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Influence of recycled aggregates on mechanical properties of HS/HPC

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Abstract

Recently, aggregates derived from demolished concrete structures were of relatively low strength, and applications were of secondary importance. Since a short time, the necessity of demolition of structures with strong concrete, like building frames or bridge beams, has appeared and created the source of recycled aggregate of quite new generation. Besides of obvious environmental aims recycling of concrete has gained new economical aspects. Concrete in responsible structures, with strength of 40–70 MPa for instance, was originally mixed from aggregate of good quality, e.g. granite or basalt, and with large amount of cement. The aggregate obtained from crushing of such structures retained some binding abilities as may be activated by means of silica fume or fly ash admixtures. Generally, such aggregates are different from natural and, consequently, concrete made with use of them has specific properties. The results of research on mechanical properties of structural recycled high performance concrete (RHPC) are presented.

Keywords: Bond; Compressive strength; Creep; Freezing and thawing; High-strength/high-performance concrete; Recycled aggregates; RHPC; Shrinkage; Tensile splitting strength

1. General remarks

Reuse of aggregates from demolished concrete structures was introduced into practice many years ago, and from the beginning it has been considered in main two environmental aspects: solving the increasing waste storage problem and protection of limited natural sources of aggregates [1,2]. At present, plenty of demolished reinforced-concrete or prestressed-concrete structures, originally erected from concrete of moderate or high strength, creates the significant source of rubble aggregate of relatively good quality [3,4]. This situation is particularly characteristic for the countries in Central and Eastern Europe, where the intensive programs of modernization and reconstruction for roads, bridges, municipal and industrial structures started in 1990-ties. Not uncommonly it is necessary to demolish structures relatively young, for instance fifteen years old or less, because the functional features do not fit with the new projects [5]. Such situations are typical at road bridges, for which the prestressed concrete beams with spans 15–18 m are not sufficient now, and have to be removed to widen the span of structures to overpass new roads.

To answer the questions of designers of mix composition as well as doubts of designers of structures a wide program of tests has been undertaken. The particular aim was to clarify the way how to obtain high-performance concrete using aggregates from demolished structures made formerly from moderate- or high-strength concrete, and what properties could be obtained in such concrete by introduction of silica fume and superplasticizers. In such aggregates, apart from the obvious environmental aims of concrete recycling, there is a new economical aspect. Originally mixed with large amount of cement the crushed concrete retains some binding abilities, particularly when carbonated zone is not too deep. It may be activated with silica fume or fly ash admixtures. Some savings in cement consumption on this way have been reported [6,7].

2. Program of tests

The program was considered according to the questions placed by producers of concrete mixes as well as designers of structures. Therefore, general tasks of the research work were to obtain the recipe rules and basic properties of recycled concrete in the range of strength, deformations and long-term behaviour. Concrete spec-

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imens with fine and coarse aggregates crushed from original concrete of about 35–70 MPa, in comparison with similar concrete specimens with partial or total use of natural (new) aggregate were the main subjects of experimental testing. The basis for comparisons was HPC with designed strength $f_{cm(28)} = 60$ MPa from new aggregate, with consistence class V-2.

The influence of the content of Portland cement, superplasticizers and silica fume on early/final properties was taken into consideration in the tests too.

Recycled aggregates were taken from six different structures demolished under supervision of the authors. These structures were well known from previous investigations, even from the period of execution. Five of them were made with crushed granite coarse aggregate and one with basalt. The structures when demolished were two, five or seven years old. Recycled aggregates were used about two or three months after crushing.

After some pilot series (named R1–R4), six groups of specimen series (R5–R9 and R11), with different aggregates gained from crushed structures, have been finally selected for the full tests. The tests concerned: properties of recycled and new aggregates, concrete compressive strength up to 90 days, tensile splitting strength, secant modulus of elasticity and stress–strain relation specimens, bond tests, shrinkage, creep, and freeze-thaw durability.

The general sequence of tests was the following:

1. Selection and testing of original concrete in structure (core samples and non-destructive tests), crushing and screen classification of recycled aggregate.
2. Tests of basic properties of recycled aggregates (specific gravity, bulk density, moisture content, absorption and pH were the parameters taken into consideration).
3. Design of concrete mixes from natural, mixed, or fully recycled aggregates, to obtain comparable series.
4. Preparing series of specimens for testing, with uniform curing for all series.
5. Tests of cylinders and cubes for compressive strength at 1, 3, 7, 14, 28, 56 and 90 days.
6. Tests of cylinders by splitting to obtain tensile strength at ages between 1 and 90 days.
7. Tests of secant modulus of elasticity and Poisson's ratio at 28 days.
8. Tests of stress–strain relation on cylindrical specimens at 28 days.
9. Bond tests by pull-out method (according to RILEM-1970 method [8]).
10. Measuring shrinkage and creep on prismatic specimens during 360 days period.
11. Freezing and thawing tests (according to the Polish Standard, similar to ASTM C 666 B).

3. Recycled aggregates

Mixes content and mechanical properties of original concrete were obtained from laboratory tests on cylindrical specimens at the time of structures erection – series A to F. Additionally, a number of samples (remained from the period of structures execution) was tested at the time of concrete crushing – series D, E, F.

The available basic data for these sources of recycled aggregates are presented in Table 1(a) and (b). Notation in Tables: $f_{cm(28)}$ – mean compressive strength (28-days); $E_{cm(28)}$ – secant modulus of elasticity (mean values at 28 days); ρ_{cm} – mean volumetric density.

4. Mixes in series of specimens with recycled aggregate

The groups of specimen series with recycled aggregates and accompanying comparable series were designed with the following recycled aggregates:

group R5 with A;	group R6 with B;
group R7 with C;	group R8 with D;
group R9 with E;	group R11 with F.

Six mixes of concrete have been provided in each group; cement, water and aggregate mass was almost constant, while the composition of aggregate was changed in the following way:

R5.1, R6.1, R7.1, R8.1, R9.1 and R11.1 – comparable mixes with new aggregate only, granite or basalt, respectively; in all these series mean 28-day strength about 60 MPa was assumed, and consistence class V-2 (see Table 4).

