CASEE
Central and South Eastern Europe

Szkoła Główna Gospodarstwa Wiejskiego w Warszawie

Sustainable development in civil engineering based on recycled concrete aggregate.

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NUMBERS:

- European Union in 2010 produced **2.51 billion** tons of waste.
- Construction and demolition activities generated, about **859 million** tons of waste (34% of total)
- Mining and quarrying activities produced, about **672 million** tons of waste (27% of total)
  - 97% of these two sectors waste was mineral or soils coming from excavated earth, road construction waste, construction and demolition waste, waste rocks
  - Only 24% of these wastes was hazardous, **so about 1.12 billion tons of waste can be potentially reuse.**

Why we do not use recycled aggregates (RA)?

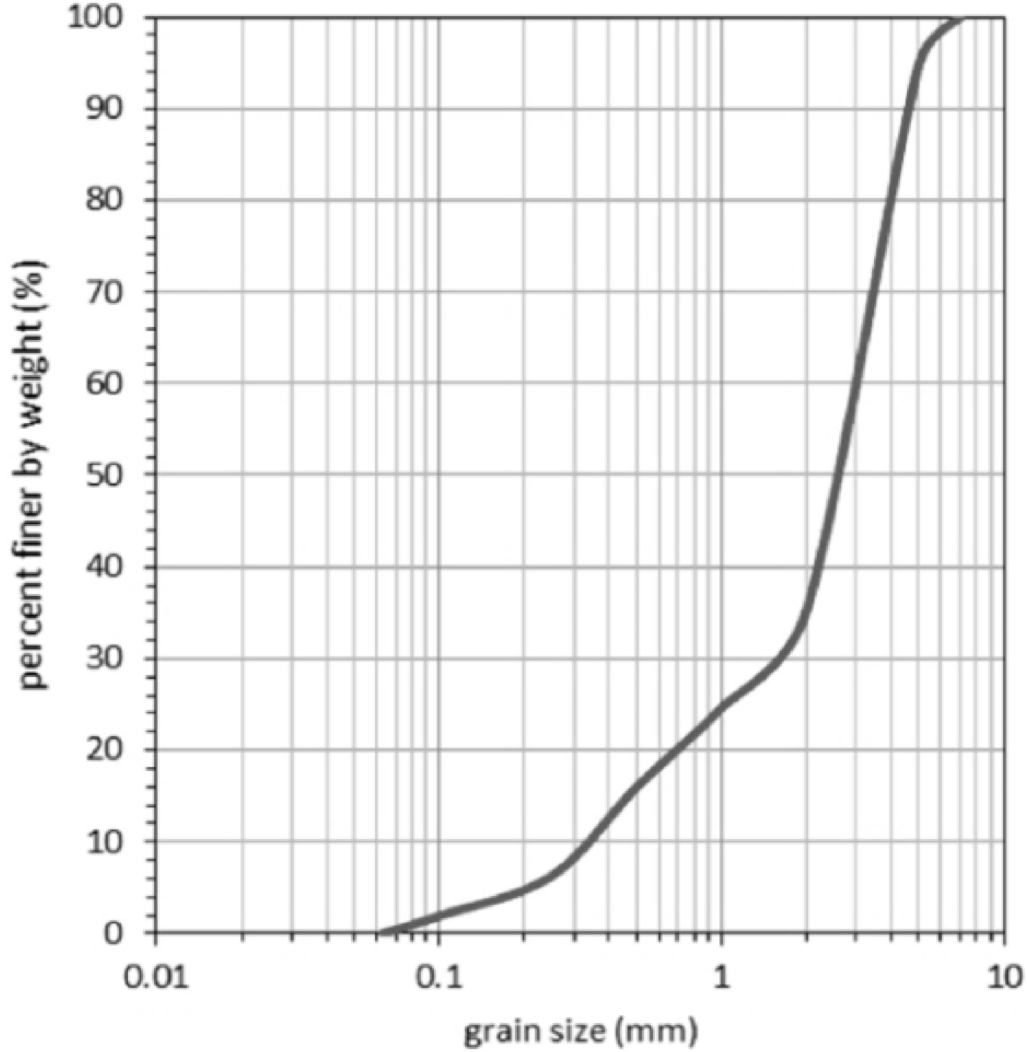
- From economic point of view use of RA is not always good solution.
  - RA has to be transported to the construction site from recycling facilities.
  - RA mixture has to be preparing with rigorous selection, mainly because of different origins.
- Crushing properties of RA.
- Many properties of RA are not well known still.

