Alternative fillers and active admixtures from by-products and quarry dusts in asphalt mixtures – can they be beneficial ?

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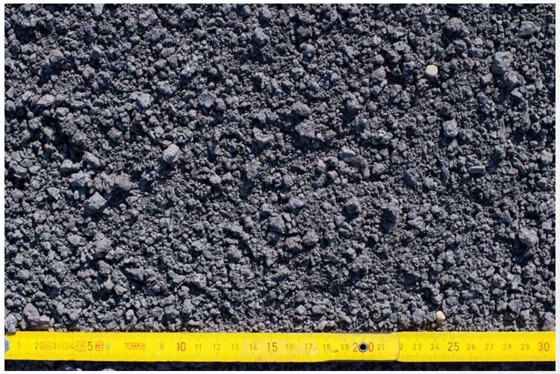
What are potentially usable materials?

- backhouse filler and quarry dust;
- fly-ashes (silicious or fluidized combustion bed)
- blast furnace slag, pan slags, BOF and similar steel production slags;
- cement kiln dust
- fine ground recycled concrete




Potential use cases of these materials in pavements

In asphalt mixtures:

- as an alternative to regular limestone filler
- as a hydrophobization agent
- as a stiffening mineral additive

In granular bound layers:

- active filler (e.g. in cold recycling)
- alternative binder – if alkali activated or with sufficient pozzolan content

Fillers in asphalt mixtures

What is commonly tested on fillers

Regularly requested tests:

- delta ring and ball (EN 13179-1)
- particle size distribution specifically for 0/0,125 mm particles
- assessment of fines - Methylene blue test => presence of clay particles (EN 933-9)

Useful tests:

- determination of loose bulk density and voids (EN 1097-3)
- determination of the voids of dry compacted filler (EN 1097-4)
- determination of the water content (EN 1097-5)
- determination of the particle density of filler – pycnometer method (EN 1097-7)
- chemical properties

Chemical characterization

Possible to test according to EN 13043:

- water solubility (EN 1744-1, part 16)
- susceptibility to water (EN 1744-4)
- content of carbonates in calcerous fillers
- content of calcium hydroxide in blended fillers

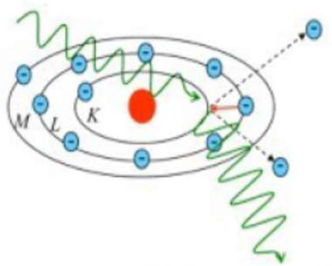
Nice-to-have:

- X-ray fluorescent spectrometry (XRF analysis) for elemental composition
- X-ray diffraction analysis for information about the crystallographic structure
- specific surface area (Blaine or BET)

How XRF can be useful?

Primary radiation

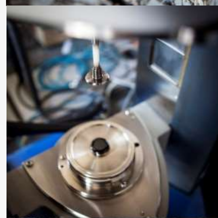
Radiated electron



Secondary fluerescence

Compound	m/m%	StdErr		Element	m/m%	StdErr
SiO2	51,33	0,24		Si	24	0,11
CaO	22,74	0,21		Ca	16,26	0,15
Al2O3	13,1	0,17		Al	6,93	0,09
K2O	4,13	0,04		K	3,43	0,04
Fe2O3	3,06	0,2		Fe	2,14	0,14
MgO	2,12	0,07		Mg	1,28	0,04
SO3	1,83	0,07		Sx	0,733	0,028
Na2O	1,12	0,06		Na	0,829	0,044
TiO2	0,21	0,022		Ti	0,126	0,013
BaO	0,115	0,011		Ba	0,103	0,01
Cl	0,0911	0,0062		Cl	0,0911	0,0062
SrO	0,0447	0,0026		Sr	0,0378	0,0022
MnO	0,0425	0,0036		Mn	0,0329	0,0028
ZnO	0,018	0,0009		Zn	0,0145	0,0007
Rb2O	0,0154	0,0009		Rb	0,0141	0,0008
ZrO2	0,0105	0,0015		Zr	0,0078	0,0011

Example of ground recycled concrete sample

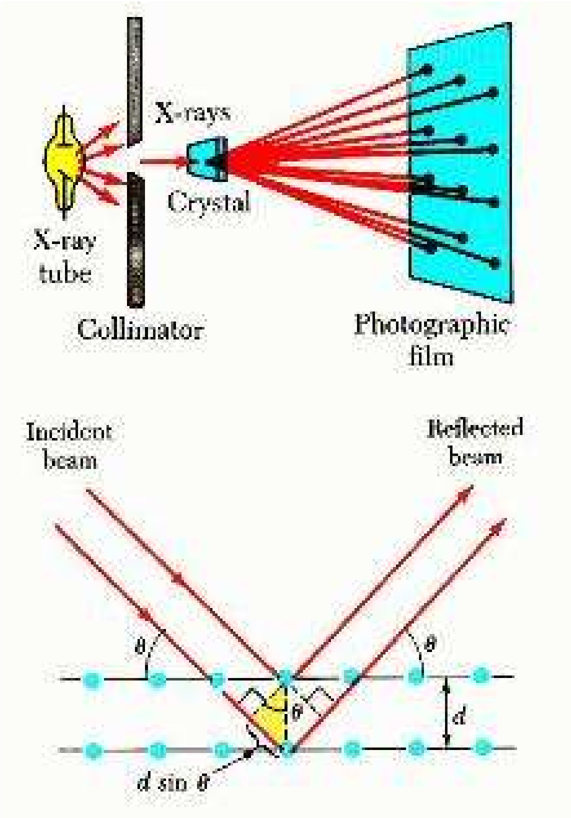

How XRF can be useful?

Compound	Chornice (lom)	Chornice (obalovna)	Bystřec (lom)	Chlum (lom)	Bystřec (obalovna)	Brant (vratný filer)	Libochovany	Vratný filer PKB	Svrčovec	Chrtníky	Litice	Velké Hydčice (JVM)	filer DAS	Vranov
	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%	m/m%
SiO2	56,07	60,97	50,59	55,86	46,58	57,35	41,90	53,98	57,30	34,40	36,35	2,86	53,74	49,36
Al2O3	21,71	20,57	18,01	24,45	17,02	21,35	18,73	18,98	18,55	18,39	16,93	5,09	17,28	21,71
Fe2O3	6,73	3,65	10,85	2,04	13,55	9,14	11,67	8,40	9,29	16,10	10,34	0,55	8,94	5,68
CaO	4,41	4,35	5,71	2,31	5,95	1,28	11,93	6,91	1,84	12,92	22,34	65,40	5,84	11,18
MgO	3,51	2,39	6,03	0,59	8,49	3,65	7,82	3,95	3,73	15,01	9,42	24,55	5,05	4,62
SiO2 a CaO	60,48	65,32	56,30	58,17	52,53	58,63	53,83	60,89	59,14	47,32	58,69	68,26	59,58	60,54
SiO2/CaO	12,7	14,0	8,9	24,2	7,8	44,8	3,5	7,8	31,1	2,7	1,6	0,0	9,2	4,4

This can help to provide some indication about hydrophobicity of the mineral material

How XRD can be useful?

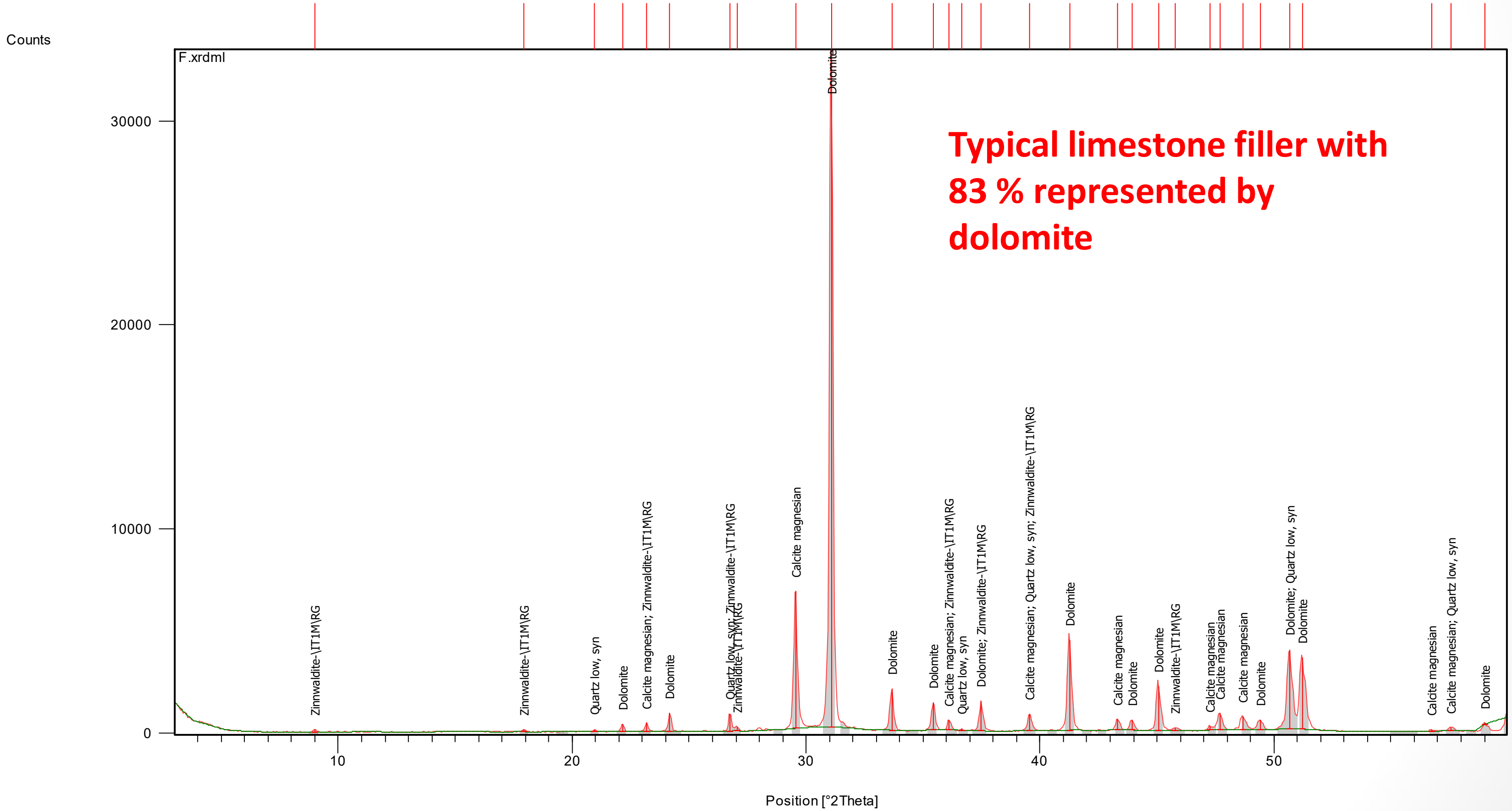
The analysis provides information about chemical composition and crystalline constitution of materials.



Compound name	SemiQunat (%)		Přepočet SiO_2	
	Chornice - QD	Chornice - BF	Chornice - QD	Chornice - BF
Quartz low, syn	52	49	52	49
Albite, disordered	13	-	8,76	-
Albite low	-	34	-	22,91
Amesite-2\ITH\RG#2	12	-	2,58	-
Nontronite	4	2	1,45	0,73
Phlogopite-1\ITM\RG	2	-	0,86	-
Augite	11	-	5,31	-
Calcite, magnesium, syn	-	4	-	0
Dolomite	-	1	-	0
Microcline, intermediate	-	9	-	5,83
Muscovite, chromian	5	2	2,26	0,9
SiO_2 celkem			73,22	79,37

Example of a quarry dust

How XRD can be useful?



Example of assessment of alternative fillers

Material	Filler name
Velké Hydčice limestone quarry dust	Ref.-LQD
Brant quarry dust	Brant-QD
Zbraslav back filler (HMA plant Kladno)	Zbraslav-BF
Bystřec quarry dust	Bystřec-QD
Bystřec back filler (HMA plant Bystřec)	Bystřec-BF
Chornice quarry dust	Chornice-QD
Chornice back filler	Chornice-BF
Plešovice quarry dust	Plešovice-QD
Finely ground recycled concrete (D2 highway)	D2-RC
Fine fractions of blast furnace slag from Kladno ironworks	Kladno-S
Finely ground granulated blast furnace slag from Třinec ironworks	Třinec-S
Finely ground waste gypsum boards	WGB
Plešovice quarry dust + CEM II 42.5 (20:3 wt.), 50% grinding	Plešovice-QD+CEM
Plešovice quarry dust + talc (10:1 wt.), 50% grinding	Plešovice-QD+T

specific use of waste

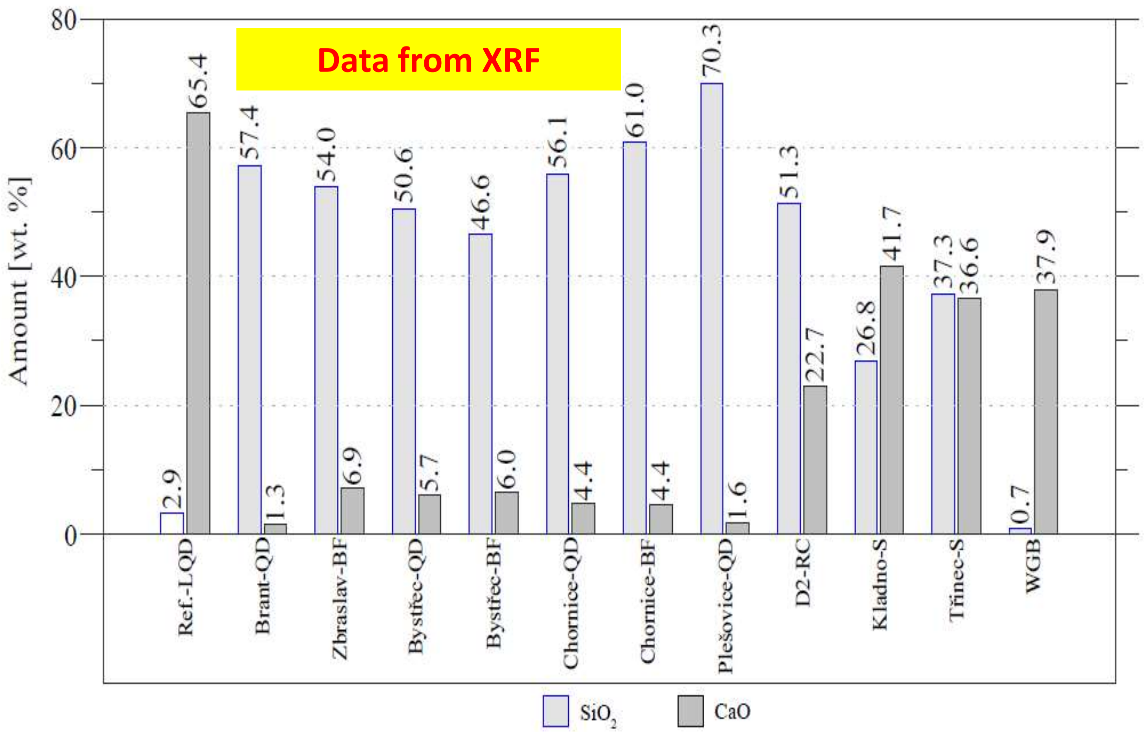
hydrophobized fillers



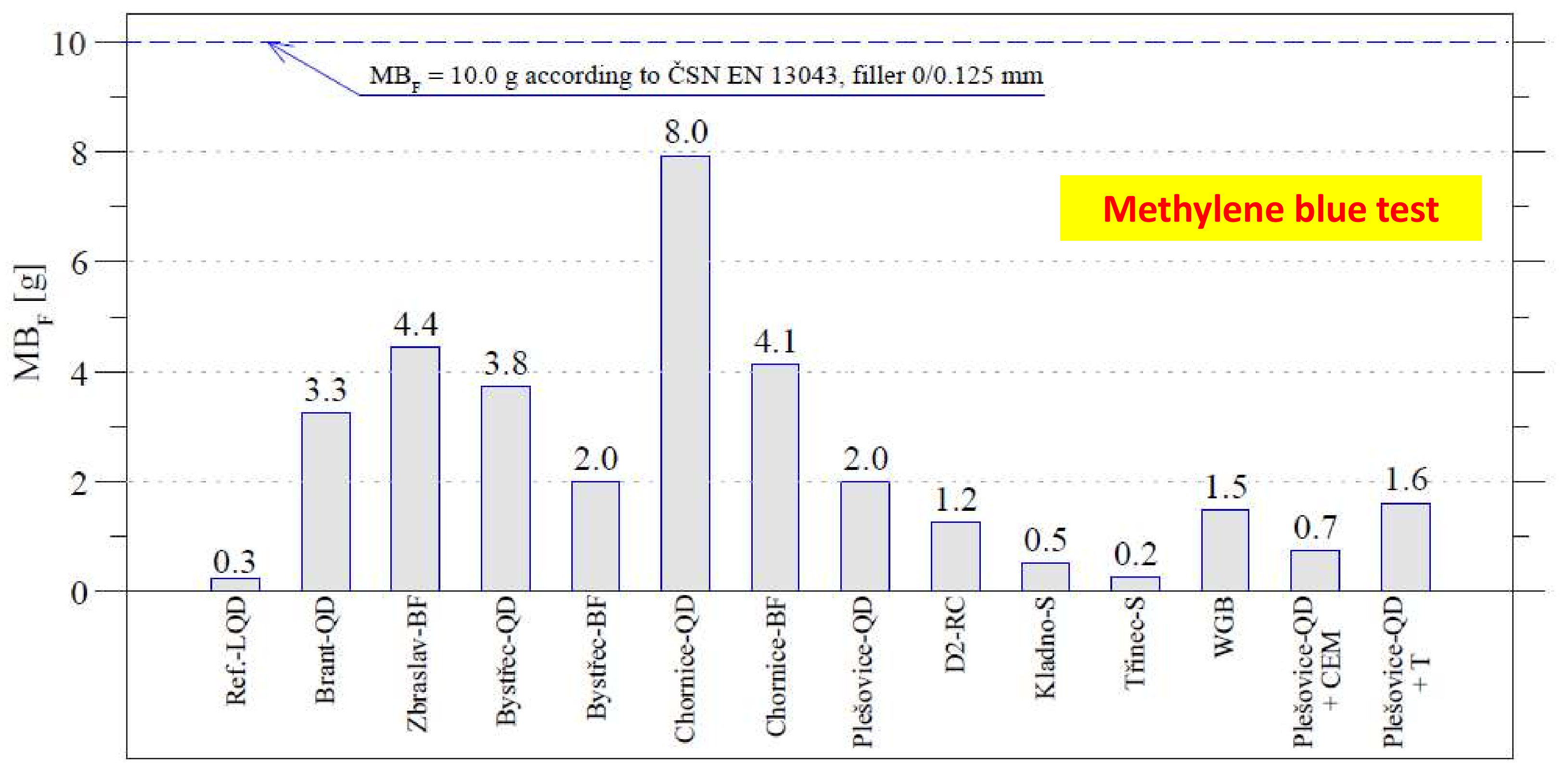


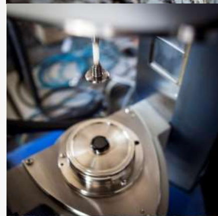
Example of assessment of alternative fillers