R5.2, R6.2, R7.2, R8.2, R9.2 and R11.2 – mixes with recycled aggregate 2–16 mm and new (natural quartz) sand 0–2 mm.

R5.3, R6.3, R7.3, R8.3, R9.3 and R11.3 – mixes with fine and coarse recycled aggregate only.

R5.4, R6.4, R7.4, R8.4, R9.4 and R11.4 – comparable mixes with new aggregate only, granite or basalt, respectively, with silica fume (SF/PC = 10%) and superplasticizer (SP/PC = 3%) added.

R5.5, R6.5, R7.5, R8.5, R9.5 and R11.5 – mixes with recycled aggregate 2–16 mm and new natural sand 0–2 mm with silica fume (10%) and superplasticizer (3%) added.

R5.6, R6.6, R7.6, R8.6, R9.6 and R11.6 – mixes with recycled aggregate only, with silica fume (10%) and superplasticizer (3%) added.

Compositions of mixes in all six groups are presented in Table 2 for granite coarse aggregate, and in Table 3 for basalt coarse aggregate. The same kind of cement was used in all mixes. Mixes with silica fume

Table 1
Mixes of original concrete with granite coarse aggregate and basalt coarse aggregate

Mix sign	Mix components (kg/m^3)									Properties		
	Portland cement			Water	Granite			Plasticizer	Silica fume (dry)	$f_{cm(28)}$ (MPa)	$E_{cm(28)}$ (GPa)	ρ_{cm} (kg/dm^3)
	PC30	PC45	PC50		0–2	2–8	8–16					
(a) *Granite coarse aggregate*												
A	–	386	–	164	659	565	659	–	–	41.6	23.9	2.39
B	550	–	–	190	587	503	587	–	–	50.6	27.2	2.38
C	–	550	–	200	561	231	858	5.5[a]	27.5	63.2	28.7	2.38
D	290	–	–	145	706	605	706	2.9[a]	–	35.6	24.4	2.40
E	–	–	571	145	530	497	630	36.0[b]	28.6	66.0	28.7	2.42

Mix sign	Cement PC45	Water	Sand (quartz) 0–2	Basalt 2–8	Basalt 8–16	Superplasticizer	Silica fume (dry)	$f_{cm(28)}$ (MPa)	$E_{cm(28)}$ (GPa)	ρ_{cm} (kg/dm^3)
(b) *Basalt coarse aggregate*										
F	571	145	498	590	723	36.0	28.6	72.3	40.6	2.54

[a] Ordinary plasticizer, 30% water-solution.
[b] Superplasticizer, 24% water-solution.

Table 2
Mixes with granite aggregate-groups R5–R9; mass content in [kg/m^3]

Mix no.	PC35 (30)[a]	Water[b]		Sand-new		Granite aggregate-new				Granite aggregate recycled				SP	SF
		Basic	Added	0–1	1–2	2–5	5–8	8–11	11–16	0–2	2–4	4–8	8–16		
R5.1	500.0	180.0	–	314.2	209.5	261.8	349.1	305.5	305.5	–	–	–	–	–	–
R5.2	500.0	180.0	27.0	292.0	194.6	–	–	–	–	–	162.2	324.4	648.8	–	–
R5.3	500.0	180.0	61.0	–	–	–	–	–	–	472.3	157.4	314.9	629.7	–	–
R5.4	454.5	126.0	–	330.7	220.5	275.6	367,5	321,5	321.5	–	–	–	–	15.0	45.5
R5.5	454.5	126.0	29.0	307.5	205.0	–	–	–	–	–	170.7	341.4	682.9	15.0	45.5
R5.6	454.5	126.0	74.2	–	–	–	–	–	–	497.1	165.7	331.4	662.8	15.0	45.5
R6.1	500.0	180.0	–	314.2	209.5	261.8	349.1	305.5	305.5	–	–	–	–	–	–
R6.2	500.0	180.0	–	291.3	194.2	–	–	–	–	–	161.7	323.4	646.9	–	–
R6.3	500.0	180.0	34.3	–	–	–	–	–	–	470.3	156.8	313.5	627.1	–	–
R6.4	454.5	126.0	–	330.7	220.5	275.6	367.5	321.5	321.5	–	–	–	–	15.0	45.5
R6.5	454.5	126.0	7.1	306.6	204.4	–	–	–	–	–	170.2	340.4	680.8	15.0	45.5
R6.6	454.5	126.0	50.0	–	–	–	–	–	–	495.0	165.0	330.0	660.0	15.0	45.5
R7.1	500.0	180.0	–	314.2	209.5	261.8	349.1	305.5	305.5	–	–	–	–	–	–
R7.2	500.0	180.0	–	291.3	194.2	–	–	–	–	–	161.7	323.4	646.9	–	–
R7.3	500.0	180.0	42.9	–	–	–	–	–	–	470.3	156.8	313.5	627.1	–	–
R7.4	454.5	126.0	–	330.7	220.5	275.6	367.5	321.5	321.5	–	–	–	–	15.0	45.5
R7.5	454.5	126.0	10.0	306.6	204.4	–	–	–	–	–	170.2	340.4	680.8	15.0	45.5
R7.6	454.5	126.0	35.7	–	–	–	–	–	–	495.0	165.0	330.0	660.0	15.0	45.5
R8.1	500.0	180.0	–	314.2	209.5	261.8	349.1	305.5	305.5	–	–	–	–	–	–
R8.2	500.0	180.0	7.7	293.1	195.4	–	–	–	–	–	162.7	325.4	650.8	–	–
R8.3	500.0	180.0	66.2	–	–	–	–	–	–	474.3	158.1	316.2	632.4	–	–
R8.4	454.5	126.0	–	330.7	220.5	275.6	367.5	321.5	321.5	–	–	–	–	15.0	45.5
R8.5	454.5	126.0	5.4	308.5	205.6	–	–	–	–	–	171.2	342.5	685.0	15.0	45.5
R9.1	500.0	180.0	–	314.2	209.5	261.8	349.1	305.5	305.5	–	–	–	–	–	–
R9.2	500.0	180.0	–	294.6	196.4	–	–	–	–	–	163.7	327.3	654.7	–	–
R9.3	500.0	180.0	26.7	–	–	–	–	–	–	478.2	159.4	318.8	637.6	–	–
R9.4	454.5	126.0	–	330.7	220.5	275.6	367.5	321.5	321.5	–	–	–	–	15.0	45.5
R9.5	454.5	126.0	–	310.1	206.7	–	–	–	–	–	172.3	344.5	689.0	15.0	45.5
R9.6	454.5	126.0	7.3	–	–	–	–	–	–	503.3	167.8	335.6	671.1	15.0	45.5

[a] In the group of series R5 cement PC30 was used.
[b] 'Basic' water used in concrete mix became completed for recycled concrete with 'added' water to drip recycled aggregate.