Why we do not use recycled aggregates (RA)?

- The most difficult task:
  - Convincing designers and contractors who are attached and aware of the natural aggregate behavior.

Material:

- Recycled concrete aggregate with sandy gravel (saGr) gradation curve created from C16/20 concrete



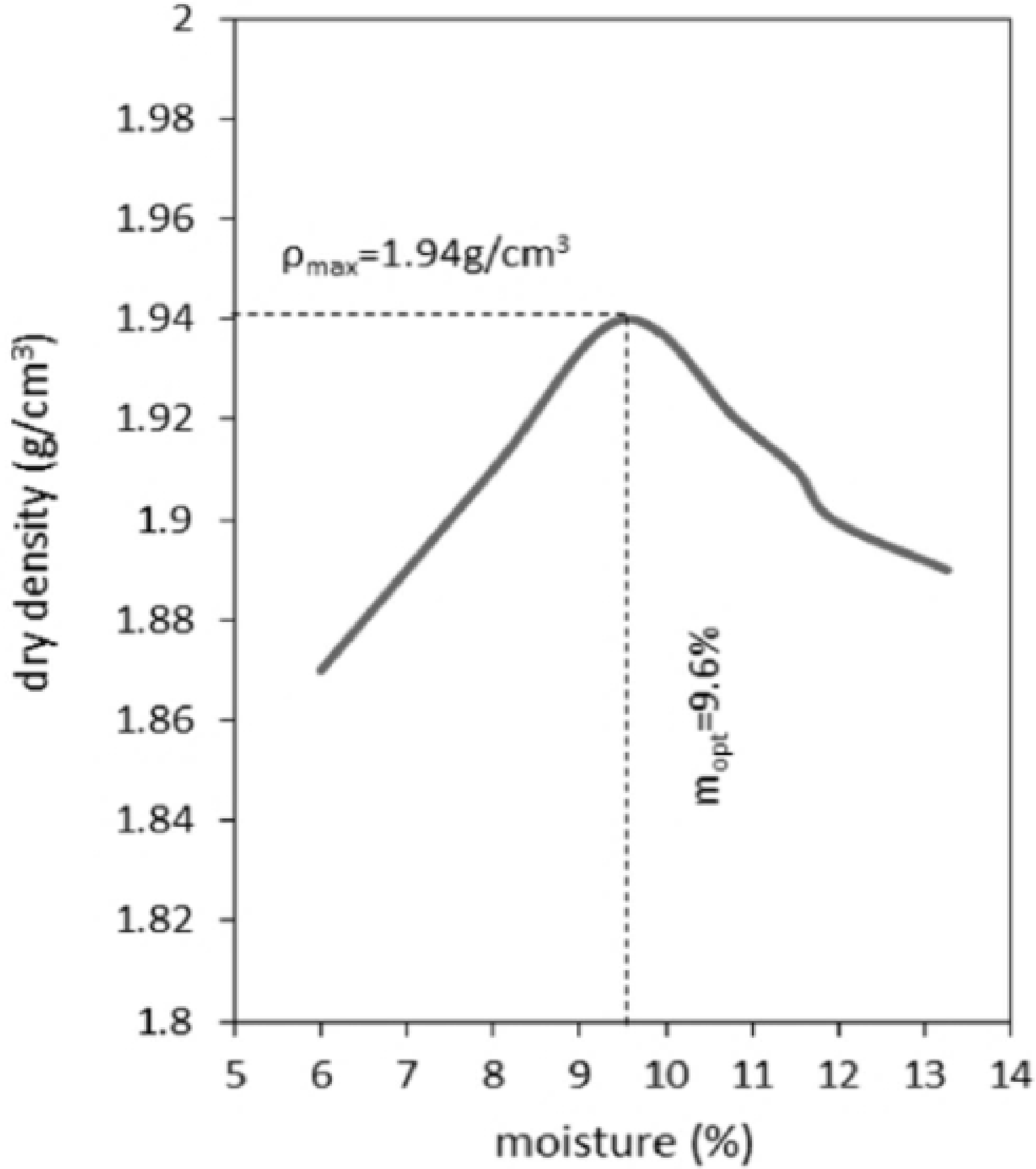
Result for the soil gradation curve [Sas et al. 2016]

