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SELECTION TESTS FOR RECYCLED RADIOACTIVE SAND OBTAINING METHOD

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Abstract. Our research involves developing two-stages crushing process for radioactive concrete that will produce recycled fine aggregate which is reused as mortar for filling containers. The tests were carried out on non-radioactive material (reference original concrete) because the radioactive concrete was not available at that time.

Key words: crushed concrete, recycled concrete aggregates, reuse and recycling of radioactive waste, waste disposal volume reduction, waste usage ratio.

1. INTRODUCTION

The concrete radioactive waste that will be generated from dismantled structures of VVR-S nuclear research reactor from Magurele (*e.g.*: biological shield of the reactor core and hot cells) represents an estimated amount of about 70 tons. In addition to these radioactive wastes, it will be generated an amount of about 1000 tons of non-radioactive concrete (which will be treated as conventional waste) resulted from demolition of structures that have been decontaminated and free released. The disposal of these radioactive wastes will determine the decrease of final disposal capacity and increased costs, in fact a lower economic feasibility.

Until now the solid low activity radioactive waste (LLW) was pre-placed in containers and cementation with mortar made from cement and natural fine aggregates, providing a fill ratio of the container of approximately 50 vol. % for concrete. Ishikura *et al.* [1, 2] showed that radioactive concrete recycling can be a major solution for reducing the volume of waste and a contribution for saving natural resources and environmental protection. A review of the methods developed so far for recycling radioactive concrete has been done by Deju *et al.* [3].

Based on a two-stages crushing process for radioactive concrete we will develop such an innovative technology that uses fine recycled aggregates as filler, to try to meet the proposed specification. We expect the designed process to provide a substantial increase of filling ratio for radioactive waste containers. In this way, the final volume of disposed LLW is significantly reduced with beneficial economic effects.

Based on research results, the specification will be finalized and proposed to be adopted as a normative document by the nuclear regulatory body.

The tests were carried out on non-radioactive material (reference original concrete) because the radioactive concrete was not available in a good time.

2. PROPOSED TECHNICAL SPECIFICATION

For using the radioactive concrete as recycled fine aggregate (sand) in the mortar, for LLW cementation in containers, we proposed as targets to be achieved, that recycled sand and mortar, should comply with the folowing requirements established in Japan by Ishikura *et al.* [2]:

– **flow-rate:** 16 to 50 s for efflux time through a standardized flow cone (p-cone time), given by the American Standard of Testing Materials C 939;
– **maintaining fluidity of the mortar**: more than 60 minutes without separation (no bleeding);
– **compressive strength of the mortar**: 30 N/mm^2 (300 kgf/cm^2) minimum after 28 days;
– **mortar fill ratio in waste form**: 95 vol.% minimum;
– **fine aggregates diameter**: 2.5 mm maximum;
– **the proportion of recycled sand used in mortar**: minimum 900 kg/m^3.

3. CHARACTERIZATION OF RAW MATERIALS

3.1. NATURAL AGGREGATE CHARACTERIZATION

To characterize the natural aggregates (Lafarge) used to prepare the necessary concrete experimental activities, there were carried out a series of measurements on aggregate sorts: 0–4, 4–8, 8–16 (natural river aggregate) and sorts 4–8, 8–16 (crushed natural river aggregate) as follows:

a. Apparent density of the natural aggregates was measured by picnometer method, according to SR EN 1097-6: 2002 provisions (Table 1). After evaluating the results obtained it is found that the apparent density of the natural aggregates is practically constant for both aggregates (due to the fact of the same chemical and petrographic nature). The influence of aggregate size is not relevant.

Table 1

Apparent density of the natural aggregates

Aggregate	Apparent density of the aggregates (kg/dm^3)		
	Sort (mm)		
	0–4	4–8	8–16
River aggregate	2.617	2.630	2.632
Crushed river aggregate	–	2.630	2.620

b. Bulk density was determined for loose and compacted state (Table 2). The results show that the apparent density in pile depends on the compaction degree and size aggregates. For crushed aggregate the densities are lower due to the micro-cracks and roughness.

Table 2

Apparent density in pile on sizes, for natural aggregates

Aggregate	Bulk density (kg/m^3)					
	Sort (mm)					
	0–4		4–8		8–16	
	loose	compacted	loose	compacted	loose	compacted
River aggregate	1590	1682	1500	1574	1481	1671
Crushed river aggregate	–	–	1362	1455	1324	1553

c. The aggregate shape was evaluated according to EN 933-4:2002 and SR EN 933-3:2002 provisions (Table 3). The aggregate shapes are good and the obtained values fits in the limits imposed by the specific norms.