Table 3
Mixes with basalt aggregate-group R11; mass content in [kg/m^3]

Mix no.	PC35	Water		Sand		Basalt-new		Basalt-recycled				SP	SF
		Basic	Added	0–1	1–2	2–8	8–16	0–2	2–4	4–8	8–16		
R11.1	500.0	180.0	–	285.3	285.3	570.1	760.1	–	–	–	–	–	–
R11.2	500.0	180.0	–	254.6	254.6	–	–	–	169.6	339.2	678.5	–	–
R11.3	500.0	180.0	13.3	–	–	–	–	502.9	167.6	335.3	670.6	–	–
R11.4	454.5	113.0	–	305.9	305.9	611.3	815.0	–	–	–	–	15.0	45.5
R11.5	454.5	113.0	6.7	272.9	272.9	–	–	–	181.9	363.8	727.7	15.0	45.5
R11.6	454.5	113.0	20.0	–	–	–	–	539.3	179.8	359.5	719.1	15.0	45.5

(SF) and superplasticizer (SP) were designed on the basis of mixes without admixtures, by replacing 10% of cement by silica fume, with correction of water content. This additional volume of water was determined on experimental way, to obtain the similar consistence of mixes.

5. Test results

5.1. General

The number of specimens in each test was six and the mean values were taken into consideration; smaller series of three specimens were used in tests for moduli and σ_c–ε_c relations. The large number of results may be presented for selected range in synthetic form only. The compressive and tensile (splitting) strength were tested after 1, 3, 7, 14, 28, 56 and 90 days, using cylindrical specimens ∅150 × 300 mm. Moduli of elasticity (secant) and Poisson's ratios as well as relations σ_c–ε_c were tested on cylindrical specimens after 28 days. Additionally, compressive strength and bond strength by pull-out method were tested on cube specimens $150 \times 150 \times 150$ mm^3 after 28 days. Such cubic specimens were also used in freezing and thawing tests (50 or 150 cycles). Tests of shrinkage and creep were done on prismatic specimens $100 \times 100 \times 500$ mm^3 during the period of full three years at least.

5.2. Compressive strength

Most characteristic results for compressive strength are presented in Table 4. The development of strength up to 90 days shows the differences between concrete with new, partially recycled and fully recycled aggregates. For selected groups of series the results are shown in form of comparable diagrams in Fig. 1. Two groups of series have been selected: group R7 with granite aggregate (mix C of recycled aggregate), and group R11

Table 4
Mean values of cylinder compression strength $f_{cm(t)}$, modulus of elasticity E_{cm}, and Poisson's ratio ν_{cm} for ordinary (new) and recycled aggregate concrete

Mix series	Mean value (MPa) of compression strength $f_{cm,cyl}$ after days							Mean value of the secant modulus $E_{cm(28)}$ (GPa)	Mean value of Poisson's ratio $\nu_{cm(28)}$
	1	3	7	14	28	56	90		
R5.1	17.2	31.2	40.6	44.8	48.4	49.7	50.8	30.0	0.17
R5.2	18.2	29.7	37.1	41.3	44.5	47.1	49.3	27.4	0.19
R5.3	14.8	26.6	33.1	36.1	38.7	41.6	44.7	22.3	0.20
R5.4	31.8	44.7	52.3	60.9	68.3	71.2	73.6	32.3	0.17
R5.5	28.7	46.6	53.7	59.7	63.1	65.6	66.2	30.7	0.19
R5.6	27.7	43.5	48.9	52.8	56.4	60.9	62.8	25.7	0.18
R6.1	27.3	36.5	41.2	45.0	48.9	51.9	53.2	30.9	0.18
R6.2	23.9	35.4	39.3	42.3	46.1	49.6	53.1	28.1	0.20
R6.3	19.4	30.9	35.8	39.5	42.4	44.2	45.1	23.2	0.22
R6.4	44.2	65.6	72.8	80.7	85.3	87.7	89.9	35.8	0.18
R6.5	43.7	62.4	69.7	75.1	79.2	82.0	84.3	34.8	0.19
R6.6	40.0	49.9	57.3	62.9	67.7	71.3	73.9	29.1	0.22
R7.1	27.3	36.5	41.2	45.0	48.9	51.9	53.2	30.9	0.18
R7.2	24.6	38.2	44.3	48.5	52.5	55.4	56.1	30.1	0.20
R7.3	22.6	32.2	39.5	44.3	50.7	55.1	55.6	24.9	0.21
R7.4	44.2	65.6	72.8	80.7	85.3	87.7	89.9	35.8	0.18
R7.5	43.0	62.4	73.1	81.9	89.2	95.3	96.7	34.3	0.19
R7.6	41.0	57.8	66.7	74.7	81.1	85.2	86.0	29.2	0.21
R8.1	27.3	36.5	41.2	45.0	48.9	51.9	53.2	30.9	0.18
R8.2	14.2	30.4	36.8	41.3	45.2	48.8	52.1	27.5	0.19
R8.3	11.9	26.8	33.9	38.6	42.0	43.9	46.3	21.3	0.19
R8.4	44.2	65.6	72.8	80.7	85.3	87.7	89.9	35.8	0.18
R8.5	36.7	51.5	60.0	67.1	72.9	76.2	78.5	34.4	0.19
R9.1	27.3	36.5	41.2	45.0	48.9	51.9	53.2	30.9	0.18
R9.2	24.3	35.9	41.8	46.0	49.6	53.8	55.4	28.5	0.20
R9.3	22.7	32.1	38.8	42.0	45.1	48.0	49.9	23.3	0.21
R9.4	44.2	65.6	72.8	80.7	85.3	87.7	89.9	35.8	0.18
R9.5	42.3	60.2	68.4	73.9	80.4	85.3	88.2	32.4	0.20
R9.6	35.3	53.3	63.5	70.1	77.0	84.4	87.5	29.2	0.21
R11.1	14.1	30.3	42.7	49.7	52.3	55.8	57.4	39.8	0.21
R11.2	13.0	31.7	42.3	48.2	54.4	58.7	62.2	36.5	0.21
R11.3	13.6	30.1	39.0	44.8	48.2	51.5	55.1	29.8	0.22
R11.4	34.6	52.8	65.2	76.7	85.1	91.2	97.5	47.2	0.20
R11.5	29.9	49.4	59.1	71.6	79.8	87.1	94.1	39.4	0.21
R11.6	28.6	43.3	56.1	65.4	72.1	76.2	80.1	33.2	0.21