Geotechnical properties of recycled concrete aggregate (RCA)

Optimum moisture content (m_{opt})

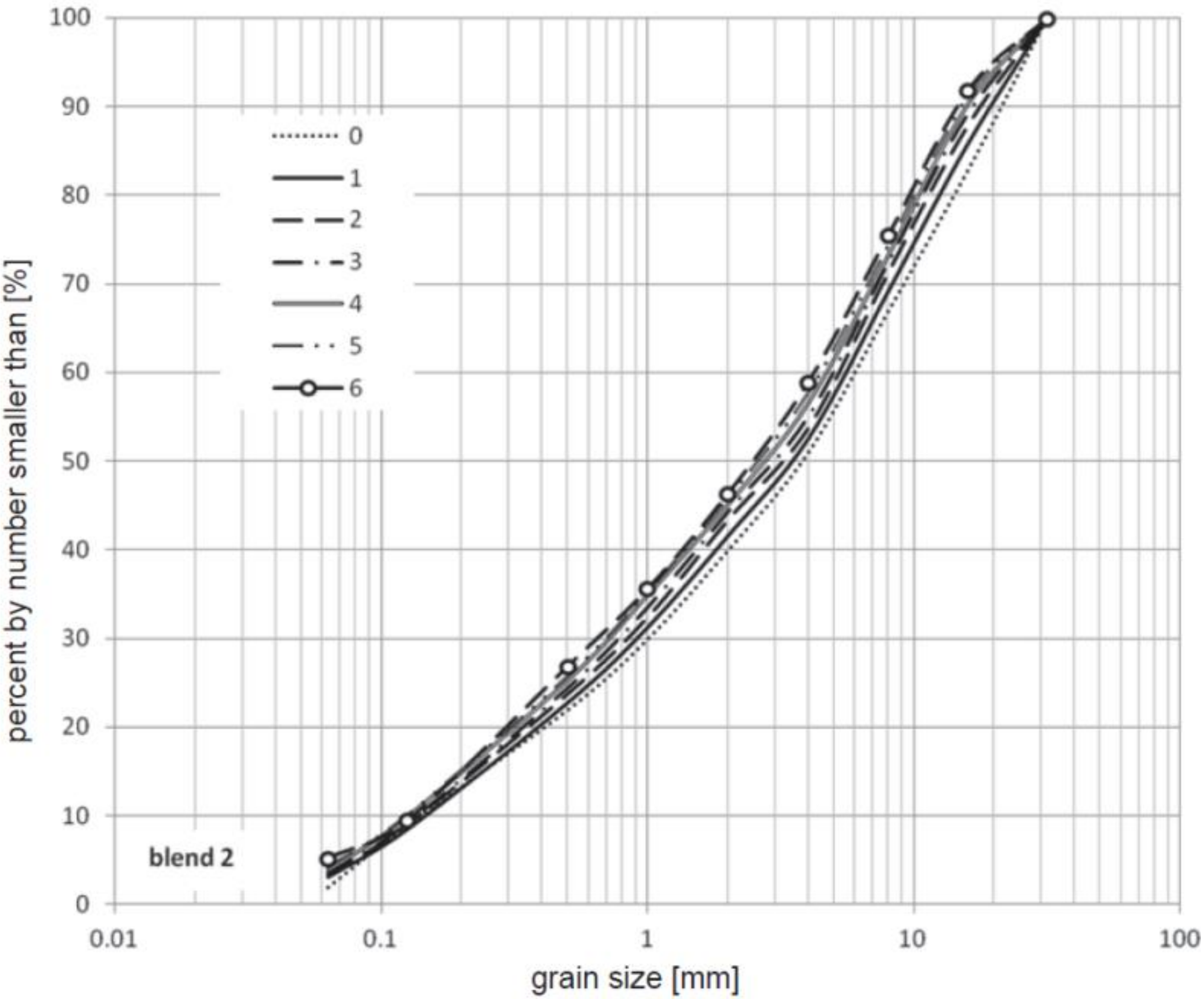
Proctor test

Optimum moisture content (m_{opt})



Result for Proctor test for the RCA [Sas et al. 2016].

