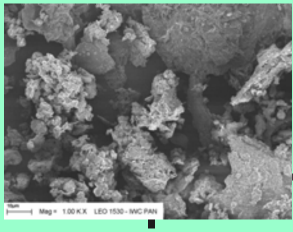
INSTITUTE OF FUNDMENTAL TECHNOLOGICAL RESEARCH
POLISH ACADEMY OF SCIENCES
WARSZAWA, POLAND

Michal A. Glinicki

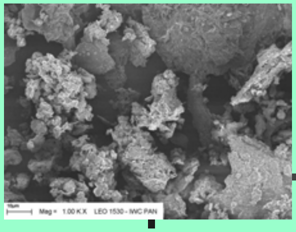
Efficiency of CFBC fly ash as secondary cementitious material in structural concrete

Anna Maria Workshop 2008



Contents

1. Terminology
2. Resources of CFBC fly ash
3. Characterization of CFBC fly ash
4. Partial replacement of cement in concrete
   - strength efifciency
   - durability efficiency
5. Conclusions



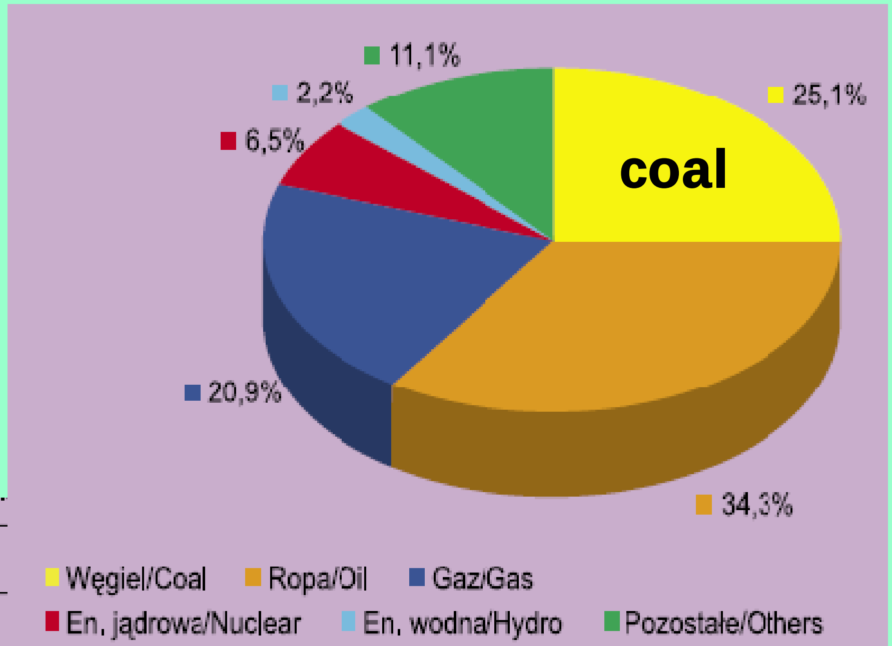
Terminology

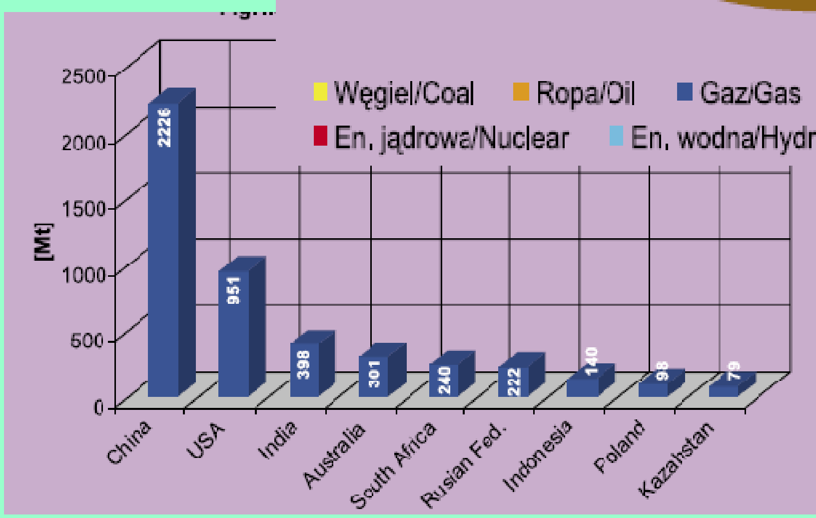
CFBC fly ash = Circulating Fluidized Bed Combustion fly ash
i.e. the solid residue from coal combustion in fluidized bed boilers in power plants, collected by electrostatic or mechanical precipitation of dust like particles in flue gases
C – stands for type of the boiler: „Circulating"

CFBC technology allows to meet strict emission control regulations - „clean coal technology".
When the coal is burned in CFBC boiler with an addition of SO_2 sorbent (usually limestone) the capture of SO_2 takes place „in situ".
The solid combustion residues consist of coal ash and the products of desulphurization.

Other possible names: - "fluidized bed combustion byproducts"
"solid residue from fluidized bed coal combustion"

World primary energy production in 2004





Main producers of hard coal in 2005

Udział/Share (%) 1971	2004	Specification
40,0	39,8	Coal
20,9	6,7	Oil
19,3	19,6	Natural gas
2,1	15,7	Nuclear fuel
23,0	16,1	Hydro energy
0,7	2,1	Renewable and others
100,0	100,0	Total

Shares of different fuels in the world electricity production

GLOBAL FORECAST OF ENERGY DEMAND IN 2030

From 2002 to 2030:
- the global demand for primary energy will increase by 60%
- the world production of electricity will double

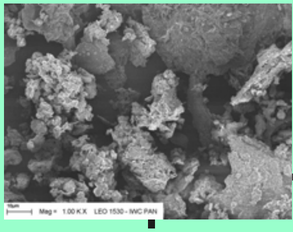
With the expected consumption, the proven reserves of fossil fuels will be sufficient for:
- **coal : almost 200 years,**
- **oil : 35 to 40 years,**
- **natural gas : 40 to 50 years.**

FORECAST OF PRIMARY ENERGY DEMAND: shares of different fuels

Struktura Structure (%)		Specification
2002	2030	
23,4	22,0	Coal
34,6	34,9	Crude oil
21,5	25,3	Gas
6,8	4,7	Nuclear energy
2,2	2,2	Hydro energy
11,5	11,4	Other renewables
100,0	100,0	Total World