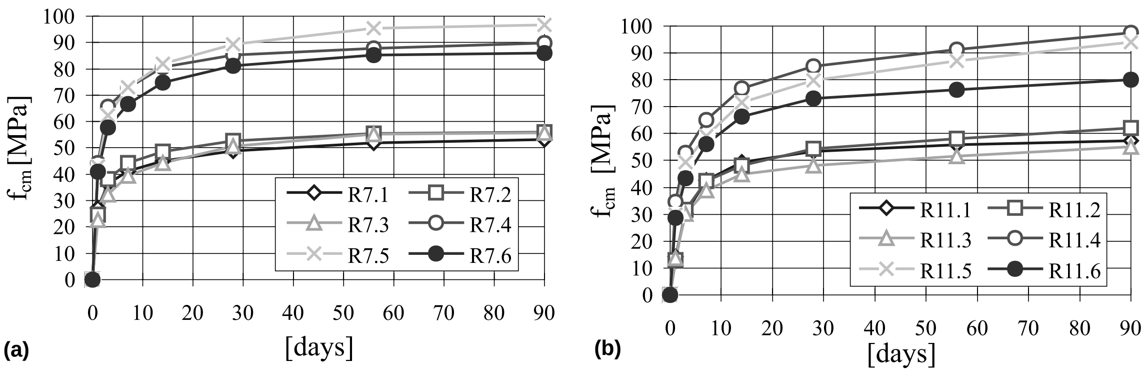

Fig. 1. Diagrams of compressive mean strength development in 90 days: group R7 of series with granite aggregate; group R11 of series with granite aggregate.

with basalt aggregate (mix F of recycled aggregate). In both groups there are visible two bundles of diagrams the lower one for concrete without admixtures and the higher one for those with silica fume and superplasticizer. Taking into account all results it may be stated that differences between the bundles are particularly significant in the groups R7, R9 and R11, where recycled aggregates were from HSC (over 60 MPa). In some cases the results for series with recycled aggregates and addition of new sand are very similar or even higher (like in group R7) than for comparable concrete with quite new aggregates.

Table 4 contains also mean values of most important parameters for deformation predictions: secant modulus of elasticity, E_{cm}, and Poisson's ratio, v_{cm}.

5.3. Tensile strength

The detailed results are presented in Table 5, and selected results for splitting tensile strength are shown in Fig. 2 for the same groups of mixes as in Fig. 1. The differences between the bundles for series with and without admixtures are not so clear like at compression, but the advantage from use of admixtures is visible. Here, the mixes with new aggregates are always stronger, but still influence of admixtures is much more important than contribution of recycled aggregate.

5.4. Relation σ_{cm}–ε_{cm}

The relation σ_{cm}–ε_{cm} tested after 28 days is compared for groups R7 (granite) and R11 (basalt) in Fig. 3. Each diagram is based on the mean values from three specimens tested. Three characteristic values may be compared in these diagrams:

1. Compression cylindrical strength, $f_{cm(28)}$ as a maximum stress recorded in tests.
2. Recorded strains, ε_c, accompanying maximal stresses.
3. Inclination of curves corresponding with modulus of elasticity E_{cm}.

The differences in values of $f_{cm(28)}$ between HSC with new aggregate in comparison with HSC with recycled coarse aggregate are in the range from −4.6% to +26%. Such a comparison of differences between HSC with new aggregate and HSC with entirely recycled aggregate indicates differences in the range from +5% to +34%.

Much more linear behaviour of concrete with admixtures is visible in Fig. 3 and this observation is irrespective of the kind of aggregate used. The significant differences in strains at failure of specimens are connected with the kind of aggregate; as a rule, concrete with recycled basalt aggregate has much more brittle character than concrete with recycled granite aggregate.

5.5. Bond tests

As some former publications (see [2]) indicated serious doubts in proper bond when recycled aggregate was used, special emphasis was laid on bond tests. The pull-out method recommended by RILEM in 1970 [8] was used, and specimens 28 days old were tested. In each series of six cubic specimens with embedded steel bars there were prepared three with round bars ∅14 mm, and three with ribbed bars of the same nominal diameter. Table 6 presents bond stresses recorded in tests of three groups of the specimen series with granite aggregate (R5, R8 and R9) and for the group of series with basalt aggregate (R11). The curves in Fig. 4 present characteristic cases of relation between bond stress at failure by slipping, τ_b, and slip of bars, Δ. Apart from the obvious advantages from ribbed bars (bundles of the upper three curves in each diagram), the significant influence of admixtures is visible, particularly in the shape of curves at early slips. There are no significant differences whether recycled or new aggregates have been used.

