CONCRETE FOR MINOR AND MEDIUM SIZE HYDRAULIC STRUCTURES

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In minor and medium size hydraulic structures usually no special low heat cement is used but only an ordinary, puzzolanic one of the type C 350 (of at least 35 MPa 28-day compressive strength) with say 10—20 percent of fly ash or 20—40 percent of blast furnace slag. The aggregate is mostly natural rounded gravel and river sand with a maximum size $d_{\max} = 32$ or 48 mm (square mesh). Sometimes, in shortage of coarse gravel or near to quarries, crushed stone (mostly basalte or andesite) is used for part of coarse aggregate from say 16 to 48 mm. If the dimensions of the structure (walls, piers, slabs, etc.) make it possible, a special poor concrete is cast as core concrete with higher $d_{\max}$ and with a cement dosage as low as 150 kg/m^3, and another external facing concrete is cast mostly simultaneously with the former one but with higher cement dosage and lower water/cement ratio to meet the requirements not only for strength but also for watertightness, frost and abrasion resistance.

To improve workability in spite of lower w/c ratios, almost everywhere a water reducing plasticizer (W.R.A.) is applied, mostly of the cheapest type, on lignosulfonate basis. As the puzzolanic cements mentioned above are "slow" enough, usually no retarding admixtures are necessary, nevertheless they offer the advantage to cast the concrete without construction joints. Water reducing admixtures based on lignosulfonate are known to retard setting as demonstrated by e.g. Fletcher [1].

1. Basic materials, specimens and methods

Tests were made in the laboratory of our *Department of Building Materials* upon commission by the *Authority of Hydrology and Waterways OVH*. The tests involved the following variables:

- *cement dosages*: 150—225—300—375 and 450 kg/m^3 (the latter for external frost and abrasion resistant concretes);

- *cement types*: mainly 350-ppc 10 (28-day compressive strength min. 35 MPa) portland cement with 10 percent of fly ash, occasionally air entraining cement produced for that very purpose with colophony resin, and in a few cases also a specially blended puzzolanic cement mixed of 75 percent pure portland cement (450 pc, 28-day compressive strength min. 45 MPa) and 25 percent of finely ground trass;
- *aggregate*: (well graded, with a grading curve in the middle of zone No 1, "good") with $d_{\max} = 16$, 32 and 48 mm, resp. The substitution of particles 16/48 mm with crushed andesite was studied, too, and in a few cases (as the Danube sand does not contain the necessary amount of fines below 0.25 mm) the addition of quicksand was also tested.

All concretes were made to have the same consistence with a compacting factor $CF = 0.80 \ldots 0.85$, thus very different water/cement ratios. Beside CF chosen to provide equal workability both the slump and V-B vibration time(s) were measured.

200 mm cubes were cast to determine compressive strength, then standard slabs $200 \cdot 200 \cdot 120$ mm were made with $d_{\max} = 32$ and $400 \cdot 400 \cdot 200$ mm with $d_{\max} = 48$ mm for watertightness tests. The tests began with a water head of 2 bars for 48 hours, then the pressure was increased by 2 bars daily up to 8 bars.

To simulate the effect of bedload on bottom slabs of structures, six concrete slabs $400 \times 400 \times 120$ mm were mounted with watertight joints on the frame of the *Deval* drum containing a charge of 10 kg of coarse quartzite aggregate and some water. The drum was then rotated in one direction and the other for 18 hours each. This method was developed and has been used to control the quality of abrasion resistant concretes for Danubian hydraulic structures in the F.R.G. [2] and in Czechoslovakia [3]. Thus it is rightly called "*Danube* method". The first test of 2×18 hours was applied at the age of 90 days of specimens followed by another 2×18-hour cycle on the same faces of the same slabs now 1 year of age. The slabs have been turned by 90° to achieve still smoother abraded surfaces.

Frost resistance tests were made on rich concretes with $d_{\max} = 16$ mm according to the Hungarian Standard (cooling in air down to -15 to -18 centigrades and thawing in water at laboratory temperature). Prisms $70 \cdot 70 \cdot 250$ mm were first tested in bending then modified cube strength was determined on the broken halves both of reference specimens continuously immersed in water and of freeze tested specimens after 30, 60 and 120 cycles.

