening provided necessary proof of a non-cracked structure.

Originality
The originality of the presented research, in the area of "sustainable production", is based on a very low clinker factor approach (about 33% of total cementitious material) as well as on the design of a strong and highly durable concrete using computer simulations and quantitative microstructural data to support the optimal selection of multiple mineral additions and chemical additives. The design approach was effectively applied in construction of modern "green" energy production plants.

Chief contributions
This paper focuses on determining the technical requirements for concrete foundation blocks to be used in the construction of wind turbines operated under very aggressive conditions in the Baltic Sea. Furthermore, it was shown that such requirements can be met using highly-engineered air-entrained concrete of low clinker factor, containing CEM III/A 32.5N HSR NA cement and an appropriate amount of silica fume.

Keyword[1]s: *durability of concrete, air void system in concrete, sustainable production,heat of hydration*

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[*]**Corresponding author: E-mail: mglinic@ippt.gov.pl, Tel. (+48) 22 8261281, Fax. (+48) 22 8267380**

1. Introduction

Ensuring the durability of concrete exposed to chemical attack is especially difficult when concrete is also subjected to destructive physical aggression, such as repeated freezing and thawing, abrasion and the peeling of the concrete's surface as a consequence of abrasion, cavitation and erosion. In order to obtain the proper durability under such conditions, chemical composition of the binding agent should be very carefully chosen. Calcium hydroxide content in the binding agent hydration products should be reduced to a minimum and high quality aggregates should be used in the concrete production process. The durability of concrete to a large extent is determined by the type of additives used, as well as their compatibility with a binding agent.

Durability design of concrete structures in severe environments was a subject of numerous publications, recently integrated into a monograph including also current experience with the field performance of existing concrete structures (*Gjorv, 2009*). When using different cementitious materials and modern chemical admixtures the use of simple terms like "water/cement ratio" or "water/binder ratio" for specifying concrete quality is not sufficient. As a consequence, there is a need for a performance-based specification for concrete durability.

The development of performance-based specifications for concrete exposed to highly aggressive marine environment was undertaken for construction of prefabricated foundations of wind power turbines. The experience gained in designing and producing such concrete elements utilized in severe environment of the Baltic Sea is presented here in the form of a case study. Total of 210 wind turbine foundation blocks were produced in Poland, using about 120 000 m^3 of concrete mix. They were transported to their final destination on barges and placed at the bottom of the sea to form a wind farm between the cities Gedser and Rødby (the southern coast of Denmark) in 2002–2005. In 2006 production of another 48 wind power turbines foundation blocks was initiated. These blocks were placed in the vicinity of Malmö (Sweden). In 2010 an additional 90 wind power turbine foundation blocks were manufactured, forming the Rødsand 2 wind farm. Appropriate ballasting on-site ensured stability of the foundation blocks. The depth of the sea at the resting place of the foundation blocks varied from 7.5 to 12.5 m. Mass of the reinforced concrete foundation before ballasting was about 1,300 tonnes, and 1,800 tonnes after ballasting. The turbine mast height from sea level was approximately 100 m.

The use of class C 45/55 concrete, in accordance with EN 206-1, was foreseen in the design. During exploitation the components of wind power turbines are subjected to extremely aggressive environmental conditions: freezing and thawing in the presence of seawater, as well as seawater's chemical and physical impacts. The following exposition classes were established: XC4 – corrosion caused by carbonization, surfaces exposed to water, wet and dry periodically; XF4 – aggressive effects of freezing and thawing, highly saturated with water, the splash zone in the marine buildings; XS3 – corrosion caused by chlorides derived from seawater, tide zones, splashes and aerosols; XM3 – aggression caused by abrasion, extremely high risk of abrasion- according to EN 206-1.