Filler	d_{32} [µm]	d_{43} [µm]	SSA [cm^2/cm^3]
Ref.-LQD	3.51	12.75	9262
Brant-QD	5.12	30.78	7711
Zbraslav-BF	6.16	42.68	6704
Bystřec-QD	5.94	39.81	3397
Bystřec-BF	4.81	53.74	3312
Chornice-QD	15.18	42.56	3201
Chornice-BF	15.69	58.16	2988
Plešovice-QD	7.83	27.21	3109
D2-RC	3.43	9.32	11013
Kladno-S	9.36	38.84	6408
Třinec-S	9.99	57.01	5006
WGB	3.71	10.98	9377



Example of assessment of alternative fillers





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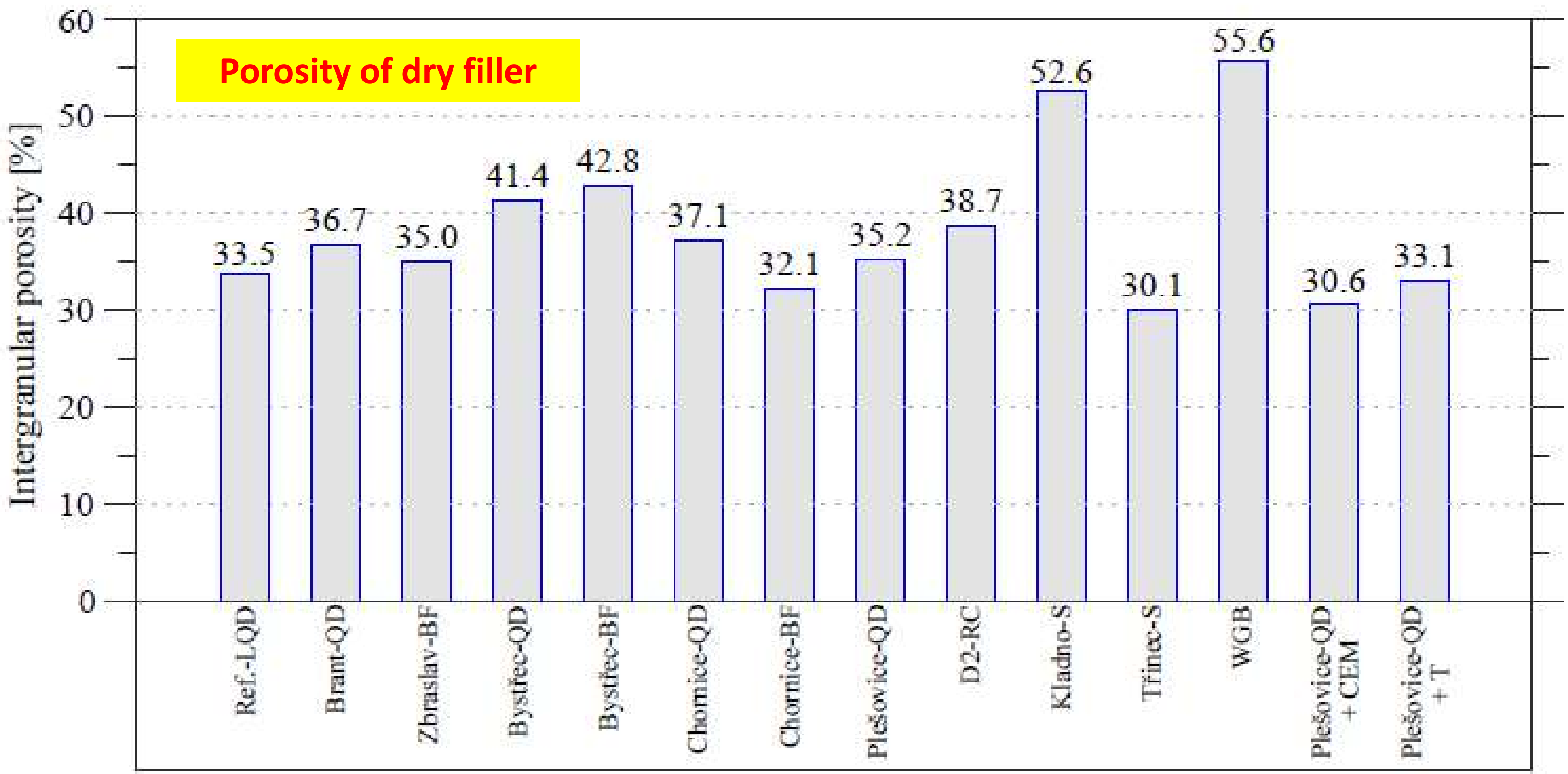

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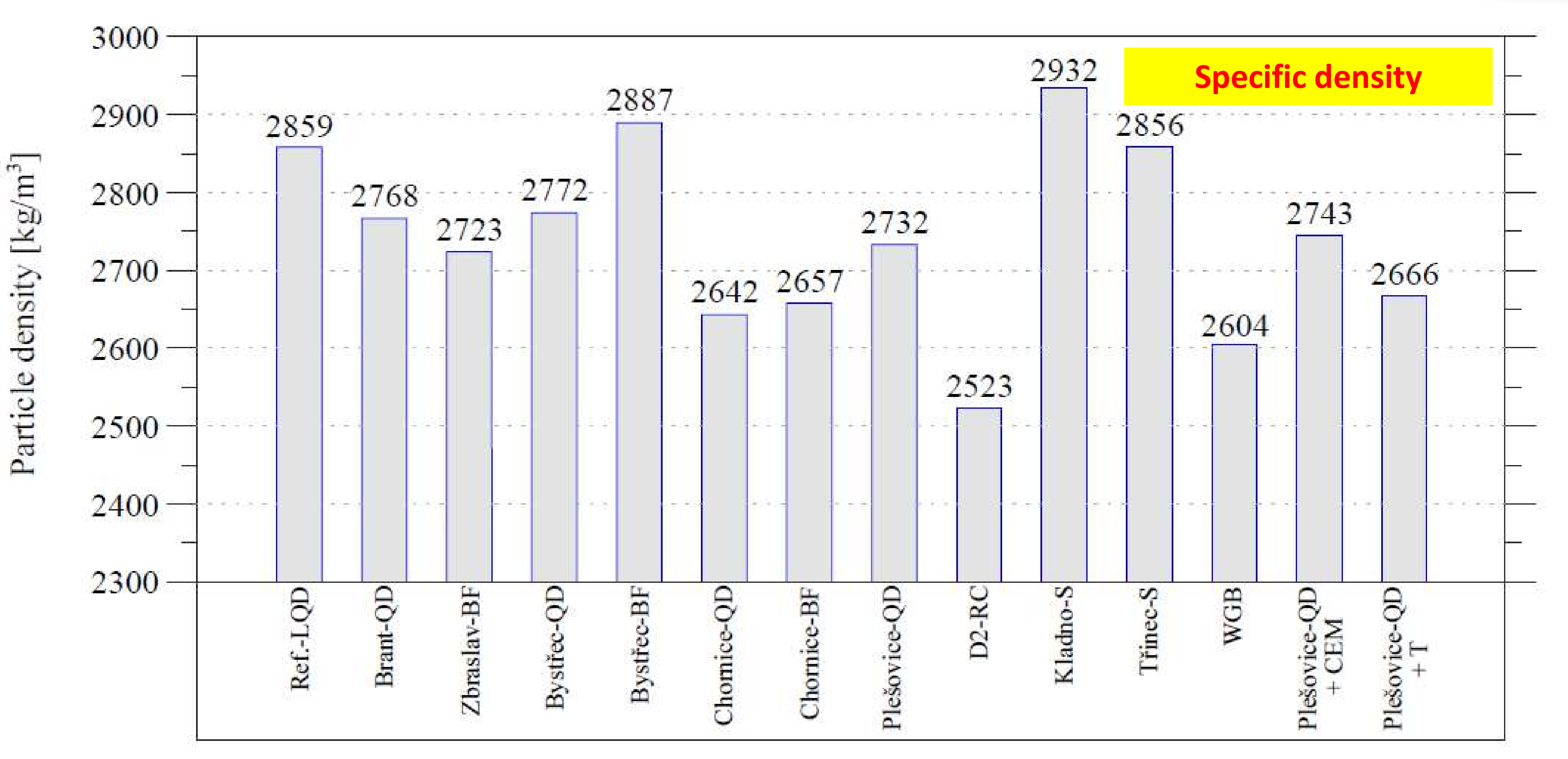
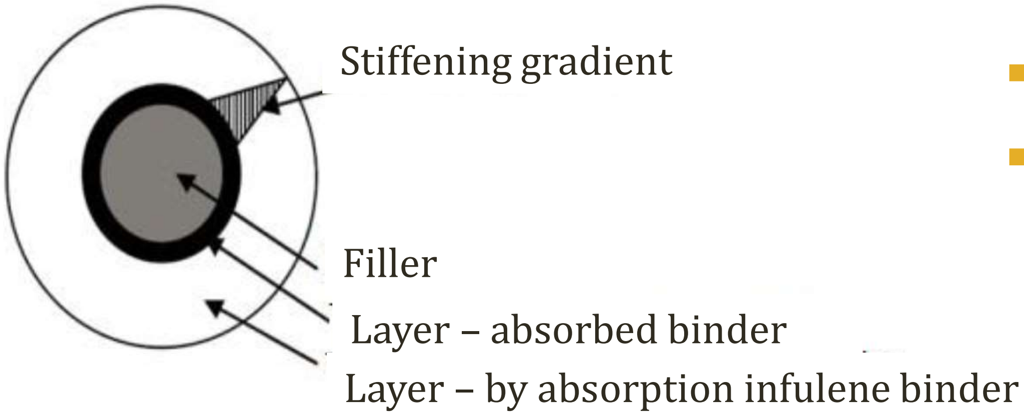


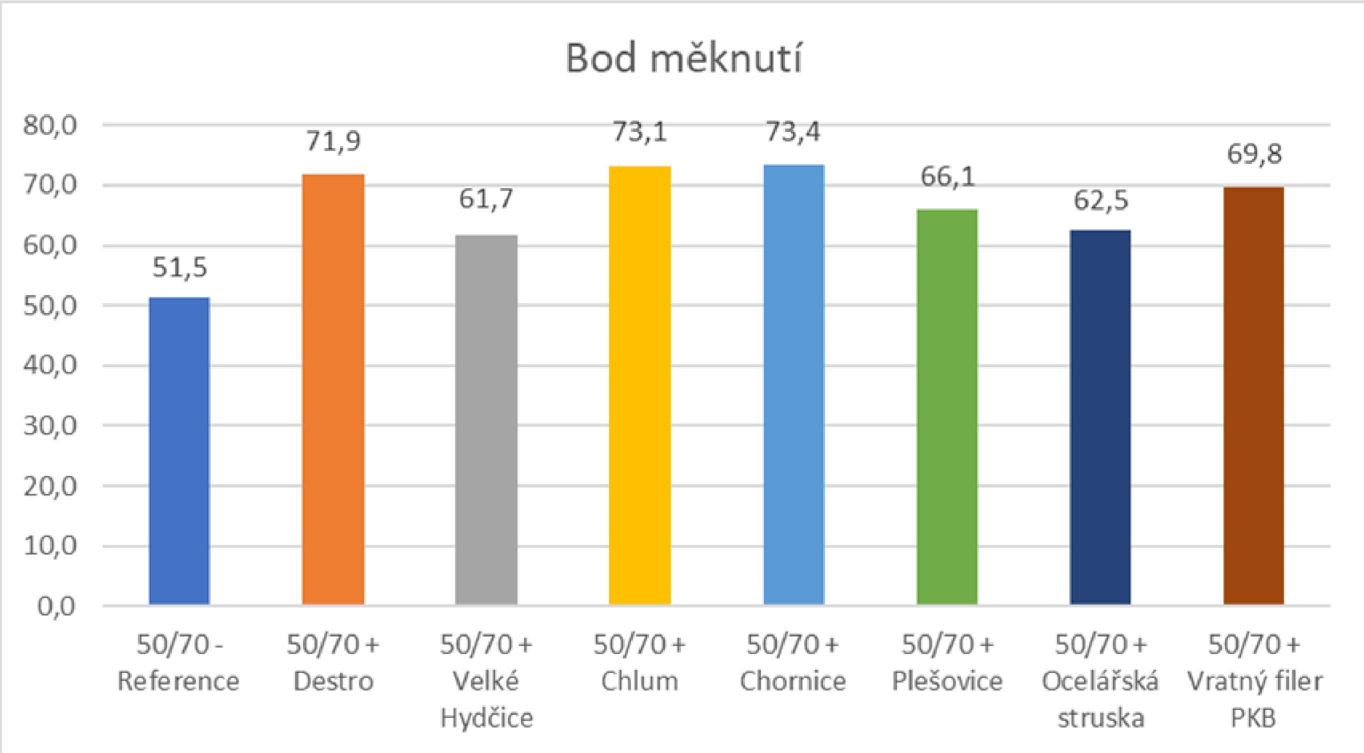
Possibilities how to think about the filler stiffening effect



Possible tests (regular and alternative):

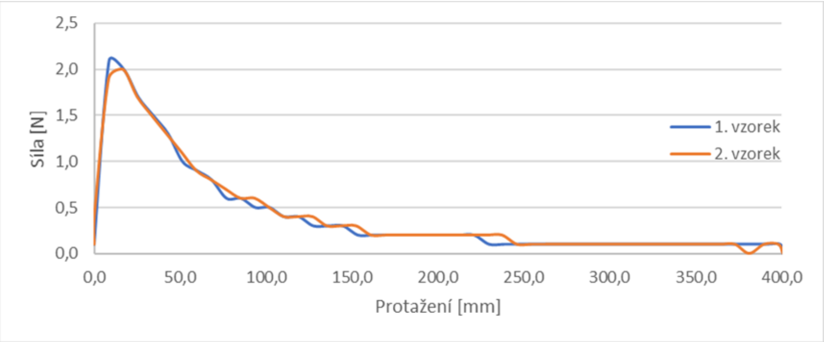
- delta ring and ball (EN 13179-1)
- ductility / force duktility (e.g. at 25°C)
- MSCR test
- frequency sweep test

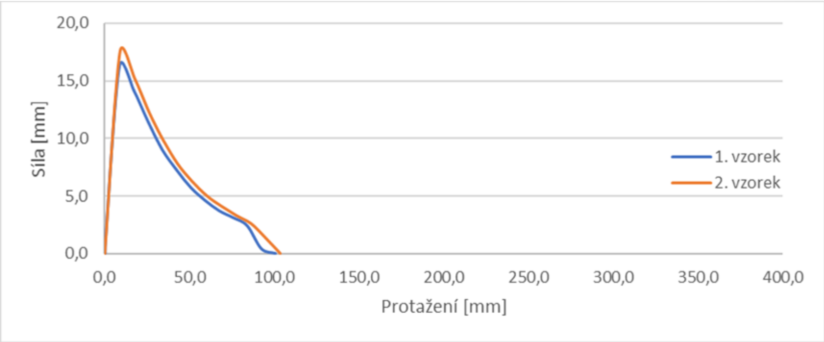
Possibilities how to think about the filler stiffening effect



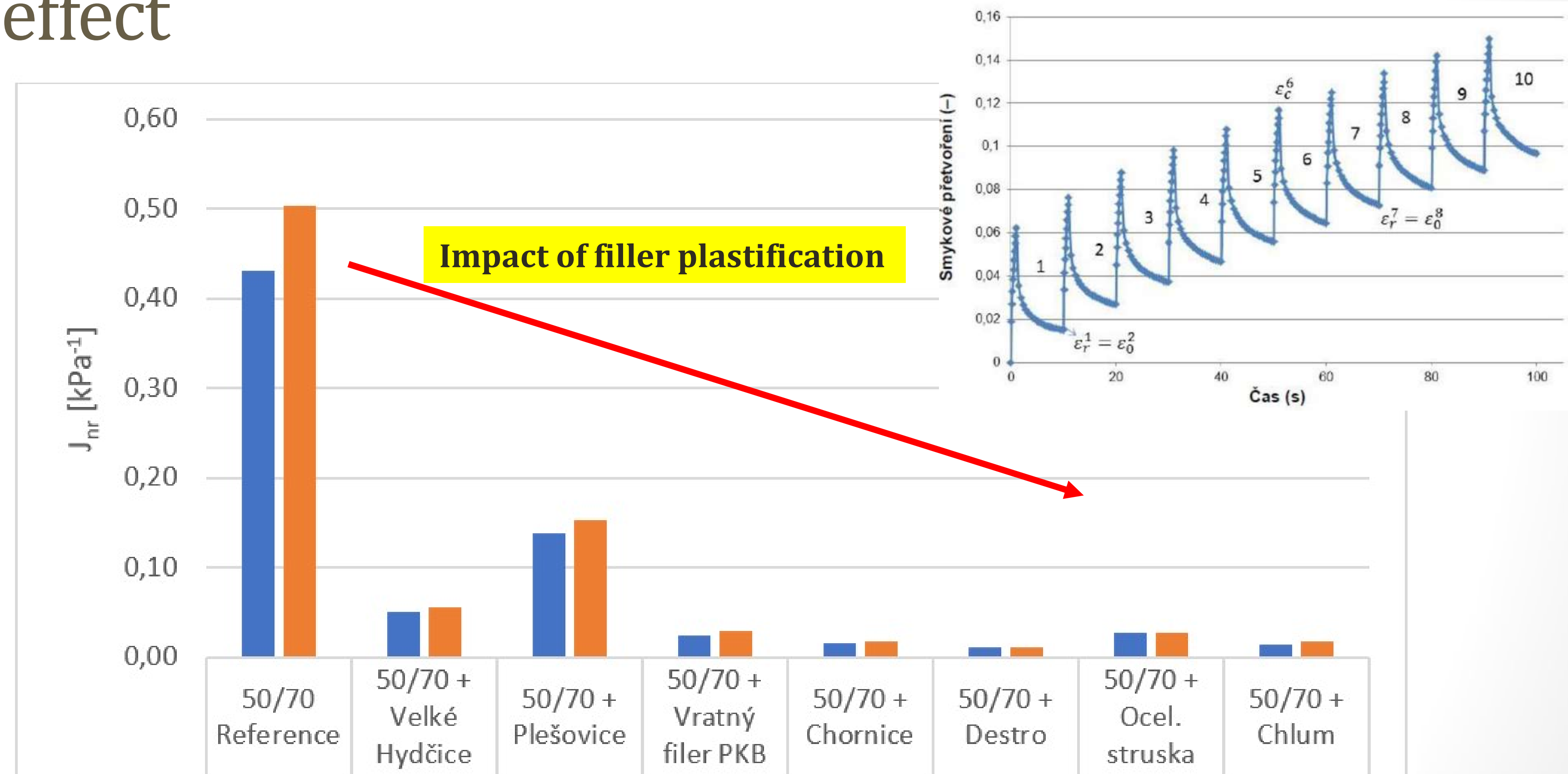
Possibilities how to think about the filler stiffening effect

