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THE EFFECT OF LIMIT VALUES OF SILICEOUS FLY ASH CONTENT ON THE DURABILITY OF CONCRETE STRUCTURES IN RELATION TO EXPOSURE CLASSES

D. LOGOŃ[1]

The paper concerns the use of limit value of siliceous fly ash content in concrete structures, with the application of various types of cements - based on the current standards and taking into consideration the requirements concerning current exposure classes. The conclusions were based on a review of literature, the results of scientific research, conclusions from expert opinions and buildings and structures supervision reports. In summary, it has been concluded that the use of limit content of siliceous fly ashes may result in negative changes in the properties of composites, which should be ruled out or confirmed by appropriate tests, taking into account the precisely defined composition of concrete, cement and the applied additives and admixtures. It has been emphasised that the problem concerns composites with the increased and limit values of fly ash content, especially as regards cements with the lowered content of clinker and high content of additives and admixtures (affecting the physical and mechanical properties of cement composites). Attention has been drawn to the need to modify the exposure classes, to focus on the requirements concerning the properties of concrete and not the composition - in order to achieve the expected durability.

Keywords: durability, siliceous fly ash, content limit, exposure classes, frost resistance

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[1] PhD. Dominik Logoń, Wrocław University of Science and Technology, Faculty of Civil Engineering, pl.Grunwaldzki 11, 59-377 Wrocław, Poland, e-mail: dominik.logon@pwr.edu.pl

1. THE EFFECT OF THE ADDITION OF SILICEOUS FLY ASH ON THE PROPERTIES OF CEMENT COMPOSITES

The effect of the addition of siliceous fly ash on the properties of concretes has been documented in many standards (norms) and research publications [1-27].

As shown by previous papers [1,2,3] a small addition of siliceous fly ash (with respect to cements with high content of clinker) has an advantageous effect on a number of properties: e.g. it increases strength, deformability and tightness as a result of the pozzolanic reaction; it additionally prolongs the setting time and limits shrinkage and the quantity of emitted heat [4,5,6]. The excessive amount of fly ash results in e.g. a decrease in strength (compression/tension), Young's modulus and frost resistance [7,8,9,10]. The limit value of an additive content in concrete that does not cause a considerable decrease in its strength and frost resistance is determined at 30% of the Cem I mass [5]. The discussion on the impact of fly ash additive on the change of concrete properties is broad and each time requires the specification of details [11,12]. Fig.1 shows the effect of fly ash content on the change in the strength of cement matrix in a long period of time (up to 5 years).

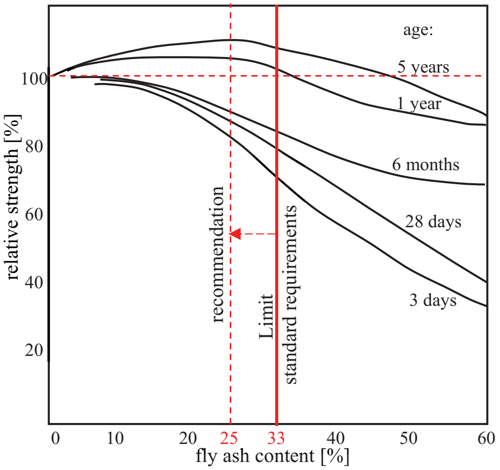

Fig. 1. The effect of fly ash content in cement (% of mass) on the strength – based on [5,12]

A longer increase in strength, when using higher content of the additive (over 10%), has been well recognised [2,5,13] – it shows that the assumed physical and mechanical properties are achieved not after 28 days of hardening but after 90, or even 180, days of curing. What has been found [5,12] is the lack of negative impact of the additive (within the range of 20-33% of the Cem I cement mass) on the compressive strength in the period of 1-5 years. Too slow an increase in strength up to 180 days, with the fly ash content over 20%, is significant and affects the differences in the properties of the matrix with and without the additive in the period of up to 1 year of composite bonding. Numerous studies indicate a possibility of obtaining strength values comparable to the matrix (without the additives) after 28 days of hardening, when using the maximum 33% permissible values of fly ash content [2,13,14].

The ITB 206/77 instruction limited the fly ash content to 30% of the cement mass in reinforced concrete, and provided that the fly ash additive should not be used in compressed concrete or in concrete structures in which the thickness of the reinforcement concrete cover is less than 2 cm.