More detailed comparison of bond behaviour is presented in Fig. 5. It is shown that the greatest differ-

Table 5
Mean values of tensile (splitting) strength $f_{ctm(t)}$, cube compression strength $f_{cm(28),cube}$, absorption, consistence and volumetric density ρ_{cm} for recycled concrete

Mix series	Mean value (MPa) of tensile (splitting) strength f_{ctm} after days:							$f_{cm(28),\ cube}$ (MPa)	Absorption (%)	Consistence		Volumetric density ρ_{cm} (kg/m^3)
	1	3	7	14	28	56	90			VEBE (s)	Class	
R5.1	2.2	3.1	3.5	3.8	4.1	4.2	4.4	64.0	1.7	14	V-2	2400
R5.2	1.9	2.9	3.3	3.7	4.0	4.3	4.5	55.8	3.1	12	V-2	2320
R5.3	1.5	2.4	2.9	3.2	3.5	3.8	3.9	49.9	4.4	12	V-2	2230
R5.4	2.9	3.6	4.2	4.6	5.0	5.3	5.4	88.3	0.5	17	V-2	2420
R5.5	2.7	3.3	3.7	4.1	4.5	4.9	5.1	74.4	2.1	14	V-2	2370
R5.6	2.4	2.9	3.4	3.9	4.3	4.5	4.7	68.9	2.7	15	V-2	2270
R6.1	2.4	2.9	3.2	3.4	3.6	3.8	3.9	64.0	1.5	16	V-2	2390
R6.2	2.3	2.7	3.0	3.2	3.4	3.6	3.8	55.8	3.1	16	V-2	2350
R6.3	2.1	2.4	2.7	3.0	3.2	3.5	3.7	51.7	5.0	17	V-2	2260
R6.4	3.6	4.4	5.1	5.5	5.8	6.1	6.2	102.3	0.6	16	V-2	2460
R6.5	3.3	4.2	4.7	5.1	5.3	5.5	5.6	85.6	1.6	16	V-2	2360
R6.6	2.9	3.8	4.2	4.5	4.8	5.0	5.1	81.2	2.2	18	V-2	2290
R7.1	2.4	2.9	3.2	3.4	3.6	3.8	3.9	64.0	1.5	16	V-2	2390
R7.2	2.3	3.0	3.4	3.7	4.0	4.2	4.3	60.8	3.2	16	V-2	2330
R7.3	2.1	3.0	3.3	3.5	3.6	3.7	3.8	58.5	3.6	14	V-2	2260
R7.4	3.6	4.4	5.1	5.5	5.8	6.1	6.2	102.3	0.6	16	V-2	2460
R7.5	3.5	3.9	4.3	4.8	5.2	5.5	5.7	96.1	1.3	13	V-2	2360
R7.6	2.9	3.5	4.0	4.4	4.8	5.1	5.3	93.4	1.5	15	V-2	2290
R8.1	2.4	2.9	3.2	3.4	3.6	3.8	3.9	64.0	1.5	16	V-2	2390
R8.2	1.8	2.7	3.0	3.3	3.5	3.7	3.8	60.9	4.2	14	V-2	2370
R8.3	1.8	2.4	2.8	3.1	3.2	3.3	3.5	51.2	4.5	16	V-2	2240
R8.4	3.6	4.4	5.1	5.5	5.8	6.1	6.2	102.3	0.6	16	V-2	2460
R8.5	3.2	3.8	4.2	4.4	4.6	4.8	5.0	87.0	1.2	13	V-2	2360
R9.1	2.4	2.9	3.2	3.4	3.6	3.8	3.9	64.0	1.5	16	V-2	2390
R9.2	2.0	2.9	3.3	3.6	3.8	4.1	4.3	58.4	1.7	16	V-2	2280
R9.3	1.7	2.6	3.0	3.2	3.5	3.8	4.1	53.1	2.4	16	V-2	2210
R9.4	3.6	4.4	5.1	5.5	5.8	6.1	6.2	102.3	0.6	16	V-2	2460
R9.5	2.7	3.6	4.1	4.5	4.8	5.1	5.3	90.8	1.0	12	V-2	2350
R9.6	2.4	3.3	3.8	4.3	4.6	4.9	5.1	89.2	1.6	18	V-2	2290
R11.1	1.5	2.4	3.1	3.8	4.2	4.6	4.9	60.2	3.6	12	V-2	2530
R11.2	1.4	2.3	2.9	3.6	4.0	4.4	4.8	63.3	4.7	12	V-2	2380
R11.3	1.3	2.1	2.8	3.4	3.8	4.1	4.4	58.6	7.4	13	V-2	2280
R11.4	2.6	3.8	4.6	5.3	5.8	6.3	6.8	95.9	1.3	17	V-2	2540
R11.5	2.2	2.7	3.8	4.6	5.1	5.6	6.0	87.9	2.5	11	V-2	2400
R11.6	1.7	2.5	3.3	4.0	4.6	4.9	5.3	83.3	4.4	15	V-2	2320

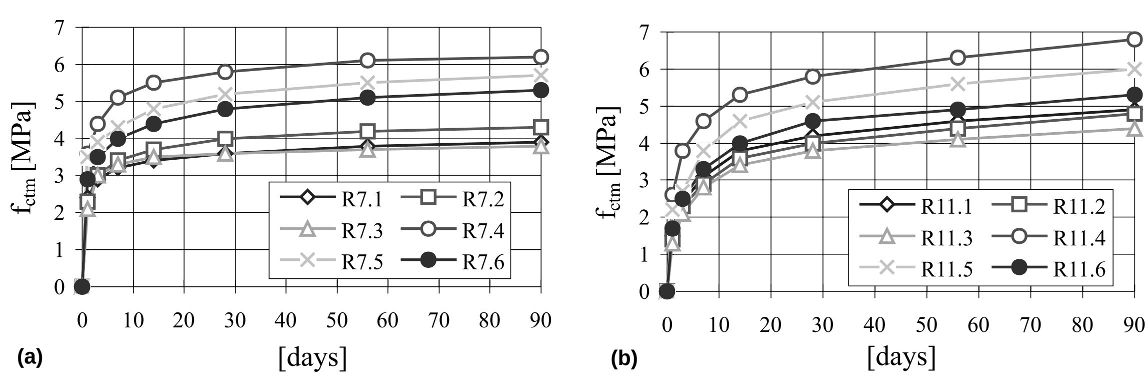

Fig. 2. Diagrams of tensile mean strength development in 90 days: group R7 of series with granite aggregate; group R11 of series with basalt aggregate.