Vzorek	ΔL [mm]	F_{max} [N]	$E_{celková}$ [J/cm²]
50/70 - Reference	400,0	2,1	0,1647
50/70 + Destro	59,7	20,1	0,6022
50/70 + Velké Hydčice	390,4	13,2	0,8057
50/70 + Chlum	85,1	20,0	0,7365
50/70 + Chornice	97,8	22,7	0,8428
50/70 + Plešovice	102,3	17,0	0,6989
50/70 + Ocelářská struska	191,5	13,7	0,6951
50/70 + Vratný filer PKB	110,1	17,6	0,7367



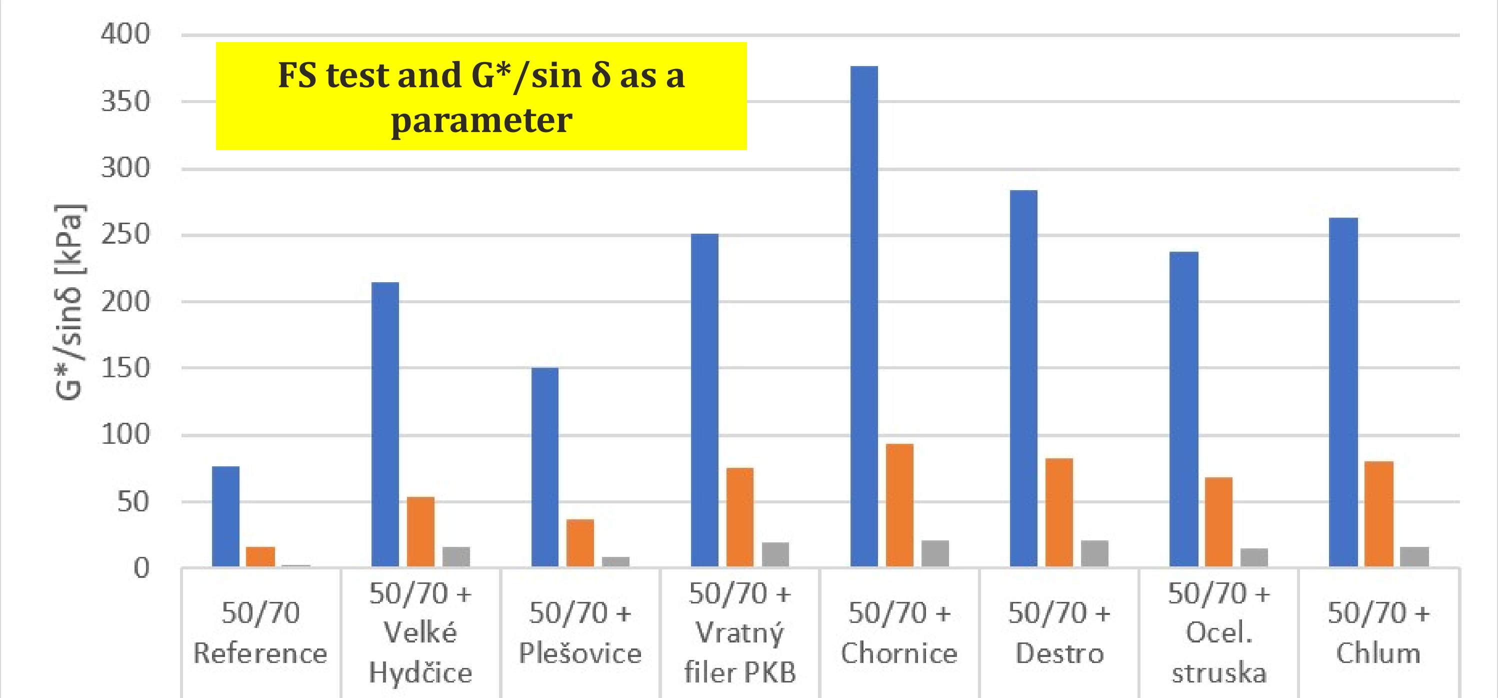


Possibilities how to think about the filler stiffening effect



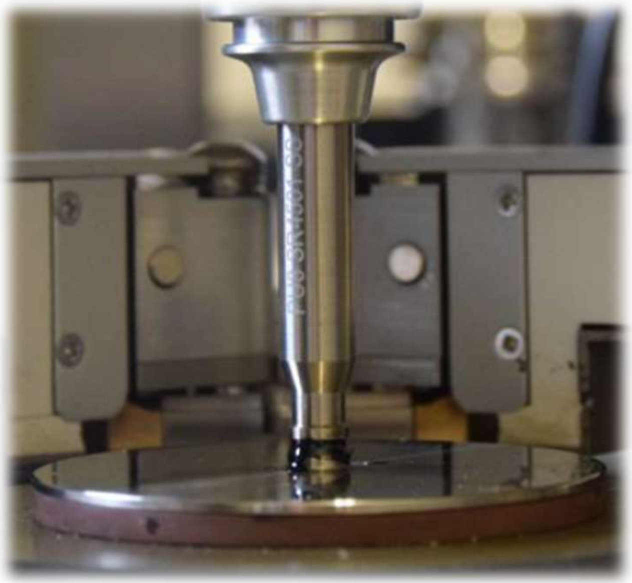
	50/70 Reference	50/70 + Velké Hydčice	50/70 + Plešovice	50/70 + Vratný filer PKB	50/70 + Chornice	50/70 + Destro	50/70 + Ocel. struska	50/70 + Chlum
0,1 kPa	0,43	0,05	0,14	0,02	0,02	0,01	0,03	0,02
3,2 kPa	0,50	0,06	0,15	0,03	0,02	0,01	0,03	0,02

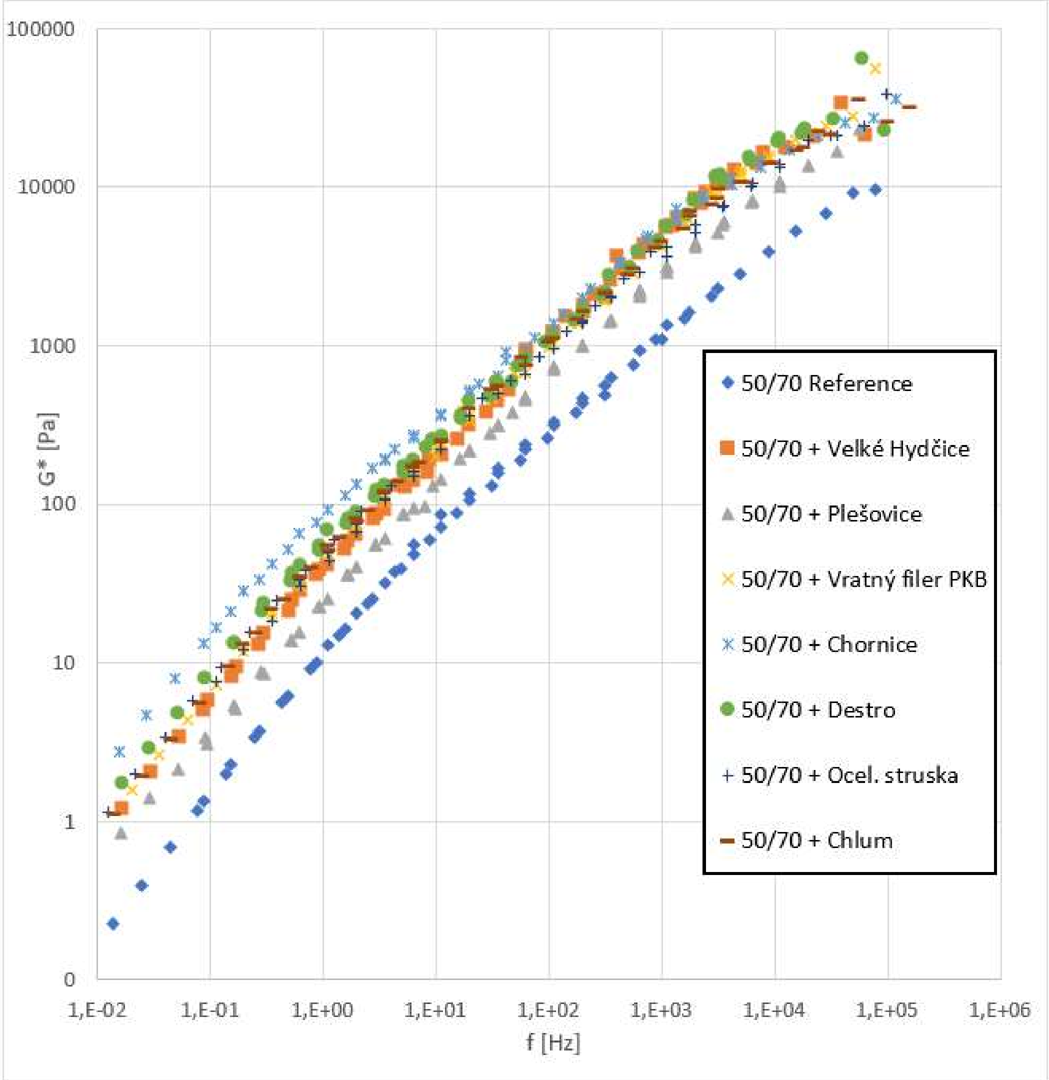
Possibilities how to think about the filler stiffening effect



	50/70 Reference	50/70 + Velké Hydčice	50/70 + Plešovice	50/70 + Vratný filer PKB	50/70 + Chornice	50/70 + Destro	50/70 + Ocel. struska	50/70 + Chlum
40 °C	76	214	150	251	377	284	238	263
50 °C	17	54	37	76	94	83	69	80
60 °C	3	16	9	20	21	21	16	16

Or using master curves





Adhesion and the relation to asphalt durability

Adhesion definition (two of many): **Bitumen performs the adhesive function that binds mineral material particles to form an asphalt mix coating.**

or

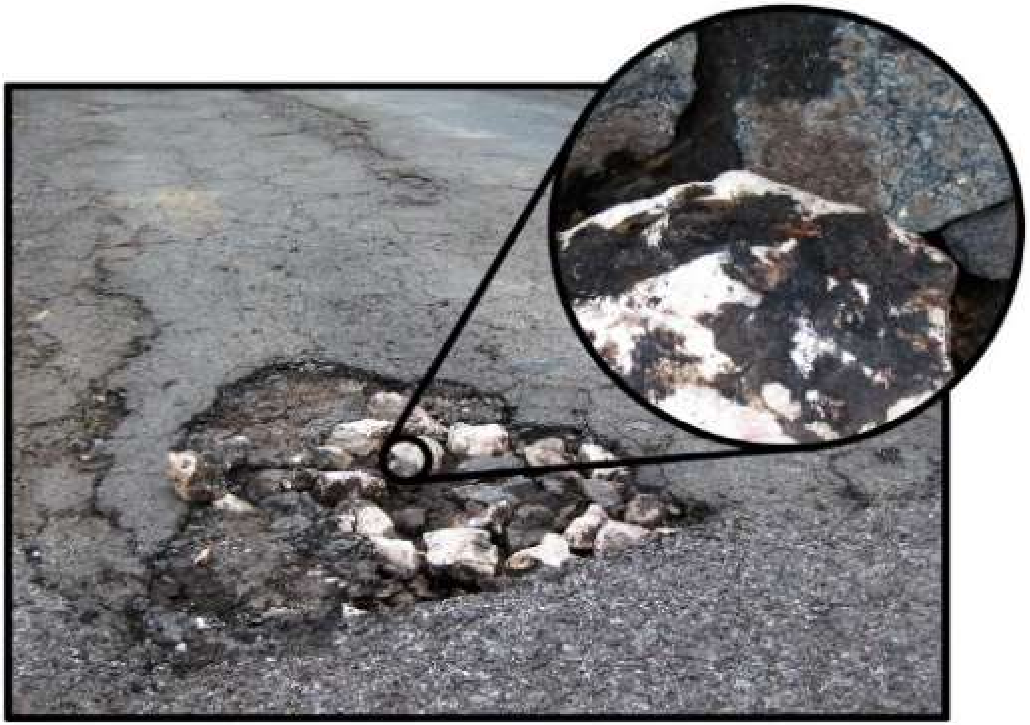
The tendency of staying together for two dissimilar material – in case of asphalt mix bitumen and aggregate.

Adhesion influences structural stability, service performance and damage evolution (durability) of asphalt layers

Durability related degradation or damage to the asphalt mixtures in the pavement structure can be caused mainly by:

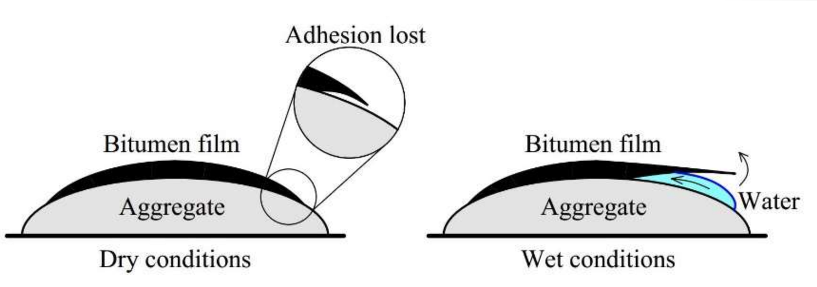
- loss of adhesion (bond) between the bituminous binder and the aggregate
- loss of cohesion within the bitumen film

Adhesion and the relation to asphalt durability



It affects the overall durability of the asphalt mix, particularly due to the ingress of water or moisture at the interface between the two material phases.

- bitumen (type, modification, origin)
- aggregates and fillers (acidic, alkali)



Adhesion and theories behind

Adhesion is mutual interaction between aggregate particle and the bitumen leading to firm coating of the binder and adhering to the aggregate surface.

It is still of the most complicated phenomena we have in asphalt mixtures.

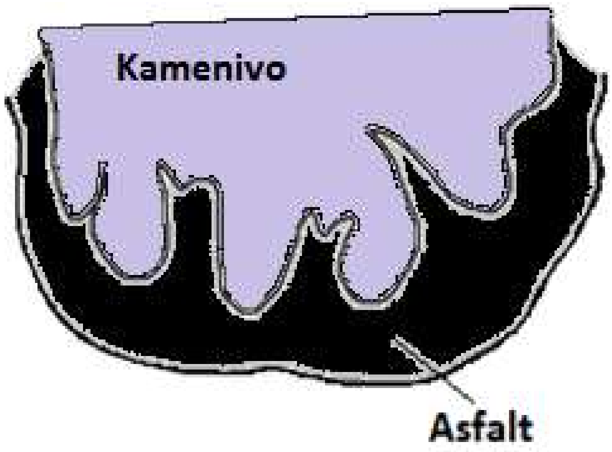
Theories you can find:

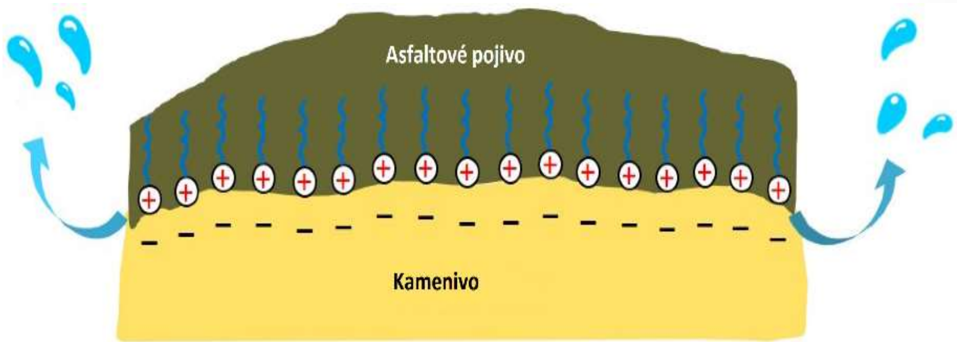
- **Mechanical theory** – bitumen will penetrate into the irregular aggregate surface with rough texture generating a mechanical interlock between the binder and aggregate (influence of texture and wettability)

  Not easy to measure the interlock directly.

- **Chemical reaction theory** – adhesive bond is caused by a chemical reaction between carboxylic acid components in bitumen and alkali component in aggregate. The relative affinity has been repeatedly quantified between aggregate surfaces and the functional bitumen groups including the moisture sensitivity of aggregates with different chemical and mineral compositions.