It has been found [11], that the quantitative prediction of the effect of fly ash on concrete strength is not possible if we don't specify exactly the composition of concrete (including the mineralogical composition of cement and additives). The obtained discrepancies show that the generalised conclusions in this respect are not clear. It should be emphasised that it is possible to assess the impact of high additive volume on the designed properties of specific concrete with specific cement, but it requires the confirmation of the obtained composite properties by means of appropriate tests (with strictly defined compositions).

Fig. 2 show the effect of fly ash additive on compressive strength of concrete in the case of 28- and 90-day compression [2,15]. The predicted changes in properties in a longer period of 180 days will enable a further significant increase in compressive strength [18].

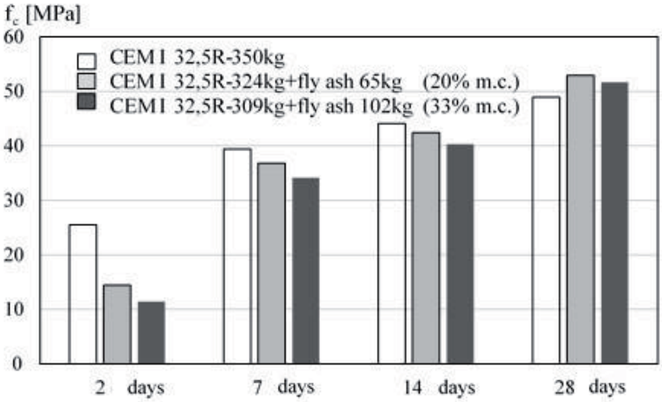

Fig. 2. The effect of siliceous fly ash additive on compressive strength [2]

The addition of 33% of fly ash causes a slight decrease in compressive strength compared to 20% additive, which shows that the optimum fly ash content (for that composition) has been exceeded (the studies of other authors [16], indicate the 33-40% content of the additive as the optimum one).

It was noticed [15] that increasing the content of various siliceous fly ashes (type A, B and C) above 25% (such an amount of the additive to cement corresponds to 20% content of the additive as a binder) results in a decrease in compressive strength. The obtained results indicate that the precise definition of limit values of siliceous fly ash content is debatable and depends on the composition of the composites.

Fig.3 shows the effect of the addition of fly ashes (type: A, B and C) on the frost resistance of concrete - 56 freeze/thaw cycles on the basis of PKN-CEN/TS 12390-9:2007, with the quality assessment on the basis of Swedish standards SS 137244, [15]. Additionally, the requirements of standard PN-EN 13877-2 are presented. Reducing fly ash content below 20% with respect to CEM I cement does not result in significant changes in frost resistance with w/b<0.45. Exceeding the limits of 33% and increase in w/c (for XF1 max. w/c=0.55, table 4) results in a significant drop in durability with 56 freeze/thaw cycles.

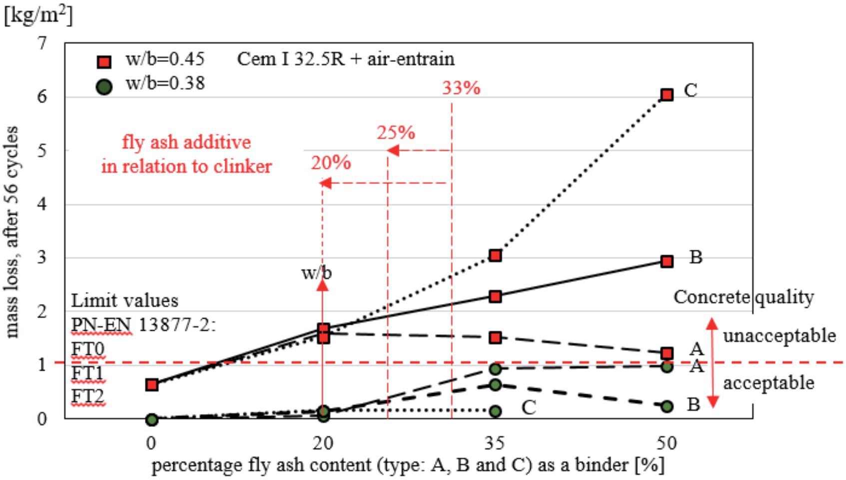

Fig .3. Frost resistance of concrete based on the results of [15]

Conclusions from the conducted tests show that the use of the maximum standard content of fly ashes may significantly decrease the durability of composites (including air-entrained concretes). The obtained data confirm the possibility of obtaining discrepancies in the results concerning the frost resistance of concretes with high content of fly ashes [5,10], which are determined by too many factors (e.g.: w/c, quality of air-entrainment, strength, test method) for the assessment of the composites to be conducted on the basis of their composition.