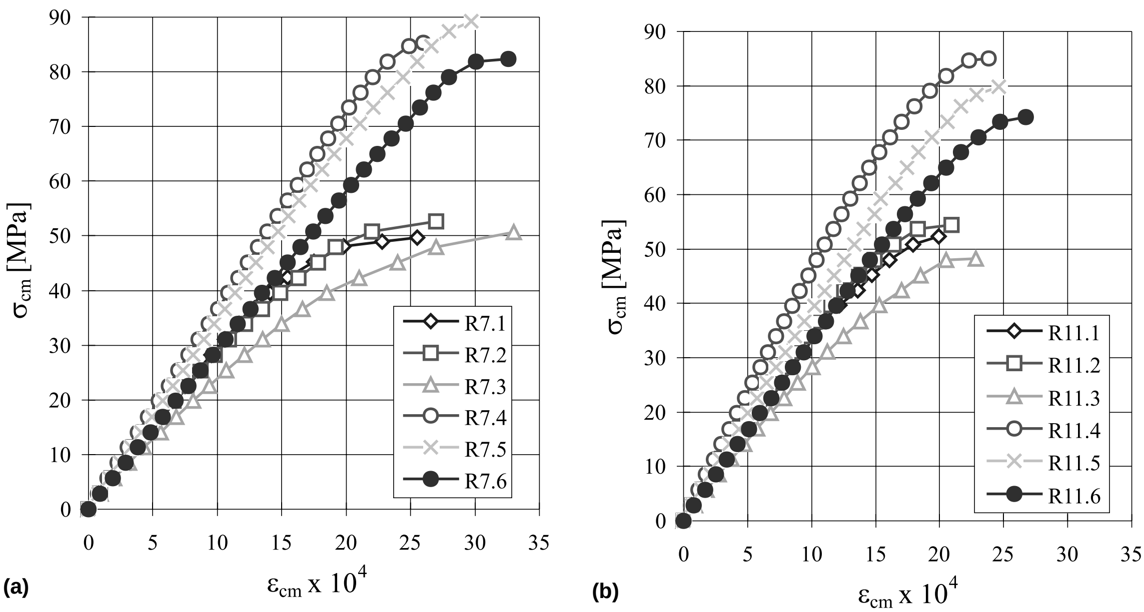

Fig. 3. Diagrams of mean relation σ_{cm}–ε_{cm} in series: group R7 with granite aggregate; group R11 with basalt aggregate.

Table 6
Bond strengths in concrete with recycled aggregate[a]

Mix series	f_{cm} (MPa)	f_{ctm} (MPa)	Round bars (220 MPa)		Ribbed bars (410 MPa)		$\tau^r_{0.01}/\tau_{0.01}$	τ^r_b/τ_b
			$\tau_{0.01}$ (MPa)	τ_b (MPa)	$\tau^r_{0.01}$ (MPa)	τ^r_b (MPa)		
R5.1	48.4	4.1	6.2	11.3	11.5	29.1	1.85	2.58
R5.2	44.5	4.0	3.3	8.0	9.1	27.3	2.73	3.41
R5.3	38.7	3.5	3.6	6.5	8.6	24.1	2.39	3.71
R5.4	85.3	5.8	11.7	17.7	22.3	35.2	1.91	1.99
R5.5	63.1	4.5	12.8	16.2	23.3	34.1	1.82	2.10
R5.6	56.4	4.3	9.8	13.2	19.3	30.3	1.97	2.09
R8.1	48.9	3.6	6.2	11.3	11.5	29.1	1.85	2.58
R8.2	45.2	3.5	3.8	8.2	11.9	26.8	3.13	3.27
R8.3	42.0	3.2	3.4	7.8	9.1	23.7	2.68	3.04
R8.4	85.3	5.8	11.7	17.7	22.3	35.2	1.91	1.99
R8.5	72.9	4.6	11.9	16.8	22.2	32.6	1.87	1.94
R9.1	48.9	3.6	6.2	11.3	11.5	29.1	1.85	2.58
R9.2	49.6	3.8	3.5	8.3	10.8	26.4	3.09	3.18
R9.3	45.1	3.5	3.3	7.1	8.3	23.7	2.52	3.34
R9.4	85.3	5.8	11.7	17.7	22.3	35.2	1.91	1.99
R9.5	80.4	4.8	11.7	18.7	19.9	42.0	1.70	2.25
R9.6	77.0	4.6	10.4	18.3	16.7	38.5	1.61	2.10
R11.1	52.3	4.2	5.0	9.3	9.5	26.0	1.90	2.80
R11.2	54.4	4.0	3.6	8.1	6.3	24.4	1.75	3.01
R11.3	48.2	3.8	3.0	6.5	5.8	22.9	1.93	3.52
R11.4	85.1	5.8	14.6	24.1	22.2	46.0	1.52	1.91
R11.5	79.8	5.1	12.9	23.0	23.6	45.4	1.83	1.97
R11.6	72.1	4.6	10.5	21.6	17.6	43.1	1.68	2.00

[a] $\tau_{0.01}$ – stress recorded at initial slip 0.01 mm, τ_b stress recorded at failure by slipping.

ences are between bond of round and ribbed bars (dark vs. white columns), the next level of differences is connected with admixtures added, and only in the third row the influence of recycled aggregates is visible.