CRUSHING PROPERTIES



RCA gradation curve after 6 repetitions of Proctor test [Sas et al. 2015 a].

California Bering Ratio (CBR)

$$CBR = \frac{p}{p_s} \cdot 100\%$$

- $\boldsymbol{p}$ is measured pressure for studied material
- $\boldsymbol{p_s}$ is pressure to achieve equal penetration on standard material

California Bering Ratio (CBR)

References	Type of the aggregate	CBR (%)	Standard used
Bennert and Maher [2008]	NA RCA	182 169	Not mentioned
Jimenez et al. [2011]	NA RCA	152 97-138	UNE 103502
Melbouci [2009]	RCA	128	NF 94-078
Poon et al. [2007]	NA RCA	83 66	BS 1377-4
Sas et al. [2012]	RCA	78-91	PN-S-02205:1988
Sas et al. [2015b]	RCA	80-147	PN-EN 13286-47:2012

Resilient Modulus (M_R)

$$M_r = \frac{\Delta q}{\varepsilon_r}$$

- Δq stress difference of cyclic stress
- ε_r resilient strain.

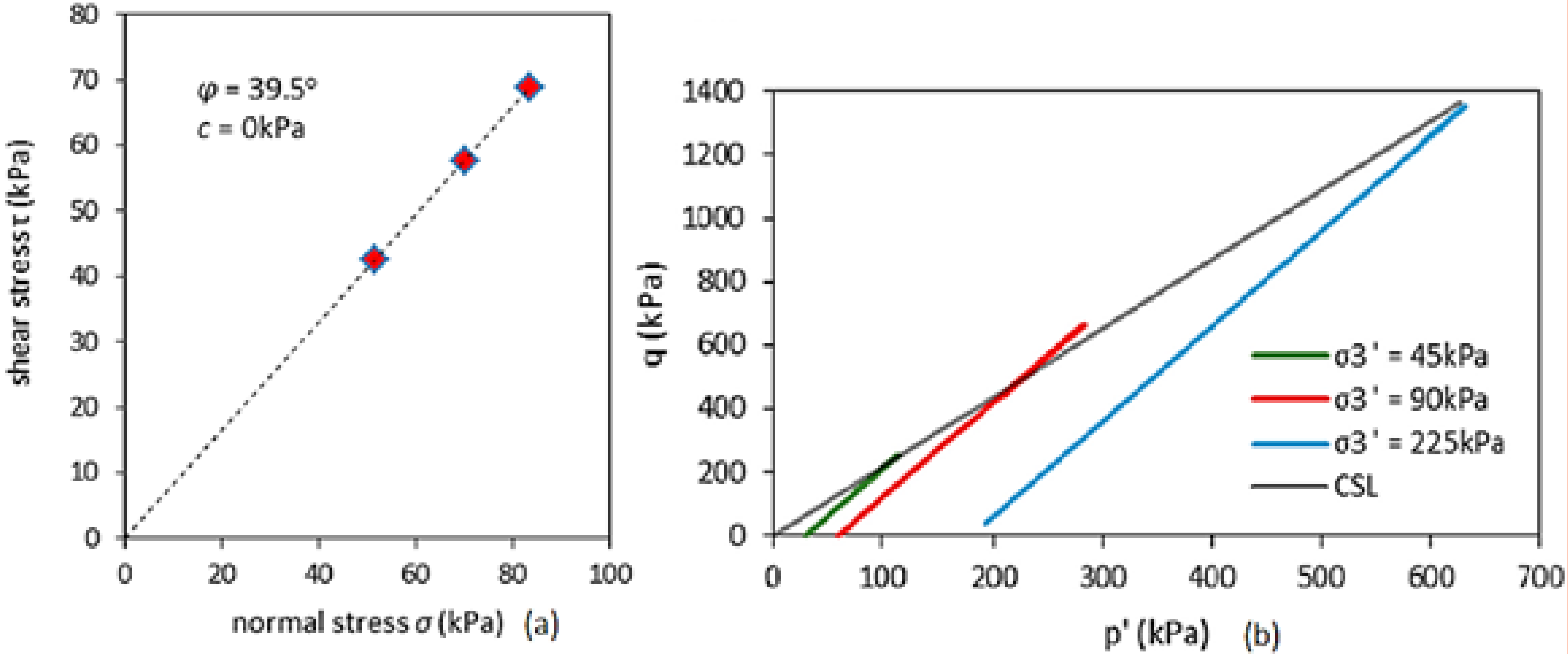
Resilient Modulus (M_R)