2. LIMIT CONTENT OF SILICEOUS FLY ASH ACCORDING TO PN-EN 206 / EN 450-1

The division of concrete additives and the requirements regarding properties are defined in standard PN-EN 206 [17], which presents the principles of using fly ash in concrete composition according to the concept of "k" factor (table 1), pursuant to EN 450-1, [18].

PN-EN 206 limits the content of fly ash included in the value of "k" factor (as a substitute of a part of Portland cement) through the condition: fly ash/cement ≤ 0.33% in terms of mass in CEM I cement and fly ash/cement ≤ 0.25% in Cem II/A (in accordance with EN 197-1, [19]). Standard PN-B-06265:2004, excludes CEM II/A-V, which may contain 6-20% of siliceous fly ash [20].

Table 1. The principles of using the "k" factor as per PN-EN 206 / EN 450-1

Kind of type II additive	"k" factor	Maximum content of the additive	Comments
Siliceous fly ash	0.4	fly ash/cement ≤ 33%	refers to CEM I
		fly ash/cement ≤ 25%	refers to CEM II/A

Table 2 presents the permissible ranges of mineralogical compositions of selected cements (CEM I, CEM II and CEM III).

Table 2. Examples of compositions of cements used on the basis of [19]

Name		Composition % of mass		
		clinker	blast furnace slag	secondary components
Portland cement	**CEM I**	← **95-100**	**-**	**0-5**
Slag Portland cement	**CEM II /A-S**	↘ **80-94**	**6-20**	**0-5**
	CEM II /B-S	65-79	21-35	0-5
metallurgical cement	CEM III /A	↔ 35-64	36-65	0-5
	CEM III /B	↔ 20-34	66-80	0-5
	CEM III /C	↔ 5-19	81-95	0-5

If the limit values of fly ash content are exceeded, the water/binder ratio cannot be calculated using the following equation: $w/b=w/c+k\cdot additive$. Most publications do not follow that recommendation, which may have a significant impact on the interpretation of the obtained test results based on.

The number of types of cements used in the production of concrete [19], significantly exceeds that presented in table 2. The interpretation of results should not be based on the wide ranges of cement components (clinker, blast furnace slag, fly ash) permitted by the norm. The composition of each of the cements used in tests should be precisely described. This refers mainly to CEM II/B-S, CEM III, CEM IV and CEM V.

For the purpose of assessment of granular blast furnace slag as a mineral additive, the requirements contained in PN-EN 197-1 are used [19]. For the production of ready-mixed concrete compliant with PN-EN 206, [17], category A siliceous fly ash compliant with standard [18], (PN-EN 450-1) should be used. Domestic fly ashes fulfilling the requirements of the standard are the product of combustion of hard coal dust in conventional boilers, in power plants or heat and power plants, and their composition (fineness and loss on ignition, table 3, [14,18,21]) is determined by a number of rheological, physical and mechanical properties [2,13,23], which may have a significant impact on the interpretation of test results.

Table 3. Examples of use of category A, B and C fly ashes on the basis of [21]

Country	Category A (loss on ignition ≤ 5 %)	Category B (loss on ignition 2-7 %)	Category C (loss on ignition 4-9 %)
Belgium	yes	yes (in exposure class XF fly ash content below 25% of cement mass)	no
Czech Republic	yes	yes	yes
Finland	yes	no in exposure class XF	no
France	yes	no in class XF4	under discussion
Germany	yes	no	no
Italy	yes	yes	under discussion
UK	yes	yes	no

Cements with a high content of that additive CEM II/B, CEM III/A decrease the content of capillary pores and seal the concrete structure – limiting its water permeability [1]. It should be noted that the potential use of additional amounts of fly ash additive content, especially in CEM II/B-S, CEM III, CEM IV and CEM V, is possible only with the application of the equivalent performance of combinations concept (EPCC [17]). It should be noted that in the case of the cements in question the possibility of adding more fly ash will be significantly limited due to the smaller amount of clinker compared to CEM I and CEM II/A. In such cases the required properties of concrete should be confirmed by appropriate tests. The results of those tests cannot be generalised and applied to cements from various cement plants because the norm permits significant differences in the mineralogical composition of cements CEM II/B-S, CEM III, CEM IV and CEM V.