5.6. Shrinkage

Selected representative results from long-term tests are presented in Fig. 6. Diagrams of development of

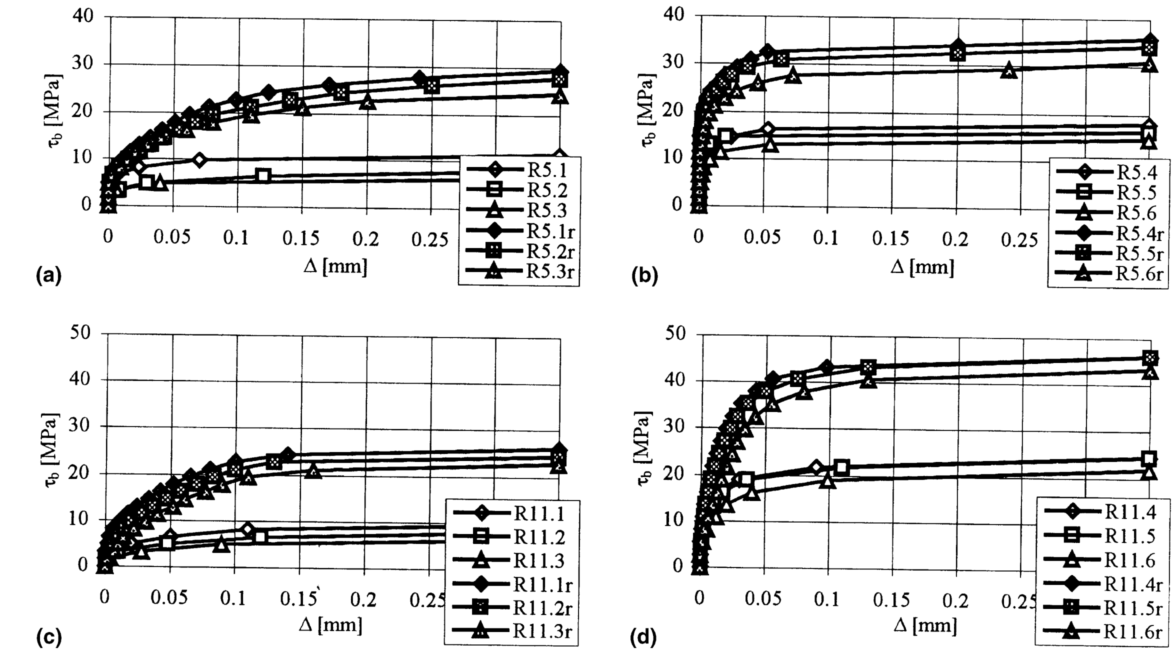

Fig. 4. Diagrams of mean relation of bond stress, τ_b vs. slip of bar, Δ; group R5 of series with granite aggregate: (a) without admixtures; (b) with admixtures, group R11 of series with basalt aggregate; (c) without admixtures; (d) with admixtures; (*r* ribbed bars).

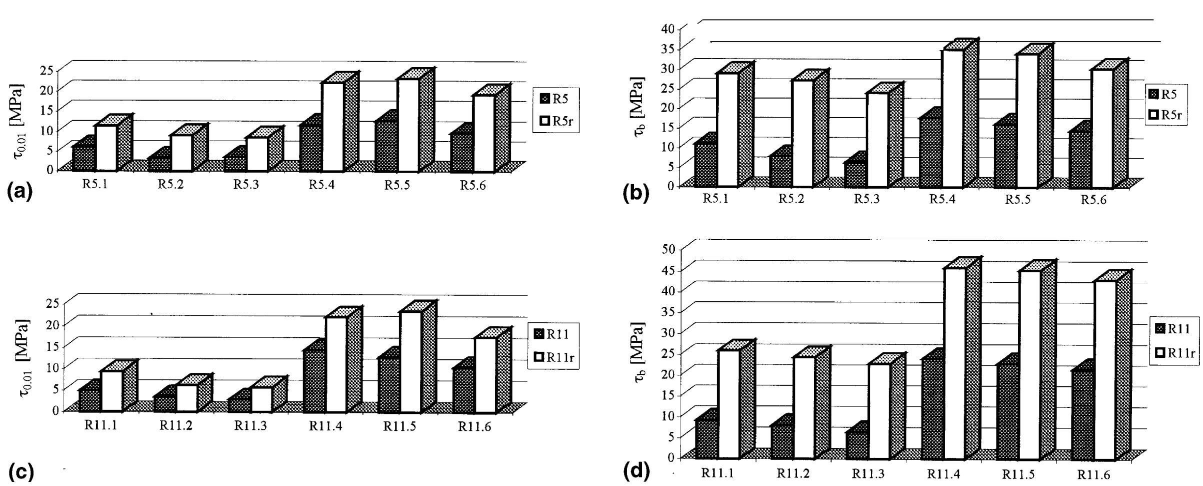

Fig. 5. Comparisons of bond stresses $\tau_{0.01}$ and τ_b for round and ribbed (*r*) bars: (a), (b) group R5 of series of concrete with granite aggregates; (c), (d) group R11 of series of concrete with basalt aggregates.

shrinkage deformation, ε_{cs}, in full one year period are showed for two groups of specimens, both with recycled aggregate obtained from HPC structures, over 60 MPa. The shape of curves and final one-year values are very similar in the group R7 with granite and in the group R11 with basalt. But the influence of recycled aggregate is significant. Shrinkage of concrete specimens with fully recycled aggregate is 35–45% higher than in concrete with new aggregate.

5.7. Creep

Some results from one-year tests are presented in Fig. 7. Test results for creep in normal laboratory conditions are not so clear like for shrinkage, but generally the tendency is reversed: for specimens with recycled or mixed aggregate the creep after one year is even up to 20% lower than for concrete with new aggregate. These differences are visible particularly for concrete without admixtures – see the upper three bundles in both parts of

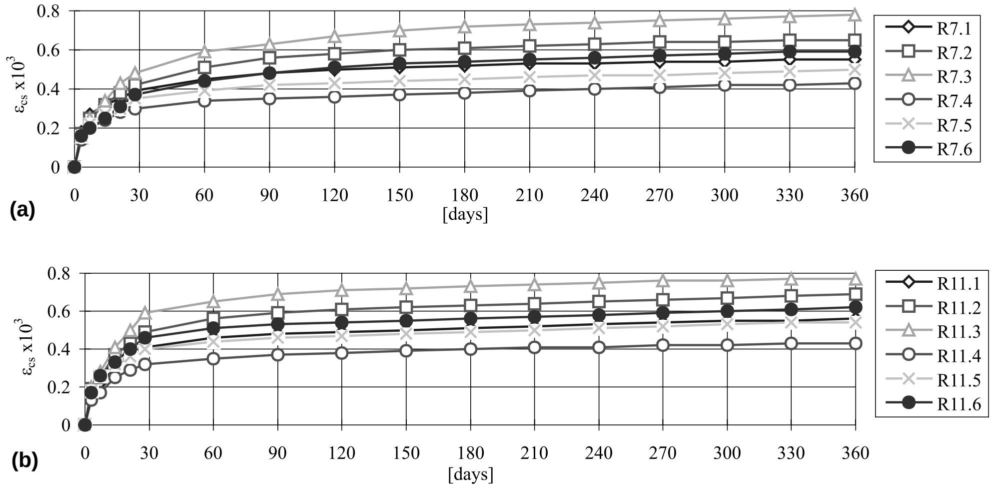

Fig. 6. Shrinkage, ε_{cs}, development in 360 days: group R7 of series concrete with granite aggregates; group R11 of series concrete with basalt aggregates.

