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KVANTITATIVNA I KVALITATIVNA ANALIZA ELEMENATA IZRAĐENIH OD BETONA U VETROPARKU

QUANTITATIVE AND QUALITATIVE ANALYSIS OF CONCRETE ELEMENTS IN WIND PARK

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Izgradnja vetroparka prestavlja kompleksan poduhvat, koji uključuje brojne aktivnosti, koje je često nemoguće sinhronizovati i uklopiti u odgovarajući vremenski okvir. Iz tih razloga se u određenim slučajevima pojavljuje osnovana sumnja u vezi sa kvalitetom već izgrađenih elemenata konstrukcije. U takvim slučajevima neophodno je pokrenuti odgovarajuće procedure za procenu, pri čemu su odgovaruće metode procene kvaliteta betona ugrađenog u konstrukciju definisane u okviru standarda. Statističke metode su implementirane u analizu betonskih elemenata, prateći stroga pravila što, u slučaju da su ove metode sprovedene korektno i od strane obučenog osoblja, omogućuje precizan i ispravan uvid u situaciju. Cilj ovog rada je da opiše takvu proceduru, na bazi obimnog ispitivanja na terenu i naknadne analize. U ovom istraživanju je uzet veliki broj uzoraka – 255 kernova – iz 17 betonskih konstruktivnih elemenata vetrogeneratora (od ukupno 57 vetrogeneratora). Čvrstoća pri pritisku ugrađenog betona je procenjena na bazi ovog seta rezultata. Ovo mehaničko svojstvo se pokazalo kao dobar parameter za procenu ostalih aspekata kvaliteta betona, mehaničkih karakteristika i trajnosti.

Ključne reči: *vetropark; beton; ispitivanja na licu mesta; čvrstoća pri pritisku; statistička analiza.*

Establishing a wind park presents a complex enterprise, which involves numerous activities, often impossible to synchronize and drive into the appropriate time-frame. Therefore, in some cases, based on reasonable suspicion, a concern rises regarding the quality of already built components of structures. In such cases the launch of suitable assessment procedures is required. Standards then define proper methods of in-situ assessment of concrete quality. Statistical methods are implemented in the analysis of the concrete components following the strict rules which, if executed correctly by the well trained personnel of accredited institutions, provide exact and valid insight in the situation. This paper aspires to describe such procedure on the basis of thorough in-situ investigation and the subsequent analysis. In this study, a large number of 255 core samples was taken from 17 wind tower concrete structure elements – foundations (out of 57 wind towers in total), and the compressive strength of already placed concrete was evaluated based on this set of results. The compressive strength is proved to be a good parameter for evaluating other aspects of concrete quality, mechanical properties and durability.

Key words: *wind park; concrete; in-situ investigation; compressive strength; statistical analysis.*

1 Introduction

A global society, our modern civilization as we know it, changes in a pace governed by its' own laws. The fact we all can agree upon is that the current industry, in the form that we recognize

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it today, is expected to stay for decades. At the same time, a rising awareness of the human impact on the environment calls for the fast change in the direction of sustainability. We reached the point where some extrapolation models of the current industry trends forecast the catastrophic outcomes, which are to occur in not so far future [1].

In order to provide any notable modifications in various branches of industry, specific skills have to be adopted by the professionals in the area – the skills that include not only the excellent understanding of the know-how in their areas of expertise, but also cutting edge knowledge in the materials, technologies and environmental effects. Nowadays, a number of new materials and technologies emerged, with the respect to environmental awareness. Such cases show that from now on evolution of any industry can, and must be strongly bonded with sustainable development [2].