Tabel 3

Acceptance criteria for aggregate shape

Characteristics	Acceptance criteria	Results	
		River aggregate sort 12.5/16	Crushed river aggregate sort 12.5–16
b/a	$\geq$ 0.66	0.75	0.78
c/a	$\geq$ 0.33	0.53	0.51
$C_{v,\ mean}$	$\geq$ 0.20	0.36	0.32
SI	–	2.5% (SI_{15})	13% (SI_{15})
A	–	5.3% (FI_{15})	18.2% (SI_{20})

d. Sand equivalent was determined according to SR EN 933-8:2001 provisions. From river aggregate 0–4 sorts was extracted by sieving a 0–2 one. The results for the equivalent of sand are: SE_1 = 98.8%, SE_2 = 98.4%.The arithmetic mean value, SE = 98.6%, show a very clean sand due to almost total absence of fine clay components.

e. The aggregate size were measured for 5 sorts: 0–4, 4–8, 8–16 (river aggregate) and 4–8, 8–16 (crushed river aggregate) sorts. There were used 0.125, 0.250, 0.5, 1, 2, 4, 8 and 16 mm sieves. After sieving, the rest of the sieve was weighed on each sieve, according to SR EN 933-1:2002 (Part 1) provisions (Table 4).

Table 4

The aggregate size on sorts

Size mesh sieve (mm)	Aggregate size in wt.%				
	River aggregate (mm)			Crushed river aggregate (mm)	
	0–4	4–8	8–16	4–8	8–16
31.5	0	0	0	0	0
16	0	0	5	0	1
8	0	8	96	2	87
4	1	86	100	83	100
2	21	99	100	99	100
1	46	100	100	100	100
0.5	72	100	100	100	100
0.25	92	100	100	100	100
0.125	99	100	100	100	100
0 (pan)	100	100	100	100	100

f. Fine aggregate content in coarse aggregates was determined according to SR EN 933-1:2002 provisions (Table 5).

Table 5

Fine aggregate content in coarse aggregates

Aggregate	Fine content wt. %		
	Sort (mm)		
	0–4	*4–8*	*8–16*
River aggregate	0.9	0.13	0.177
Crushed river aggregate	–	0.25	0.138

Another type of assessment for aggregate fineness is represented by the fineness module. The analysis of fineness aggregate was obtained on particle size sorts, by adding R – cumulative percentages of aggregate mass – retained on the standard series sieves (0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 31.5 mm). Using data obtained from the formula size analysis and refinement modulus (RM) was obtained the results (Table 6) showing that the crushed river aggregate is more than fine river aggregate part for the same particle size sorts. The module values show that crushed river aggregate has much finer part than river, for the same aggregate sorts. U.S. standards prescribe using of a set of sieves: 0.150, 0.300, 0.600, 1.18, 2.36, 4.75, 9.5, 19, 38.1 mm. In this case, the refinement modulus values are between 2 and 4 for the fine aggregates (sand) and between 6.5 and 8 for the coarse aggregates [4].

Table 6

Fineness module for aggregate

Aggregate	Fineness module (MF)		
	Sort (mm)		
	0–4	4–8	8–16
River aggregate	3.31	5.93	7.01
Crushed river aggregate	–	5.84	6.88

g. Water absorption coefficient in coarse aggregates was determined according to SR EN 1097-6:2002 provisions for aggregates larger than 4 mm. Two samples were taken of each sort unit. The results (average of two determinations) are presented in Table 7. It is found that the values are in acceptable range for this type of unit.

Table 7

Water absorption coefficient in coarse aggregates

Aggregate	Water absorption coefficient (vol. %)		
	Sort (mm)		
	0–4	4–8	8–16
River aggregate	–	1.40	0.95
Crushed river aggregate	–	1.95	0.98

h. Los Angeles abrasion test. The river and crushed river aggregates, sort 8-16, were subjected to Los Angeles (LA) test (according to **SR EN 1097-2:2002** provisions) yielding acceptable coefficients: LA = 32% for river aggregate and LA = 30.7% for crushed river aggregate, corresponding values for concrete civil engineering (to < 35%).

3.2. CHARACTERIZATION OF NATURAL SAND 0/2, 5 mm

From the sort 0–4 of natural river aggregate, was separated by sieving a fraction of 0–2, 5 which was used for the preparation of N-type mortar in the mortar tests reference.

3.3. CHARACTERIZATION OF CEMENT TYPE

One of the determining characteristics of concrete is cement strength class. At the same strength class mortars and concrete durability depends on the chemical and mineralogical composition of cement, correlated with additional components.