The world is not threatened by the danger of coal shortage

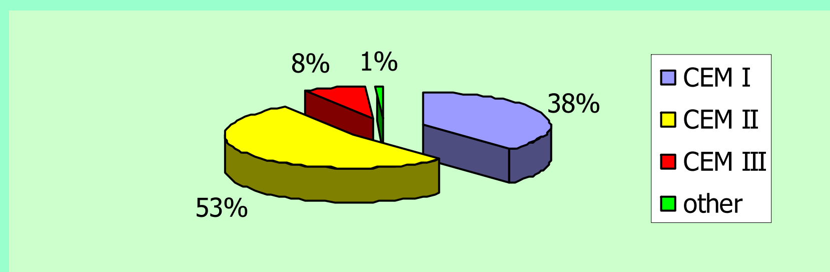
Resources of CFBC fly ash in Poland

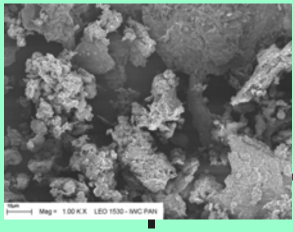


coming in 2008/2009:
new power generation unit 460 MW in Lagisza power plant
world's biggest supercritical fluidized bed combustion boiler for hard coal
efficiency 45%, Foster-Wheeler

Power plant	2005 Ash production in thousands tonne		
	fly ash	bottom ash	total
E power Turow	1 200	300	1 500
E+H power Zeran	120	40	160
E+H power Czechowice Dziedzice	40	10	50
E power Jaworzno II	100	50	150
E+H plant Katowice	100	30	130
E+H power Tychy	20	5	25
E power Siersza	75	25	100
E power Chorzow	100	25	125
Total	1 763	487	2 250

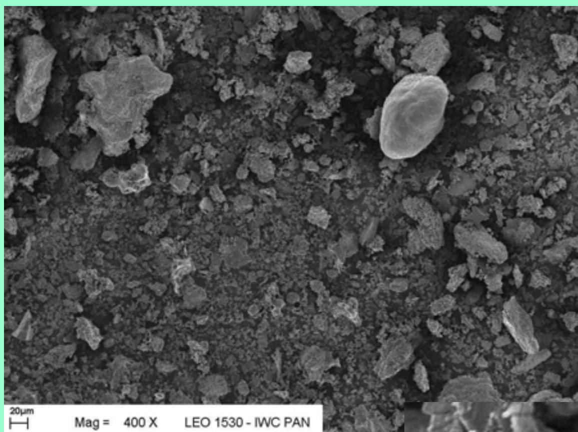
to compare:
cement production in Poland (2007): 16 732 000 tonne

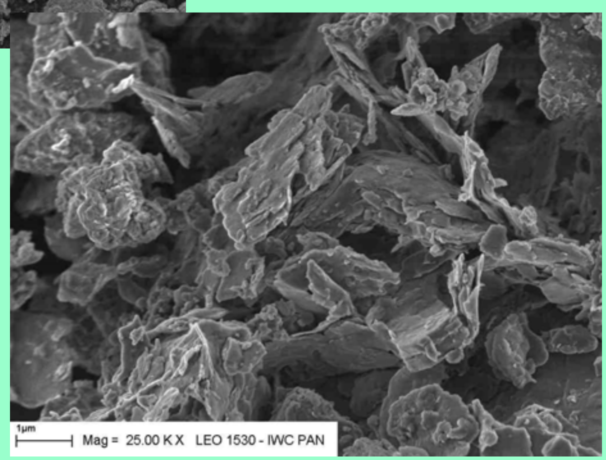




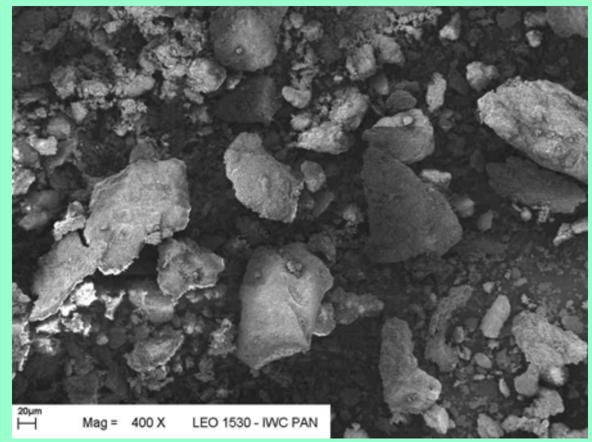
Characterization of CFBC fly ash

shape and grain size





CFBC FA Katowice (hard coal)
grain size [µm]:
mainly below 1
max 80
min below 1



CFBC FA Turow (lignite)
grain size [µm]:
mainly 4-5
max 120
min below 1

Chemical composition of cement and three CFBC fly ashes

Hard coal, various sources — CFBC FA Warsaw

Hard coal — CFBC FA Katowice

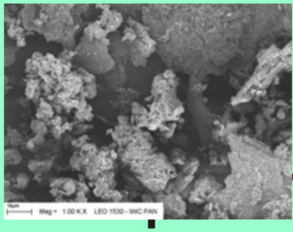
lignite — CFBC FA Turow

Test parameters	Contents				Requirements of EN 450-1:2005 for fly ash for concrete
	cement CEM I	CFBC FA Warsaw	CFBC FA Katowice	CFBC FA Turow	
SiO_2 , [% by mass]	20.38	34.36	47.46	36.47	the sum of contents $SiO_2 + Al_2O_3 + (Fe_2O_3) >= 70$
Al_2O_3 , [% by mass]	5.4	20.82	23.29	28.40	
CaO , [% by mass]	63.04	12.22	7.48	15.95	*)
SO_3 , [% by mass]	2.5	6.58	3.56	3.80	not more than 3.0
Cl^- , [% by mass]	0.02	0.12	0.08	0.03	not more than 0.10
CaO free, [% by mass]	0.84	1.79	0.35	4.75	not more than 1.0 or 2.5 and **)
MgO, [% by mass]	1.74	4.02	3.10	1.65	not more than 4.0
Fe_2O_3, [% by mass]	2.82	6.29	7.53	4.40	-
Loss on ignition, [% by mass]	1.66	11.77	3.30	2.73	<= 5 : Category A 2-7: Category B 4-9: Category C
Unburned carbon content by TGA-DTA, [% by mass]	-	3.9	0.3	-	-

*) the content of reactive calcium oxide ≤ 10.0%

**) soundness : the expansion in accordance with EN 196-3 not greater than 10mm

Monitoring of CFBC fly ash composition variability



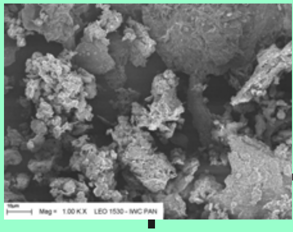
CFBC flay ash Turow (lignite)