The trends in the energy industry are showing massive impact of sustainable development. Thermal Power Plants present the main source of energy in Serbia, burning high volumes of coal, and producing hectares of landfills with bottom or fly ash, which can be partially used in the civil engineering industry as pozzolanic material [3]. The increase in renewable energy sources in Serbia, including sun, water, wind, geothermal energy and biomass, provide scarce but highly promising effects regarding reduction of CO_2 and better environmental impact. There are measures undertaken in order to support faster and better implementation of industrial complexes based on renewable energy sources [4]. In the sphere of wind energy, reports testify of the significant impact in Serbia – wind energy has been recorded to be harvested here since 2012, with the remarkable increase from 1 up to 374 MW/year [5]. Wind parks in Serbia, more and more rapidly installed by investors from Abu Dhabi, Italy, Belgium and Holland are being erected in the optimal locations, including Tutin, Kula, Alibunar, Vršac, Dolovo, Kovačica, and region near Danube river [6, 7].

All of the above testify of the pace which wind energy industry in Serbia found itself. A number of challenges are always involved in such enterprises, including various exceptions from the planned procedures. In such cases, decisions have to be made in real time, having numerous unforeseen consequences. Positive outcomes as results of such decisions are more likely to occur when proper operations are done by the expert personnel, trained according to the contemporary technical frame of regulations and standards.

With respect to the framework of political commitment to continue approaching the European Union, a wide range of standards was changed in Republic of Serbia, including ~~the~~ several that cover investigations of the already built concrete elements and structures. The change is mostly conducted in the manner of replacing SRPS standards (previously SCS, or even earlier JUS) with the related EN standards, valid in the European Union. A newly adopted set of standards regulating the mentioned field evolved from DIN, BS and such previous national regulative of the European countries. Nevertheless, the change in engineering practice called for a radical innovation of these standards, in order to competently answer the contemporary demands, present in practice.

In order to provide a reliable assessment of the concrete quality in all erected wind turbines, the concrete installed in the foundations of wind turbines in a wind park presented in Figure 1 was thoroughly investigated and analyzed based on the valid set of standards.

Figure 1 – Concrete elements (foundations) of wind tower

Although the producers of concrete and the executors of concrete works demonstrated the needed skills, weather conditions during concrete works, as well as the procedural difficulties regarding the validity of reports on control concrete samples, required the launch of procedure referring qualitative and quantitative in situ tests of concrete, followed by the standardized final quality assessment.

2 Assessment of in-situ compressive strength in concrete elements

Concrete presents an artificial composite material, obtained by hardening the mixture of binder and aggregate. Unlike mortar, which includes only fine aggregate, concrete contains aggregate grains with no upper limit in size. In most cases, the binding mixture consists of cement and water, providing relatively cheap but durable composite, produced in quantity of over 3.8 t per capita on Earth [8,9].

Usually, in order to provide proper insight into properties of the produced and placed concrete, two groups of specimens are made and tested. Concrete samples of the first group are regarded as preliminary, produced to provide proof of the quality of concrete which is yet to be used. Concrete samples of the second group are control samples, periodically taken during the concrete works at the building site, at the time of placement.

Sometimes a third group of samples have to be taken to provide additional information important for assessment of concrete which was already placed. In such cases these samples, usually cylindrical and called core samples, have to be extracted from the hardened concrete structure. Core samples are usually taken according to the standard procedure, and the statistical analysis of the obtained results is also conducted according to the standards. Main standard covering this topic is SRPS EN 13791 [10], which replaced the previous standard SRPS U.M1.048 [11] (or even earlier JUS U.M1.048). Although the new standard was adopted in 2008 the older one remained active until 2018 mostly due to the fact that it was authoritative according to the national concrete design code BAB’87 from 1987.

2.1 Methods for determination of in-situ compressive strength

In some situations, a practical requirement to determine the quality of concrete in already erected structure or its elements arises. Usually, compressive strength of concrete is determined, but also some other properties, such as: water permeability, freeze-thaw resistance, chemical resistance, modulus of elasticity etc. Some of the most common cases that require this action are:

- No specimens were taken from fresh concrete, or their number is insufficient for the specific investigation,
- Results of investigation of specimens taken from fresh concrete fail to satisfy the prescribed conditions (failure of quality),
- Suspicion in the credibility of the test results arises,
- Adaptation, expansion, upgrades of existing structures or similar,
- Disputes on the relation investor – contractor, contractor – supervisor etc.,
- When certain minor or major damage, accidents or demolition of constructed elements~~,~~ or structures happen.