To achieve the recycled aggregate concrete and mortar was used Lafarge cement CEM V A (S-V) 42.5 N, that ensures better resistance to chemical agents or freeze-thaw attack and which displays the following characteristics:

– grinding finesse – on 90 μm sieve: 0.4 wt. % according to SR EN 197-1:2011 provisions;

– the amount of water to paste consistency standard: 176 ml for A = 35.2%, according to SR EN 196-3+A1:2009 provisions;

– compressive strength (minimum 32.5 N/mm2), determined under standard conditions according to EN 196-1 provisions, on normal mortars after 28 days, represents the strength class of cement. The value obtained for compressive strength (42.8 Mpa) indicates that the cement meets class 42.5 MPa.

4. CHARACTERIZATION OF NATURAL AGGREGATE CONCRETE

4.1. ORIGINAL CONCRETE BATCHES

For experiments were obtained following batch of:

– original concrete C25/30 necessary to selection of four crushers with different working principles (stage 2) the first two of them suitable for recycling concrete;

– original concrete C16/20, C25/30 and C35/45 used to establish optimal crusher (stage 2) of the first two types of crushers chosen based on properties of recycled sand mortars obtained;

– five original concrete types with different compressive strength (C25/30A; C25/30B; C25/30C; C25/30D C25/30E, respectively) needed to assess the effect of the original properties of recycled aggregates concrete crushing (stage 2) on the hammers crusher.

4.2. ESTABLISHING OF CONCRETE COMPOSITION

The establishing of concrete composition aims to determine the quantities of components required for preparing of one m^3 of fresh concrete. The Concrete composition was determined so as to ensure getting workability, durability and resistance necessary by using of a minimum cement quantity. Proportion: water, cement, aggregates and additives were determined according to ref. [5].

4.3. CHARACTERIZATION OF FRESH CONCRETE

Mixed concrete proportions were calculated to fulfill the following conditions:

a) slump test S2 (50 ÷ 90 mm);
b) preliminary compressive strength according with concrete type;
c) aggregate river 0/16 mm on 3 particle size sorts: 0/4, 4/8 and 8/16 mm;
d) super-plasticizer additive / high range water reducer.

For concrete batches was used Lafarge cement CEM VA (W) 42.5 N and Glenium 27 as super-plasticizer additive (Table 8). Concrete composition was recalculated (especially for water and cement) in order to obtain optimum conditions (workability, compressive strength) – water correction 5% for B8 ÷B10.

In Table 9 are shown the experimental values for:

– slump test (Abrams cone determined);
– real amount of water added;
– density of fresh concrete;
– amount of air in fresh concrete.

Also in the last column are presented the experimental observations that helped establishing the final composition.

To emphasize the influence of compositional factors on the characteristics of recycled aggregates, there were produced five compositions derived from C25/30, by modifying: the nature of the aggregate, the ratio W/C, Ag/C, cement content, additive dosage. The five compositions labeled A to E are shown in Table 10, along with base composition C25/30.

Table 8

Reference concrete composition (for 1 m^3 of concrete)

Sample	Concrete class	Ag[1)] on sorts for 1 m^3 concrete (kg)	S[2)] from total aggregate (%)	C[3)] (kg)	Ag[1)]/C[3)]	W[4)]	W[4)]/C[3)]	Ad[5)] (l)
B8	C25/30	0/4–815.9 4/8–453.3 8/16–543.9	45	345.5	5.25	190	0.55	3.3
B9	C35/45	0/4–762.0 4/8–423.4 8/16–508.0	45	475	3.56	190	0.40	4.5
B10	C16/20	0/4–864.5 4/8–480.3 8/16–576.4	45	270.4	7.10	175.8	0.65	2.57

[1)]Ag – aggregate; [2)]S – sand; [3)]C – cement; [4)]W – water; [5)]Ad – Glenium 27 as super-plasticizer additive/highly efficient water reduce.

Fine and coarse river aggregates on three sorts: 0–4; 4–8; 8–16. Maximum aggregate size: $d_{max.}$= 16mm; Passing: T_4 = 45%; T_8 = 70%; T_{16} = 100%; Size composition: 0–4 = 45%; 4–8 = 25%; 8–16 = 30%.

4.4. CHARACTERIZATION OF HARDENED CONCRETE

All hardened concrete samples; both cubes and cylinders were form-released mold after one day and kept in water at 20°C ± 2°C to test the strength compression. Preparation and storage of samples for strength testing was done from 7 to 28 days, in order to verify the concrete class. Compression strenght test was performed, according to EN 12390-3:2010 provisions using a 3000 kN hydraulic press that meets EN 12390-4:2010 provisions. Previously, samples (cubes and cylinders) were weighed and measured to calculate geometric bulk density (Table 11).