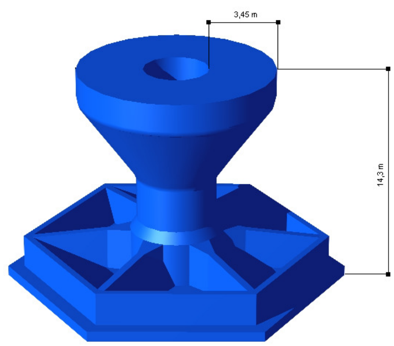

Figure 1: Wind power turbine foundation

Environmental factors played a decisive role in the selection of a material solution yet they were not the only ones taken into consideration. The upper part of a wind turbine foundation, also referred to as the "cup" is a massive part with a diameter of 7 m (Fig 1). During production of such components additional difficulty is caused by excessive heating of the concrete and the formation of temperature gradients which result in dangerous stresses in concrete that in turn can cause scratches and cracks in the finished product.

2. Materials and methods

2.1. Characteristics of cement and concrete mix

Cement CEM III/A 32.5N HSR NA was used in the production of concrete (Table 1). It contained about 60% of ground granulated blast furnace slag (GGBFS). The composition of the concrete mix is given in Table 2.

Table 1: Characteristics of CEM III/A 32.5N HSR NA

LOI [%]	SO_3 [%]	Na_2O_{eq} [%]	Water demand [%]	Initial setting time [min]	Hydration heat after 41 h [J/g]	Le Chateliere test [mm]	Cl^- [%]	Compressive strength [MPa]		
								after 2 days	after 7 days	after 28 days
2.75	1.99	0.96	31.2	252	185	0.6	0.09	9.6	25.8	50.4

Table 2: Mix design composition C 45/55

Components	Quantity [kg/m^3]	Density [kg/dm^3]	Volume [dm^3/m^3]
Natural sand 0-2 mm	700	2.65	263
Crushed gneiss 2-8 mm	271	2.70	100
Crushed gneiss 8-16 mm	510	2.70	188
Crushed gneiss 16-32 mm	350	2.70	130
Cement CEM III/A 32.5 NA HSR LH	345	3.10	111
Silica fume	17	2.20	8
Water	140	1.00	140
Plasticizer 0.5% mass of cement	1.81	1.07	1.69
Superplasticizer 0.7% mass of cement	2.53	1.14	2.22
Air entraining admixture 0.25% mass of cement	0.86	1.00	0.86
Air, dm^3	–	–	55
Total	2344	–	1000

2.2. Techniques

Basic properties of concrete mix and hardened concrete such as slump, density, air content and compressive strength were determined using standard test methods. Moreover, a determination of a number of concrete properties that have a direct impact on the durability of the wind power turbine foundations was made. The resistance of concrete to cyclic freezing and thawing was ensured by the proper selection of chemical additives with emphasis being placed on air-entraining. The compatibility of air-entraining additives with the binding agent was confirmed using Air Void Analyzer (AVA) and by examination of the air void microstructure in hardened concrete using microscopic analysis. Two principal parameters were assumed to determine the resistance of concrete to aggressive action of freezing and thawing: the content of air voids smaller than 300 μm in diameter and the spacing factor of air voids in concrete mix. The concrete resistance to freezing and thawing was experimentally verified by testing the resistance to scaling in the presence of 3% NaCl solution, in accordance with standard EN 12390-9 as well as Polish standard PN-B/88-06250.

Experimental study performed in accordance with PN-B/88-06250 requires preparation of 12 cubic, 150x150x150 mm, concrete samples. The samples are stored for 28 days under conditions where relative humidity is greater than 95% and at a temperature of 20°C ± 2ºC. After 28 days of ageing, 6 samples are placed in water which has a temperature of 20°C ± 2ºC while the remaining six samples are subjected to cycles of freezing and thawing at a rate of 3–4 cycles per day. Freezing takes place in air and thawing in water. After 200 cycles, the samples undergo compression strength testing. Frost resistance is determined by a drop in compression strength and a loss of mass in the samples subjected to cyclic freezing as compared to the control samples which were stored in water at 20ºC. Frost resistant concrete is one with a mass loss of less than 5% and a loss of compression strength smaller than 20%.

Temperature distribution analysis in the concrete was performed using the Danish Technological Institute system, used for measuring concrete's heat of hydration, simulating the behavior of fresh concrete in the structure and monitoring of concrete in the component.

3. Results and discussion

3.1. Basic properties of concrete mix and concrete

The specified requirements for concrete mix and hardened concrete properties were met: the slump: S4 = 160–210 mm, the air content: 4.5–6.5% v/v, the compressive strength after 28 days of ageing >59 MPa. Table 3 summarizes the average values for selected parameters of the concrete mix and hardened concrete.