The illustration of the procedures for these purposes is given in Figure 2.

Two groups of methods are conducted in such cases, destructive and non-destructive.

Destructive methods involve cutting samples from the construction elements and their laboratory testing [12], as well as testing the whole elements or constructive systems on site, mainly by reaching their fracture point.

Non-destructive methods, developed to provide additional information on the investigated placed concrete and to overcome the problem of small number of core samples extracted from the concrete structure, are based on the correlation (by means of mathematical regression and fitting) between compressive strength and physico-mechanical property that is being tested (density, ultrasonic pulse velocity, hardness, pull off or pull out strengths etc.). The advantages of non-destructive methods over destructive are: elements are tested without damage, large number of investigations in short time, possibility of repeating tests, etc. The disadvantages of these methods, besides the fact that the property tested is not the property needed, is that the correlations can be quite weak. The most common non-destructive methods used for in-situ investigations are: Schmidt hammer [13], pull-out test [14], and ultrasonic pulse velocity [15].

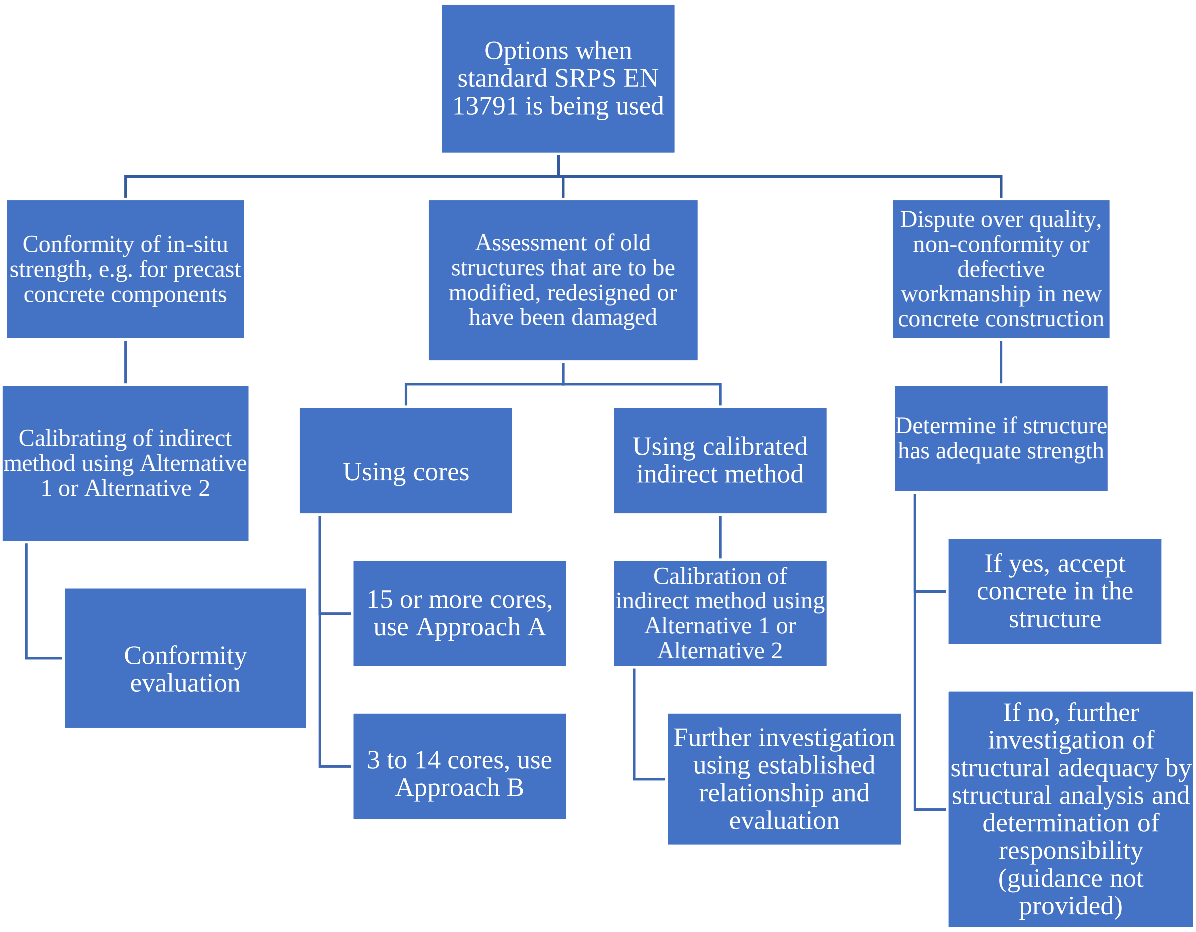

Figure 2. Cases when standard SRPS EN 13791 is used [10]

2.2 Assessment of in-situ concrete compressive strength

Standard SRPS EN 13791 gives guidelines when the quality assessment of structural concrete is needed, with or without the aid of combined methods. The combined methods include destructive and one or more of the previously mentioned non-destructive testings, resulting in a correlation and assessment of in-situ concrete compressive strength. Nevertheless, these methods can’t be used as a replacement for the tests denoted by SRPS EN 206 [16], because of the specified range of the cases they cover. In terms of utility, standard SRPS EN 13791 is not applicable in cases when:

- indirect methods are used without correlation with core sample strengths,
- assessment is made on the basis of tests on core samples of diameter Ø smaller than 55 mm, and
- less than 3 core samples served for assessment.