All specimens were moist cured in the moulds for the first day, stored under water for six days and then in ambient (rather dry) air till testing.

(The frost resistance specimens were water saturated before beginning with freezing-thawing cycles.)

Strength tests were made at 28 and 91 days, watertightness tests at 90—100 and 160—180 days, and frost resistance tests at about 150 days of age.

2. Test results

2.1 *Consistence*

The compacting factor method (suggested first in England) has been chosen as a reference method for preparing mixes of about equal consistence.

Rather similar *CF* values were obtained either in standard-size (BS 1881) or in extra size apparatuses, these latter being needed for testing concretes made with max. 48 mm aggregate according to the recommendations of *Transport and Road Res. Lab.* (UK). Our results deviate from those published by the *Road Research Laboratory* suggesting that *CF* (small) = 0.70 was equivalent to *CF* (big) = 0.735 and the difference would disappear according to a linear relationship until *CF* (small) = *CF* (big) = 1.00.

The equality of consistences based on *CF* values of two different mixes does not mean absolutely equal slumps or V-B vibration times. According to Fig. 1 the *CF* versus V-B time relationship is different between lean and rich concretes. The V-B method is more sensitive for lean mixes, and it is

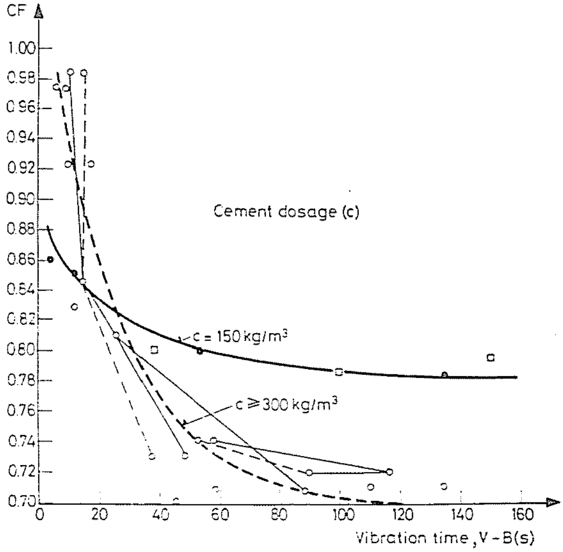

Fig. 1. V-B vibration time (s) vs. compacting factor *CF* for rich and lean mixes (several cement types drawn in thin lines [9])

recommended for use in site laboratories. Typical results (shown in Table 1) point out the sensitivity of V-B meters to the difference between plasticized and reference concretes where other methods fail.

Table 1

Consistence numbers for concretes $d_{\max} = 48$ mm and 300 kg/m^3 cement dosage

Consistence number	without WRA	with WRA
Slump, mm	5	16
CF (small apparatus)	0.82	0.83
CF (big app.)	0.84	0.85
V-B time (s)	20	5 (!)
w/c ratio	0.46	0.45

Symbol WRA: plasticizer used as water reducing admixture (PLASTOL made in Hungary).

2.2 *Compressive strength*

One problem was to determine the excess gain in strength between 28 and 91 days due to a water reducing plasticizer.

Typical results for lean mass concretes with $d_{\max} = 48$ mm are shown in Table 2. It is interesting to see concretes almost without water reduction

Table 2

Compressive (cube) strengths at 28 days and 91 days R_{c28d} and R_{c91d}, resp.

Cement dosage kg/m^3		Compressive strength MPa and percent				Consistence and w/c ratio	
		R_{c28d}		R_{c91d}			
		∅	WRA	∅	WRA	∅	WRA
150	MPa	24	28	30	35	CF 0.82	0.81
	percent		100 →		→ 125		
						V=B (s) 21	22
		100	115	124	145	w/c 0.79	0.82
300	MPa	42	47	53	55	CF 0.83	0.84
	percent		100 →		→ 118		
						V=B (s) 20	5
		100	111	126	130	w/c 0.46	0.45

Symbols: ∅ = unadmixed, WRA = water reducing admixture but with 0.4 percent lignosulfonate-based PLASTOL (produced by KEMIKAL, Hungary) to exhibit higher strength values at different ages than do either reference concretes or plasticized concretes. The strength gain in lean concretes is still more perspicuous.

