EQUIVALENT AGE FOR BLAST FURNACE SLAG AND FLY ASH PORTLAND CEMENTS

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A relationship for assessing concrete strength even at varying temperature has long been badly missed for determining stripping and de-scaffolding times especially in the case of cold-weather concreting.

This fact was underlying the idea to describe the concrete maturity by a single number, or to refer it to a hardening curve recorded at a given temperature, e.g. 20 °C. Namely in chemical processes such as cement setting, temperature increase about proportionately accelerates chemical reactions. Strength, representing a given condition of involved reactions, is function of the concrete age and the concrete (storage space) temperature.

Since the early '50s, several researchers have been concerned with this problem. SAUL, RASTRUP and SECO-C.S.T.C. have published the following formulae joined by formulae developed by us:

1. Saul: $t_{20} = \frac{T_i + 10}{30} t_i$

2. Rastrup: $t_{20} = t_i 2^{\frac{T_i - 20}{15}}$

3. SECO-C.S.T.C.: $t_{20} = 0.3 \left(1 + \frac{T_i}{10}\right) t_i$

4. Suggested for blast furnace slag portland cement:

$$t_{20} = t_i \left[2^{\frac{T_i - 20}{15}} - 0.15 \left(\frac{T_i - 20}{15}\right)^2\right]$$

5. Suggested for fly-ash portland cement:

$$t_{20} = t_i \left[2^{\frac{T_i - 20}{15}} - 0.2 \left(\frac{T_i - 20}{15}\right)^2\right]$$

where

T_i — concrete temperature, °C;

t_i — concrete age, days;

t_{20} — equivalent time (days) needed for the concrete to achieve the same strength at 20 °C as during a time t_i at T_i °C. For varying temperature, the equivalent age is obtained by summing.

Several checks were made on the validity of these formulae. NYKÄNEN considered Saul's formula to be valid to portland cement at a storage temperature above 0 °C while RASTRUP indicated +2° to +45 °C as the range of validity of his own formula. In his tests made on 30 different cements, BRANDT found Saul's formula to be valid in the temperature range of 5 to 20 °C for portland cements C 325 and 225. At the same time, hardening curves at 5 °C, calculated by Saul, deviated upwards for portland cement 425, and downwards for heterogeneous cements, from the real one. According to the tests by AMMAR, DUTRON, MOTTEN and DUBOIS, in the temperature range of 0 to 10 °C the SECO-C.S.T.C. formula, at 5 °C the Rastrup formula give the better approximation. They underline them, however, to be approximative, and to be valid mainly to portland cement. Validity of the tests has also been checked earlier at this Department. Based on SIZOV's and on our tests, the strength of concrete stored below 20 °C was in fact always lower than that obtained with the mentioned formulae.

Obviously, the quoted tests are not the only ones, but a few from many others. Among them, tests by WALZ and BONZEL (1961) are referred to, on the hardening of nine cements (including blast furnace slag portland cements) involving standard cement paste specimens, varying the time of storage at 20 °C and lower temperatures without having examined the equivalent age.

Our research work consisted in checking validity of these formulae to Hungarian blast furnace slag cements and fly-ash-portland cements and possibly suggesting other formulae.

1. Experimental

The research involved the following cements:
Portland cement 450 from *Vác*, symbol: V 450 pc (reference)
Blast furnace slag p.c. from *Vác*, symbol: V 350 kspc 20
Blast furnace slag p.c. from *Vác*, symbol: V 350 kspc 40
Blast furnace slag p.c. 20 from *Hejőcsaba*, symbol: H 350 kspc 20
Blast furnace slag p.c. 40 from *Hejőcsaba*, symbol: H 350 kspc 40
Fly-ash-portland cement 350 10 from *Beremend*, symbol: B 350 ppc 10
Fly-ash-portland cement 350 20, symbol: B 350 ppc 20.