There is a logical difference between the strength of the (preliminary or control) standard concrete samples for compressive strength test and the strength of concrete in the structure. The concrete in structure is usually under unfavorable environmental conditions, causing the expected strength decrease of up to 15%. This effect is defined as a ratio of in-situ characteristic strength to characteristic strength of standard specimens, as presented in Table 1, and also attributed to the material partial factor.

Table 1. Minimum characteristic in-situ compressive strength for the SRPS EN 206 compressive strength classes [17]

Compressive strength class according to SRPS EN 206	*Ratio of in-situ characteristic strength to characteristic strength of standard specimens*	*Minimum characteristic in-situ strength N/mm²*		*Minimum characteristic strength of standard specimens N/mm²*	
		Cylinder	*Cube*	*Cylinder*	*Cube*
C8/10	0.85	7	9	8	10
C12/15	0.85	10	13	12	15
C16/20	0.85	14	17	16	20
C20/25	0.85	17	21	20	25
C25/30	0.85	21	26	25	30
C30/37	0.85	26	31	30	37
C35/45	0.85	30	38	35	45
C40/50	0.85	34	43	40	50
C45/55	0.85	38	47	45	55
C50/60	0.85	43	51	50	60
C55/67	0.85	47	57	55	67
C60/75	0.85	51	64	60	75
C70/85	0.85	60	72	70	85
C80/95	0.85	68	81	80	95
C90/105	0.85	77	89	90	105
C100/115	0.85	85	98	100	115
Note: The in-situ compressive strength may be lower than that measured on standard test specimens taken from the same batch of concrete. The ratio 0.85 is part of the partial factor γ_c for ultimate limit state of concrete, according to SRPS EN 1992 [18]					

Results of compressive strength tests obtained for cores with diameter Ø and height H of 100 mm can be regarded as equal to those for 150 mm cubes. If the cores of diameter Ø=100-150 mm are tested, and if their length to diameter ratio equals 2, these results can be regarded as equal to the values for cylinders of diameter Ø=150 mm and height H=300 mm. The cube and cylinder with such dimensions are standard samples for compressive strength class determination. Of course, all of the mentioned samples have to be produced and cured under the same conditions in order to hold these correlations valid. If different size samples were taken from the structure, a proper conversion has to be constructed in a suitable manner to uniform the results for analysis.