Adhesion and theories behind



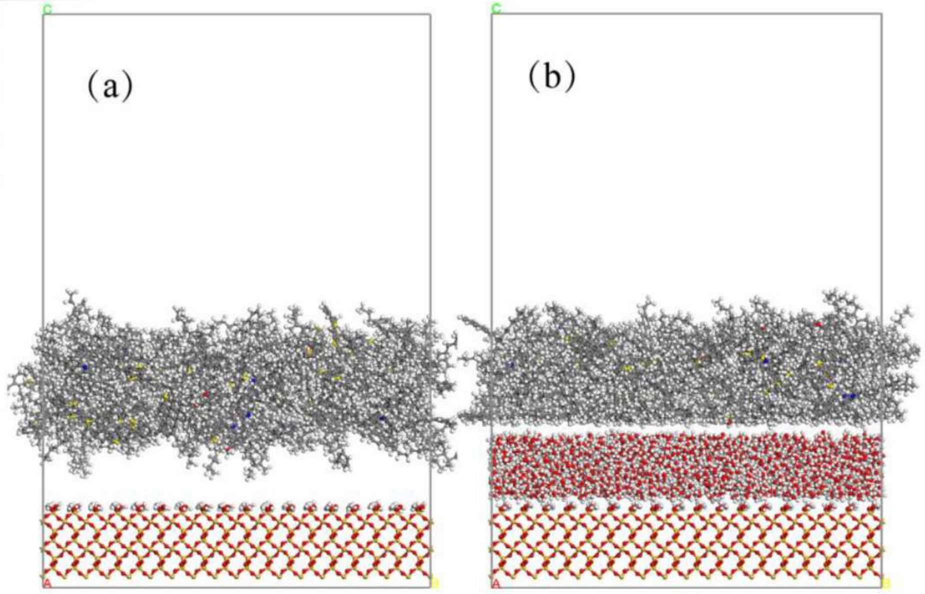


Adhesion and theories behind

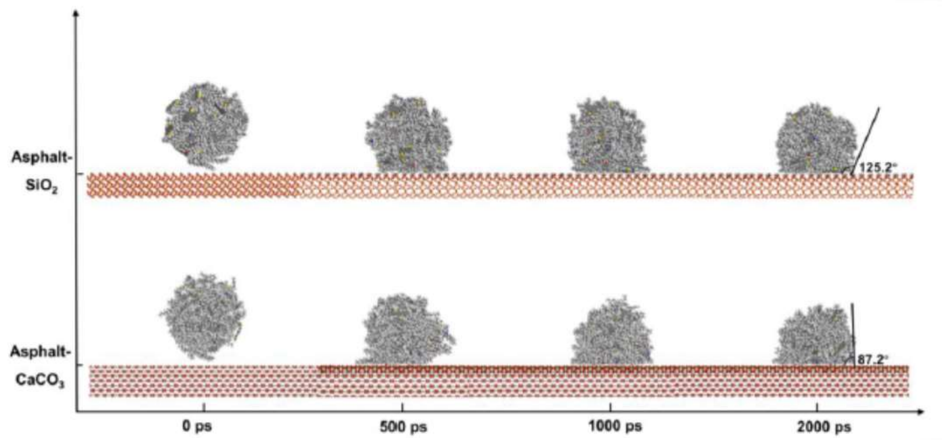
- **Molecular orientation theory** – suggestion that the main reason of adhesion is caused by the orientation alignment of polar bitumen molecules on aggregate surface. When bitumen comes to contact with aggregates surface, the polar molecules of bitumen will orient themselves in the direction of polarization of the aggregate ions so as to satisfy the energy demands of aggregates (water molecules are more polar and may easier meet the energy demands).

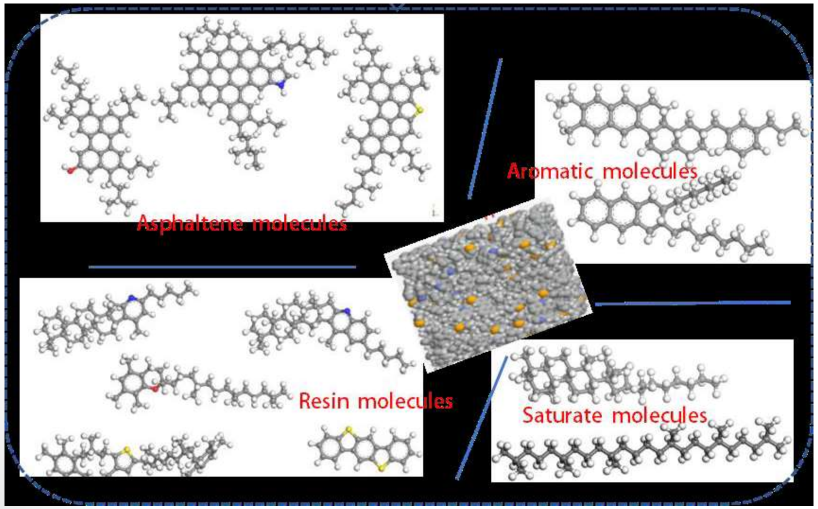
- **Electrostatic theory** – adhesive strength could be attributed to the needed strength to separate the charged surface in overcoming the Coulombic forces. The electrostatic interaction between surfaces in the presence of an aqueous medium is different from the pure Coulombic forces of water containing dissolved ions. Solid surface (aggregate) will be charged in the presence of water for its high dielectric constant, which results in two charged layers to be formed (can be measured by zeta potential or electrokinetic potential)

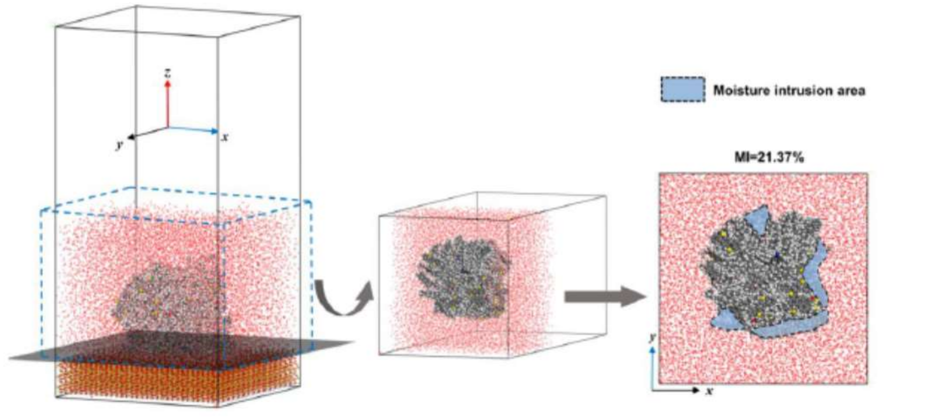
  Zeta potential is not easy to be obtained.



Playing with Molecular Dynamics





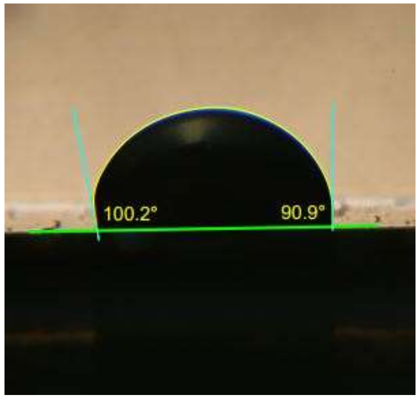


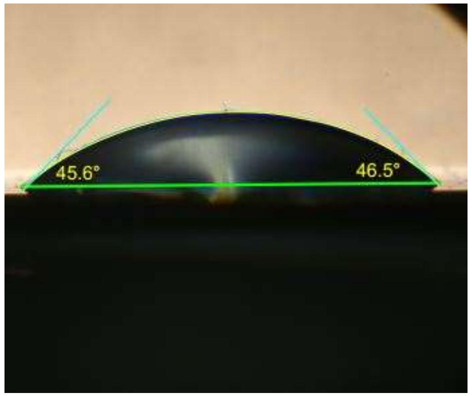
Adhesion and theories behind

- **Weak boundary theory –** indicates that adhesive damage may happen due to the low cohesive strength in the interface region (impact of dust, dissolution of compounds at the aggregate surface after contacted with water)

  Difficult to quantify and control.

- **Surface structure theory** – adhesion mainly depends on aggregate surface structure. Thus, should be better for the aggregate with a rougher surface. The contact angle and contact area of aggregate are considered to be two main factors of influencing interfacial adhesion in this theory





Adhesion and theories behind

- **Surface free energy theory (thermodynamic theory)** – been widely used to interpret the adhesion property currently. It indicates that energy exchange will happen when the aggregate surface is wetted by bitumen. Surface free energy for a material is defined as the needed energy to separate the liquid or solid to coin a new interface in a vacuum. Uses total surface free energy which is composed by Lifshitz-van der Waals component and acid based (polarity) component .

  For asphalt mixtures, the work of adhesion between bitumen and aggregate is the work done or energy needed to separate these two materials to create a new unit of area for each material in vacuum.

Cohesion and what is the difference

In order to achieve the desired bonding of the individual components of the asphalt mix, a compact, cohesive system must be created. Adhesion, as already mentioned, is therefore the interaction between the aggregate and the binder that leads to the binder adhering firmly to the aggregate surface. It is the interaction between both.

But in the mixture we have many various aggregate particles coated by bitumen.

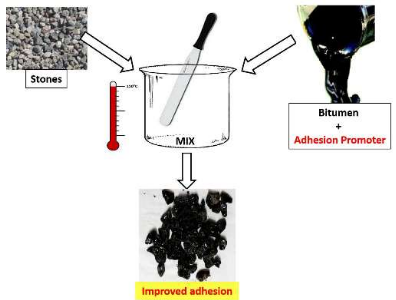
This interconnection of individual aggregate particles is then called cohesion.

Therefore we have either adhesive or cohesive failure in asphalt composite.

Testing adhesion and moisture susceptibility

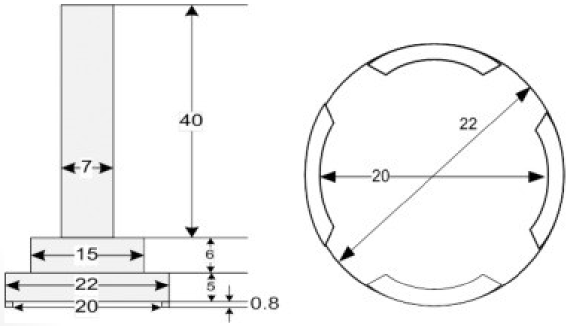
Still very very tricky topic…..

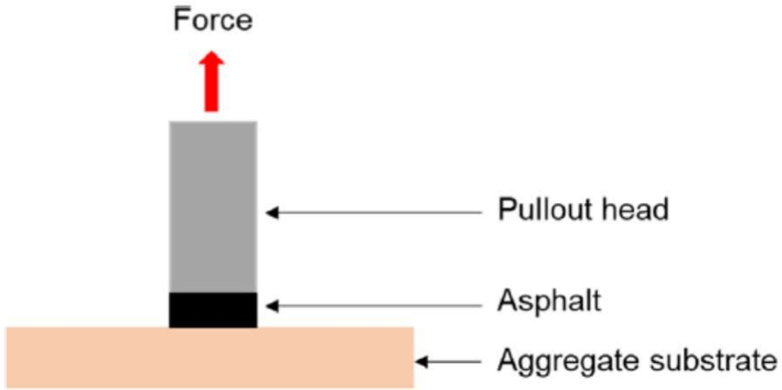
- EN 12697-11 for the determination of the affinity between aggregate and bitumen: (a) rolling bottle test, (b) static immersion test, (c) boiling water stripping method
- ASTM Boiling water test
- Immersion test at elevated temperature (CZ procedure)

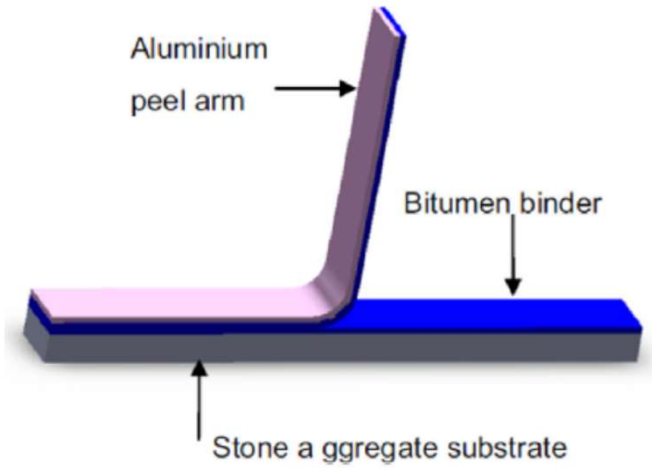


Testing adhesion and moisture susceptibility

- Pull-off or direct-pull tests (BBS, PATTI)
- Peel tests

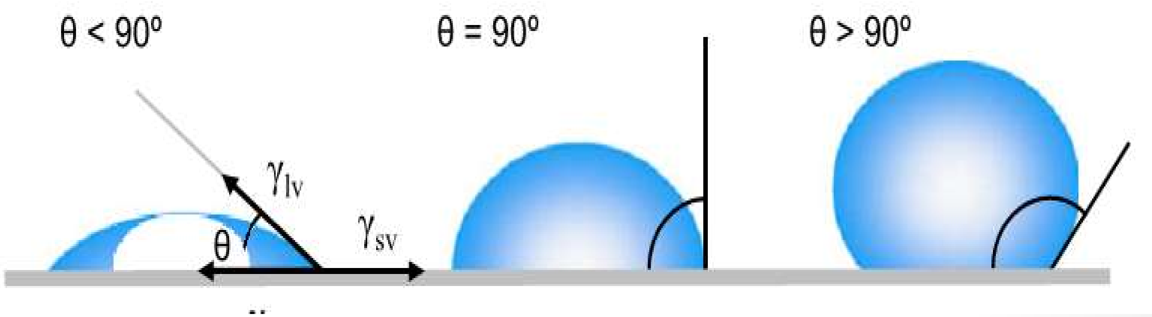






Testing adhesion and moisture susceptibility

- Contact angle methods
  - Sessile drop method
  - Column wicking method.
  - Wilhelmy plate method
- Calorimetric method



Testing adhesion and moisture susceptibility

- present approach in Europe often subjective

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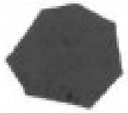
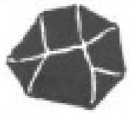
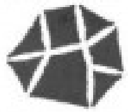
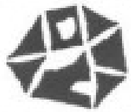
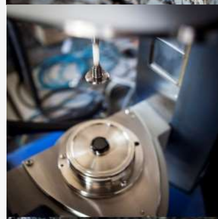
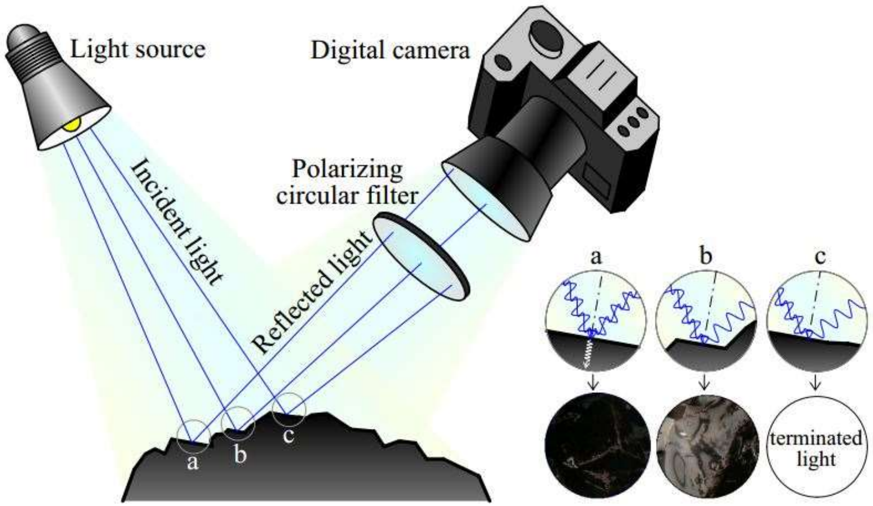
100	
90	
80	
70	



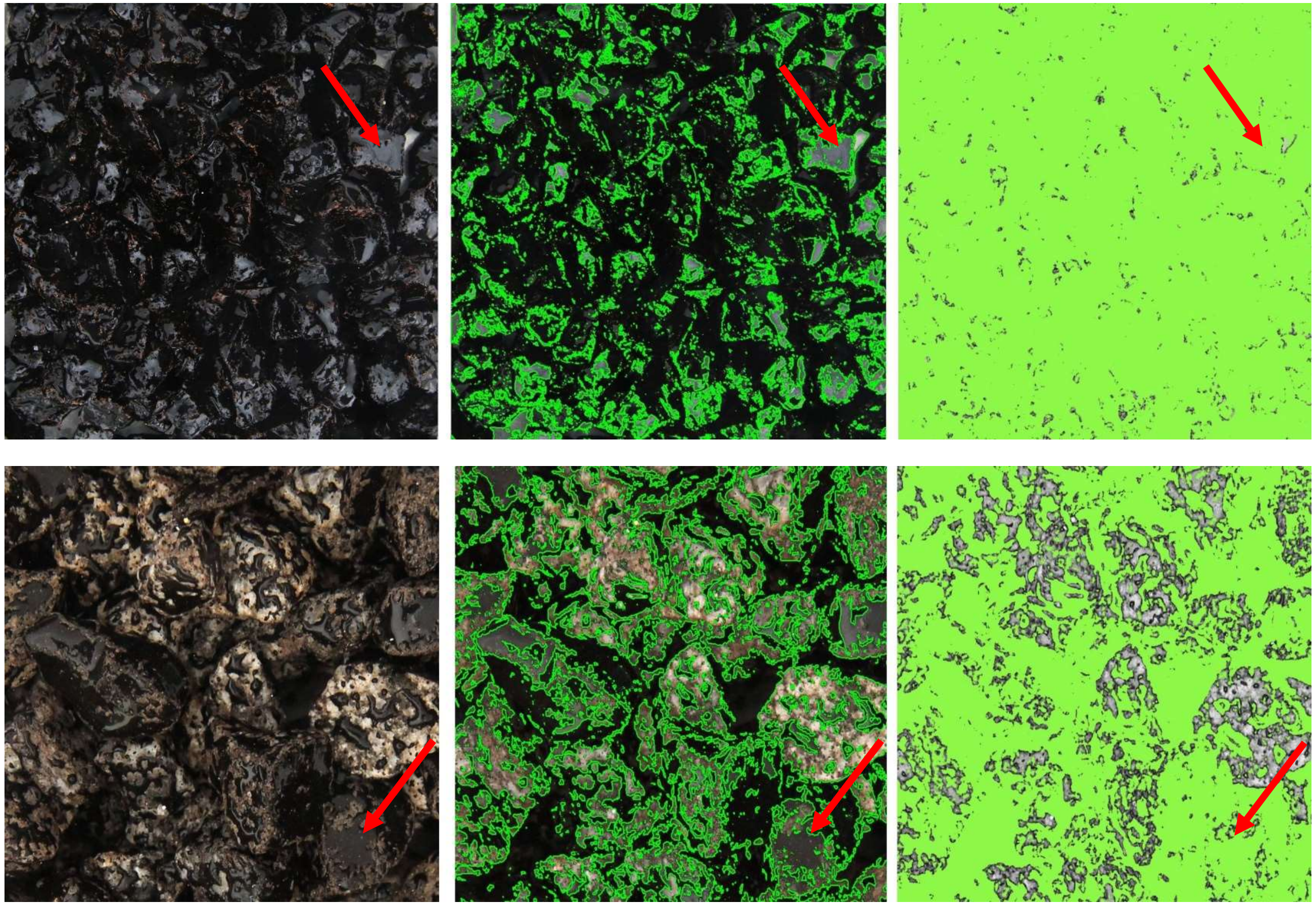
Testing adhesion and moisture susceptibility