3. LIMIT VALUES OF SILICEOUS FLY ASH CONTENT ON THE DURABILITY OF CONCRETE STRUCTURES IN RELATION TO EXPOSURE CLASSES

Exposure classes apply to traditional ordinary concretes specified in PN-EN 206 (fig.4) but they do not apply to concretes with a high content of fly ashes (over 33% m.c.), [17]. The above norm indicates the possibilities of using each of the various types of cement in concrete depending on the exposure classes [20]. The requirements of exposure classes based on the composition of traditional concrete (minimum w/c, cement content, class of concrete, air content) are not accurate with respect to non-traditional cement composites, tab.4, [17].

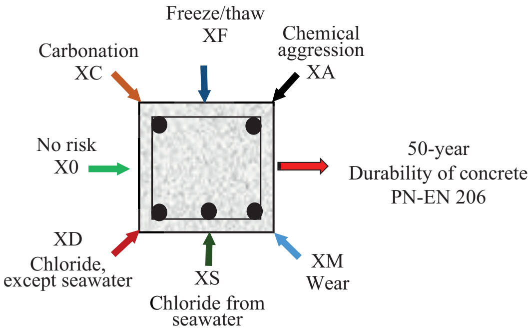

Fig. 4. Exposure classes according to PN-EN 206:2016 [17]

Exposure classes can be controlled more precisely on the basis of the properly selected (requires further specification) requirements regarding physical and mechanical properties. Such an approach makes it easier to present requirements not only with respect to structural concretes but also to the universally used protective layers [22], the properties of which are often difficult to compare to the properties (exposure classes) of reference concrete.

The test consists in the verification of the designed degree of frost resistance (F) of concrete. The frost resistance of concrete corresponds to the N indicator, which equals the number of predicted years of use of the structure (F50-F300) on the basis of PN-B-06265 the so-called “ordinary method”.

Due to climate changes, the number of freeze-thaw cycles in the autumn-winter season often rises significantly, Fig.5.

The number of the cycles differs depending on the longitude and latitude of the project location. Based on the observation of meteorological data, a number of examples can be presented where 7 freeze/thaw cycles per week can occur. In consequence of the increase in the number of cycles, the assumption of a 50-year frost resistance on the basis of the number of freeze/thaw cycles equalling 50 is frequently not correct (the number of times temperature crosses 0ºC in the autumn/winter season of a given year may exceed 20-30 cycles). In order to determine the required number of freeze/thaw cycles it is necessary to analyse the meteorological data from recent years for the construction project location taking into consideration the potential climate changes.

Table 4. Description of exposure class XF and the corresponding concrete composition [17]

Symbol of exposure class	**Description of environment Examples of occurrence of exposure classes**	**Limit values for concrete composition**			
		Max. w/c	**Minimum cement content when using type II additive, kg**	**Min. concrete class**	**Other requirements**
Corrosion caused by freezing / thawing XF					
XF1	Moderate saturation with water	0.55	300	C30/37	-
XF2	Moderate saturation with water with de-icing materials	0.55	300	C25/30	Air content 4%
XF3	Strong saturation with water without de-icing materials	0.50	320	C30/37	
XF4	Strong saturation with water with de-icing materials	0.45	340	C30/37	

In the case of a low fly ash content in cement composites, the changes of physical and mechanical properties (e.g. compressive/tensile strength or Young's modulus) are linear. After the limit values are exceeded, those properties are difficult to predict.

The impact of fly ash additive on a change in frost resistance is characterised by a point after crossing which it is visible that there is no linear relationship between the additive content and frost resistance. When the fly ash content is low we can observe linear changes, whereas after the limit values for fly ash content are exceeded a significant decrease in frost resistance occurs (especially for a large number of cycles F≥100 [22,24]). It has been found in many publications that the frost resistance of composites with fly ash additives can be improved by means of air entraining materials [5,13,15]. It should be emphasised that the effectiveness of air entrainment can be different due to varying fly ash content in concrete and the application of various types of cements with different compositions [15,25].