Although as many as possible core samples have to be obtained for the proper assessment of in-situ strength of concrete, their number can be defined based on the volume of concrete in test region (one or several structure elements made of the same concrete) and based on the specific motive for in-situ investigations. At least three core samples have to be taken out of the test region (in the case of core samples with diameter Ø=50 mm, three times more than in the case of core samples with diameter Ø=100 mm). In such analysis, stability of the structure element and constructive system must be always taken into account.

2.3 Criteria for compressive strength assessment

There are two approaches in assessment of compressive strength on the basis of core samples strength. The approach A is used when at least 15 core samples are cut out from the structure, providing the assessed compressive strength as the lower value of:

$$f_{ck,is} = f_{m(n),is} - k_2 \cdot s\,, \tag{1}$$

$$f_{ck,is} = f_{is,low} + 4 \tag{2}$$

where:
$f_{ck,is}$ – the assessed compressive strength,
$f_{m(n),is}$ – the average value of compressive strength obtained on n core samples,
$f_{is,low}$ – the lowest value of compressive strength of n tested samples
s – standard deviation of compressive strength (or fixed value of 2,0 N/mm^2, in cases when calculated standard deviation is lower than that value)
k_2 – coefficient equal to 1.48, unless national regulations state otherwise.

The approach B is used when 3 to 15 core samples are taken out from the structure:

$$f_{ck,is} = f_{m(n),is} - k, \quad (3)$$

$$f_{ck,is} = f_{is,low} + 4, \quad (4)$$

where the coefficient k depends on the number of compressive strength tests results made on core samples, as stated in Table 2.

Table 2. Values of the coefficient k depending on the number of test

Number of compressive strength tests results made on core samples	*Coefficient k*
10-14	*5*
7-9	*6*
3-6	*7*

In the case when indirect (non-destructive) methods are used, they can provide valuable additional information to the data obtained by testing limited number of core samples. For such purpose, based on the test results, a correlation between the indirect test and the compressive strength must be made.

Alternative 1 to provide a valid correlation defines direct relationship with the core samples, where at least 18 pairs of results (value obtained by indirect method, and the compressive strength of concrete related to this particular value) cover the test region. Best relationship is obtained by regression analysis of these values, and it has to statistically enable safety level where 90 % of the strength values are expected to be higher than the estimated value. In such tests, a characteristic compressive strength can be calculated, as an average result of at least 15 different core samples for particular test region, and using the calculated standard deviation (or fixed value of 3 N/mm^2, depending on which is higher).

Alternative 2 uses the basic curve from the standard SRPS EN 13791, as follows.

1. For rebound hammer:

$$f_R = 1.25 \cdot R - 23,\ 20 \le R \le 24, \quad (5)$$

$$f_R = 1.73 \cdot R - 34.5,\ 24 \le R \le 50, \quad (6)$$

2. For ultrasonic pulse velocity:

$$f_V = 62.5 \cdot V^2 - 497.5 \cdot V + 990,\ 4 \le V \le 4.8, \quad (7)$$

3. For pull-out method:

$$f_F = 1.33 \cdot (F - 10),\ 10 \le F \le 60, \quad (8)$$

where f_R, f_V and f_F present compressive strength, R is rebound value, V is ultrasonic pulse velocity, and F is pull-out strength value.

The basic curve has to be adjusted to the specific situation by correcting (moving) it to the new level defined by the test results obtained on core samples. At least 9 pairs of results have to be obtained to calculate the value Δf, for which the basic curve has to be moved to suit specific conditions:

$$\Delta f = \delta f_{m(n)} - k_1 \cdot s, \quad (9)$$

In this formula, value δf presents distance between each in-situ compressive strength obtained on core sample and the value given by the basic curve, as seen in Figure 3, which presents geometrical interpretation of δf. The coefficient k_1 is taken from the Table 3. Analogically, a characteristic compressive strength can be evaluated in a similar manner as previously explained.