Component	Contents. %; date of delivery		
	1.02.2007	*18.05.2007*	*4.09.2007*
LOI. 1000°C/1h	3.40	5.45	2.45
SiO_2	47.18	40.59	46.95
Fe_2O_3	6.80	9.40	7.48
Al_2O_3	25.62	21.18	23.30
TiO_2	1.08	0.96	0.92
CaO	5.84	11.60	8.45
MgO	0.15	1.70	1.86
SO_3	3.62	5.34	3.80
Na_2O	1.18	1.22	1.20
K_2O	2.36	1.83	2.60

CFBC fly ash Katowice (hard coal)

Component	Contents. %; date of delivery		
	1.02.2007	*1.04.2007*	*4.07.2007*
LOI. 1000°C/1h	2.73	3.07	3.52
SiO_2	36.47	34.28	29.96
Fe_2O_3	4.40	4.70	5.30
Al_2O_3	28.40	24.90	21.20
TiO_2	3.84	2.65	2.20
CaO	15.95	21.50	26.34
MgO	1.65	2.32	2.54
SO_3	3.80	4.00	4.67
Na_2O	1.64	1.83	1.82
K_2O	0.62	0.70	0.66

CFBC fly ash source	Free CaO contents, %		
	1.02.2007 *1.02.2007*	*1.04.2007* *18.05.2007*	*4.07.200* *4.09.2007*
Turow	4.75	8.61	10.00
Katowice	3.40	1.20	2.26



Concrete strength development

In four years numerous concrete mixes were manufactured at constant workability **in pairs**: **pure cement mix** and **20% cement replacement mix**

Materials used:

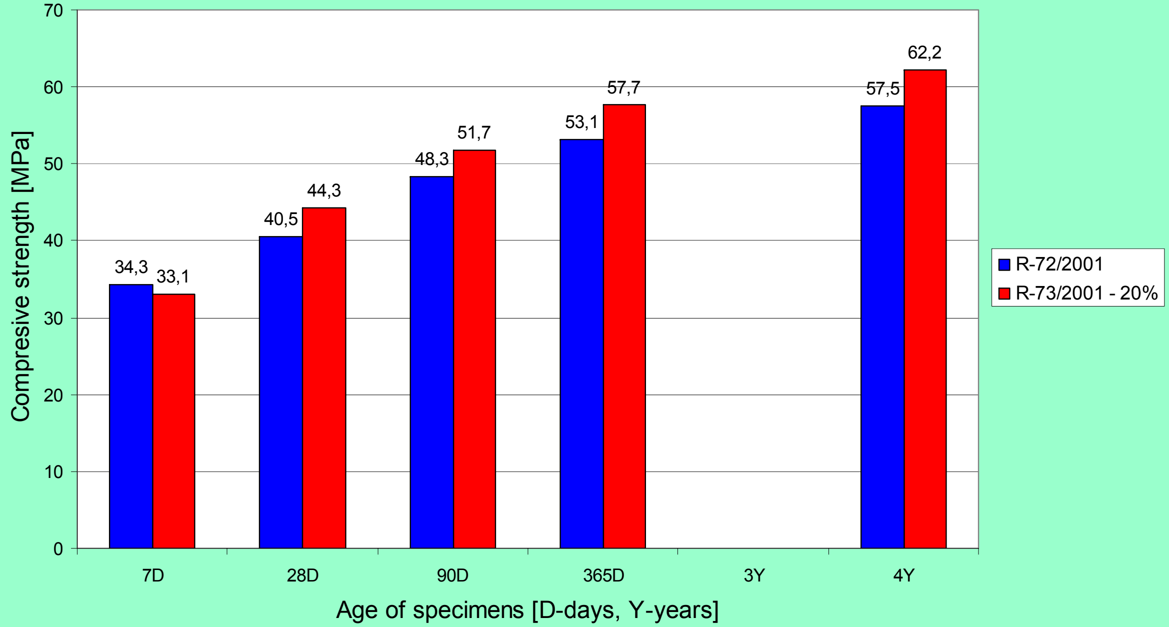
- cement CEM I 32.5R- the content 350 kg/m^3 or 300 kg/m^3
- CFBC fly ash from hard coal combustion
- aggregates: natural gravel 2-8mm, 8-16mm
- chemical admixture, water (+9% for CFBC FA mixes)

Range of variability of chemical composition of CFBC fly ash:

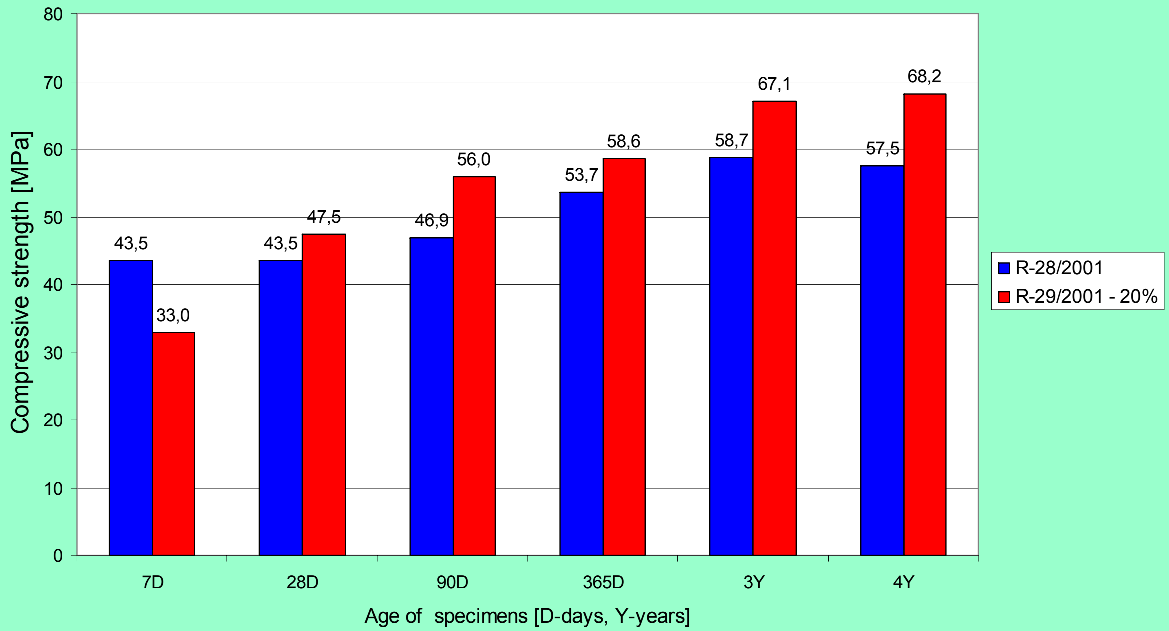
SiO_2 : 25.8 – 40.9%, Al_2O_3 :16.2 – 21.1%,