- laboratory semi-automatic methods and their limitations
  - gray level thresholding
  - entropy-based segmentation
- based on the determination of the local entropy - the image structure of the assessed material is based on the assumption that smooth surface belongs to the binder, while the rough surface belongs to the aggregate
- key part: sharpness of the acquired image guarantees a detailed structural drawing of the imaged materials

Testing adhesion and moisture susceptibility

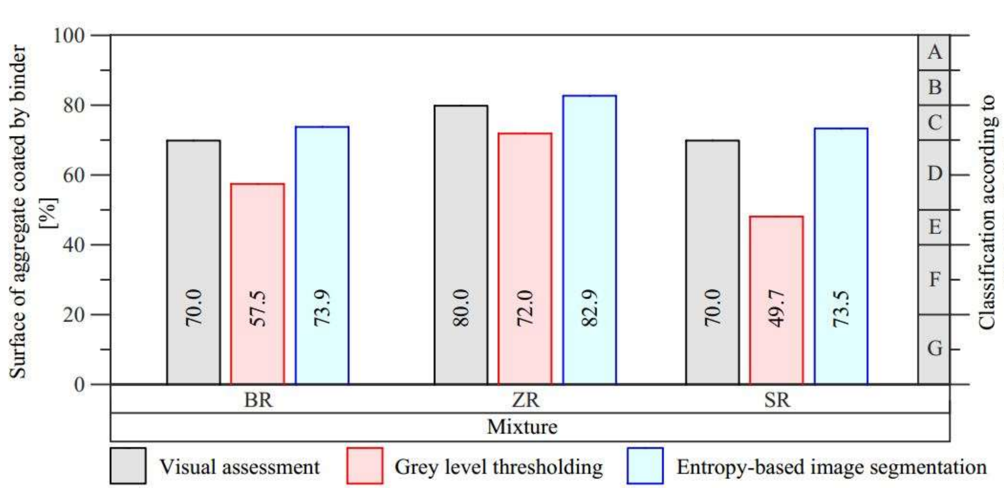


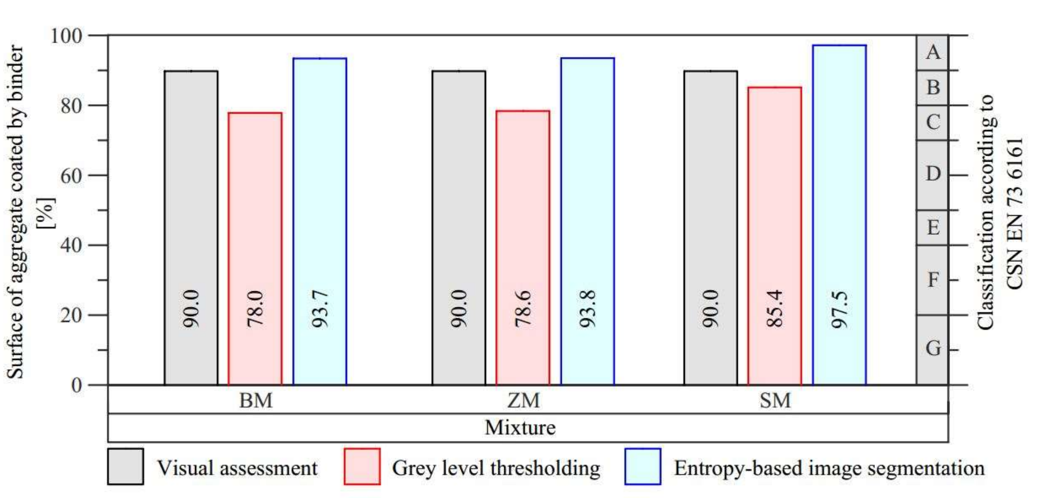
Testing adhesion and moisture susceptibility



Original photo GLT EIS

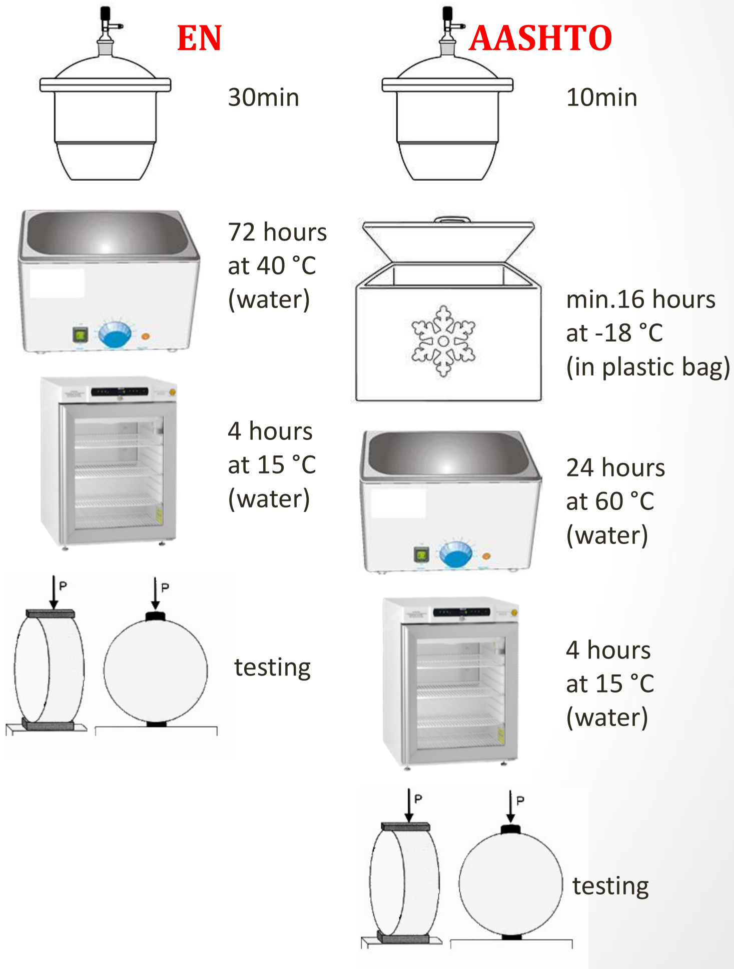
Testing adhesion and moisture susceptibility





Testing adhesion and moisture susceptibility

- Hveem stability
- Marshall immersion
- Lottman and modified Lottman test
- Indirect tensile strength ratio
- Direct tensile strength ratio
- Immersion compression
- Double punch test (ratio between the shear strength in compression after and before exposure of specimens to moisture
- Cantabro test

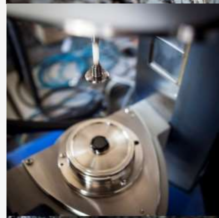


Example of assessment of alternative fillers

Filler suitability test according to EN 1744-4:2006, Annex A

- asphalt mixture of AC 8 type with exactly given amount of filler
- paving grade 160/220
- voids content 5,5±0,5%
- compaction 2x50 blows and dividing test specimens into two groups
- wet group in water bath at 40°C for 48 hrs

Component	Dry content portion [wt.%]	Total content [wt.%]
Coarse aggregate 5/8 mm	25.0	23.4–23.5 (depending on the aggregate type)
Medium-size aggregate 2/5 mm	25.0	23.4–23.5 (depending on the aggregate type)
Fine aggregate 0.125/2 mm	40.0	37.4–37.6 (depending on the aggregate type)
Added filler	10.0	9.4
Bitumen 160/220	—	6.0

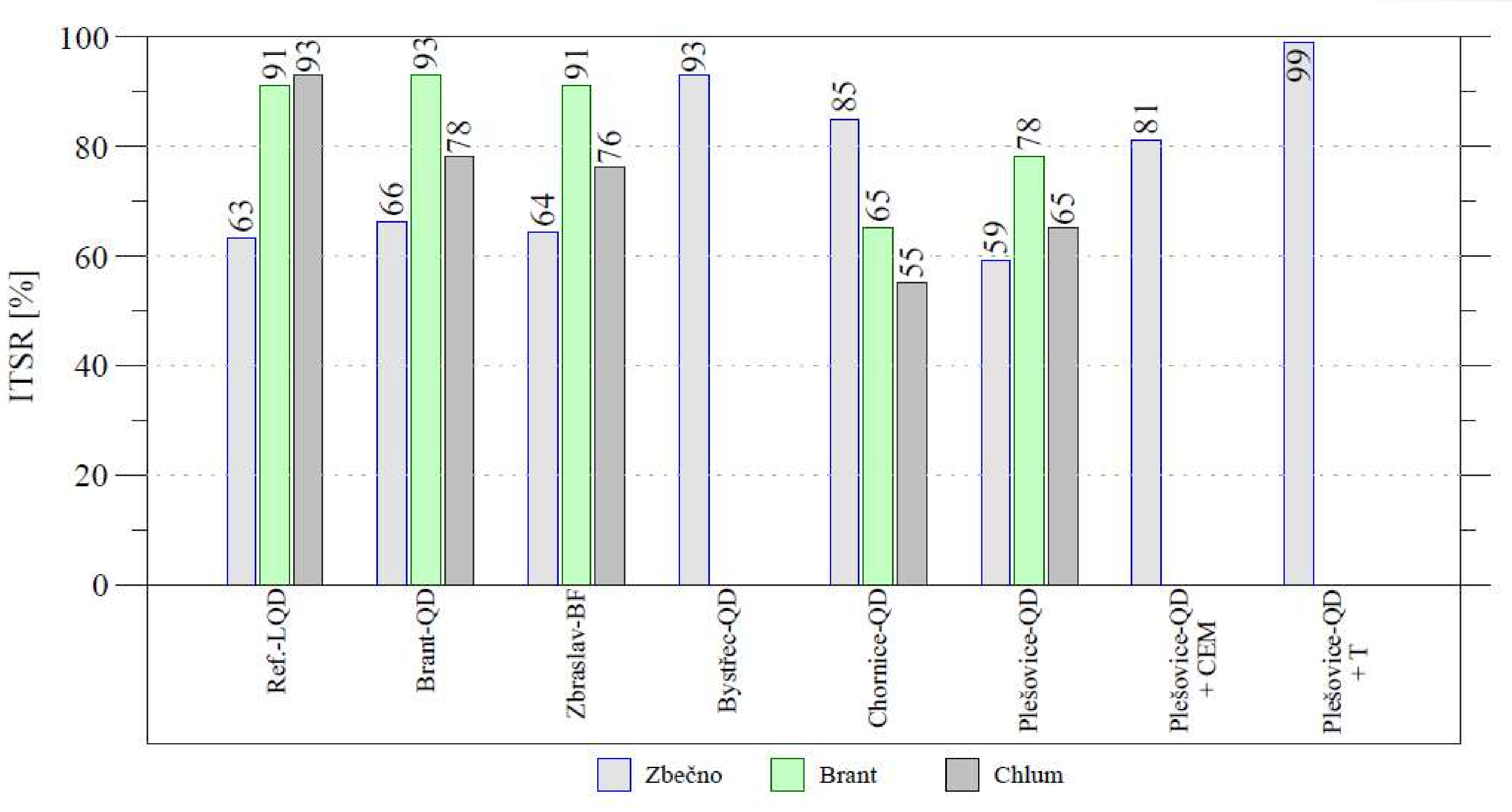

Example of assessment of alternative fillers

Filler suitability test according to EN 1744-4:2006, Annex A

- assessment by Marshall stability ratio and Marshall stiffness ratio (tested typically at 60°C)
- you can run normal stiffness prior as well

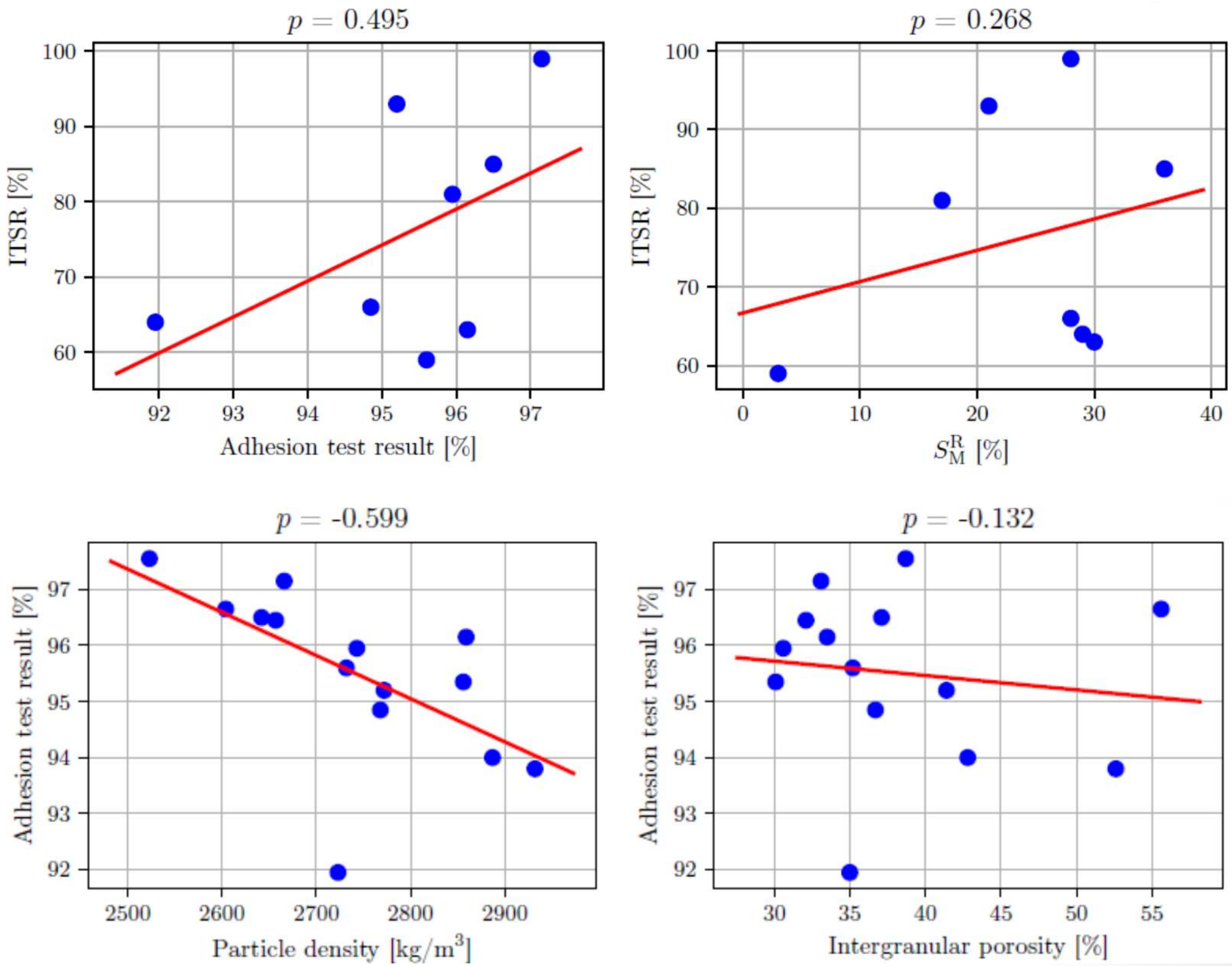
$$S_M^R = \frac{S_M^{dry} - S_M^{wet}}{S_M^{dry}} \times 100\,[\%]$$

$$T_M^R = \frac{T_M^{dry} - T_M^{wet}}{T_M^{dry}} \times 100\,[\%]$$


100
80
60
40
20
0
ITSR [%]
63
91
93
66
93
78
64
91
76
93
85
65
55
59
78
65
81
99
Ref.-LQD
Brant-QD
Zbraslav-BF
Bystřec-QD
Chornice-QD
Plešovice-QD
Plešovice-QD + CEM
Plešovice-QD + T
Zbečno
Brant
Chlum

Filler	S_M [kN]	S_M^R [%]	T_M [kN/mm]	T_M^R [%]	E (15 °C) [MPa]	Voids [%]	ITS [MPa]	ITSR [%]
Zbečno aggregate								
Ref.-LQD	9.0 6.3	30	4.1 1.9	54	4793 4339	6.5	1.2 0.7	63
Brant-QD	8.1 5.8	28	3.2 1.6	50	3890 4252	5.0	1.4 0.9	66
Zbraslav-BF	9.2 6.5	29	3.5 1.9	46	4182 4525	6.2	1.4 0.9	64
Bystřec-QD	10.1 7.9	21	3.5 2.2	37	3852 3769	5.1	1.1 1.0	93
Chornice-QD	7.4 4.8	36	2.4 1.2	50	3776 3755	6.7	1.3 1.1	85
Plešovice-QD	7.5 7.3	3	3.0 2.3	23	4554 4477	5.3	1.2 0.7	59
Plešovice-QD +CEM	10.1 8.4	17	2.9 2.2	24	4261 4466	3.6	1.5 1.2	81
Plešovice-QD +T	9.2 6.6	28	3.7 1.9	49	6225 6391	7.2	1.2 1.2	99

Example of correlations we can then play with



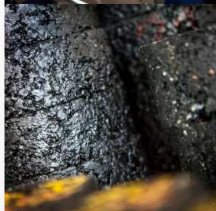
Binders and active mineral admixtures in cold recycling

When is cold recycling usually used and considered as suitable?

- if serious structural pavement problems occur (in-depth corrosion, large cracking, increased number of potholes) – for most pavement types;
- if lost in bearing capacity is evident – mainly for regional or low volume roads;
- if local repairs are anymore economic and reasonable;
- if cost-effective solution is seeked for low volume roads;
- if tar or similar hazardous substance was used in the past.