The compressive strength values for the concrete samples are presented in Table 12. The resistance class proposed in the research was verified by comparing the compressive strength with the compressive strength value specific for the concrete class, specified in the Table 12.

Table 9

The experimental values for fresh concrete

Sample	Concrete type	25 dm^3 concrete composition				Slump test (mm)	Fresh concrete density (kg/m^3)	Remarks
		Aggregate on sorts (kg)	Cement (kg)	Water (liters)	Additive Glenium 27 (ml)			
B8	C25/30	0/4–49.0 4/8–27.2 8/16–32.6	20.7	11.4^1	198	20	2340	- workable - 4% entrapped air
B9	C35/45	0/4–22.85 4/8–12.7 8/16–15.25	14.25	5.7^2	135	9	2340	- workable - 1.5% entrapped air
B10	C16/20	0/4–26.0 4/8–14.4 8/16–17.3	8.1	5.2^3	77	5	2320	- workable - 2.9% entrapped air

The actual amount of water added (liters): $^{1)}$ 9.0; $^{2)}$ 5.0; $^{3)}$ 5.0

Table 10

The concrete composition derived from C25/30 (for 1 m^3 concrete)

Sample	Concrete type	Aggregate on sorts to 1 m^3 concrete (kg)	% Sand (from total aggregate)	Cement (kg)	Ag/C	W(l)	Add. Glenium 27 (l)
1	2	3	4	5	6	7	8
Basic composition	C25/30	0/4– 815.9 4/8– 453.3 8/16–543.9	45	345.5	5.25	190	3.3
A	C25/30	0/4 842.0 4/8– 467.9 8/16–561.4	45	270.4	6.92	175.8	2.57

Table 10 (*continued*)

1	2	3	4	5	6	7	8
Sample	Concrete type	Aggregate on sorts to 1 m^3 concrete (kg)	% Sand (from total aggregate)	Cement (kg)	Ag/C	W(l)	Add. Glenium 27 (l)
B	C25/30	0/4– 855.5 4/8– 392.1 8/16–534.7	48	327.6	5.44	190	3.1
C	C25/30	0/4–759.0 4/8–421.7 (c) 8/16–506.0(c)	45	375.0	4.5	210	3.57
D	C25/30	0/4–740.9 4/8–411.6(c) 8/16–493.9(c)	45	420.0	3.92	210	4.0
E	C25/30	0/4– 814.5 4/8–452.5 8/16–543.0	45	320.0	5.65	182.4	3.0

Fine and coarse river and crushed aggregate (c), on three sorts: 0–4; 4–8; 8–16.
Maximum aggregate size: $d_{max.}$= 16 mm Passing: T_4 = 45%; T_8 = 70%; T_{16} = 100%.
Size composition: 0–4 = 45%; 4–8 = 25%; 8–16 = 30%.

The final reference recipes for C16/20, C25/30, and C35/45 together with five compositions derived from C25/30 (denoted C25/30A, C25/30B, C25/30C, C25/30D, C25/30E) were cast in sufficient quantities in order to obtain necessary recycled aggregate concrete (Table 13). Using a 3000 kN hydraulic presses equipped with sensors for displacement and load, it was determined the elasticity modulus E for the three classes of concrete (C16/20, C25/30, and C35/45) with the real compressive strength shown in Table 14. The method proved to be sensitive regarding static modulus variation with compressive strength (Table 14).

Table 11

Mass samples after 28 days of storage in water and bulk density values

Sample	Concrete class	Cubes mass (d = 15cm) at 28 days (kg)			Cylinder mass (d = 15cm h = 30cm) at 28 days (kg)	Hardened concrete apparent density (kg/m^3)
		A	B	C		
B8	C25/30	8018	8020	8078	12483	2382
B9	C35/45	7999	7971	8002	12268	2368
B10	C16/20	7962	7964	7945	12237	2358

Table 12

Maximum load and compressive strength for original concretes

Sample	Concrete class	Compression after 7 days		Compression after 28 days				Preliminary strength at 28 days
		F[1] (kN)	f_c[2] (MPa)	F[1] (kN)			f_c[2] (MPa)	(MPa)
B8	C25/30	855/ 915/ 905	39.6	979/ 1024	1035/ 1100	1076	46.3	42
B9	C35/45	985/ 870/ 1035	42.8	1411	1420	1359	62.1	56.5
B10	C16/20	515/ 455/ 510	21.9	740	826	781	34.8	29