Standard chemical and physical characteristics of the tested cements have been compiled in Table 1, and plotted in Figs 1 and 2. The aggregate was composed of graded and washed fractions. Grading curves were in the lower part of the area between limit curves A16 and B16. Four kinds of concrete

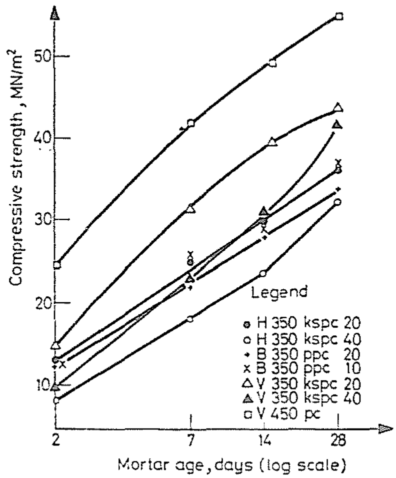

Fig. 1. Compressive strength of standard cement mortars vs. age

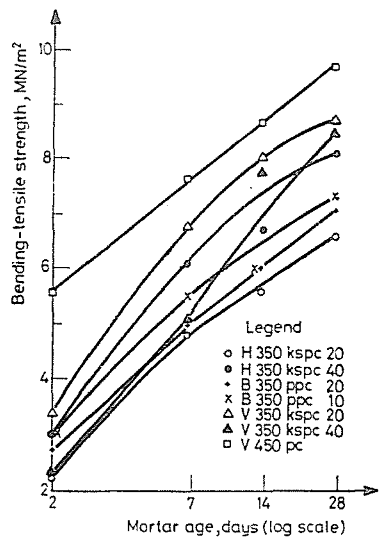

Fig. 2. Bending-tensile strength of standard cement mortars vs. age

were made from each cement type, half were planned to about B 200, and half to B 400. Half of the specimens in each concrete type were made with plasticizer *Melment L 10*. Concrete compositions, with informative consistence indices, are seen in Table 2.

Manually mixed concretes were cast to prisms 70×70×250 mm, and compacted on a vibrating table. Aggregates were previously stored at the

Table 1

Chemical and physical properties of cements

Property	Cement type						
	V 450 pc	V 350 kspc 20	V 350 kspc 40	H 350 kspc 20	H 350 kspc 40	B 350 ppc 10	B 350 ppc 20
Heating loss	3.75	2.30	1.02	1.62	1.83	1.81	2.34
SiO_2 %	19.14	21.58	24.36	23.76	25.99	23.88	26.42
Al_2O_3 %	6.37	6.31	6.80	5.97	7.63	7.72	8.23
Fe_2O_3 %	3.25	2.89	2.38	3.10	2.70	4.53	5.22
CaO %	62.62	60.83	57.73	60.19	56.50	56.90	53.80
MgO %	1.49	1.94	2.99	1.56	2.18	1.02	0.76
SO_3 %	2.62	2.25	2.14	2.06	2.31	2.05	2.34
C_3S %	56.73						
C_2S %	14.21						
C_3A %	11.81						
C_4AF %	10.25						
$CaSO_4 \cdot 2\,H_2O$	4.62						
Setting water %	0.306	0.283	0.283	0.253	0.26	0.263	0.273
Setting start	4h 15min	4h	4h 15min	3h 45min	4h	4h 15min	5h
Setting end	5h 30min	5h 30min	5h 30 min	5h 15min	5h 30 min	5h 15min	6h 15min
Density g/cm^3	3.056	3.043	3.041	3.085	3.061	3.022	2.994
Specific surface m^2/kg	299	283	262	297	314	302	279
Sieve residue % on mesh							
0.2 mm	0.40	0.30	0.35	0.40	0.40	1.00	0.50
0.1 mm	1.20	1.80	2.50	4.50	4.30	5.70	4.60
0.063 mm	5.60	9.40	8.95	15.60	14.40	14.20	19.20

desired temperature. Freshly placed specimens in moulds were put into a thermostated chamber at the desired temperature, then, after stripping, immersed into lime-saturated water. Storage temperatures were 2, 5, 10, 20 and 32 °C. Water temperatures were as planned ± 0.5 °C. Water storage was chosen to provide both for constant temperature and constant moisture. This resulted in a low standard deviation of strength results.