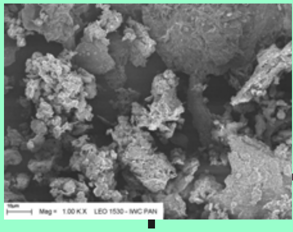
CaO: 14.5 – 24.4%, SO_3 : 6.4 – 10.7%, LOI: 5.6 do 10.2%

CUBE COMPRESSIVE STRENGTH INCREASE WITH AGE



Age	28 days= 100%		
	min	max	average
3	30,8	39,6	34,7
7	53,2	81,6	70,1
28	100,0	100,0	100,0
90	104,8	133,1	116,7
365	116,2	136,2	126,6
2 years	129,6	129,6	129,6
3 years	129,2	141,3	135,2
4 years	131,5	143,6	138,5





Strength efficiency factor

α - **efficiency factor** for CFBC FA in comparison to cement
s – total mass of binder (at 20% replacement level)

$$s = c_p + \alpha\, p = c\,(0.8 + 0.2\,\alpha)$$

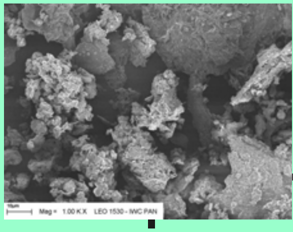
Feret’s formula for compressive strength of concrete:

$$f_c = A\left(\frac{\frac{c}{3.1}}{\frac{c}{3.1} + w + 20}\right)^2$$

f_c – strength of reference concrete

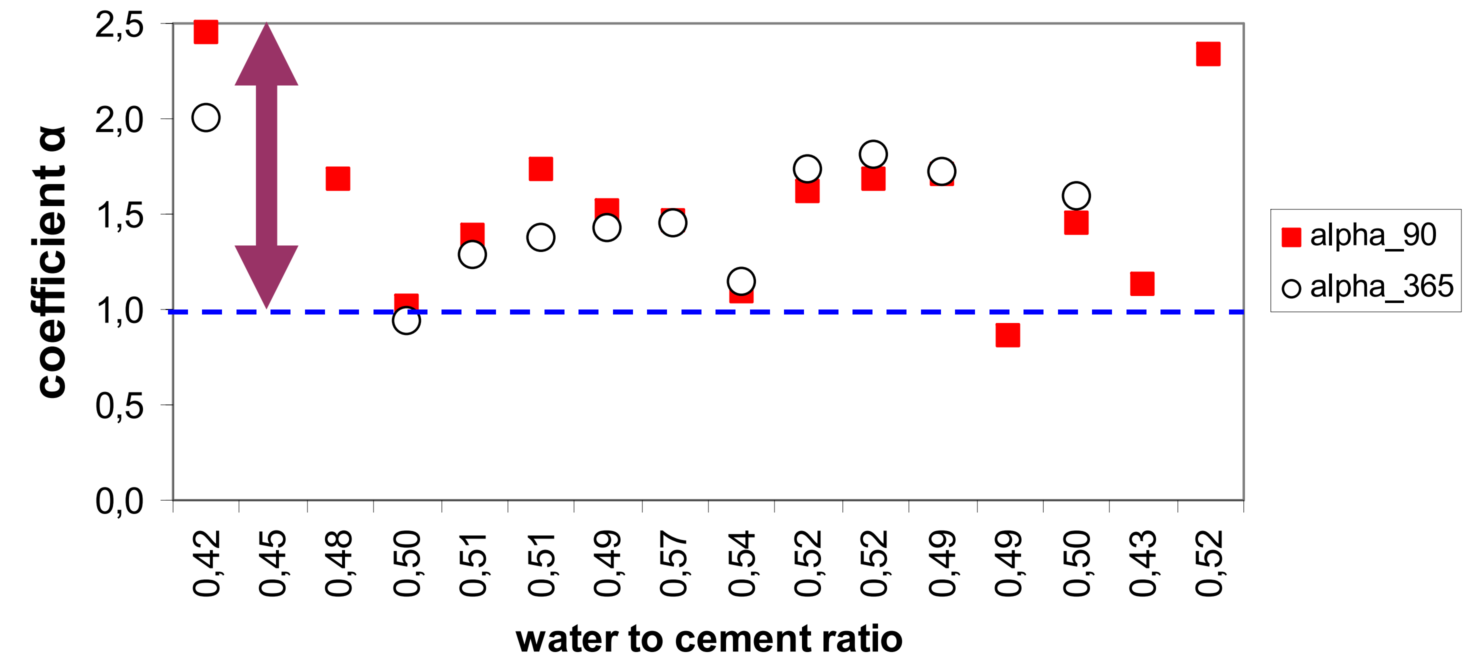
f_{cpf} strength f concrete with CFBC fly ash (20% cement replacement)

$$\sqrt{\frac{f_c}{A}} = \frac{\frac{c}{3.1}}{\frac{c}{3.1} + w + 20} \quad ; \quad \sqrt{\frac{f_{cpf}}{A}} = \frac{\frac{0.8c}{3{,}1} + \frac{\alpha\, 0.2c}{2{,}6}}{\frac{0.8c}{3.1} + \frac{\alpha\, 0.2c}{2.6} + w_s + 20}$$

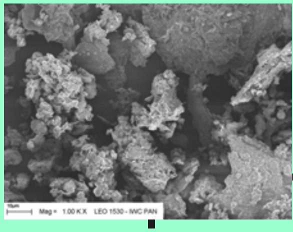


Strength efficiency factor
(variability during 4 years)

Variable sources of hard coal !



α - efficiency factor for CFBC FA in comparison to cement
α at 90 days: from 0.85 to 2.46



Variability of standard mortar strength

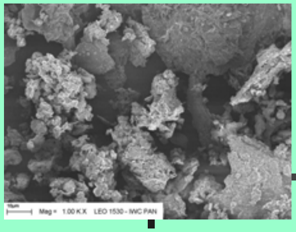
Regular quality control testing on **standard cement mortars** and **mortars with CFBC FA replacing 20% of cement**

Materials used:

- cement CEM I 32.5R
- CFBC fly ash from hard coal combustion
- standard sand 0-2mm
- water w/c = 0.5; about 9% more water in CFBC FA mortars at equal consistency