[1]F – force; [2]f_c – compressive strength

Table 13

Achieved concrete summary

Concrete class	Batches no.	Quantity (kg)	Fresh concrete properties			Hardened concrete properties	
			Average density (kg/m^3)	Slump (mm)	Occluded air (%)	Average density (kg/m^3)	f_c[1] (MPa)
C16/20	9	492	2331	50–100	2.5–3.6	2373	34.8
C25/30	24	1824	2352	40–100	1.7–3.2	2363	46.3
C35/45	9	526	2349	50–110	1.5–2.1	2358	62.1
C25/30A	9	536	2339	40–70	2.0–4.0	2371	36.4
C25/30B	9	536	2337	50–100	2.5–3.4	2352	44.6
C25/30C	9	536	2339	60–100	1.8–2.5	2369	55.5
C25/30D	9	536	2349	50–100	1.6–2.3	2378	65.5
C25/30E	9	524	2347	40–80	2.4–3.5	2380	50.8

[1]f_c – compressive strength

The modulus was determined also using a nondestructive path, by ultrasonic pulse method. The method confirmed the compliance between static and dynamic modulus: $E_d = 1.2\ E_s$.

Table 14

Static and dynamic elasticity modules

Sample	Apparent density kg/m^3	V_L[1)] (m/s)	f_c[2)] at 28 days (MPa)	E_d[3)] (N/mm^2)	E_s[4)] (N/mm^2)
B3	2368	4496	47.2	42162	38228
B5	2285	4223	26.5	31282	27840
B6	2307	4282	30.6	37200	30256
B7	2315	4435	36.9	42162	38228

[1)] V_L – ultrasonic pulse velocity; [2)] fc – compressive strength;
[3)] E_d – dynamic modulus of elasticity; [4)] E_s – static modulus of elasticity.

5. TESTS FOR SELECTION METHOD FOR PRODUCING RECYCLED SAND

5.1. SELECTION OF CRUSHERS (STAGE 2) FOR THE RECYCLING OF CONCRETE

5.1.1. OVERVIEW

The method for crushing concrete blocks and rubble recycle used to obtain recycled sand is a conventional one. It is successfully used for aggregate crushed rock or concrete blocks and can be applied also for the production of recycled sand that meets the characteristics required for the cementation of radioactive waste. To choose the most suitable crushing process and operating conditions to hereinafter crushing methods are being compared.

5.1.2. CRUSHER FOR FIRST STAGE CRUSHING

Waste concrete with maximum size of 350 mm were crushed in the first stage with a Liebhher type jaw crusher, adjusted to nominal size of 50 mm. Crushed concrete less than 50 mm was sieved in order to obtain useful sort for pre-placement, 10 to 50 mm.

5.1.3. CRUSHER FOR SECOND STAGE CRUSHING

The rest of the screening > 50 mm obtained from primary crushing of concrete was crushed in the second stage, with different working principles crushers at size < 2.5 mm, in order to produce recycled fine aggregate (sand) for the filler mortar and which fulfills the technical specifications proposed:

– jaw crusher, Retsch type, model BB 100;
– hammer crusher, Buffalo Shuttle model WA-12-H;

– ball mill, type IMEC Bucharest, with a capacity of 50 liters. Part of the material (300 kg /m^3) is substituted with powder particle size obtained by grinding sort 0/0.15 mm in a ball milling to a specific surface of > 6000 cm^2/g;
– cone crusher.

5.1.4. SELECTION OF HAMMER CRUSHER SIEVE

Compared with other types of used crusher, hammer crushers Buffalo Shuttle WA-12-H model has characteristics that can vary size distribution of the recycled sand obtained from crushing, by changing of some sieves pairs having size of holes: 3, 6, 9 and 12 mm. Attempts have been made for the crusher sieve selection which fulfills Ishikura *et al.* [1] conditions, regarding a good size distribution for cementation, equally distributed between sizes: 0–0.15, 0.15–0.30, 0.30–0.60 and 0.60–1.2 mm and an average particle size between 0.4 ÷ 0.6 mm. The values presented in Table 15 shows that the 9 mm sieve meets the requirements for performance of cementation.

5.1.5. CRUSHER ASSESSMENT AND SELECTION

Investigated crushers are: jaw crusher, ball mill, hammer crusher and cone crusher. Since it was not available a cone crusher, for comparison, was used data obtained from Ueki *et al.* [6]. Note that there are major differences in particle size distributions generated by operating conditions, except for the hammer crusher. Thus, recycled aggregates of appropriate size distribution are used instead of the natural river sand in order to produce mortar by mixing cement, water and super plasticizer.

Evaluation and selection is made by observing crushers mortar properties. They are tested using the same scale for comparing mixed mortars (W/C = 0.55 and S/C = 1.3). The fluidity, bleeding and compressive strength of these mortars are measured to judge the applicability of the material filling containers with waste (Table 19).