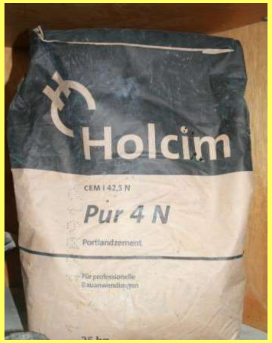





Refresh – what is cold recycling…

Foamed bitumen

Hydraulic binder



Water

Bituminous emulsion

Bitumen stabilised cold recycling mixtures

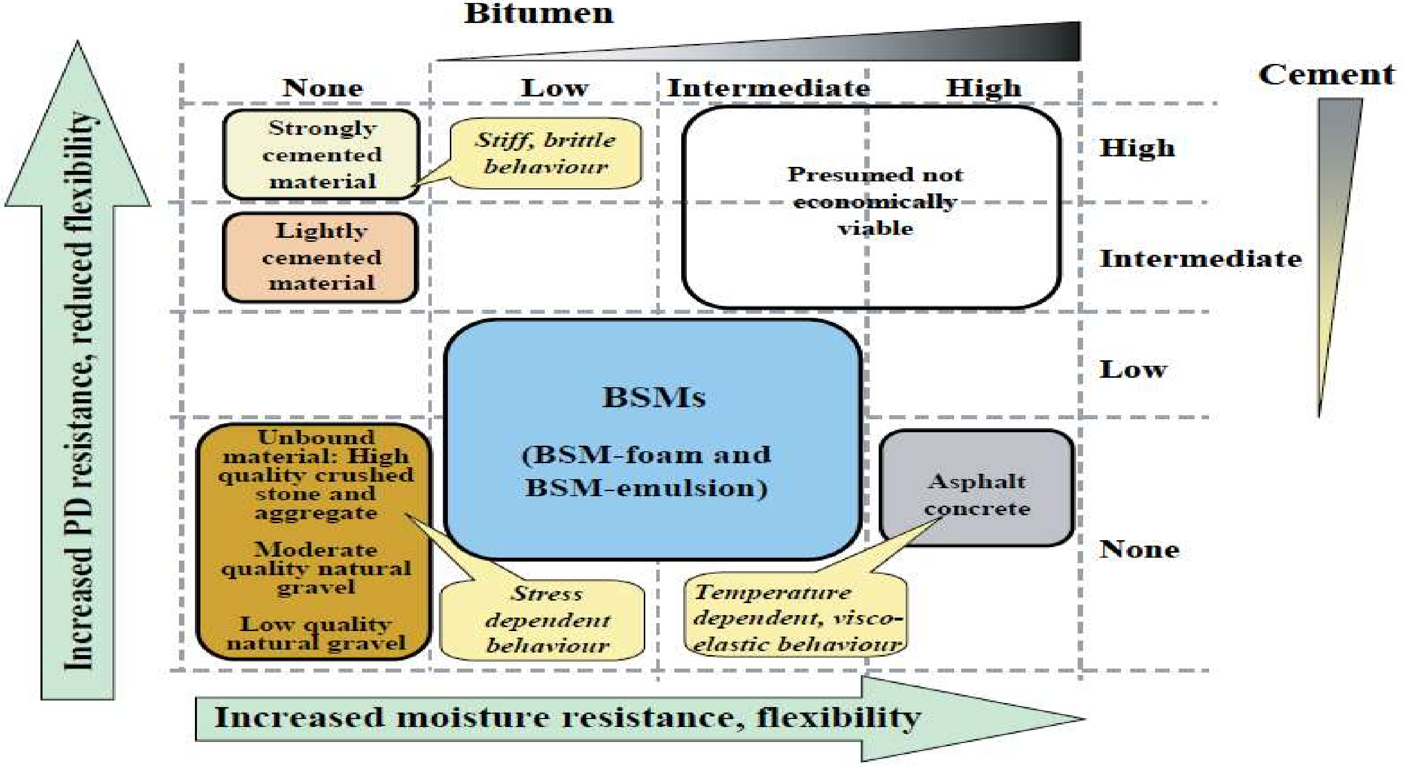

WIRTGEN

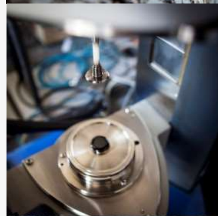

ČNES
WIRTGEN


WIRTGEN


ARP 0-8

What are the technological options for cold rec?





Cold recycling – binders typically used

- **Bituminous emulsion**: slow setting bitumen emulsions (C60B10 and similar) are the most popular, but others can be used (e.g. Norway).
- **Foamed bitumen**: a wide range of paving grade binders can usually be used. Depends on climatic conditions.
- **Cement**: majority of countries require Portland cement or Portland slag cement (CEM I 42.5/CEM II 32.5) to be used in cold recycling.
- **Special hydraulic road binders**: some countries, such as Czech Republic and Germany, have specifications for hydraulic road binders other than cement (e.g. lime or HRBs, with 32.5 or lower resistance class) to be used in road paving construction).

Cold recycling – binders typically used

Binder contents

- Collected information shows a geographical distribution among European countries:
  - Central European countries: using bituminous binders combined with relatively high contents of hydraulic binder (≈ 3 – 5 %)
  - Southern countries: using only bituminous emulsion or emulsion combined with low content of hydraulic binders (< 1.5 %)
  - Some Northern countries don’t apply cement at all, since the flexible nature of the pavements with the ability to endure frost heave in winter times require flexible base courses without rigid properties introduced by hydraulic binders.

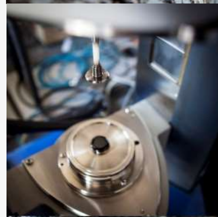
The use of **bituminous binders** together with **moderate/high cement** contents is related to climatic conditions of ***lower temperatures*** and ***relatively high humidity***, which are favourable for the use of hydraulic binders to increase bearing capacity of base/binder layers.

The hydraulic binders are required to use the water in the mixture on their hydration process. In moist regions, the base layers otherwise don’t have the possibility to dry and gain their strength.

Cold recycling – binders typically used

Typical composition

- ➡ different approaches to cold-recycling practices in different EU countries
- ➡ differences influenced by:
  - important differences in climatic conditions: e.g. moist regions requiring the use of higher amounts of cement
  - geographical and historical reasons: e.g. recycling of tar enforced the use of higher bituminous binder content in order to ensure a complete coating of the RA
- ➡ this implies different mix design approaches, namely in terms of:
  - Compaction methods
  - Curing procedures
  - Performance evaluation tests

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Cold recycling – binders typically used

Cold recycling material: Definition	acronym	Content of (residual) added bitumen	Content of mineral binder
Unbound	U	0 %	0 %
Cement stabilization	CS	0 %	1 to 6 %
Lean concrete	LC	0 %	≥ 6 %
Bitumen-stabilised material	BSM	1 to 3 %	≤ 1 %
Bitumen-cement-stabilised material	BCSM	1 to 3 %	1 to 3 %
Cold asphalt mix	CAM	≥ 3 %	0 %
Sealing cold recycled material (e.g. Sealing of tar in Germany)	SCRM	3 to 6 %	1 to 6 %

Common practice today in CZ

Typically used binders:

- cationic slow-breaking bituminous emulsion C 60 B10 or C 65 B10 **(2-3.5% binder)**
- foamed bitumen made from paving grade 70/100 or 50/70 **(1.5-3% binder)**
- Portland cement CEM I/32.5, CEM II/32.5, CEM I 42.5 **(2.5-5 % binder)**
- Commercial road hydraulic binders (SM, GEOROAD, DROHART etc.)

Typical mix requirements by road administrations and designers:

- recycle 17 to 20 cm of base or base and binder layer
- use 4 % cement and 1.5% emulsion or 4 % cement and 0.9% foamed bitumen

WHY? and WHAT IS TRICKY ABOUT THESE DESIGNS?

Cold recycling – curing during mix design

Country	BSM – Bitumen stabilized materials	BCSM - Bitumen cement stabilized materials
Czech Republic	28 days: air curing at 20°C	2 days: 90% humidity at 20°C + 26 days: 40-70% moisture at 20 °C
Finland	28 days: air curing at room conditions	28 days: 95 % humidity, 20 °C
Germany		2 days: 90% humidity at 20°C + 26 days: 40-70% moisture at 20 °C
Ireland	28 days: 20 °C	28 days: 40 °C
Norway	14 days at 95 % humidity at 5 °C	
Portugal / Spain	3 days at 50 °C	7 days at room conditions




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Common practice today (I)

- the whole family of cold recycling technologies since 2023 regulated by national technical standard (CSN 74 6147)
- cold recycling for unbound and bound layers possible

Co se recykluje[a]			Pojivo	Srovnatelná vrstva[b]
Hutněné asfaltové vrstvy[b]	Penetrační makadam, nátěry	Vrstvy bez asfaltového pojiva		
NESTMELENÉ VRSTVY – RECYKLACE BEZ POUŽITÍ POJIVA				
max. 30 %	BEZ OMEZENÍ		–	MZ[c] ČSN 73 6126-1
STMELENÉ VRSTVY – RECYKLACE S POUŽITÍM POJIVA[d]				
max. 50 %		BEZ OMEZENÍ	cement / hydraulické silniční pojivo	SC $C_{3/4}$ ČSN 73 6124-1
min. 50 %		max. 50 %	cement / hydraulické silniční pojivo + asfaltová emulze / zpěněný asfalt	SC $C_{3/4}$ ČSN 73 6124-1
min. 80 %	max. 20 %		asfaltová emulze / zpěněný asfalt	SC $C_{1,5/2}$ ČSN 73 6124-1

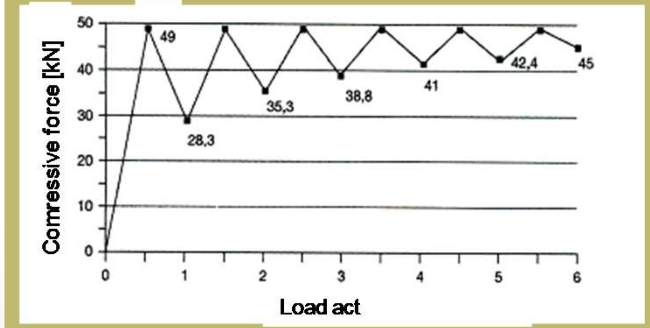
Common practice today (II)

Vlastnost		Požadavky na směsi s použitím pojiva			
		C	CA	A	C, CA
Označení směsi		0/32, 0/45		0/32	0/63
Laboratorní srovnávací objemová hmotnost a optimální vlhkost		Deklarovaná hodnota			
Dálnice	Min. pevnost v tlaku R_c po 28 dnech[a] Odolnost proti mrazu a vodě	$C_{3/4}$ 85 % pevnosti R_c	–	–	–
	Pevnost v příčném tahu R_{it} po 7 dnech[b] Odolnost proti vodě min.	–	0,30 až 0,70 MPa 75 % pevnosti R_{it}	–	
Ostatní komunikace	Pevnost v příčném tahu R_{it} po 7 dnech[b] Odolnost proti vodě min.	0,30 až 0,70 MPa 75 % pevnosti R_{it}	0,30 až 0,70 MPa 75 % pevnosti R_{it}	Min. 0,2 MPa 60 % pevnosti R_{it}	

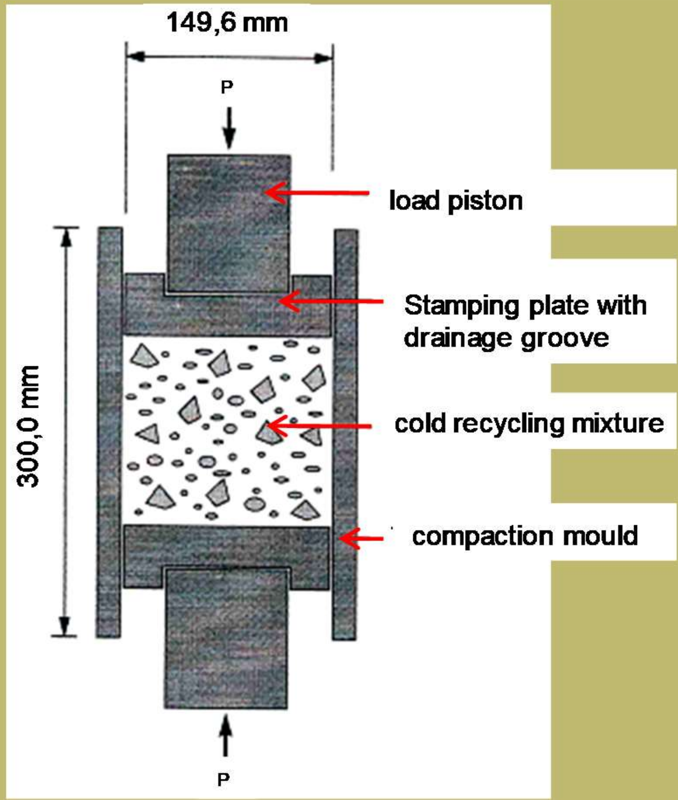
[a] Zkouší se jako směsi stmelené cementem podle ČSN 73 6124-1. Platí i pro směsi 0/45 s maximálním podílem nadsítného 15 %.

[b] Zkouší se podle Přílohy A. Platí pro směsi 0/32 a 0/45 s maximálním podílem nadsítného 15 %.

Common practice today - compaction

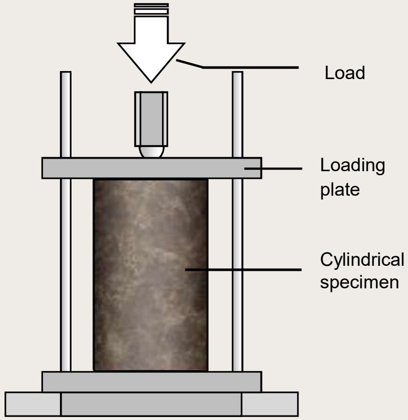


Static pressure compaction

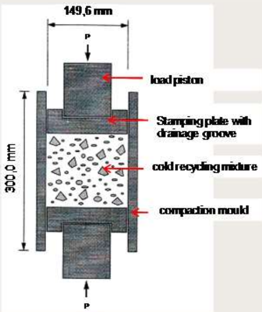


Indirect tensile strength test (destructive) @15°C

Common practice today - compaction



Static compaction	Marshall compaction	Proctor compaction	Duriez test	Gyratory compaction
CZ, DE, P, S, I	**PL, partly U.S.**		**F, UK, IE**	**F, UK, IE, F, AUS**



Are they comparable ????

Alternative pozzolana or alkali-activated binders

What sources do we have?

- cement kilm dust or lime production dust
- traditional silica fly-ash
- fly-ash from fluidized combustion
- bottom ahs from fluidized combustion
- blast furnace slag incl. granulated
- pan slag and BOF slag (steel production slag)

- binders to fulfill EN 13282-1 -2
- geopolymers
- active admixtures based on priciples known from concrete mixtures

Side effect ✓

Czech-based alternative binders

TFA – ternary fly-ash-based binder

- binder based on sulfate-calcium CFBC fly ash from a brown-coal power plant.
- fly ash arising from the fluidized coal combustion process with ground limestone. mixed with water containing plasticizing additives for improvement of the rheological properties.
- subsequently mechanically activated together with ground limestone and other additives to achieve specific refinement.
- several development generations of TFA tested and used since 2018.
- beside cold recycling or hydraulic bound granular mixtures used in concrete and for shotcrete of Prague subway.

Czech-based alternative binders

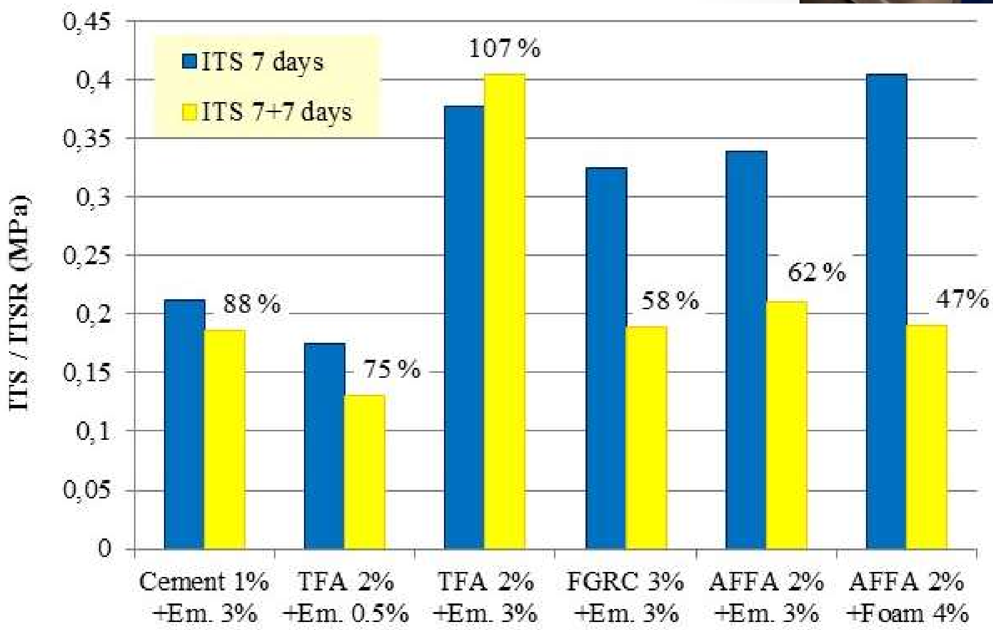
AFFA – mechanical-chemically activated fluidized bed combustion fly ash

- Produced by using high-speed grinding (HSG) in special disintegrators
- HSG leads to finer pulverization, homogeneous particle distribution, higher surface area and increase amount of internal energy in the material which chemically activates pulverized fly ash
- Material is getting pozzolanic properties with limited occurance of unwished minerals like ettringite
- The activation during milling is reached by adding small controlled amount of Portland clinker, lime hydrated or gypsum
- It can be used as alternative binder, active filler or admixture for blended binders.

Czech-based alternative binders (case TFA)

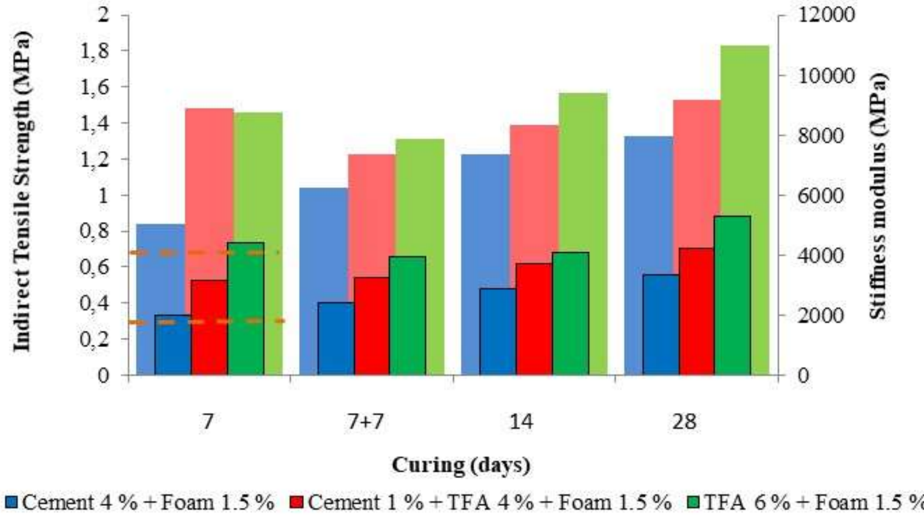
- significantly lower ITS for the mix with only 0.5 % of bituminous emulsion.surprisingly, reference mix (3 % emulsion, 1 % cement) did not come close to the minimum value (ITS 0.3 MPa)
- only mixtures with cement and TFA meet the moisture susceptibility limit (75 %).