Specimens taken from the water at the time of testing were subjected to bending-tensile tests by third-point loading over a span of 210 mm, then the tested prism ends were tested in compression using 5000 sq.mm pressure plates.

Table 2

Concrete compositions and appr. consistence indices

Concrete No.	Cement kg/m³	w/c	Plasticizer	Slump cca. cm	Spreading cca. cm
1	300	0.55	—	1—2	35—38
2	280	0.57	2% Melment L 10	1—2	35—38
3	400	0.4	—	1—2	35—38
4	400	0.45	2% Melment L 10	6—10	40—44

2. Evaluation of test results

Test results on every concrete were first plotted vs. concrete age. One measurement result is average from 6, and from 3 compressive, and bending-tensile test results, respectively.

Second, fitting lines of strengths were plotted. The third step was to apply fitting lines to make eight comprehensive tables like Table 3.

These tables have led to the conclusion that, referring the concrete hardening process to that of 28-day concretes hardened at 20 °C, the timely development of the compressive strengths of the tested four types of concretes can be considered as identical for each cement type and storage temperature. On the other hand, timely development of bending-tensile strengths of concretes B 200 and B 400 would differ.

Thereafter, formulae for calculating the equivalent age were checked by comparing them with test data exemplified in Figs 3 and 4. Because of the poor approximation, formula (4) is only suggested for blast furnace slag-portland cements, and its modified form, formula (5) for fly-ash-portland cements.

Formulae have been compared in Fig. 5.

Tables 4 and 5 have been compiled by means of formulae suggested for assessing the equivalent age. Use of these tables and Fig. 6 will be illustrated on two examples.

Example 1

For a mean temperature of 15 to 25 °C, Table 30 in ÉSZKMI 19—79* specifies a stripping time of four days. Beginning with the day of concreting, the following mean temperatures have been recorded at the site:

1st — 2nd day	4 °C	2 days
3rd — 5th day	8 °C	3 days
6th — 10th day	6 °C	5 days
11th — 14th day	10 °C	4 days

* Technical Guides of the Min. of Building 19—79

Table 3

Hardening of concretes B 200

Cement type	Storage temp. °C	Concrete compressive strength, % at				
		1	2	7	14	28
		days of age				
	32	40	56	83	94	100
V 450	20	16	24	65	82	100
pc	10	5	14	45	66	86
	5	—	4	35	52	73
	2	—	1	24	43	64
	32	30	46	75	92	109
V 350	20	15	32	64	82	100
kspc 20	10	3	19	49	65	83
	5	—	10	38	55	70
	2	—	1	29	45	60
	32	26	45	77	95	113
V 350	20	10	28	62	80	100
kspc 40	10	—	12	44	62	80
	5	—	4	32	47	63
	2	—	—	22	38	52
H 350	32	30	47	77	94	110
kspc 20	20	13	31	64	82	100
	10	3	19	48	64	80
	5	—	10	37	52	66
	2	—	1	27	42	57
	32	17	35	70	88	108
H 350	20	7	26	61	80	100
kspc 40	10	—	10	44	62	80
	5	—	—	32	50	66
	2	—	—	22	40	55
	32	31	48	77	94	110
B 350	20	16	34	65	82	100
ppc 10	10	—	15	46	63	79
	5	—	2	32	49	65
	2	—	—	22	40	54
	32	28	45	76	94	110
B 350	20	14	30	63	82	100
ppc 20	10	—	10	43	60	78
	5	—	—	28	45	62
	2	—	—	18	35	50

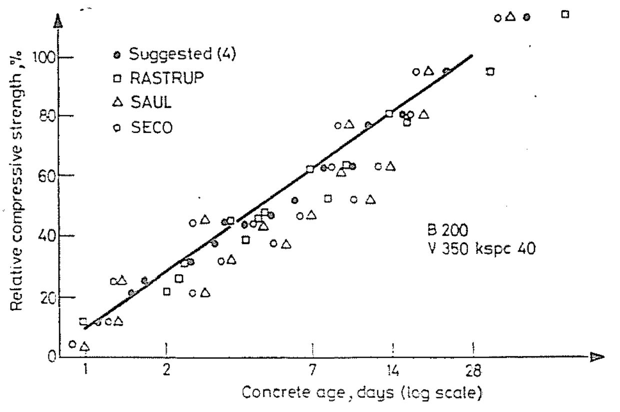

Fig. 3. Concrete strengths converted to storage at 20 °C (example for blast furnace slag portland cement)