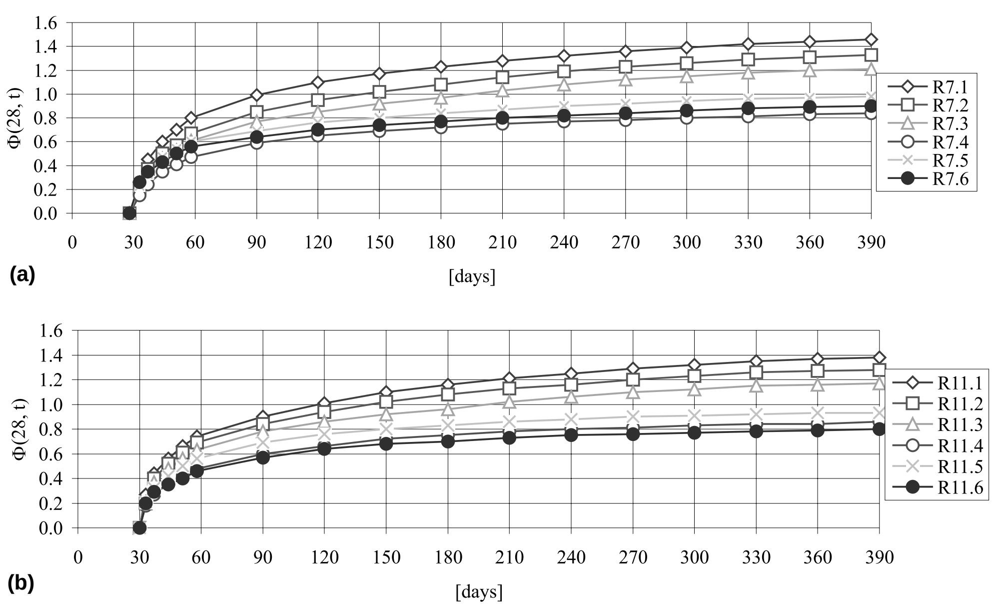

Fig. 7. Creep coefficient, $\Phi(28, t)$, development in 28 + 360 days: group R7 of series concrete with granite aggregates; group R11 of series concrete with basalt aggregates.

Fig. 7. It seems that in practice the joint influence of shrinkage and creep may be only slightly greater for recycled concrete in comparison with concrete from new aggregate.

5.8. Freezing and thawing

Typical freezing and thawing tests were performed with series of 3 + 3 cubic specimens of concrete 28 days old. Three specimens were subjected to basic 50 cycles of freezing and thawing while the remaining three were the linked sample for final comparison. Several enlarged series of HPC specimens were tested also up to 150 cycles. In all cases neither any damages to concrete were recorded nor weight drop was measured greater than 0.5%. Compressive strength of concrete after 50 cycles was measured very similar to the linked specimens; the range of changes was from −5.9% to +10.3%, with the mean value +4.4%.

6. Conclusions

Main mechanical properties of HSC made from recycled aggregate are presented in the paper and compared with series of corresponding concrete from new aggregates. The tests were done with use of different recycled aggregates obtained from original moderate- or high-strength concrete, 2–7 years old, crushed up to 3 months before use.

Following general conclusions have been derived from the analysis of test results:

- Properties of original concrete has significant influence on mechanical properties of recycled aggregate concrete; it is possible to obtain recycled concrete with higher compressive strength than the original one.
- Mix design of recycled concrete is very similar to the procedure for concrete with natural (new) aggregate; corrections in water content are necessary to obtain proper workability, but the changes in water/cement ratio may be relatively small.
- The replacement of fine fraction 0–2 mm in recycled aggregate by natural sand always changes for the better the properties of recycled concrete.
- Properties of recycled concrete may be significantly improved by admixtures of superplasticizers and silica fume, similarly to cases of concrete with natural aggregates.

More detailed conclusions concerning particular properties are the following:

(1) Compressive strength, f_{cm28}, was achieved over 80 MPa using recycled aggregate from original concrete about 60 MPa, using reasonable content of admixtures. The characteristics σ_c–ε_c at compression appeared very similar for concrete with natural and recycled aggregate, with slightly lower modulus of elasticity in recycled concrete.

(2) Tensile strengths for mixes with new aggregates are always higher, but the differences are not greater than 10% for 28 days old concrete; the influence of admixtures on tensile strength is much greater than influence of introduction of recycled aggregate.

(3) The values of bond stress at failure, τ_b, were measured lower for recycled aggregate concrete, particularly for plain round bars. For concrete with fully recycled aggregate the average drop was up to 20% while in case of replaced fine aggregate with natural sand it was up to 8% only.

(4) Regarding problem of freezing resistance it was stated that HPC made from recycled aggregate, when subjected to freeze-thaw action, had similar or better durability compared to the concrete made with natural aggregate. This conclusion is supported by standard tests with 50 cycles of freezing and thawing, with 24 h cycle (air-freezing and water-thawing).

(5) The long-term tests showed the higher shrinkage and slightly lower creep in recycled concrete in comparison with concrete with natural (new) aggregate of similar strength.

Finally may be concluded that recycled aggregates obtained from moderate- or high-strength concrete with original granite or basalt aggregates appeared fully useful component for HPC. For many reasons the replacement of fine fraction with natural sand is advisable. This research work was the basis for further tests of reinforced concrete members with use of recycled HPC.

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