Hydraulic binder	Content	Bituminous binder	Content	Indirect Tensile Strength (MPa)	Moisture susceptibility (%)
Cement	1.0%	Bituminous emulsion	3.0%	0.21	88%
TFA	2.0%		0.5%	0.18	75%
TFA	2.0%		3.0%	0.38	107%
FGRC	3.0%		3.0%	0.32	58%
AFFA	2.0%		3.0%	0.34	62%
AFFA	2.0%	Foamed bitumen	4.0%	0.40	47%



Czech-based alternative binders

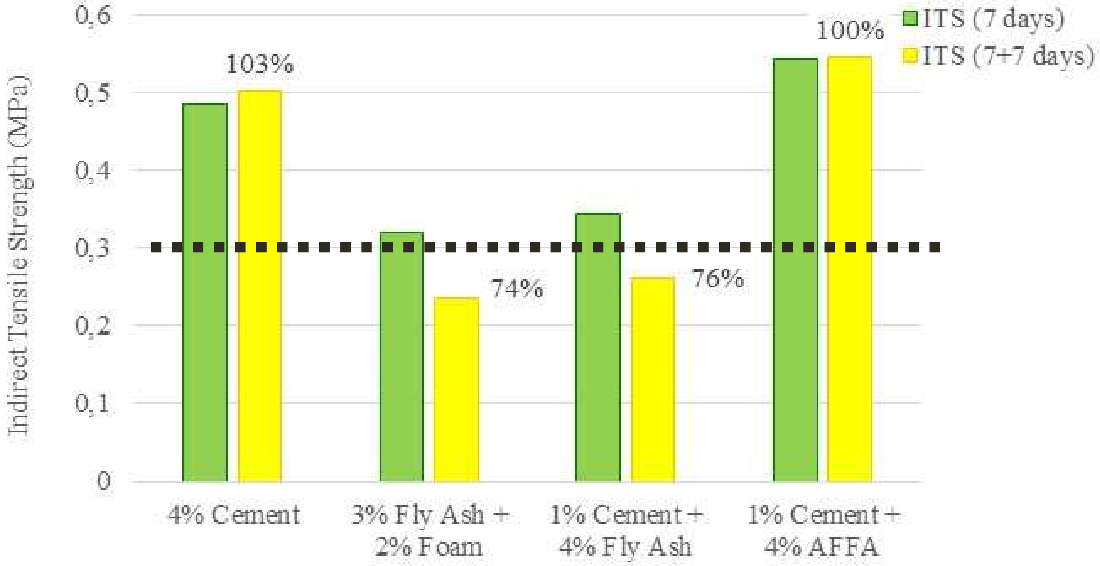
Cement	TFA_2017	Foamed bitumen	ITS_7	ITS_{14}	ITS_{28}	ITSR (ITS_{7+7}/ITS_7)
4.0%	-	1.5%	0.33	0.48	0.56	1.22
1.0%	4.0%	1.5%	0.53	0.62	0.70	1.03
-	6.0%	1.5%	0.73	0.68	0.88	0.90
Cement	**TFA_2017**	**Foamed bitumen**	**$Stiffness_7$**	**$Stiffness_{14}$**	**$Stiffness_{28}$**	**SM_{7+7}/SM_7**
4.0%	-	1.5%	5047	7337	7974	1.24
1.0%	4.0%	1.5%	8899	8320	9176	0.83
-	6.0%	1.5%	8744	9394	10970	0.90



- with increasing amount of used hydraulic binders and curing - stiffness, strength and deformation characteristics increase (sometimes too much)
- 6 % TFA exceeds the maximum ITS threshold - fast growth of strength - risk of cracks
- almost 11000 MPa stiffness (IT-CY) at 15 °C is very high

Czech-based alternative binders

Cement	Fly ash	AFFA	Foamed bitumen	ITS_7 (MPa)	Moisture susceptibility (%)
4.0%	-	-	-	0.48	103%
-	3.0%	-	2.0%	0.32	74%
1.0%	4.0%	-	-	0.34	76%
1.0%	-	4.0%	-	0.54	100%



- cold rec mixes with untreated fly ash behave significantly worse than mixtures with AFFA or cement

Trial section with 1st application of AFFA in Europe

Quality	Unit	Reference mix (4 % cement)	Alternative 1 (1 % cement + 4 % AFFA)	Alternative 2 (2 % foamed bitumen + 3 % AFFA)	Requirement for production control test
ITS after 7 days	MPa	1.00	0.39	0.25	0.25 MPa
ITS after 7+7 days	MPa	1.25	0.42	0.18	-
Moisture susceptibility	%	125.7 %	108.8 %	74.0 %	min. 75 %

- Simple 1:1 substitution of standard cement with an fly-ash based alternative binder is not possible, but… there are effective options
- To combine AFFA with limited amount of cement
- Add higher amount of AFFA and avoid cement => technical problems: necessary to apply thick layer (small density of AFFA)
    - threatened by wind
    - the recycler rolls the AFFA in front of it – potential reduction of the actual binder content in the final mix

Trial section with 1st application of AFFA in Europe

Slags as by-products from iron and steel production

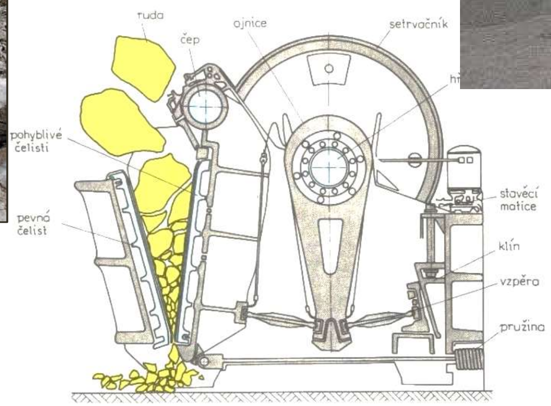
- blast furnace slag (BFS) is ‘waste’ product of iron production in blast furnace in granulated form is widely used in cement industry
- one of the most voluminous waste from the entire manufacturing industry (beside fly-ash)

2017	World production
Pig iron	1,2 bill. tones
Blast furnace slag *(estimation)*	approx. 320 mil. tones
Crude steel	1,7 bill. tones
Steel slag *(estimation)*	approx. 200 mil. tones

- the chemical and mechanical composition of slags differs and cannot be generalized in any way, the properties depends on quality of iron ore, used technology, used slagging agents and fluxes, later cooling of the slag etc.

Primary stage of slag treatment

Stabilized waste on land disposal



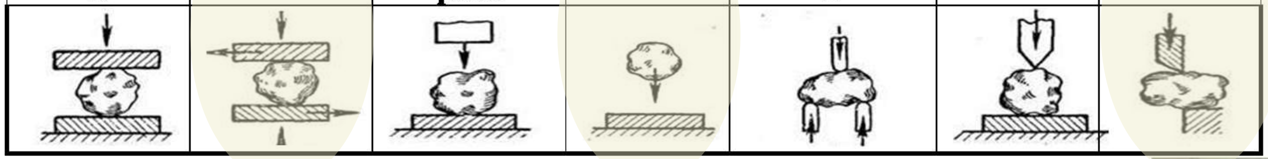
Crushing and sorting

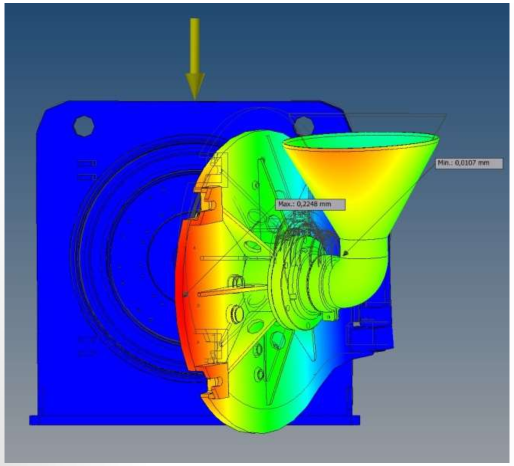
Sorted fractions of BFS aggregate

Option for secondary stage of treatment

High-speed grinding using disintegrators – the principle

1 Compressio n	2 Shear	3 Compression pulse	4 Free hit	5 Stroke/Flexio n	6 Chopping	7 Cutting





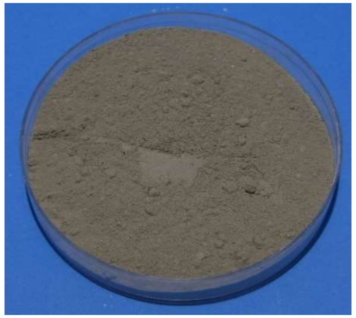
Option for secondary stage of treatment

High-speed grinding using disintegrators – suitable materials

- all kinds of recyclable composites (concrete, bricks, asphalt)
- slags, foundry sands, fly-ash
- sludge from aggregate/stone processing
- various backhouse and flue (quarry) dusts or waste fillers
- waste from sewage water treatment
- alternative upgrading of natural granular materials (volcanic tuff, zeolites, diatomaceous soils, silica sand)

Recycled concrete

Stone sludge



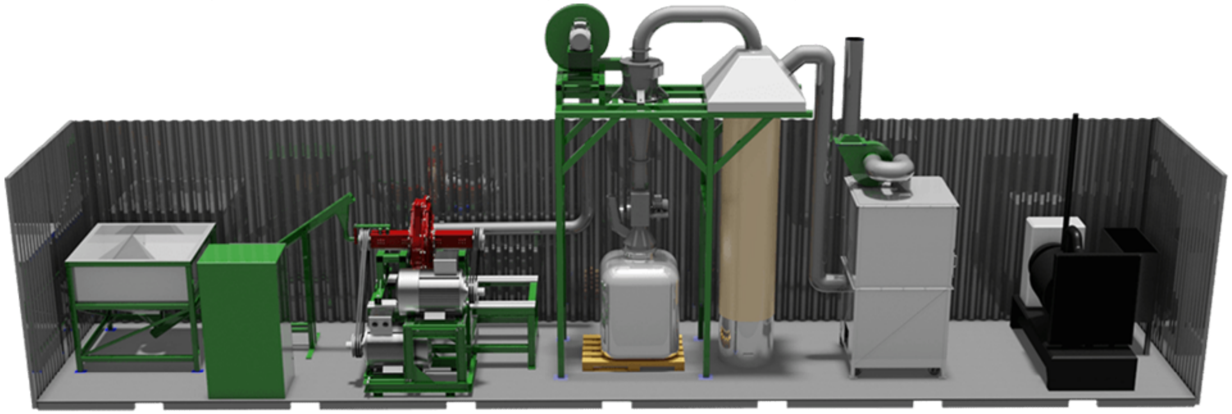
Flue dust

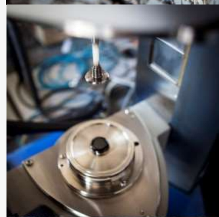
Marble cutting waste

Option for secondary stage of treatment

High-speed grinding using disintegrators – suitable materials

- not always applicable without specific treatment if same or better quality and durability required;
- for higher added value of reused material usually modifications, needed (use of additives, processing like mechanical activation);
- grinding commonly understood as the process of refining particle size while increasing specific surface of the material;
- use for homogenization, drying, pulverizing and activation





Option for secondary stags of treatment

High-speed grinding using disintegrators – principle

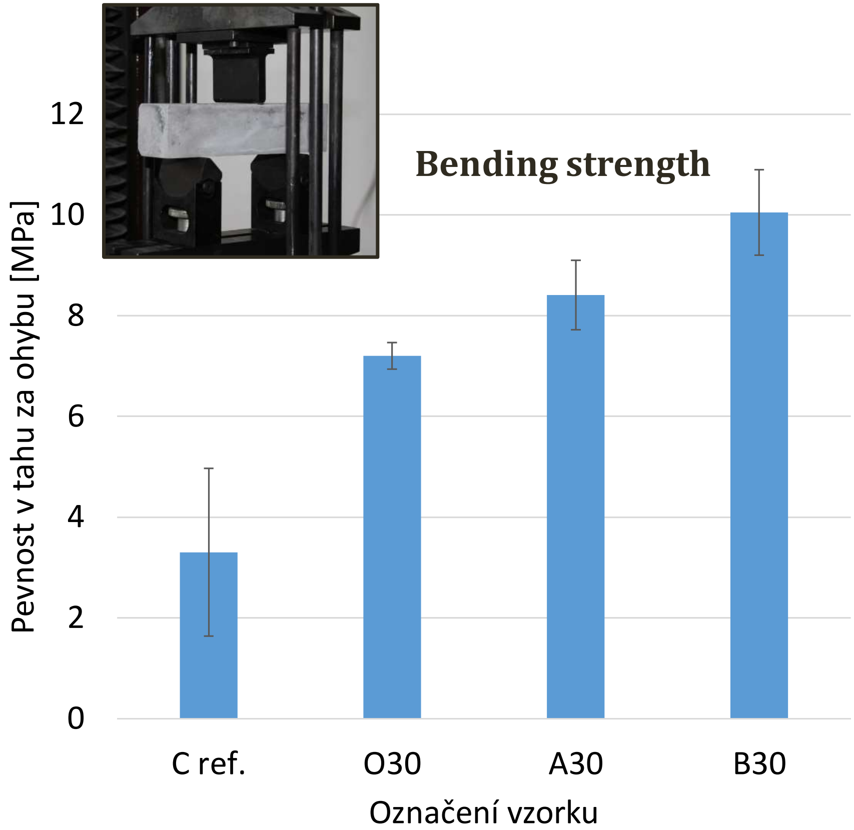
- mechanical-chemical activation by high-speed grinding (HSM) can be identified as an alternative of modifying material properties;
- associated with high-energy presence. This energy results from the grinding process and is not self-perpetuating but plays an important role, which facilitates reactiveness => energy transmitted to the particles of treated materials;
- potential in the area of producing alternative functional binders or active fillers and admixtures for other industries;
- HSM process is accompanied in various materials with significant elevation in internal energy, creating:
  - **higher content of micron and submicron particles,**
  - **formation of electrically active centers and defect networks,**
  - **creating very rugged surfaces of active particles and liberation of free radicals on this surface.**