Compressive strength of mortars at 28 and 90 days

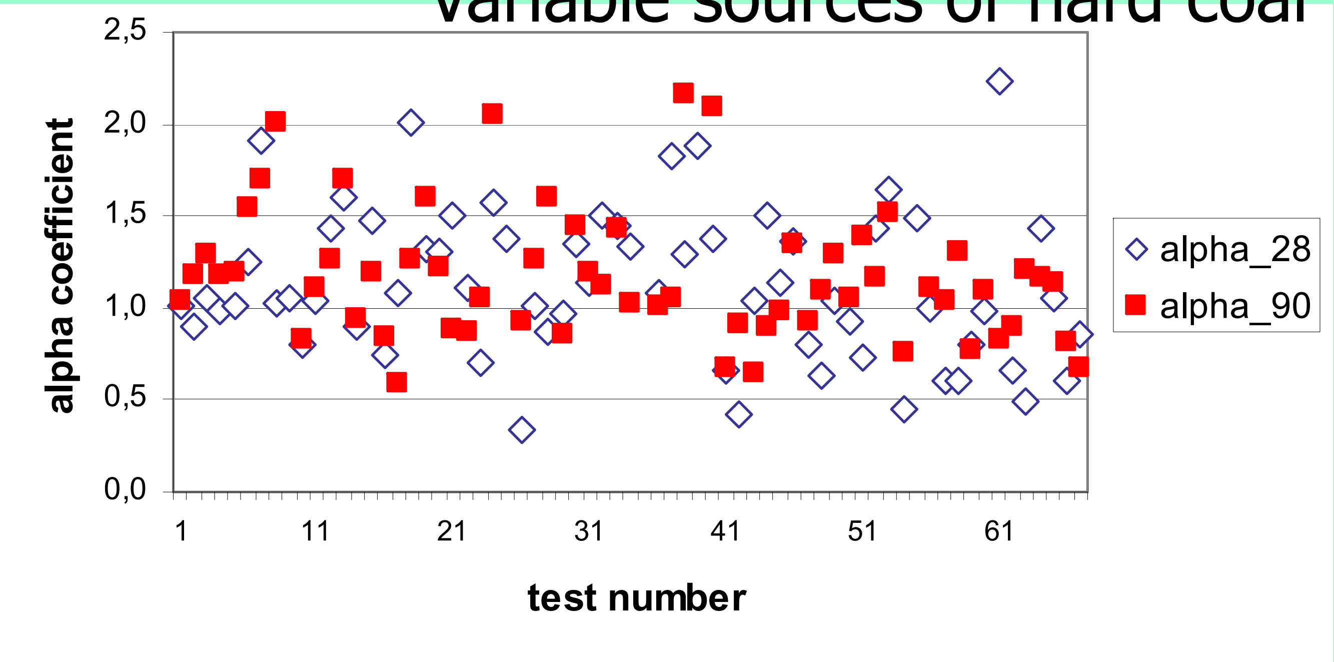
Tested regularly at 10 days interval for 2 years



Strength efficiency factor on mortars -variability during 2 years

Variable sources of hard coal !

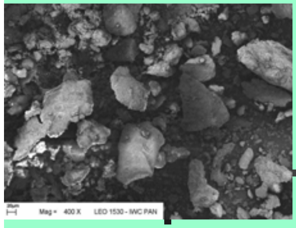
average α:
1.12 at 28 days
1.20 at 90 days



α - **efficiency factor** for CFBC FA in comparison to cement
s – total mass of binder (at 20% replacement level)

$$s = c_p + \alpha\ p = c(0.8 + 0.2\alpha)$$

XC Durability:
air permeability of concrete



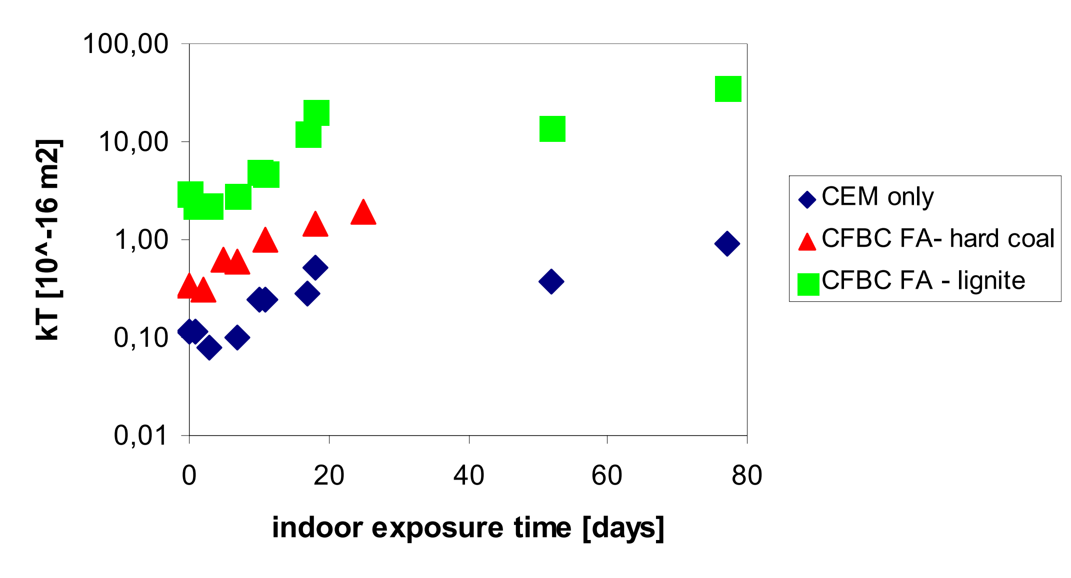
Torrent air permeability test method
specimens: slabs 500x500x100mm (5 measurements each)
curing: in 95% RH/20C for 56 days then storage in dry laboratory conditions

Concrete mixes

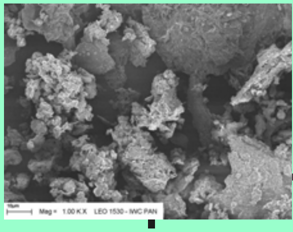
at equal workability :

1. cement CEM I only
2. cement CEM I 80%+ CFBC FA Katowice 20%
3. cement CEM I 80%+ CFBC FA Turow 20%

- water-reducing admixture
- bazalt aggregate max.16mm (not regular gradation)
- water to cement ratio 0,50



XF Durability: air void system in concrete



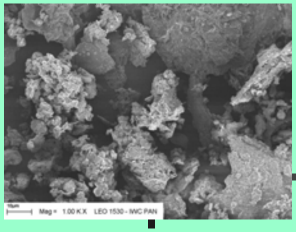
Materials:
-cement only
-CFBC FA Warszawa (FLW) at 20%, 30% and 40% replacement
-CFBC FA Katowice (FLW) at 20%, 30% and 40% replacement