5.1.6. THE CHARACTERISTICS OF MORTAR FILLING

The results presented in Table 16 shown that:

– **ball milling**: recycled sand containing fine particles lead to more faster exceeded the limit of fluidity;
– **cone crusher**: recycled sand containing coarse particles displays good flow characteristics, but exceeded the bleeding limit which can lead to high porosity in the filling material;
– **jaw crusher**: recycled sand has a good behavior and having good bleeding characteristics and compressive strength;

– **hammer crusher**: recycled sand has bleeding characteristics and compressive strength better than the ones obtained with a jaw crusher.

Table 15

Size distribution obtained on C25/30 concrete, crushed to second stage with hammer crusher, Buffalo Shuttle model WA-12-H

Sort (mm)	wt [%]			
	Crusher sieve 3 mm	Crusher sieve 6 mm	Crusher sieve 9 mm	Crusher sieve 12 mm
5–12	–	–	–	1.16
5–9	–	–	–	–
2.5–5	–	0.75	4.62	8.00
1.25–2.5	1.98	4.80	11.99	14.41
0.6–12.5	13.13	14.54	19.07	19.57
0.3–0.6	23.87	23.65	20.69	20.67
0.15–0.30	24.14	27.58	18.16	19.93
0–0.15	36.88	28.68	25.46	16.27

The time flow of mortar through flow cone is, in order: cone crusher, hammer crusher, jaw crusher, ball mill. This confirms UEKI *et al.* [6] findings. The mortar which uses material powder shows the lowest fluidity, when the others crushers displaying fluidity comparable even after 60 minutes. Bleeding is a special case of segregation represented by separation of water on the mortar surface due to the incapacity to retain all the mixing water by the solid constituents. Cone crusher displays the highest value of bleeding. A high value of mortar bleeding leads to higher porosity in the hardened mortar.

The mortars obtained by crushing in jaw crusher show a good performance. Jaw crusher has the disadvantage of a high dimension. The best performance for the mortar is obtained with the hammer crusher. Hammer crusher has smaller size and a higher productivity. Jaw crushers and hammers were chosen to produce recycled aggregate.

5.2. DETERMINING OF THE OPTIMUM CRUSHER

Recycled fine aggregates (sand) are obtained using the first two types of crushers (jaw crusher and hammer crusher respectively). Optimum crusher is chosen depending on properties of mortar obtained with recycled sand, by crushing the three types of original concrete C16/20, C25/30 and C35/45, which displays different values for compressive strength.

Table 16

Crusher assessment and selection using C25/30 concrete

Crusher type	Mix Composition (kg)			SP[8] Additive (%)	VM[9] Additive (%)	p-cone (s) at min				Density (kg/m^3)
	W[5]	C[6]	S[7]			0	15	30	60	
CC[1]	0.55	1	1.3	1.0	0.5	36	40	51	75[10]	1923
CF[2]	0.55	1	1.3	1.0	0.5	25	29	31	36[10]	1930
MB[3]	0.55	1	1.3	1.0	0.5	36	Bleeding[11]			1948
CCO[4]	0.55	1	1.3	1.0	0.5	20	21	23	27[12]	N/A

NOTE: CC[1] – hammer crusher; CF[2] – jaw crusher; MB[3] – ball mill; CCO[4] – cone crusher. W[5] – water; C[6] – cement; S[7] – sand; [8]SP – super-plasticizer; [9]VM – viscosity modifier agent.
[10] homogeneous, fluid; [11] homogeneous, fluid, bleeding 5.5 ml; [12] homogeneous, fluid, 3 vol. % bleeding (after Ueki [6]).

a. Particle size distribution. The particle size distribution obtained for recycled aggregates, sort 0–2.5, obtained from the concrete class C16/20, C25/30 and C35/45, crushed with a jaw crusher and hammer crusher respectively, are presented in Table 17, and were determined using a standard set of sieves (2.5, 2, 1, 0.5, 0.25, 0.125, 0.063 mm) according to EN 933-2:2002 provisions [6].

By comparing the size distribution of the recycled aggregate obtained with a crusher hammer from that obtained with a jaw crusher, results there is a higher proportion of coarse part (sorts 1–2, 2–2.5) in recycled aggregate, especially for higher class concrete.

b. Mortars characteristics. Mortars are tested with the same proportions in the mix for comparison (W/C = 0.55 and S/C = 1.3). To judge the applicability of the filling material in waste containers there are being measured fluidity, bleeding and compressive strength of this mortar (Tables 18–19).

It was chosen a type of crusher which produces recycled fine aggregate in mortar which has the best properties, after characterization.