Table 3: Concrete mix and hardened concrete properties

Parameter	Production during 2002-2010	
	Average result	Standard deviation
Slump [mm]	190	24
Density [kg/m^3]	2341	65
Air content [% v/v]	5.9	0.8
Compressive strength [MPa]		
at the age of 2 days	16.9	3.6
at the age of 7 days	40.2	4.2
at the age of 28 days	63.5	5.0

3.2. Air void characteristics

The total air content in the concrete mixture was determined using pressure method in accordance with EN 12350-7. Determination of air void characteristics was performed using an AVA analyzer. The AVA test results were compared to standard requirements set-forth by ASTM C457 standard. The test is an alternative to microscopic examination. The advantage of the AVA test is that information about the air void characteristics may be obtained before or during concrete mix design. Microscopic

examinations are possible soon after installation of concrete in the component and when it has reached the required sampling strength.
By controlling the spacing factor and percentage of air void with diameter less than 300 µm it can be determined whether the air introduced by air-entraining additives has a proper characteristics and whether it ensures adequate frost resistance of the concrete. It is understood that in concrete resistant to freezing and thawing the spacing factor should be less than 0.20 or less than 0.24 (*Merkblatt für die Herstellung…*). The content of air voids with diameter less than 300 µm should be higher than 1,8% (*Rusin, 2002*) . Test results of air void characteristics of concrete are shown in Figure 2. The results confirmed proper air-void characteristics.

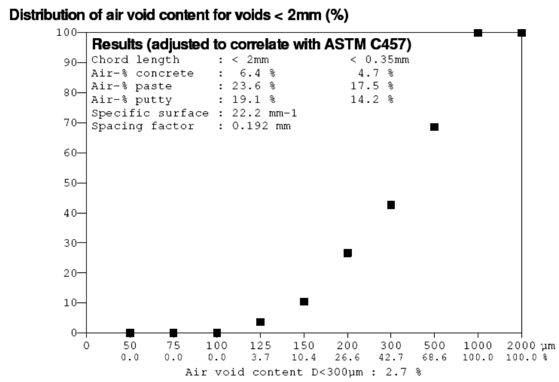

Figure 2: Air void characteristic of concrete using AVA

Additionally, the air void characteristics was determined on hardened concrete specimens using the microscopic method in accordance with EN 480-11. The examples of results obtained are summarized in Table 4. In most of the examined samples of hardened concrete the results of microscopic analysis were comparable with the results were obtained from the AVA analyzer.

Table 4: Air void characteristics in hardened concrete according to EN 480-11

Properties	Results	
The total air content [% v/v]	6.75	7.26
The total number of measured chords	424	465
The specific surface of the air void system [mm^{-1}]	21.07	21.47
Paste/air ratio	4.726	4.392
Spacing factor [mm]	0.21	0.20
The content of microvoids <300 µm [%]	2.51	2.14

3.3. Heat of hydration of concrete

Calorimetric studies of concrete were conducted in a „hydration cabin", which is a part of a system used to simulate and monitor the attributes of fresh concrete in the structure. The experiments have shown that the analyzed concrete mix distinguished by an extremely low heat of hydration (Fig.3).