Δq/No. of Cycle	**10**	**100**	**1000**
25.85	790	812	744
129.39	808	823	758
178.54	618	652	621

Resilient modulus M_r (kPa) of RCA for selected cycles [Sas et al. 2016].

Angle of internal friction (Φ) and cohesion (C)

ANGLE OF INTERNAL FRICTION (Φ) AND COHESION (C)



Results of direct shear tests (a) and triaxial tests (b) conducted on RCA [Sas et al. 2016].

Angle of internal friction (φ) and cohesion (C)

References	Soil type	Direct shear test (size of shear box in mm)	Triaxial test
Sas et al. 2016	RCA	(250x250x250) φ=39,5° C=0 kPa	φ=53° C=0 kPa
Soból et al. 2015	RCA	(250x250x250) φ=38,5-40,3° C=0 kPa (120x120x120) φ=39,7-41,5° C=0 kPa	
O'Mahony 1997	RCA	(300x300x179) φ=39,5-42° C=0 kPa	
	Sand	(300x300x179) φ =33° C=0 kPa	

PERMEABILITY COEFFICIENT (K)

Permeability coefficient (k)

Hydraulic gradient [-]	Temperature [°C]	Minimum permeability coefficient [m/s]	Maximum permeability coefficient [m/s]	Interval [m/s]
0.67	18	3.31E-05	3.41E-05	9.54E-07
0.75	18	3.74E-05	3.87E-05	1.26E-06
0.83	18	4.51E-05	4.75E-05	2.33E-06
0.67	10	2.68E-05	2.76E-05	7.73E-07
0.75	10	3.03E-05	3.13E-05	1.02E-06
0.83	10	3.66E-05	3.84E-05	1.88E-06

Results of the permeability coefficient for RCA by constant head method [Sas and Maciorowska 2012]

MAXIMUM SHEAR MODULUS (G_{MAX})

$$G_{max} = \frac{\tau_{max}}{\gamma}$$

- τ_{max} maximum shear stress
- γ shear strain

Maximum shear modulus (G_{MAX})

Effective stress (MPa)	Kokusho [1980], Toyoura sand (MPa)	Delfosse et al. [2002], Fontainebleau sand (MPa)	Gabryś et al. [2016], RCA (MPa)
0.045	-	-	62
0.05	85	90	-
0.09	-	-	134
0.1	125	120	-
0.225	-	-	220
0.3	140	205	-

Chemical properties of recycled concrete aggregate (RCA)

Sources of heavy metals

Parameter	Cement	Fly ash	Sand	Gravel
SiO_2 [%]	13.95	50.40	26.66	14.34
Al_2O_3 [%]	5.35	27.31	1.76	1.31
Fe_2O_3 [%]	4.88	4.79	1.00	0.74
TiO_2 [%]	-	1.50	0.09	0.07
CaO [%]	61.44	7.29	30.85	36.24
MgO [%]	1.20	1.49	6.89	8.59
MnO [%]	0.55	0.06	0.04	0.03
SO_3 [%]	2.95	0.46	0.01	0.01
K_2O [%]	0.78	1.52	0.24	0.10
Na_2O [%]	0.22	0.28	0.22	0.14
P_2O_5 [%]	0.17	1.06	0.00	0.00
Cr [mg/kg]	97.70	343.60	31.0	44.0
V [mg/kg]	41.0	336.0	5.0	6.0
Ba [mg/kg]	217.0	1645.0	17.0	23.0
Sr [mg/kg]	218.0	1723.0	127.0	129.0

Chemical composition of raw materials used in the production of concrete [Rosik-Dulewska and Karwczyńska 2008].