Characteristics of mortars using recycled aggregates by crushing with the hammer crusher and jaw crusher respectively show no significant differences. We can still notice that to achieve the same flow properties, water content can be reduced by choosing hammer crusher, which simultaneously improves the quality

Table 17

Particle size distribution for recycled aggregate (stage 2)

Sort (mm)	Hammer crusher			Jaw crusher		
	C16/20	C25/30	C35/45	C16/20	C25/30	C35/45
2–2.5	8	8	10	4	19	14
1–2	11	9	12	16	13	16
0.5–1	26	28	27	32	29	31
0.25–0.5	21	21	21	20	16	20
0.125–0.25	19	18	14	14	11	11
0.063–0.125	11	11	12	11	11	7
0–0.063	4	5	4	3	1	1

of the mortar, reduce production costs and increase the amount of recycled concrete. Moreover hammer crusher has the advantage to be more compact in size and to have a closed crushing chamber.

The equipment can be placed in a temporary enclosure to prevent dissemination of radioactive aerosols. Hammer crusher is optimal for concrete recycling.

With this crusher we verify applicability of the production process of filling material, by testing five different compressive strength of concrete (C25/30A; C25/30B; C25/30C; C25/30D C25/30E, respectively).

5.3. THE ORIGINAL CONCRETE PROPERTIES INFLUENCE ON RECYCLED AGGREGATES

a. Size distribution. Size distribution obtained for recycled aggregates, sort 0–2.5, from five different types of original concrete compressive strength (C25/30A; C25/30B; C25/30C; C25/30D and that C25/30E), crushed with hammers are shown in Table 20. We observe similar distribution obtained for particle size made with recycled aggregates impact crusher, independent of the distribution studied.

b. Mortar characteristics. To compare the mortars, they are tested with the same proportions in the mixture (W/C 55% and S /C 1.3). There were measured: fluidity, bleeding and compressive strength to determine the applicability of the mortar as filling material for radioactive waste containers. The fluidity is good even after 60 minutes of preparation of the mortar (Table 21). Hardened mortars show a good resistance to compression. The fluidity and compressive strength can be maintained within the limits required by the proposed specification, independent of the original recycled concrete properties if using the process developed.

Table 18

Fresh mortar properties obtained with recycled aggregates

Sample	Mix composition (kg)			Ad. SP (%)	Agent MV (%)	Flow-time (s) at min				Dens. (kg/m^3)	Remarks
	W	C	S			0	15	30	60		
C16/20hi$_1$	0.55	1	1.3	2	0.5	37	40	45	52	1927	homogenous, fluid
C16/20j$_1$	0.55	1	1.3	1	0.5	35	39	47	54	1922	homogenous, slight segregation after one hour
C25/30$_{h1}$	0.55	1	1.3	2	0.5	38	43	46	55	1929	homogenous, slight segregation
C25/30h$_2$	0.55	1	1.3	1	0.5	41	bleeding			1898	7 ml bleeding (Ts = 0.022cm)
C25/30j$_1$	0.55	1	1.3	1	0.5	58	–	–	–	1964	homogenous, fluid
C35/45h$_1$	0.55	1	1.3	2	0.5	39	44	51	58	1893	Homogenous, segregation after one hour
C35/45j$_1$	0.55	1	1.3	1	0.5	37	56	–	–	1902	homogenous, fluid

h – hammer crusher; j – jaw crusher; W – water; C – cement; S – sand

Table 19

Apparent density & mechanical strength for recycled hardened mortars

Sample	S/C	Mean apparent density (Kg/m$^{3)}$	Mean bending strength (MPa)	Mean compression strength (MPa)
C16/20h$_1$	1.3	2104	8.14	36.5
C16/20h$_2$		2065	6.70	32.0
C16/20h$_3$		2090	7.66	32.5
C16/20j$_1$	1.3	2005	7.81	31.2
C16/20j$_2$		2054	8.03	34.2
C16/20j$_3$		2049	7.87	35.0
C25/30h$_1$	1.3	2071	8.19	35.7
C25/30h$_2$		2060	6.19	36.8
C25/30h$_3$		2047	6.40	35.5
C25/30j$_1$	1.3	2072	5.88	34.9
C25/30j$_2$		2055	6.23	29.8
C25/30j$_3$		1975	6.43	31.0
C35/45h$_1$	1.3	2113	8.30	38.0
C35/45h$_2$		2085	7.21	34.5
C35/45h$_3$		2078	7.40	34.4
C35/45j$_1$	1.3	2037	6.51	26.4
C35/45j$_2$		1980	6.21	26.4
C35/45j$_3$		2015	6.89	29.0

h – hammer crusher (stage 2); j – jaw crusher (stage 2)