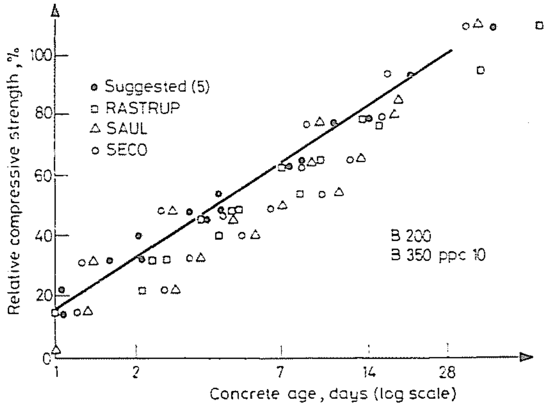

Fig. 4. Concrete strengths converted to storage at 20 °C (example for fly-ash portland cement)

Question: Is it allowed to strip the structure made with 350 kspc 20 at 14 days of age? Calculating according to Table 4:

$T_i = 4$ °C; $t_{20} = 0.61$ day
$t_i = 2$ days
$T_i = 8$ °C; $t_{20} = 1.44$ days
$t_i = 3$ days
$T_i = 6$ °C; $t_{20} = 1.96$ days
$t_i = 5$ days
$T_i = 10$ °C; $t_{20} = 2.25$ days
$t_i = 4$ days

$t_{20} = 6.25$ days $t_{perm} = 4$ days

thus, the structure can be stripped. Equivalent age at 10 days would be $t_{20} = 4.01$, stripping is permitted at 10 days of age.

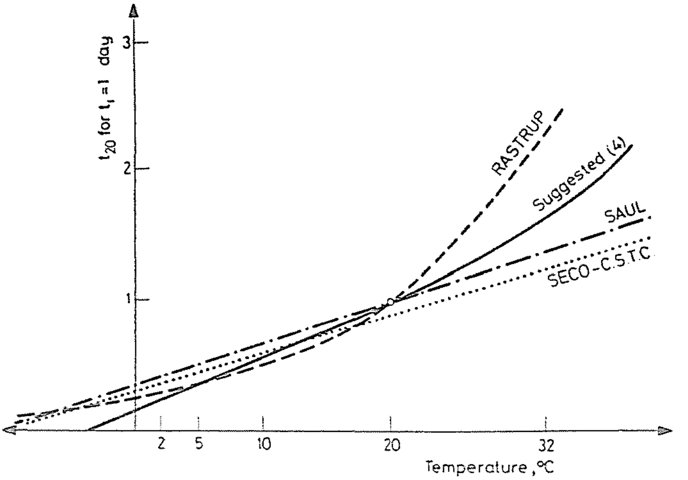

Fig. 5. Comparison of formulae suggested for calculating equivalent age

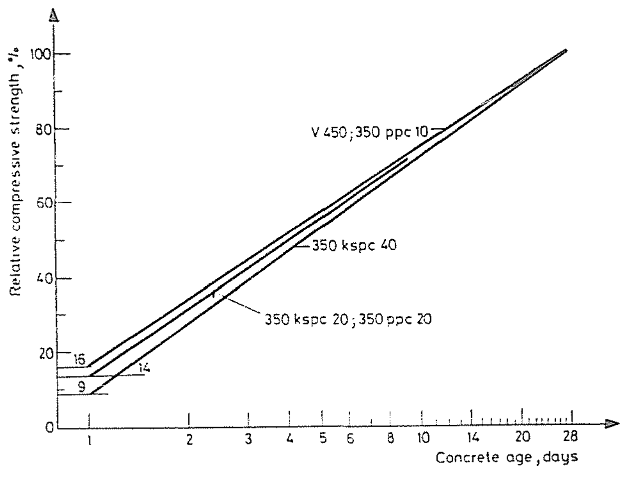

Fig. 6. Concrete hardening at 20 °C

Example 2

Design concrete strength is 28 MN/sq.m. The applied cement is 350 kspc 20 from Vác. What is the expected concrete cube strength at 14 days assuming air temperatures indicated in Example 1?