Strength results for the most common mixes with $d_{max} = 32$ mm are shown in Fig. 2. The shaded area representing the strength gain at 91 days (a typical age for acceptance tests on hydraulic structures) due to an admixture tapers for higher cement dosages, a hint to use *lean* concretes of say 150 to 200 kg/m^3 cement dosage *and* admixtures.

The change of aggregate grading from $d_{max} = 32$ to 48 mm is also very beneficial: the surplus strength due to this change (Table 3) is more marked with lean concretes [4].

The use of crushed stone instead of well-rounded coarse gravel (16—48 mm) increases the compressive strength R_{c91d} only for higher (300 kg/m^3) cement dosages (59 MPa instead of 55) but reduces the strength of lean concretes (150 kg/m^3) by impairing the workability of harsh lean mixes and increasing the water demand.

The discussed results yield conclusions on the efficiency of cement dosage. The efficiency numbers, i.e. the ratios of compressive strength, MPa,

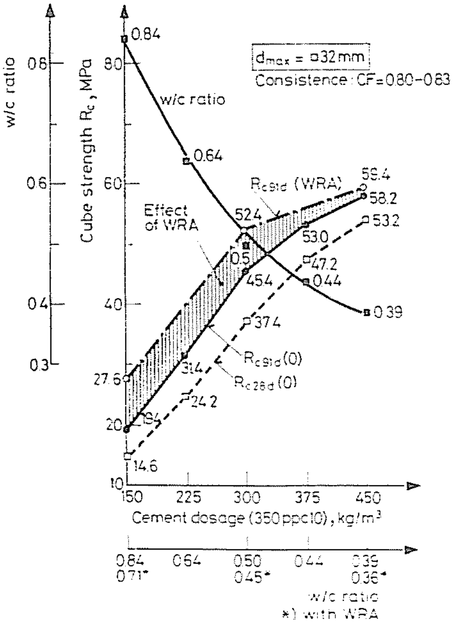

Fig. 2. The effect of cement content and w/c ratio (consistence $= CF$ 0.80 . . . 0.83) on compressive strength of concrete with $d_{max} = 32$ mm at various ages and without/with water reducing admixture (WRA) (0) = without WRA, unadmixed

Table 3

Compressive strength gain (percentage) due to grading and $d_{max} = 48$ instead of 32 mm (100 percent)

Cement dosage kg/m³	R_{c28d}	R_{c91d}	
	∅	∅	WRA
150	167	156	128
300	113	118	106

Symbols: ∅ = unadmixed, WRA = water reducing admixture

to the cement content, kg/m³ of different concretes are found in Table 4. For every age and type (with $d_{max} = 32$ or 48 mm and with or without water reducing agent) a highest efficiency exists.

Table 4

Efficiency numbers of cement dosage (MPa/kgm⁻³) for compressive strength

Cement dosage kg/m³	$d_{max} = 32$ mm			$d_{max} = 48$ mm		
	∅	∅	WRA	∅	∅	WRA
	28 days	91 days	91 days	28 days	91 days	91 days
150	9.6	12.6	$\boxed{18.0}$	$\boxed{15.9}$	$\boxed{19.6}$	$\boxed{23.0}$
225	10.6	13.7	(17.5)	(14.3)	(17.8)	(20.1)
300	12.3	$\boxed{14.8}$	17.3	13.8	17.4	18.0
375	$\boxed{12.4}$	13.8	(14.6)	not tested		
460	11.7	12.6	12.9	not tested		

Symbols: ∅ = unadmixed; WRA = water reducing admixture
Interpolated values in parentheses

The efficiency numbers begin to shift towards lower cement dosages (i.e. higher w/c ratios for the given constant consistence) with increasing concrete age arguing for acceptance tests to be made at an age of 91 or even 182 days rather than the actual 28 days as the strength of lean concretes tends to that of richer mixes in course of the curing period, — even without moist curing, which, of course would be still more favourable. The highest efficiency number belongs to concrete characterized by higher d_{max}, prolonged curing time and admixture of WRA. With cements of higher puzzolana content these phenomena would be even more marked except the effect of admixture largely dependent upon the type and amount of the puzzolanic constituent.