Table 20

Size distribution for recycled aggregate

Sort (mm)	wt %				
	C25/30A	C25/30B	C25/30C	C25/30D	C25/30E
>2.5	0	0	0	0	0
2–2.5	4	6	6	6	5
1–2	9	12	9	12	9
0.5–1	27	30	28	28	28
0.25–0.5	22	20	21	21	22
0.125–0.25	19	15	20	16	18
0.063–0.125	13	12	12	12	11
0–0.063	6	5	4	5	7

Table 21

The original concrete properties influence on recycled aggregates

No.	Mixture composition (kg)			Ad. SP[4)] (%)	Agent VM[5)] (%)	p-cone (s) at min				Density (kg/m^3)	Remarks
	W[1)]	C[2)]	S[3)]			0	15	30	60		
1	2	3	4	5	6	7	8	9	10	11	12
A_1	0.55	1	1.3	2	0.5	40	46	51	58	1925	Homogenous, slight segregation
A_2	0.55	1	1.3	1	0.5	44	49	53	62	1913	homogenous, fluid
A_3	0.60	1	1.3	1	0.5	38	41	51	60	1909	homogenous, fluid, slight segregation
A_4	0.65	1	1.3	1	0.5	27	29	33	40	1896	homogenous, fluid, slight segregation
A_5	0.65	1	1.3	1	0.5	26	bleeding			1900	homogenous, fluid, slight segregation, 21 ml bleeding
B_1	0.55	1	1.3	2	0.5	36	46	48	65	1936	Homogenous, segregation >A1

Table 21 (*continued*)

1	2	3	4	5	6	7	8	9	10	11	12
B_2	0.60	1	1.3	1	0.5	22	25	37	43	1917	homogenous, fluid, slight segregation
B_3	0.60	1	1.3	1	0.5	21	bleeding			1911	homogenous, fluid, slight segregation, 22 ml bleeding
C_1	0.55	1	1.3	2	0.5	39	47	56	62	1922	homogenous, fluid
C_2	0.60	1	1.3	1	0.5	28	32	38	51	1907	homogenous,slight segregation
C_3	0.60	1	1.3	1	0.5	28	bleeding			1901	homogenous, slight segregation, 20.5 ml bleeding
D_1	0.55	1	1.3	2	0.5	38	44	53	61	1919	homogenous
D_2	0.60	1	1.3	1	0.5	23	25	26	35	1895	homogenous, slight segregation
D_3	0.60	1	1.3	1	0,5	26	bleeding			1901	homogenous, slight segregation, 19.5 ml bleeding
E_1	0.55	1	1.3	2	0.5	40	49	52	66	1917	homogenous, slight segregation
E_2	0.60	1	1.3	1	0.5	35	39	45	56	1896	homogenous, slight segregation
E_3	0.65	1	1.3	1	0.5	22	28	32	45	1887	homogenous, slight segregation
E_4	0.65	1	1.3	1	0.5	24	bleeding			1892	Homogenous, slight segregation, 24 ml bleeding

1)W – water; 2) – cement; 3)S – sand; 4)SP – super plasticizer; 5)VM – viscosity modifier agent.

6. CONCLUSIONS

The research program includes:

– characterization of materials for concrete;

– calculation of the concrete composition and selection of three classes of resistance;

– determination of strength and elasticity modulus;

– studies of recycled aggregate particle size;

– optimization of injection mortar composition;

– selection of super plasticizer and viscosity modifier for concrete and mortar.

Crushing tests revealed that the best option is the impact crusher. The aggregate obtained by jaw crushing using the same fine content has higher coarse content comparing with hammer crusher. The recycled aggregate shapes obtained by hammer crushing are more cubic shaped.

For crushing there was used:

– three classes of concrete: C16/20, C25/30, and C35/45, made with 42.5 class cement (CEM V A S-V 42.5 N);
– natural river aggregate – simple and crushed;
– super plasticizer additive Glenium 27 – from BASF.

It was used the Class C25/30 as a reference for another five concrete compositions derived, in order to reflect compositional factors (W/C and S ratio and the aggregate nature).

Mortars characteristics measurements had required: compositional optimization ratio (W/S, S/C and additives), flow, bleeding, entrapped air volume and density and mechanical strength (bending and compression) measurements.

Filling ratio of containers with recycled pre-placed aggregate was determined using mortars that satisfy the requirements regarding flow and compressive strength. We have obtained good results for all processed mortars.

The results must be confirmed in the laboratory and pilot level. The research will continue to finalize the technological solution studied with radioactive concrete recycling application.

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