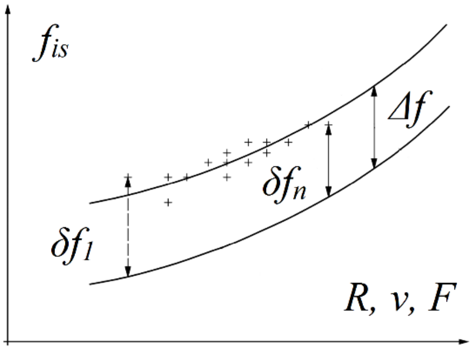

Figure 3. Geometrical interpretation of the value δf

Table 3. Coefficient k_1 values depending on the number of test pairs

Number of test pairs (n)	Coefficient k_1
9	1.67
10	1.62
11	1.58
12	1.55
13	1.52
14	1.50
≥15	1.48

The guidelines in cases when quality of concrete assessed by standard tests is doubtful include formulas valid with respect to the number of specimens. In the case where 15 or more values of compressive strength were obtained on concrete core samples, the region of concrete under inspection has acceptable strength when both following formulas are valid:

$$f_{m(n),is} \geq 0.85 \cdot (f_{ck} + 1.48 \cdot s) \tag{10}$$

$$f_{is,low} \geq 0.85 \cdot (f_{ck} - 4) \tag{11}$$

If one core sample has inadequate strength, this points to more local then global problem. Alternatively, if the parties involved come to agreement, concrete can be regarded of adequate strength if two core samples have lower strength, and the last displayed formula is valid. For small regions, concrete can be regarded as of adequate strength if only two core samples were taken and the same last displayed formula is valid.

3 Experimental assessment of in-situ compressive strength of concrete in wind park

When an industrial facility such as wind park is being built, many challenges have to be handled, resulting in various tasks and activities. Of course, these activities are sometimes impossible to synchronize and drive into the appropriate time-frame. Therefore, in some cases, when doubtful concrete batch reaches the construction site, and is placed poorly into the structure element, or poorly cured, a concern rises regarding the quality of already built in components of structures.

In specific wind park, a total number of 57 wind turbine foundations was built in a suitable area, including 24 CFA piles (continuous flight auguring, also known as auger cast piling, is a technique used in construction to create a concrete deep foundation) with diameter of Ø800 mm, and with length of 14 to 22 m for each wind tower. All of the piles have been connected to the appropriate pile supported concrete slab. The design of the whole structure suited the previously constructed load analysis, based on the site conditions [19]. Strength class of concrete was set to C 30/37, which is usual class for majority of concrete structures (residential, commercial and industrial).

The concrete works on the foundation were executed by the eligible contractor. Also, the concrete was supplied by the local plant, possessed by one of the biggest concrete providers in Serbia. Based on the supervision reports, the concrete works were done under unsuitable weather conditions (night works in winter, wind), and with concrete containing cement with low heat of hydration. As a conclusion after several meetings between the involved parties, an extensive analysis was conducted on site.

A total of 255 core samples with diameter Ø=100 mm and height H=100 mm (nominal dimensions) were taken from 17 concrete pile supported slabs, by the qualified personnel of the accredited laboratory. The positions were defined by the investor.

According to the standard SRPS EN 13791, the required quality of concrete in structure for the aimed strength class C 30/37 amounted to $f_{ck,is,cyl}$=26 MPa for the cylinder samples with diameter Ø=150 mm and height H=300 mm, and $f_{ck,is,cube}$=31MPa for the cubes of 150 mm. Also, according to this standard, compressive strength values of cylinders with diameter Ø=100 mm and height H=100 mm can be regarded equal to the compressive strengths of 150 mm cubes. Therefore, the analysis was conducted with the characteristic compressive strength of 150 mm cube ($f_{ck,is,cube}$=31MPa).