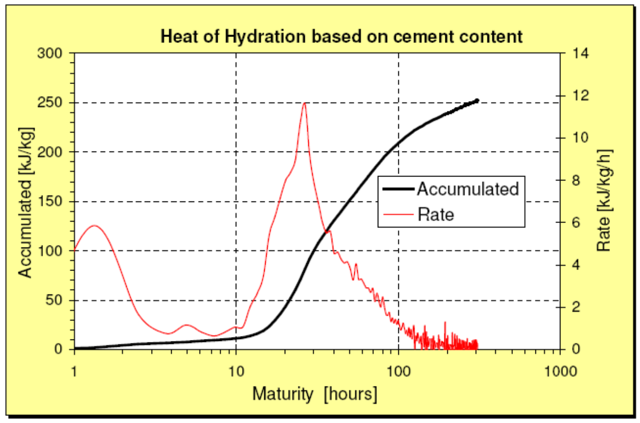

Figure 3: Hydration heat of concrete

Despite this fact, after simulating the temperature rise and its distribution in the manufactured component, it became evident that implementing a cooling system was necessary. Temperatures and temperature gradients that would be generated in the top portion of the foundation, without the use of a cooling system, were too high and could cause cracks. This would especially be the case if the ambient temperature were to rise above 20^{o}C. A system of cooling pipes was introduced around the perimeter of the foundation cup. The temperature of the flowing cooling water as well as its flow rate were adjusted as necessary. Temperatures in the each foundation's cup were monitored. The maximum internal temperature in concrete elements did not exceed 39^{o}C, and the maximum temperature gradient was lower than 10^{o}C.
The simulation of temperature distribution in the element with and without cooling are depicted in Figure 4 (*Gajewski, Szabat, 2005*).

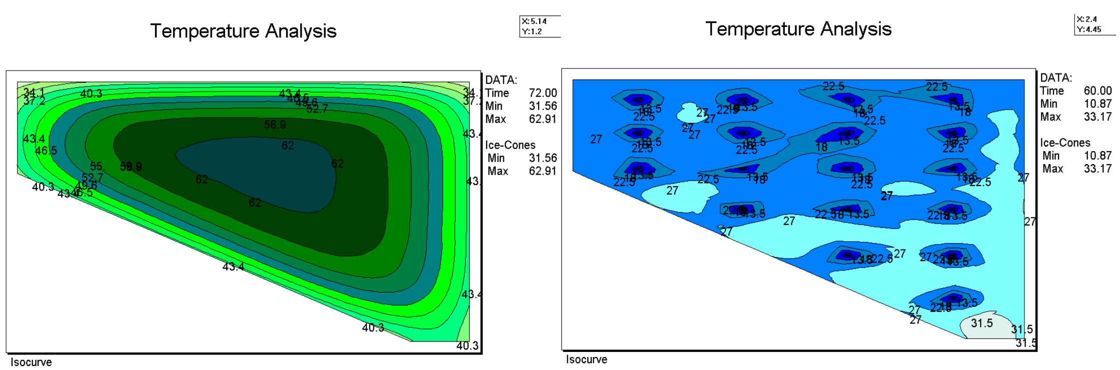

Figure 4: Simulation of temperature in concrete elements –with and without cooling

3.4. Resistance of concrete to freezing and thawing

Application of the examined binding agent and its compatibility with chemical additives yielded concrete with high resistance to repetitive freeze-thaw cycles. The results are summarized in Tables 5.

Table 5: The results of frost resistance in the presence of 3% NaCl

Area of the test surface [mm^2]	Mass of dried scaled material [g]		Mass of scaled material related to the test surface [kg/m^2]	
	after 28 freeze-thaw cycles	after 56 freeze-thaw cycles	after 28 freeze-thaw cycles	after 56 freeze-thaw cycles
7698	3.40	2.75	0.44	0.79
7698	3.35	2.30	0.43	0.73
7698	3.07	1.93	0.40	0.65
Average mass of dried scaled material kg/m^2 after 28 freeze-thaw cycles			0.42	
Average mass of dried scaled material kg/m^2 after 56 freeze-thaw cycles			0.72	
Ratio: average mass of dried scaled material kg/m^2 after 56 freeze-thaw cycles/ average mass of dried scaled material kg/m^2 after 28 freeze-thaw cycles			1.71	

The results of freeze-thaw resistance of concrete samples made according to Polish standard PN-88/B-06250 haven't exhibited mass loss, only 7.7% decrease in compressive strength was determined.

4. Conclusions

On the basis of performed tests the following conclusions can be drawn.

1. The use of an appropriate binding agent CEM III/A 32.5N HSR NA and silica fume as well as the appropriate chemical additives enabled mix design of concrete adequate for severe environment of Baltic Sea region.

2. The AVA method used to determine the air-void characteristics of concrete mix was in most cases sufficient to control the manufacturing of frost resistant concrete.

3. During hardening of concrete in the massive components of wind power turbine's foundations it is necessary to control the amount of heat released and the temperature distribution. These conditions guarantee the durability of concrete in the harsh conditions of the Baltic Sea.

5. References

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