The equivalent concrete age is 6.26 days. According to Fig. 6, the relative strength is 61 percent. Expected concrete cube strength:

$$K = 28 \cdot 0.61 = 17.1 \text{ MN/m}^2.$$

Table 4

Calculation of equivalent age (for blast furnace slag portland cement)

1) $t_{20} = t_i \left[2^{\frac{T_i - 20}{15}} - 0.15 \left(\frac{T_i - 20}{15} \right)^2 \right];$

t_{20} — equivalent age;

t_i — concrete age;

T_i — concrete temperature;

2) t_{20} — tabulated t_{20} values at constant temperature:

Concrete age, days	Concrete temperature, °C									
	20	15	10	8	7	6	5	4	3	2
	Equivalent age, days									
1	1.00	0.78	0.56	0.48	0.44	0.39	0.35	0.31	0.26	0.22
2	2.00	1.55	1.13	0.96	0.87	0.79	0.70	0.61	0.53	0.44
3	3.00	2.33	1.69	1.44	1.31	1.18	1.05	0.92	0.79	0.66
4	4.00	3.11	2.25	1.91	1.74	1.57	1.40	1.23	1.05	0.88
5	5.00	3.89	2.82	2.39	2.18	1.96	1.75	1.53	1.32	1.10
6	6.00	4.66	3.38	2.87	2.61	2.36	2.10	1.84	1.58	1.32
7	7.00	3.11	3.94	3.35	3.05	2.75	2.45	2.15	1.84	1.53
8	8.00	6.22	4.51	3.83	3.49	3.14	2.80	2.45	2.11	1.75
9	9.00	6.99	5.07	4.31	3.92	3.54	3.15	2.76	2.37	1.97
10	10.00	7.77	5.63	4.78	4.36	3.93	3.50	3.07	2.63	2.19
11	11.00	8.55	6.20	5.26	4.79	4.32	3.85	3.37	2.90	2.41
12	12.00	9.32	6.76	5.74	5.23	4.72	4.20	3.68	3.16	2.63
13	13.00	10.10	7.32	6.22	5.66	5.11	4.55	3.99	3.42	2.85
14	14.00	10.88	7.89	6.70	6.10	5.50	4.90	4.29	3.68	3.07
15	15.00	11.66	8.45	7.18	6.54	5.89	5.25	4.60	3.95	3.29
16	16.00	12.43	9.01	7.65	6.97	6.29	5.60	4.91	4.21	3.51
17	17.00	13.21	9.58	8.13	7.41	6.68	5.95	5.21	4.47	3.73
18	18.00	13.99	10.14	8.61	7.84	7.07	6.30	5.52	4.74	3.95
19	19.00	14.74	10.70	9.09	8.28	7.47	6.65	5.83	5.00	4.17
20	20.00	15.54	11.27	9.57	8.71	7.86	7.00	6.14	5.26	4.39
21	21.00	16.32	11.83	10.05	9.15	8.25	7.35	6.44	5.53	4.60
22	22.00	17.09	12.39	10.52	9.59	8.65	7.70	6.75	5.79	4.82
23	23.00	17.87	12.96	11.00	10.02	9.04	8.05	7.06	6.05	5.04
24	24.00	18.65	13.52	11.48	10.46	9.43	8.40	7.36	6.32	5.26
25	25.00	19.43	14.08	11.96	10.89	9.82	8.75	7.67	6.58	5.48
26	26.00	20.20	14.65	12.44	11.33	10.22	9.10	7.98	6.84	5.70
27	27.00	20.98	15.21	12.92	11.77	10.61	9.45	8.28	7.11	5.92
28	28.00	21.76	15.77	13.39	12.20	11.00	9.80	8.59	7.37	6.14