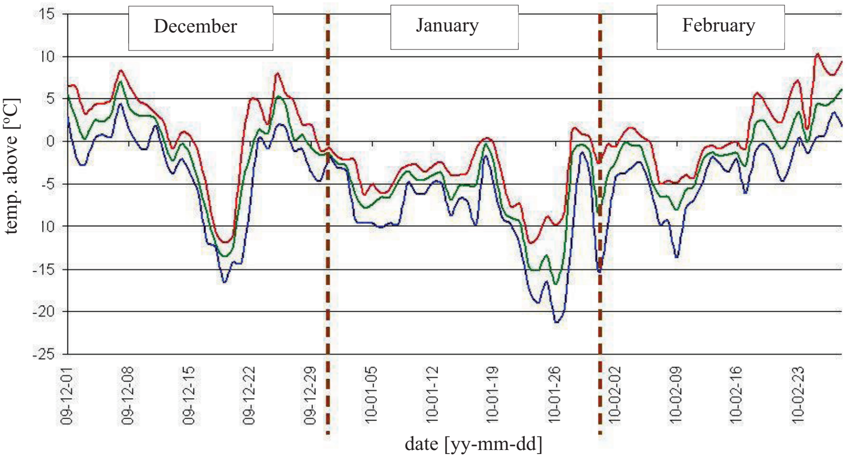

Fig. 5. The curve of air temperature (Poznań winter 2009/2010 - www.pogody.pl)

The requirements for exposure classes XF contain a general description concerning the air entrainment of concrete min. 4%. In the case of air entraining materials the requirements refer only to the volume of air without verifying whether the embedded composite (after the passage through pumps and compacting) contains the appropriate quantity of air bubbles of appropriate size and whether appropriate distance between them is ensured, which makes the verification of test results difficult [26].

CONCLUSIONS

1. The physical and mechanical properties of cement composites with a high content of siliceous fly ash (over limit content) cannot be generalized – the changes of physical and mechanical properties are not linear.
2. In order to increase the durability of concrete with fly ash in the exposure class XF it is suggested to decrease the limit values for the additive content ("k" factor - PN-EN 206 / EN 450-1): Cem I from 33% to 20-25% and Cem II/A from 25% to 15-20%.
3. The properties of cement composites made of cements CEM II/B-S and CEM III, CEM IV and CEM V with siliceous fly ash additive require to be confirmed each time with tests on the basis of

the reference concrete (due to the existing significant differences in the mineralogical composition of cement, mainly with respect to clinker).

4. The existing exposure classes, which are supposed to ensure 50-year durability of concrete should be change due to advancements regarding the modification of the composition of cement composites (including compatibility with protective layers) and climate changes. The requirements of exposure classes should focus on physical and mechanical properties of cement composites instead of the composition of traditional concrete (w/c, cement content, etc.).

5. The concept of reference concrete is correct assuming that the mineralogical composition of cement and the manner of manufacture and maintenance of the cement composite remain the same.

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LIST OF FIGURES AND TABLES

WPŁYW GRANICZNYCH ZAWARTOŚCI POPIOŁU KRZEMIONKOWEGO NA TRWAŁOŚĆ KONSTRUKCJI BETONOWYCH W ODNIESIENIU DO KLAS EKSPOZYCJI

Słowa kluczowe: trwałość, krzemionkowy popiół lotny, graniczna zawartość, klasy ekspozycji, mrozoodporność

Streszczenie:

Praca dotyczy problematyki stosowania granicznych zawartości popiołu krzemionkowego w konstrukcjach betonowych, przy zastosowaniu różnego rodzaju cementów - na podstawie obowiązujących norm, z uwzględnieniem wymagań klas ekspozycji betonu. Wnioski oparto na przeglądzie literatury [1-26], wynikach badań naukowych [13-15], wniosków z ekspertyz i nadzorów obiektów budowlanych [22]. W podsumowaniu stwierdzono, że stosowanie granicznych wartości popiołów krzemionkowych może prowadzić do niekorzystnych zmian we właściwościach kompozytów, co należy wykluczyć lub potwierdzić stosownymi badaniami, z uwzględnieniem precyzyjnie określonego składu betonu, cementu oraz stosowanych dodatków i domieszek. Podkreślono, że problem dotyczy kompozytów z podwyższoną oraz graniczną zawartość popiołu, szczególnie w odniesieniu do cementów z mniejszą zawartością klinkieru oraz dużą zawartością dodatków i domieszek (kształtujących właściwości fizyko-mechaniczne kompozytów cementowych). Zwrócono uwagę na potrzebę modyfikowania klas ekspozycji, w kierunku wymagań w zakresie właściwości betonu, a nie składu - w celu uzyskania założonej trwałości.

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