2.3 *Watertightness*

Unlike most of foreign standards, the Hungarian standard specifies specimens for watertightness tests to be immersed under water only for 6 days after being moist cured under burlap in the moulds on the first day. This mixed curing method better approaches practical site circumstances than a continuous water curing but the results show a higher standard deviation and the permeability factor is higher (see Fig. 5).

Two specimens were tested at 90—100 days and two others at 170—190 days of age. Older specimens splitted just after the pressure test were seen to show deeper penetration.

The watertightness is expressed by the fictitious ratio "g" of the pressure (water head, in m) to the maximum penetration depth b (in m) observed at the highest pressure level applied. Fictitious ratios g (= gradient) versus increasing cement content (i.e. decreasing w/c ratio) have been plotted in Fig. 3. The mixed curing method results in an optimum gradient at about 375 kg/m^3 cement dosage because shrinkage and microcracking due to a higher cement content combined with prolonged air curing impairs the beneficial effect of a lower w/c ratio. Watertightness is known to increase with age only for concretes subject to water curing; air curing works adversely [5].

Factors other than cement dosage (which was kept constant this time) such as cement type, d_{max}, water reducing admixtures and crushed stone substitution have a definite influence on the watertightness, as shown in

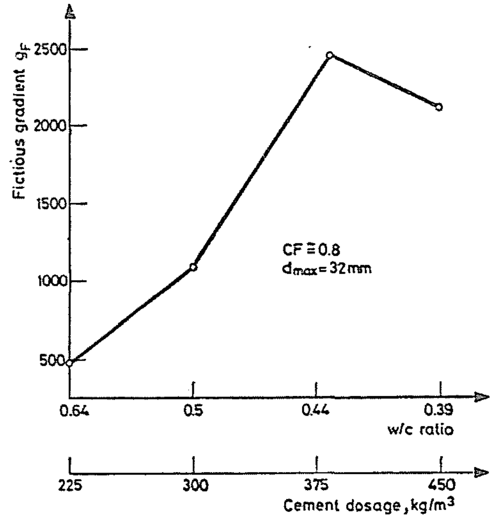

Fig. 3. The effect of cement content on watertightness, expressed in fictitious gradient i.e. ratio of water head (m) to penetration depth (m) for mixed curing

Fig. 4. As compared to the reference concrete (chosen as 100 percent) made with slightly puzzolanic cement, smaller d_{max} and without crushed stone, the improvement of cement quality (in spite of a higher w/c ratio connected with the increased specific surface, see column 1) or the increase of d_{max} and the addition of washed 16/48 mm crushed stone (providing better bond between mortar and practicles, see column 3) or coarser but naturally rounded aggregate with water reducing admixture (and lower w/c ratio than before, see column 5) result in about 50 percent improvement of watertightness. The best values, however, have been achieved by lowest w/c ratio belonging to the same workability (normal aggregate and WRA) and by the combined effect of bigger d_{max}, crushed stone and admixture. (See columns 4 and 6.)

The absolute "*g*" values can be tracked on Fig. 3, and could be improved somewhat under given circumstances by increasing the cement dosage. To clear the effect of prolonged water curing a special test was made in cooperation with the Concrete Department (Mr. DOMBI) of *Central Research and Design Institute for Silicate Industry* [8]. Concrete mixes of the same consistence with cement dosages of 300, 375 and 450 kg/m^3 and d_{max} = 12 mm (grading zone between "good" and "medium" curves B12) were cast to cubes in special moulds specially constructed by that Institute and apt both to maintain