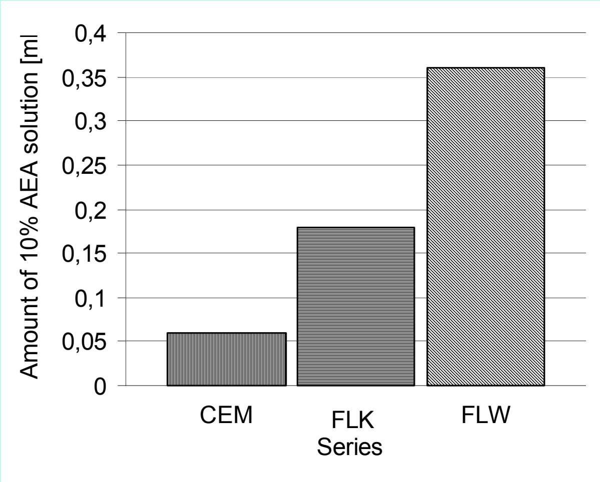
Concrete mix design:
constant water to binder ratio of 0.42
constant slump of 80 ± 20 mm
constant air-void content of 6±1%

Mix	Type of additive	Cement	Additive	Sand	Basalt 2-8mm	Basalt 8-16mm	Water	HRWR	AEA
		Content [kg/m^3]						l /m^3	l /m^3
CEM I	none	339	0	640	650	678	151	2.03	0.34
FLW20	FLW	274	69	648	657	686	152	2.74	1.37
FLW30		242	104	652	662	691	154	3.45	2.07
FLW40		209	139	657	667	696	155	4.18	2.78
FLK20	FLK	279	70	658	668	697	155	2.79	1.39
FLK30		246	105	663	673	702	156	3.51	2.11
FLK40		211	141	665	675	704	157	4.23	2.82

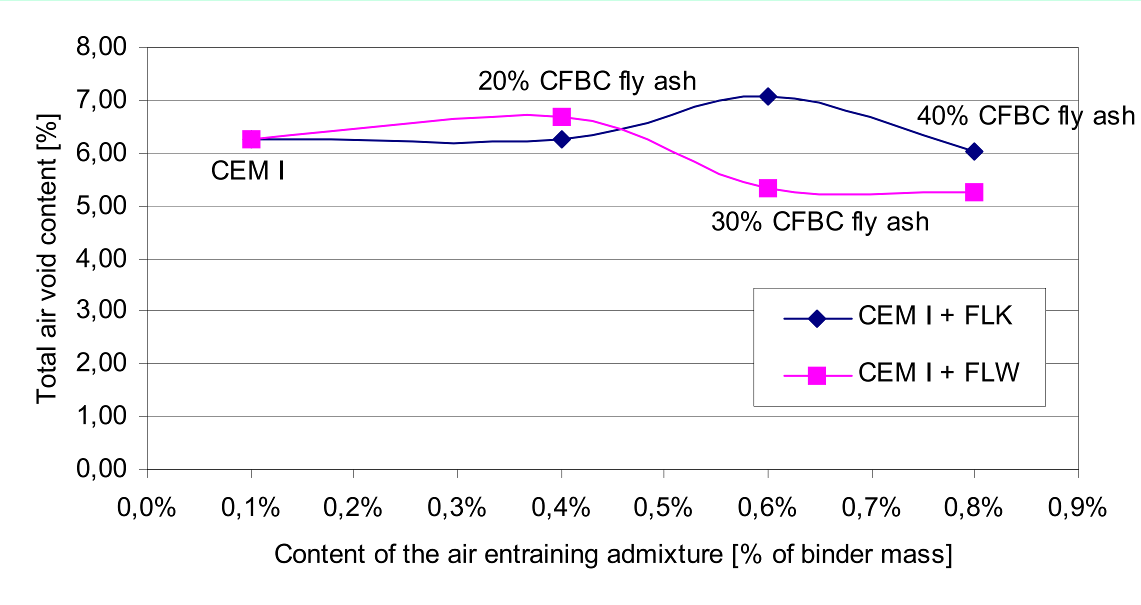
HRWR- high range water reducer, AEA- air entraining admixture

XF Durability: air void system in concrete

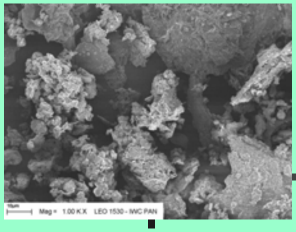




Foam index test: the amount of the 10% water solution of the air-entraining admixture necessary to achieve the bubble stability

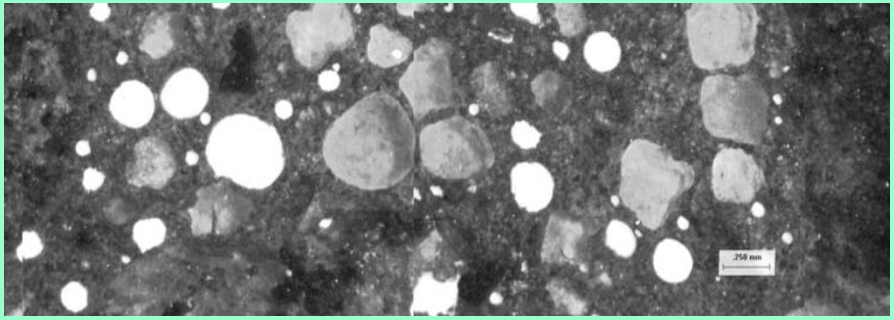


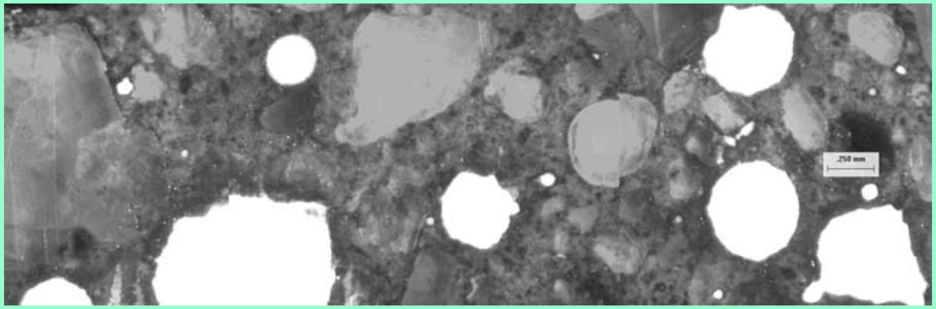
Air void content in hardened concrete as a function of amount of air entraining admixture