Table 5

Calculation of equivalent age (for fly-ash portland cement)

1) $t_{20} = t_i \left[2^{\frac{T_i-20}{15}} - 0.2 \left(\frac{T_i - 20}{15} \right)^2 \right]$;

t_{20} — equivalent age;

t_i — concrete age;

T_i — concrete temperature;

2) t_{20} — tabulated t_{20} values at constant temperature:

Concrete age, days	Concrete temperature, °C									
	20	15	10	8	7	6	5	4	3	2
	Equivalent age, days									
1	1.00	0.77	0.54	0.45	0.40	0.35	0.30	0.25	0.20	0.15
2	2.00	1.54	1.08	0.89	0.80	0.70	0.60	0.50	0.40	0.29
3	3.00	2.31	1.62	1.34	1.19	1.05	0.90	0.75	0.60	0.44
4	4.00	3.08	2.16	1.78	1.59	1.40	1.20	1.00	0.80	0.59
5	5.00	3.86	2.70	2.23	1.99	1.75	1.50	1.25	0.99	0.74
6	6.00	4.63	3.25	2.68	2.39	2.10	1.80	1.50	1.19	0.88
7	7.00	5.40	3.79	3.12	2.79	2.44	2.10	1.75	1.39	1.03
8	8.00	6.17	4.33	3.57	3.18	2.80	2.40	2.00	1.59	1.18
9	9.00	6.94	4.87	4.02	3.58	3.14	2.70	2.25	1.17	1.32
10	10.00	7.71	5.41	4.46	3.98	3.49	3.00	2.50	1.99	1.47
11	11.00	8.49	5.95	4.91	4.38	3.84	3.30	2.75	2.19	1.62
12	12.00	9.26	6.49	5.36	4.78	4.19	3.60	3.00	2.39	1.77
13	13.00	10.03	7.03	5.80	5.18	4.54	3.90	3.25	2.59	1.91
14	14.00	10.80	7.58	6.25	5.57	4.89	4.20	3.50	2.79	2.06
15	15.00	11.57	8.12	6.70	5.97	5.24	4.50	3.75	2.98	2.21
16	16.00	12.34	8.66	7.14	6.37	5.59	4.80	4.00	3.18	2.36
17	17.00	13.12	9.20	7.59	6.77	5.94	5.10	4.25	3.38	2.50
18	18.00	13.89	9.74	8.03	7.17	6.29	5.40	4.50	3.58	2.65
19	19.00	14.66	10.28	8.48	7.56	6.64	5.70	4.75	3.78	2.80
20	20.00	15.43	10.82	8.93	7.96	6.99	6.00	5.00	3.98	2.94
21	21.00	16.20	11.36	9.37	8.36	7.34	6.30	5.25	4.18	3.09
22	22.00	16.97	11.90	9.82	8.76	7.69	6.60	5.50	4.38	3.24
23	23.00	17.74	12.44	10.27	9.16	8.04	6.90	5.75	4.58	3.39
24	24.00	18.52	12.98	10.71	9.56	8.39	7.20	6.00	4.78	3.53
25	25.00	19.29	13.53	11.16	9.95	8.74	7.50	6.25	4.97	3.68
26	26.00	20.06	14.07	11.60	10.85	9.08	7.80	6.50	5.17	3.83
27	27.00	20.83	14.61	12.05	10.75	9.43	8.10	6.75	5.37	3.98
28	28.00	21.60	15.15	12.50	11.15	9.78	8.40	7.00	5.57	4.12

Summary

Sensitivity to cold of fly-ash portland cements and blast furnace slag portland cements C 350 made to concretes B 200 and B 400, stored at 2 °C, 5 °C, 10 °C and 20 °C has been examined.

Formulae, somewhat different between blast furnace slag portland cements and fly-ash portland cements, have been developed for determining the equivalent age, i.e. the age of concrete achieving the same strength at 20 °C as that cured for a time t_i at T °C.

The suggested formulae were used to establish design aids for determining the equivalent age and to assess the time needed for stripping or de-scaffolding.

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