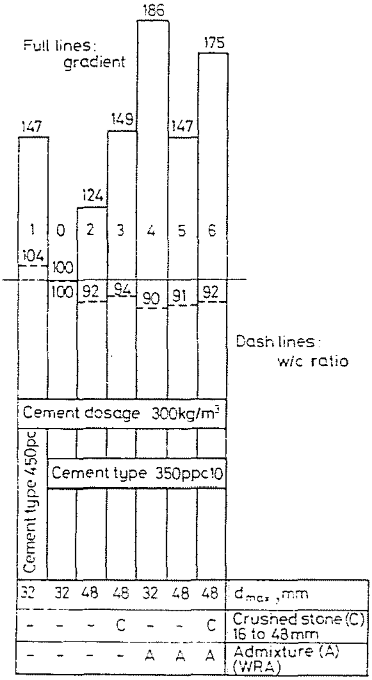

Fig. 4. Effect of several technological factors on watertightness expressed in fictitious gradient (percentage of reference concrete) for mixed curing

steady water flow by a suitably chosen water head and to accurately measure the water quantities seeping into (and out of) the specimen. The calculated water permeability factor k (mm/sec) vs. cement dosage has been plotted in Fig. 5 for two different curing schedules: specimens stored under water for 7 days (1) and for 27 days (2). Test began on the 28th day. The results confirm that longer moist (water) curing contributes to increase the watertightness at least to a degree as other best factors do: k decreases to the half (points E1 and E2) or to about 2/3 of original values (points C and D) belonging to short moist curing periods. The benefits of a higher cement dosage prevail only combined with prolonged moist curing periods.

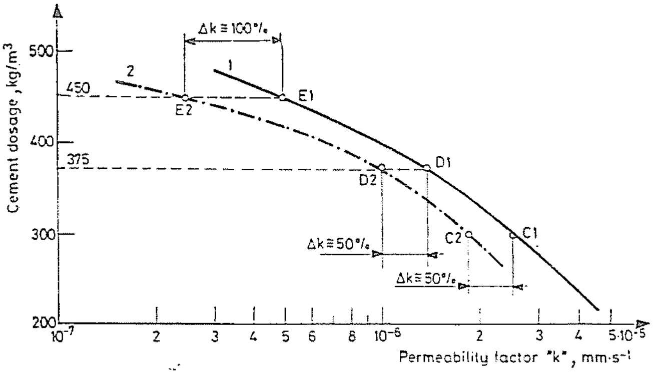

Fig. 5. The effect of cement dosage and of water curing time on the permeability factor k of concretes [8]. ① stored in water for 7 days; ② stored in water for 27 days

As for other factors: the supplementary quicksand was of advantage only in lean mixes with 150 kg/m^3 cement dosage and with smaller $d_{\max}$. Fine sand (or other fines, e.g. trass) does not improve either the compressive strength or the watertightness as a rule if the same workability is maintained by additional water alone. Blended cements with high or — as in our tests, — very high trass content may render more favourable results if drying out is hindered, concretes are moist cured and the structure itself is continuously water immersed.

2.4 *Abrasion resistance*

The average losses of volume of slabs in terms of loss of thickness (mm) due to twice 18 hours of rotation with the original revolution number 30 r/min of the *Deval* drum were compared between high strength (facing) concretes with 375, 450 kg/m^3 cement dosages and $d_{\max} = 32$ mm aggregate made with three types of cement: ordinary 350 ppc 10 (see Table 5, group II), air entrained version of the same, and blended trass cement. Based on findings

Table 5

Abrasion losses determined by the revolving drum (Danube) method

Group	Aggregate	d_{max} mm	Cement dosage kg/m^3	Abrasion mm
I.	corundum sand + pit sand and gravel	48	425—450	1.5—1.6
	pit sand and gravel, very good grading	48	425—450	1.9—2.0
[6]	pit sand + crushed andesite	48	425—450	2.2—2.4
	pit sand and gravel, medium grading	48	425—450	2.3—2.4
II.	river sand + gravel, good grading	32	450	4.7—4.8 1.8*
	river sand + gravel, good grading,	32	375	5.2 1.8*
[9]	river sand + gravel with WRA	32	450	5.2—5.9 1.6*
	river sand + gravel, good grading aerated cement + WRA	32	450	5.9 1.6*
	river sand + gravel, good grading without WRA	32	450	6.0—0.1 1.0*
III.	river sand + gravel	20, 32	390—400	2.7—2.9
[5]	river sand + basalt	32	400	3.7
	river sand + andesite	32, 48	390	42—43