Leaching properties – laboratory tests

Parameter		N1	N2	C1	Leached maximum concentrations for inert landfill class	X6	Leached maximum concentrations for non-hazardous landfill class
Metals [mg/kg]	Cr	n.d.	0.014	0.286	0.5	1.418	10
	Ni	0.004	0.013	0.028	0.4	0.042	10
	Cu	0.012	0.001	0.147	2	0.064	50
	Zn	0.058	0.003	n.d.	4	n.d.	50
	As	0.035	0.006	0.002	0.5	0.004	2
	Se	0.003	n.d.	0.033	0.1	0.058	0.5
	Mo	0.022	0.014	0.228	0.5	0.223	10
	Sb	0.007	0.002	n.d.	0.06	n.d	0.7
	Ba	1.411	0.021	2.395	20	1.578	100
Sulphate	SO_4 [mg/L]	32	41	46.5	100	141.5	2000
	SO_3 [%]	0.03	0.04	0.04		0.14	

Concentration of metal and sulphate on leach [Barnudo et al. 2012] and maximum leached concentration depending on landfill class [EU Landfill Directive 1999].

LEACHING PROPERTIES – FIELD TESTS

Concentration [µg/L]	F3W	F3E	F7	F5	Acceptance criteria[µg/L]*
As	<3.5-29	<3.5-25	<3.5-5.9	<3.5-9.6	300
Cd	<0.1-0.1	0.1-0.2	<0.1	<0.1-2.2	200
Cr	2.0-129	2.7-241	1.6-13	0.6-3.2	100
Cu	1.0-13	<0.2-28	0.4-3	0.2-26	200
Mo	7.4-139	6.4-252	1.7-17	4.9-84	1000
Ni	<0.7-4.5	<0.7-6.9	<0.7-2.0	<0.7-20	500
Pb	<2.5-2.4	<2.5-2.7	<2.5	<2.5-4.2	500
V	3.2-115	<0.3-70	1.5-13	<0.3-6.1	2000
Zn	<1.3-5.3	<1.3-5.6	<1.3-7.4	<1.3-8.3	2000

Lowest and highest concentration of metals in the collected leachates at field during the monitoring period (2006-2010) [Engelsen et al. 2012].

*Official Gazette of the Republic of Poland, Regulation of the Minister of the Environment of 18 November 2014 on the conditions to be met for the introduction of sewage into waters or to land and on substances particularly harmful to the aquatic environment.

CONCLUSION:

- From conducted revive, the most of geotechnical parameters of RCA needed for the design were given, for example:
  - optimum moisture content 9.6%
  - California Bearing Ratio for different standards from 80 to 182%
  - resilient modulus for heavy transport loading from 618 to 823 kPa
  - angle of internal friction from direct shear tests 38.5-42° and triaxial test 53°
  - permeability coefficient $2.68*10^{-5} – 4.75*10^{-5}$ m/s
  - maximum shear modulus 62 – 220 Mpa
- Concentration of metals, in both laboratory and field tests, do not exceed limits, except chromium. In general, RCA seems to be a chemically stable aggregate.

Every mentioned parameter was similar or, in some cases, even better than parameters of natural aggregate.

Main Conclusion:

In authors' opinion, RCA is a very good alternative for NA, which is still using in designers and contractors society worldwide. Over time, depleting natural resources forces engineers to use alternative aggregates. Nevertheless, RCA with similar parameters to natural aggregates can be used right now and this can prevent future construction catastrophe due to lack of experience in working with RCA.

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Thank you for your attention