XF Durability:
air void system in concrete

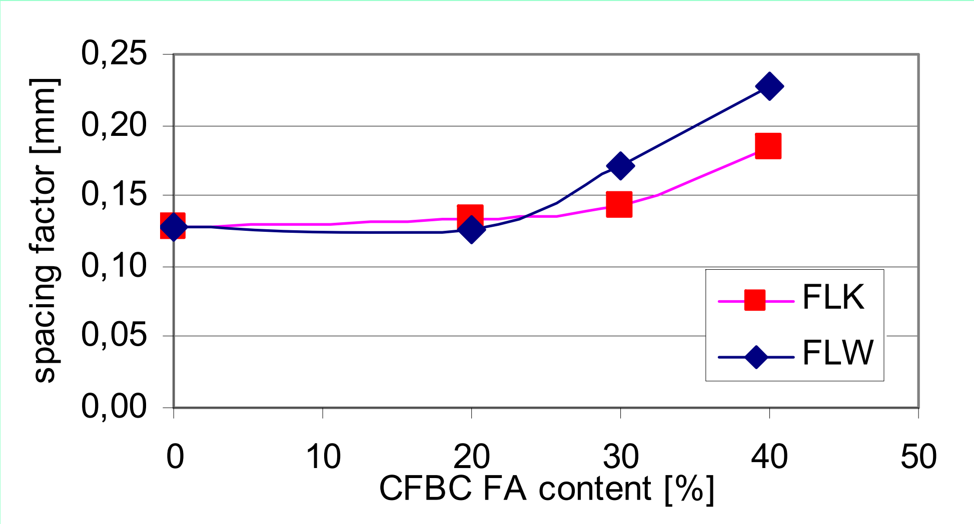
Air voids (white) in a polished section of concrete with different content of CFBC fly ash addition: left- 20% FLK, right- 40% FLW



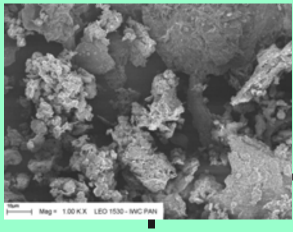


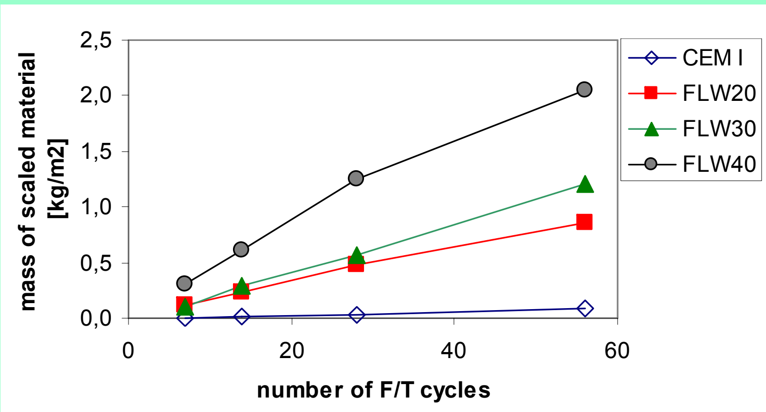
Spacing factor of air voids system versus the content of fly ash from fluidized bed hard coal combustion

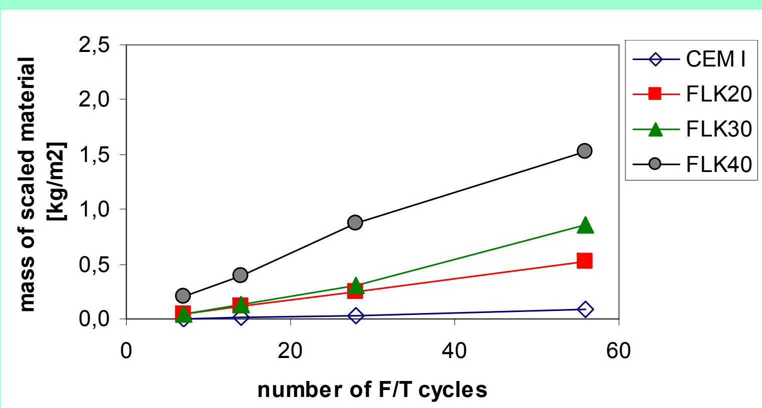
Linear traverse method using microscopic image analysis



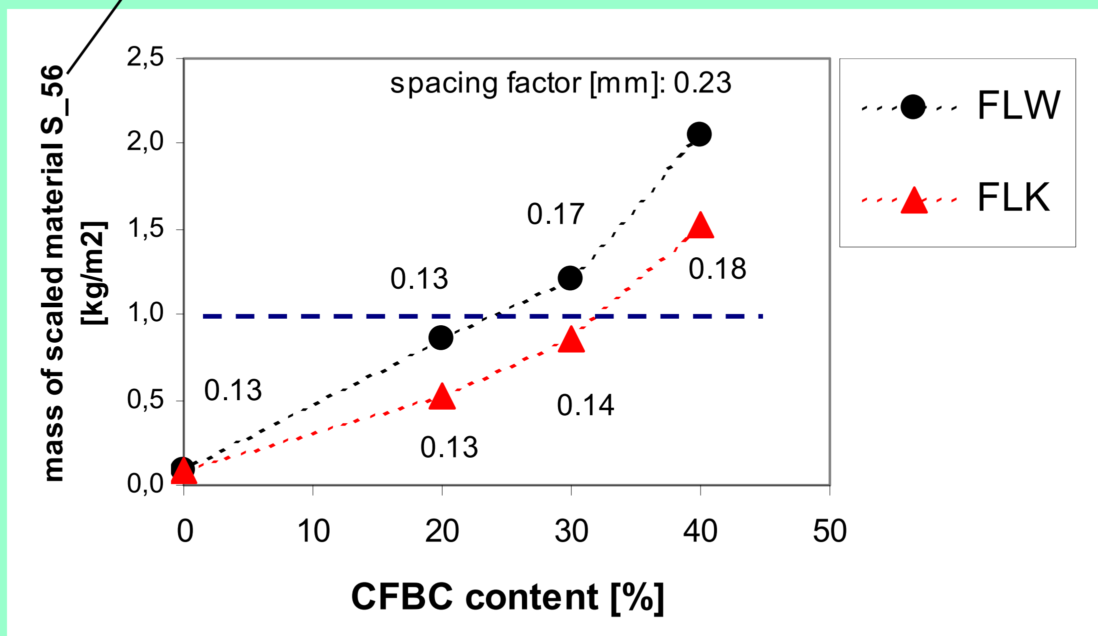
XF Durability: freeze-thaw and deicing salt resistance



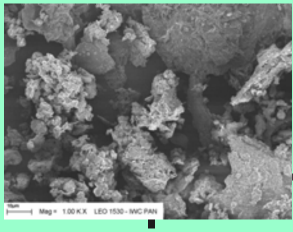




after 56 cycles (Boras method)