* 2nd test 270 days later on the same faces

of former investigations, only the most resistant quartz-type Danube gravel (1) and sand was used, as basalt (2) and andesite (3) concretes showed clearly higher abrasion losses both in the *Böhme* grinding machine and with the *Danube* method. (Abrasion losses were measured always on water saturated specimens [6], see Table 5, group III.) The main controlling factor of abrasion resistance is the hardness of coarse aggregate, the second and third ones the quality and the quantity of mortar matrix the coarse particles are embedded in. *Quality* can be improved by higher cement dosage and water-reducing non-air-entraining admixture i.e. low w/c ratio, while matrix *quantity* is kept as low as possible by using larger $d_{\max}$ and excellent grading so as to need less of fine mortar to fill out voids between coarse particles. Quality of mortar may be improved by adding corundum sand to (or instead of) common river sand (see Table 5). Concretes in group I were tested at 150—210 days of age (*Kisköre* [7]), those in group II at 91 days (1st test) and again with slabs turned by 90° but exposing the same faces at 1 year of age. (Results of the second test marked* are indicated below the first test results.) Concretes in group III were tested at about 180 days of age. Because of the differences in cement type, age and grading, the results are only comparable within groups. According to former tests [6], abrasion losses (mm) measured on *water* saturated slabs mounted on the rotating drum and in a standardized *Böhme* grinding machine are about equal, while the *Böhme* abrasion loss of *dry cubes* is less by about 15 percent than the *Danube* values.

2.5 *Frost resistance*

Frost resistance tests were carried out only with concretes of $d_{\max} =$ 16 mm intended for facing on core concrete, to learn the effect of cement type dosage and air entraining. After the specified number of freezing and thawing cycles (30, 60 and 120) the strength of these specimens was compared to that of control ones of the same age but stored in water continuously: their ratio was called frost damage factor *FDF* (for typical results see Tables 6 and 7).

Table 6

Strength development due to after-hardening and frost damage factors (FDF)

Age (days)	Cycles	∅		WRA		WRA + AEA	
		percent	FDF	percent	FDF	percent	FDF
150	0	100	—	100	—	100	—
180	30	120	0.94	116	1.15	117	1.05
235	60	123	0.63	133	0.94	136	0.99
454	120	134	1.03	140	1.01	152	1.04
Actual final strength MPa		control 68	frozen 70	control 73	frozen 74	control 52	frozen 54
w/c ratio		0.38		0.35		0.34	

Data: cement dosage 450 kg/m^3 type 350 ppc 10.

Symbols: WRA = water reducing admixture; AEA = air entraining agent; ∅ = without any admixture

Table 7

Strength of control and frozen specimens [MPa]; after-hardening of control specimens (percent) and frost damage factors

Age (days)	Cycles	Strength (MPa)		Slow hardening percent	FDF	w/c ratio
		control	frozen			
143	0	31	—	100	—	0.44
172	30	38	40	123	1.05	
224	60	42	40	135	0.95	
443	120	45	48	145	1.06	

Data: cement dosage: 300 kg/m^3 air entraining cement based on type 350 ppc 10 + water reducing admixture (WRA)

Freezing—thawing cycles started at 150 days of age. A remarkable slow-hardening (post-hardening) could be stated even after 150 days with tested and with control specimens (*FDF* $>$ 1.0). (For *FDF* values in bending of concretes listed in Tables 6 and 7 see Table 8.)