Fifteen core samples were taken from each of 17 concrete pile supported slabs of the wind turbine generators (WTG), which made the approach A suitable for the proof of the achieved strength class. This makes total of 255 core samples. The two conditions stated in this paper as equations (1) and (2) were tested for each concrete slab, i.e. for the set of 15 compressive strengths of core samples taken out of each concrete slab. On the basis of this analysis, the achieved strength classes for each pile supported concrete slab were calculated as shown in Table 4. As it can be seen from the Table, 3 concrete slabs (WTG 5, WTG 13 and WTG 15) out of 17 (which makes 17.6%) possess lower compressive strength class than required, and one concrete slab (WTG 7) had higher strength than required.

Table 4. The achieved compressive strength classes for the tested concrete slabs

Concrete slab designation	*The achieved compressive strength according to the approach A of standard SRPS EN 13791*
WTG 1	*C30/37*
WTG 2	*C30/37*
WTG 3	*C30/37*
WTG 4	*C30/37*
WTG 5	***C25/30***
WTG 6	*C30/37*
WTG 7	***C35/45***
WTG 8	*C30/37*
WTG 9	*C30/37*
WTG 10	*C30/37*
WTG 11	*C30/37*
WTG 12	*C30/37*
WTG 13	***C25/30***
WTG 14	*C30/37*
WTG 15	***C25/30***
WTG 16	*C30/37*
WTG 17	*C30/37*

The analysis of each individual compressive strength of 15 core samples revealed that several values significantly deviate from the majority. Such deviation was estimated to have more local than global character. Further setting the lower limit value of compressive strength to 28.05 MPa, according to the conditions stated in this paper as equations (10) and (11), gave guidance in determining which results can be regarded as inadequate, and therefore ruled out. The percentage of these results amounted to 12% of the total number. Having in mind that the characteristic value, in terms of concrete strength class, is defined by the condition that only 5% of the results may be lower than the calculated lower limit for the defined strength class – or only 1 out of 20, a noticeable dispersion of results occurred in this case. The assessment of durability of the concrete was based on the obtained values of strength classes, and was found to be completely in accordance with the compressive strength.

Along with the quantitative analysis of the samples, a comprehensive qualitative analysis of the concrete present in the obtained core samples was conducted in laboratory, including: visual inspection of texture and structure of surface, assessment of segregation, porosity, cracking occurrence, and quality of aggregate-paste interface zone. All the mentioned analyses showed no significant deviation from the related properties of the reference concrete.

4 Conclusions

This paper was dedicated to the broader range of the professionals involved in the energy industry, especially fast growing wind power energy industry. The aspects that should be kept in mind when there are doubts regarding the quality of the placed concrete were pointed out. Such cases shouldn't be considered as extremely extraordinary, but possible and already properly standardized. This means that standardized methods regarding such cases exist, one of which was provided here.

In the case of concrete assessment shown here, based on 15 core samples taken out of each of the 17 concrete slabs, a certain failure in concrete strength class in 3 slabs was recorded, or nearly 17,6%. Also, it was found that one of the slabs possessed higher strength class than required, which is approximately 5.9% of the total quantity of the concrete placed on site. Regarding total quantity of concrete, the failure occurred in 12% of the tested samples. Mandatory, only 5% of the results may be lower than the calculated lower limit for the defined strength class C30/37. The decision regarding continuing concrete works under unsuitable weather conditions to fulfill the timeframe goal is most probably to blame for such unfavorable result.

The importance of in-situ testing is underlined in this paper by the fact that all regular periodical reports of the concrete quality, based on control samples were positive. Obviously, a substantial conflict between the control and in-situ results originated in different curing conditions of concrete in laboratory or concrete factory, and on site. Also, an important comment must be made that a better insight in the situation could be provided if one or more non-destructive methods were used. As it was described in this paper, a good and standardized correlation can be made between such tests. Such scope of testing would provide assessment of the concrete not only on the spots where core samples were taken, but on all other parts of the structure where non-destructive method would be used.

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