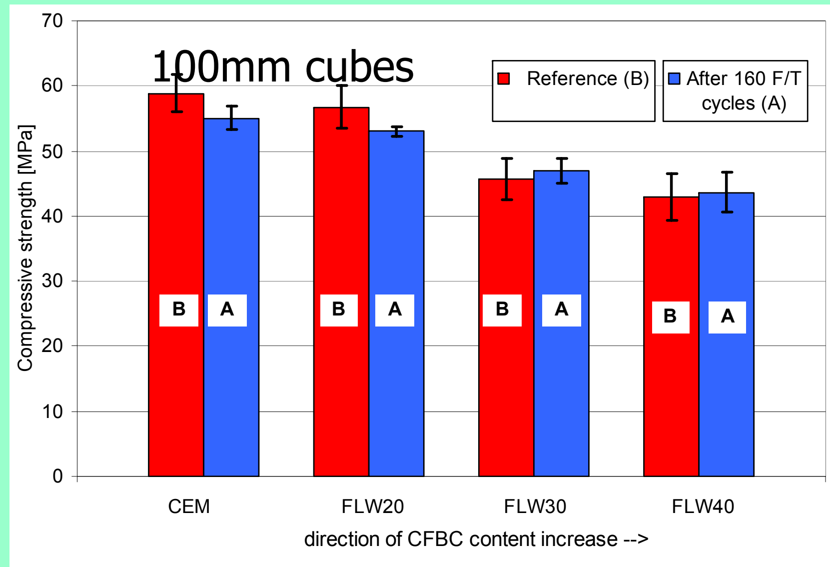
Mass of scaled material after cyclic freezing and thawing in 3% NaCl solution

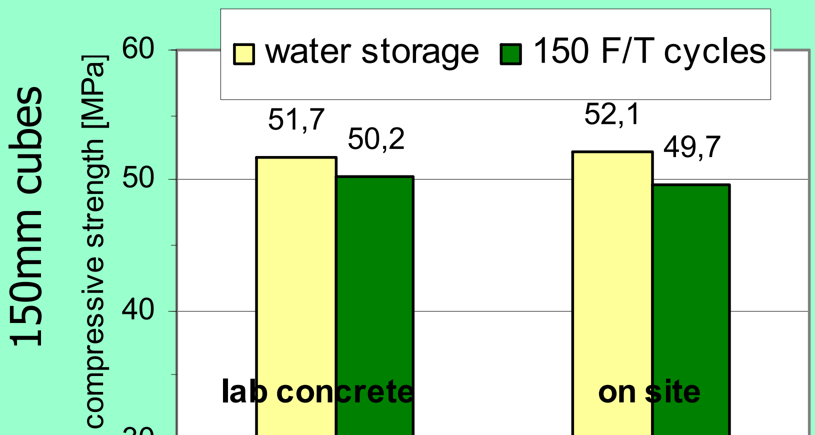


XF Durability: volumetric freeze-thaw resistance

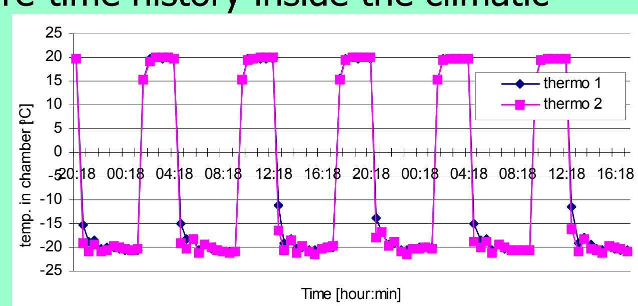
Compressive strength after cyclic freezing and thawing

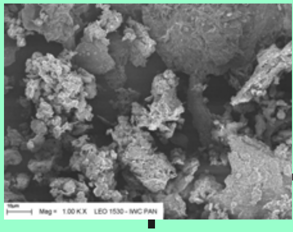
section of local road made of 35 MPa concrete containing 20% CFBC FA





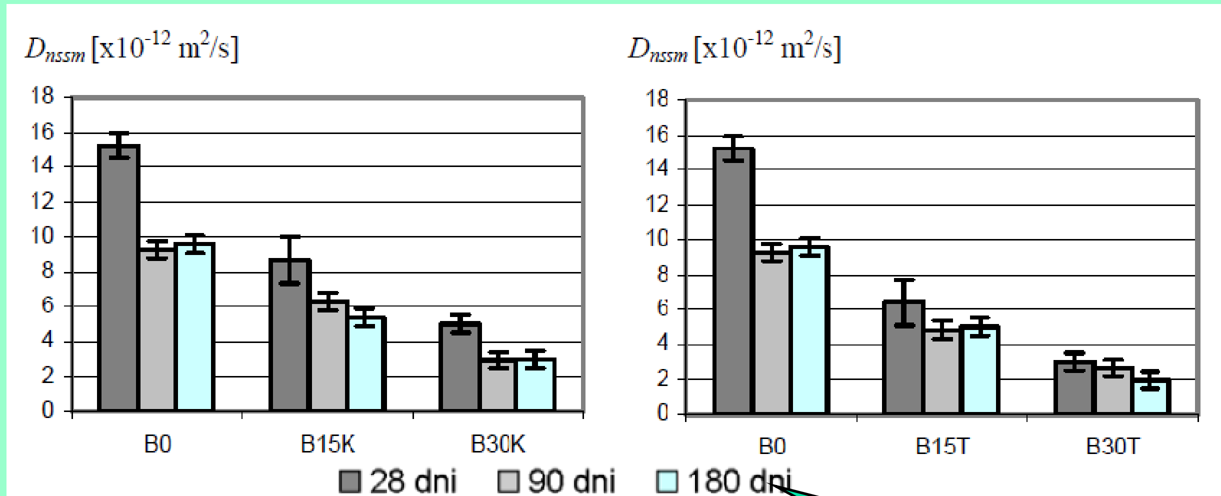
temperature-time history inside the climatic chamber





XD Durability: chloride migration

Non-steady state migration coefficient Tang/NordTest method NT Build 492



days

Concrete mixes
at equal water content :

B0 - cement CEM I 360kg/m^3, water 162 l

B15K and B30K – 15% and 30% cement replacement by CFBC FA Katowice

T15K and T30K – 15% and 30% cement replacement by CFBC FA Turow

- superplasticizer (variable content)
- natural gravel aggregate max.16mm

CONCLUSIONS

1. Potential to use of CFBC fly ash for partial replacement of cement up to 20%-30% in structural concrete together with WRA
2. At 20% replacement of cement by CFBC fly ash:

→ increase of water/binder ratio by 9 % at equal slump

→ Increase of long term compressive strength by 10-15%

→ the strength efficiency factor for CFBC fly ash was variable, although in average close to 1

3. Satisfactory air void system in concrete can be produced; decreased specific surface of voids and increased spacing factor
4. Freeze thaw durability adequate; frost salt scaling resistance – decreased with increased CFBC fly ash and unburned carbon content
5. Air permeability coefficent kT (Torrent) increased (?)
   Non-steady state chloride migration coefficient decreased

____________Thank you for your attention