Table 8

FDF values for flexural strength

Cycles	Cement type, dosage and admixture			
	350 ppc 10, 450 kg/m³			air entr. cem. 300 kg/m³
	∅	WRA	WRA + AEA	WRA
30	1.01	0.91	0.92	0.97
60	1.07	1.09	0.96	0.93
120	0.91	0.89	1.05	1.05

Symbols: ∅ — no admixture; AEA — air entraining agent; WRA — water reducing admixture

The results lead to the conclusion that *FDF* values are more reliable both for air entrained and for low w/c concretes, especially if flexural values are considered. Air entrained concretes are better even with lower initial strength. Blended cement (with 25% trass) showed worse *FDF* values (mainly for flexural strength) partly due to higher w/c ratios (e.g. 0.49—0.45—0.44 as compared to those in Table 6) partly due to negligible afterhardening and lower initial strength. Trass cement must not be used in hydraulic structures else than after careful, timely study of advantages (e.g. low heat evolution) and disadvantages (e.g. higher water demand and sensitivity to curing) by other than simple technological tests.

Table 9

Air void system characteristics

Admixture	Number of air voids mm⁻¹	Specific surface mm⁻¹	Air volume of voids L_{300} V%	Spacing factor mm
WRA + AEA	0.65	27.2	9.55	0.139
WRA + AEA	0.52	37.4	5.55	0.130
Air entr. cement + WRA	0.37	30.1	4.92	0.173

WRA = water reducing admixture; AEA = air entraining agent; L_{300} = air content (percentage by volume) of voids smaller than 300 μm

In spite of the convincing results of direct freezing and thawing tests, even the air-void system of some air-entrained concretes was measured according to ASTM C 457 (linear traverse method, see Table 9). The results in the 1st and 2nd rows are to be compared to those of the two last columns in Table 6: due to the somehow uncontrolled and too high air entraining (produced by the interaction of the WR and AE admixtures) strengths are not excellent but both frost damage factors and air void systems values guarantee excellent frost resistance and verify good correlation between direct and indirect frost resistance indices [10]. Air entraining cement was very effective, too.

3. Conclusions

Concrete, with river sand and gravel (if available), with a moderate fly-ash or blast furnace slag content and with as large $d_{\max}$ as possible can be reliably used without widespread preliminary laboratory tests for smaller and medium size hydraulic structures from the point of view of strength, watertightness and abrasion resistance. Water reducing and air entraining admixtures contribute to frost resistance even with a relatively low cement dosage of 300 kg/m^3, but the efficiency and compatibility of admixtures with cement have absolutely to be determined in preliminary tests. With higher $d_{\max}$ (e.g. 48 mm), age (e.g. 91 days) and WRA, the efficiency of cement content ranges up to 20 MPa/kgm^{-3} if lower dosages (under 300 kg/m^3) are applied, and excellent core concretes can be made with 150 kg/m^3 of cement and $d_{\max} = 48$ mm. The abrasion is smaller with quartz-type aggregates (1) than with basalt (2) or andesite (3), and losses (measured in water saturated condition by the "*Danube*" method) can be minimized with excellent grading and artifical hard sand (e.g. corundum). The worn faces of test slabs were smoother with "softer" basalt or andesite than with natural gravel as these very hard particles extruded better from the soft mortar matrix.

Watertightness can be improved by increasing $d_{\max}$, using washed crushed stone as coarse aggregate, and by a lower w/c ratio using WRA. Depending upon curing circumstances, not the best watertightness is achieved with the highest cement content (= lowest w/c ratio) if drying shrinkage can occur. Pure portland cement may be superior for frost resistant and/or abrasion resistant facing concretes. Blended trass cement needs special care and it is therefore not recommended.

According to frost resistance tests and some microscopic air void system measurements, both air entraining cement (even with a dosage of only 350 kg/m^3) and ordinary portland cement with WRA and AEA showed excellent frost resistance.

Summary

Compressive strength, abrasion and frost resistance, as well as watertightness of usual concretes (made with a portland cement of max. 10% fly ash content) for minor and medium size hydraulic structures was studied with the following variables: cement dosage from 150 to 450 kg/m^3, water reducing admixture (WRA), maximum size of aggregate (d_{max}), crushed or naturally rounded coarse aggregate, occasionally air entrained cement. The efficiency of cement dosage was determined for different ages and d_{max}. A special abrasion equipment (*Deval* drum) was applied to simulate abrasion caused by coarse bed load.

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* In Hungarian