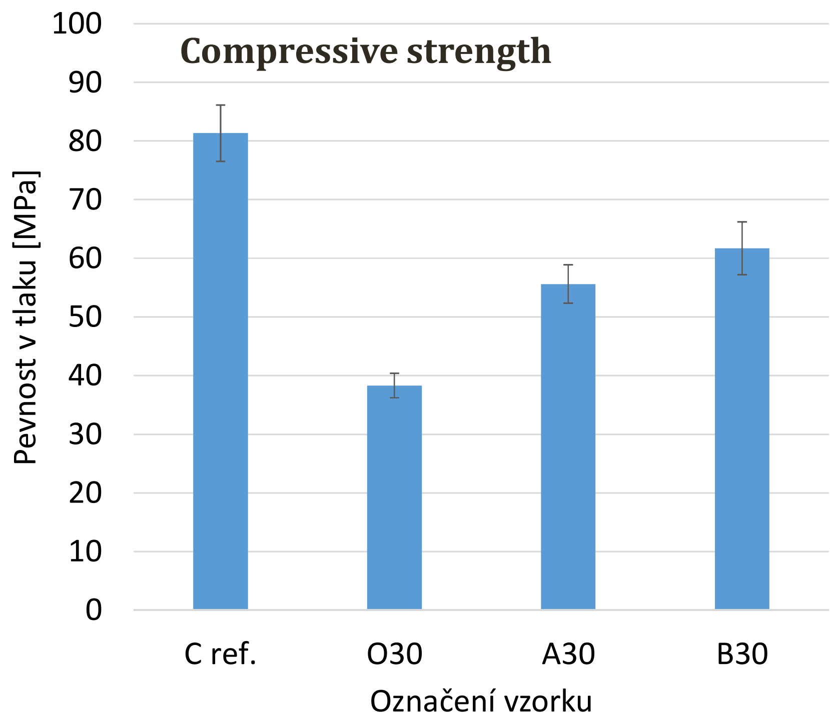




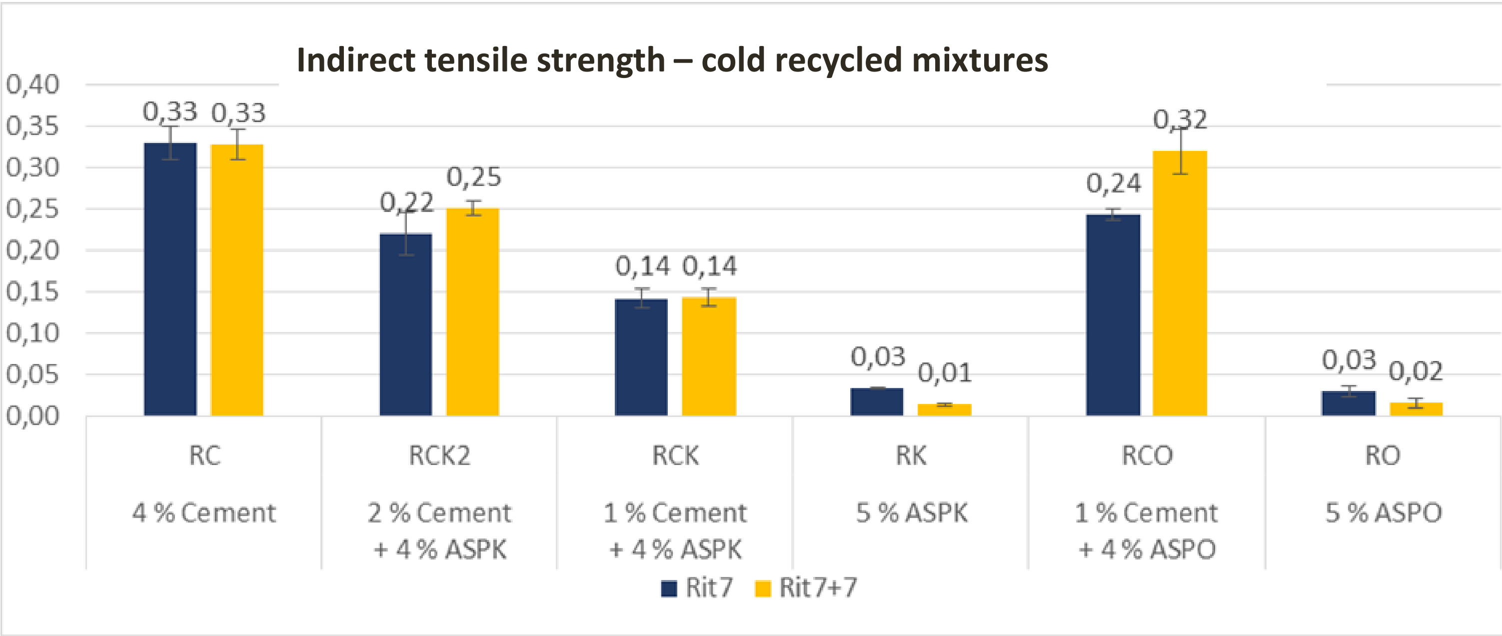
Various effects of slags

- substitution of Portland cement by ground slag (example 30 %) – cement mortars



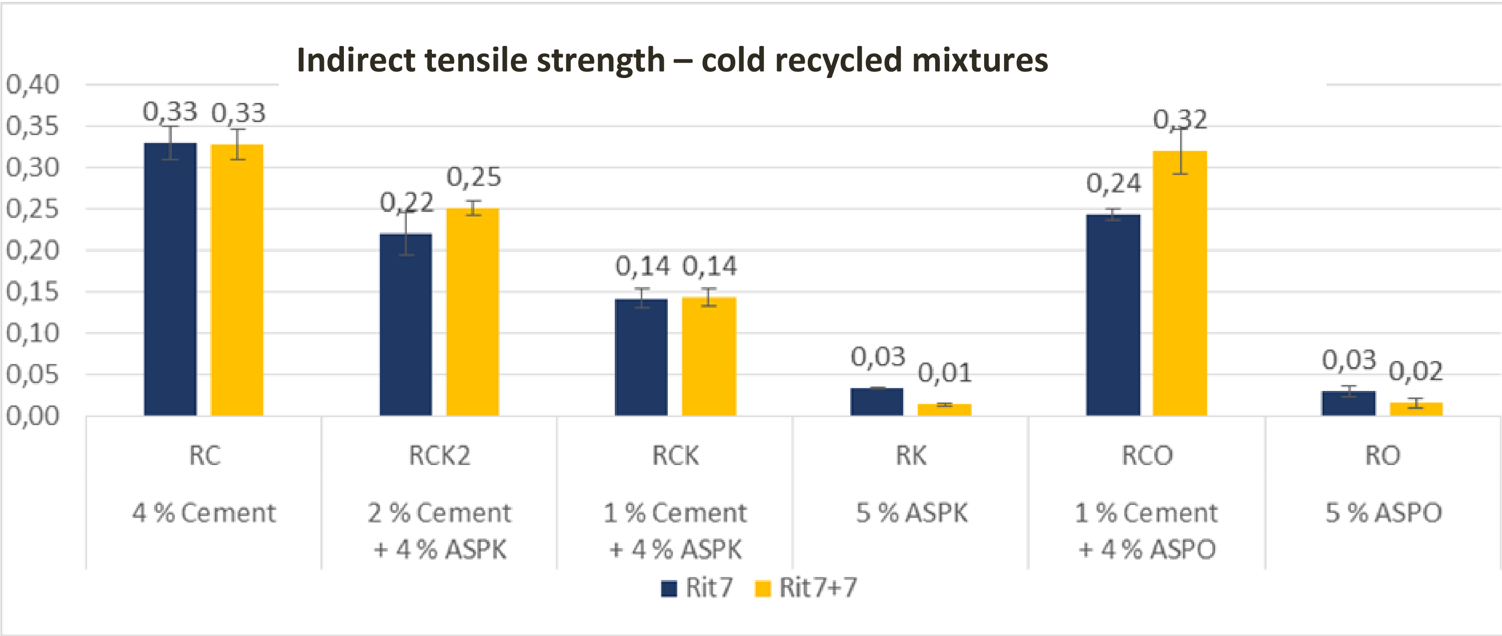


Example for ground slags in cold rec



- ASPK is activated blast furnace slag powder
- ASPO is activated steel slag powder

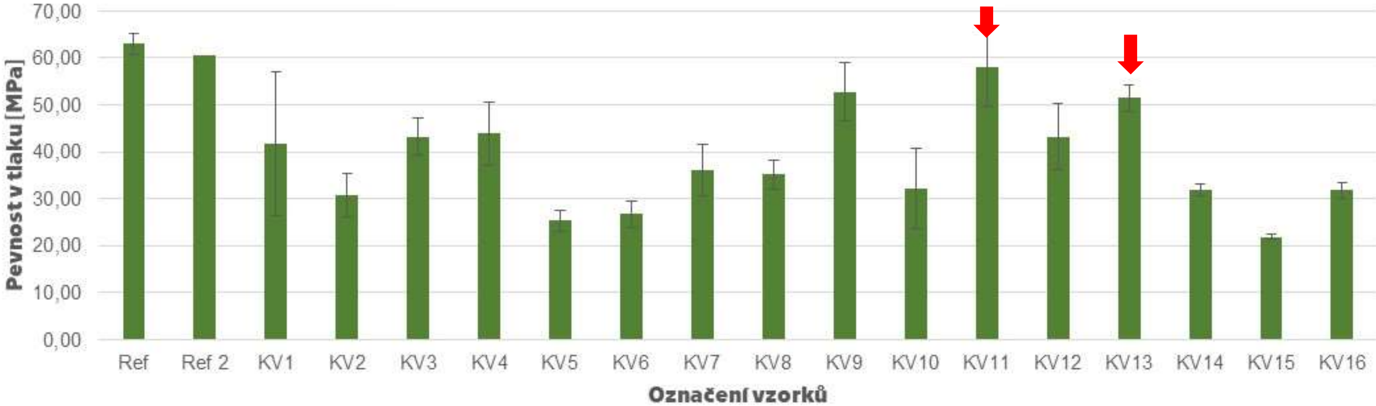
Example for ground slags in cold rec



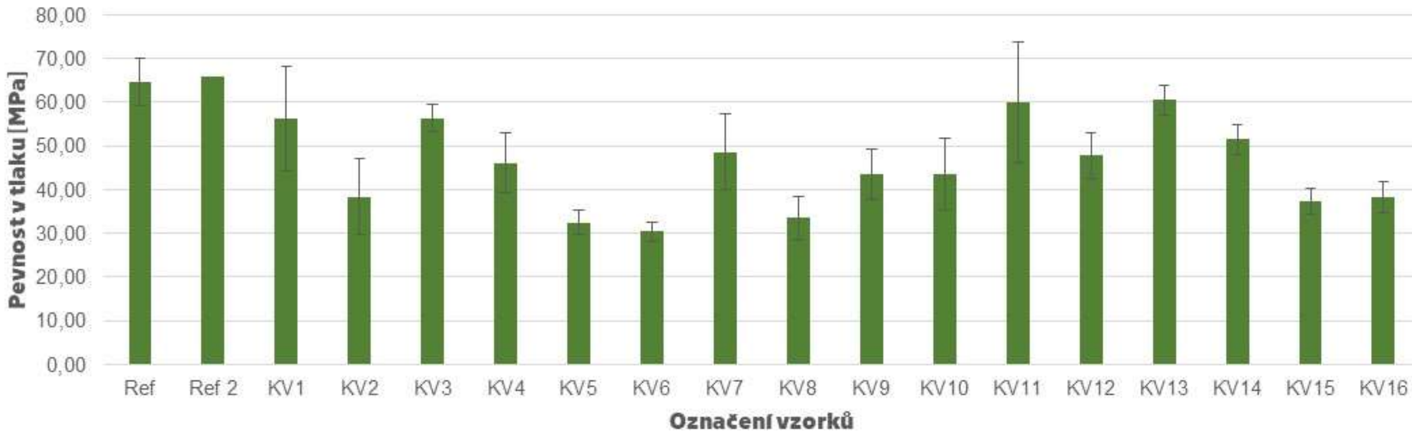
- ASPK is activated blast furnace slag powder
- ASPO is activated steel slag powder

Some of the results from developments in CZ

7 days compressive strength



28 days compressive strength



KV1: fluid + BFS 75:25 (50%)

KV3: GBFS Třinec (50%)

KV4: fluid + BFS 50:50 (50%)

KV 11: fluid + BFS 50:50 (30%)

KV 13: GBFS Třinec (30%)

Složka směsi	E_01	E_02	E_03	E_04	E_05
Betonový recyklát (Eurovia) 0/32	45,0%	45,0%	46,3%	45,0%	45,0%
Asfaltový recyklát (Eurovia) 0/32	36,0%	36,0%	37,0%	36,0%	36,0%
Asfaltový odpad výroby	9,0%	9,0%	9,3%	9,0%	9,0%
Voda	4,0%	4,0%	3,5%	4,0%	4,0%
GVS EcoCoal (mletá)	4,8%	3,0%	3,2%	0,0%	0,0%
Fluidní popílek	0,0%	1,8%	0,0%	0,0%	0,0%
Cement CEM I 42,5R	1,2%	1,2%	0,8%	0,0%	1,2%
DestroCEM 8020	0,0%	0,0%	0,0%	6,0%	0,0%
VP struska Kladno (mletá)	0,0%	0,0%	0,0%	0,0%	4,8%

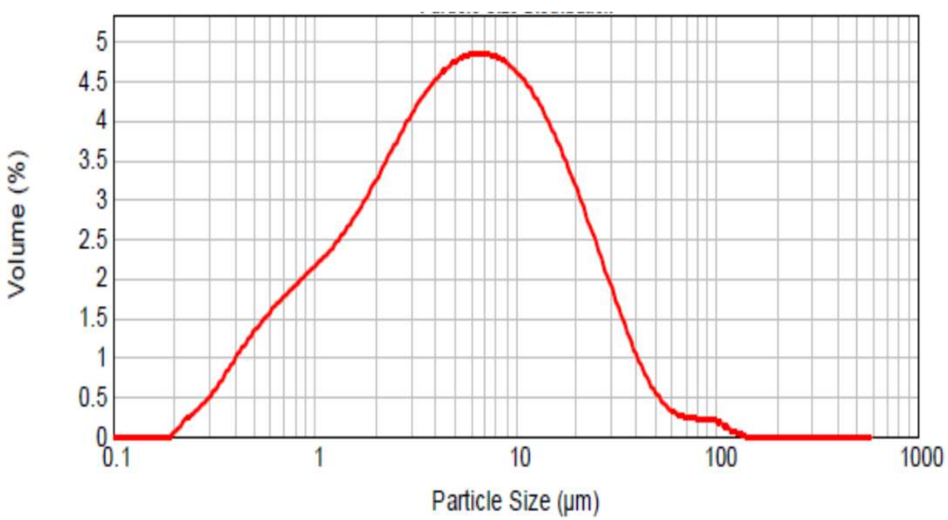
Varianta směsi	Objemová hmotnost	Sedmidenní pevnost v příčném tahu	Pevnost po uložení ve vodě	Odolnost proti účinkům vody	Modul pružnosti
	($g.cm^{-3}$)	(MPa)	(MPa)	(%)	M_{dry} (MPa)
Mix E_01	1,880	0,26	0,27	103,8	13,50
Mix E_02	1,885	0,34	0,34	99,4	23,67
Mix E_03	1,933	0,17	0,16	94,1	12,68
Mix E_04	1,884	0,41	0,42	102,6	34,54
Mix E_05	1,915	0,17	0,13	76,7	11,79

Složení směsi	E_06	E_06A	E_07	E_08	E_08A	E_01A
Asfaltový recyklát (ČVUT) 0/32	44,4%	0,0%	46,2%	44,4%	0,0%	44,4%
Asfaltový recyklát (Eurovia) 0/32	0,0%	44,4%	0,0%	0,0%	44,4%	0,0%
ŠD 0/32 (Litice)	44,4%	44,4%	46,2%	44,4%	44,4%	44,4%
Voda	5,3%	5,3%	4,6%	5,3%	5,3%	5,3%
GVS EcoCoal	0,0%	0,0%	0,0%	0,0%	0,0%	4,0%
Cement CEM I 42,5	0,0%	0,0%	3,0%	0,0%	0,0%	2,0%
DASTIT 2022	0,0%	0,0%	0,0%	6,0%	6,0%	0,0%
DestroROAD 207010	6,0%	6,0%	0,0%	0,0%	0,0%	0,0%

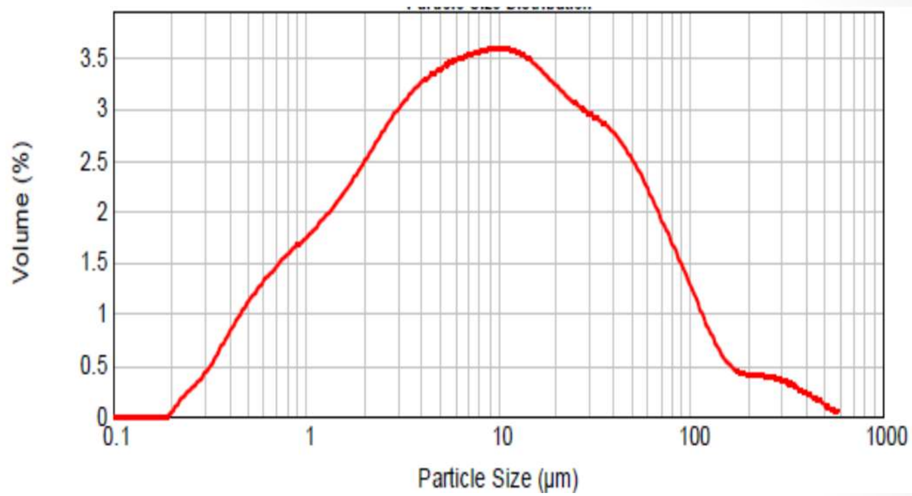
Varianta směsi	Objemová hmotnost	Sedmidenní pevnost v příčném tahu	Pevnost po uložení ve vodě	Odolnost proti účinkům vody	Modul pružnosti
	(g.cm^{-3})	(MPa)	(MPa)	(%)	M_{dry} (MPa)
Mix E_01A	1,931	0,36	0,45	123,7	25,95
Mix E_06	2,080	0,41	0,42	102,7	41,74
Mix E_06A	1,928	0,32	0,32	99,4	28,44
Mix E_07	2,099	0,45	-	-	48,04
Mix E_08	2,068	0,38	0,28	72,9	44,42
Mix E_08A	2,079	0,29	0,21	72,4	17,07

„reference mix“ → Mix E_07

Fine ground recycled concrete (FGRC) – case study

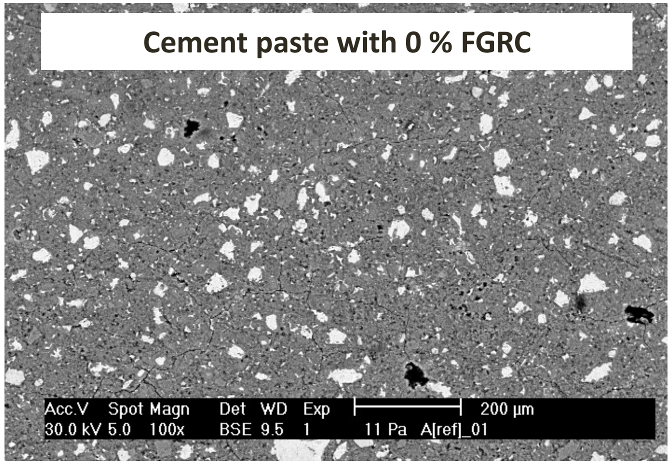


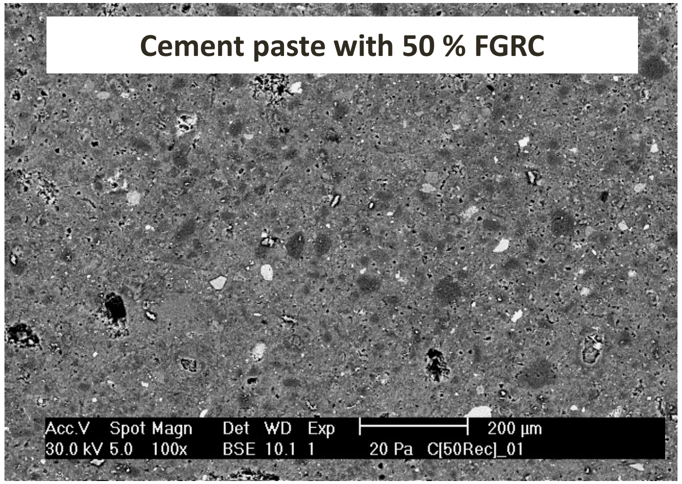
Grading curve of pulverized (mechanically activated) recycled concrete – railroad sleeper



Grading curve of pulverized (mechanically activated) recycled concrete – airport Praha - Ruzyně

Fine ground recycled concrete (FGRC) – case study





- microscope pictures show nicely particular phases of the composite;
- sample with 50 % FGRC is in comparison to reference paste showing new phases of grey color (represents aggregates from the recycled concrete);
- non-hydrated cement content was reduced nearly by 75 %, what supports the assumptions about the changed hydration process (tested by calorimetry as well).

Fine ground recycled concrete (FGRC) – case study

	2F+ 1C	2F+1C+ 2FGRC	4F+1C+ 2FGRC	2F+1C+ 4FGRC	1F+1C+ 4FGRC	2F+1C+ 6FGRC	4F+1C+ 6FGRC	2F+ 6FGRC
RAP 0/22	94.0	91.5	89.5	88.5	89.0	85.5	83.5	86.5
Water	3.0	3.5	3.5	4.5	5.0	5.5	5.5	5.5
Foamed bitumen	2.0	2.0	4.0	2.0	1.0	2.0	4.0	2.0
Cement	1.0	1.0	1.0	1.0	1.0	1.0	1.0	-
FGRC	-	2.0	2.0	4.0	4.0	6.0	6.0	6.0

	2F+3C	2F+ 3FGRC	2F	2F+ 3CFGRC
RAP 0/22	90.6	90.5	94.0	90.5
Water	4.4	4.5	4.0	4.5
Foamed bitumen	2.0	2.0	2.0	2.0
Cement	3.0	-	-	-
FGRC	-	3.0	-	-
Cement (50 %) and recycled concrete (50 %) milled together	-	-	-	3.0

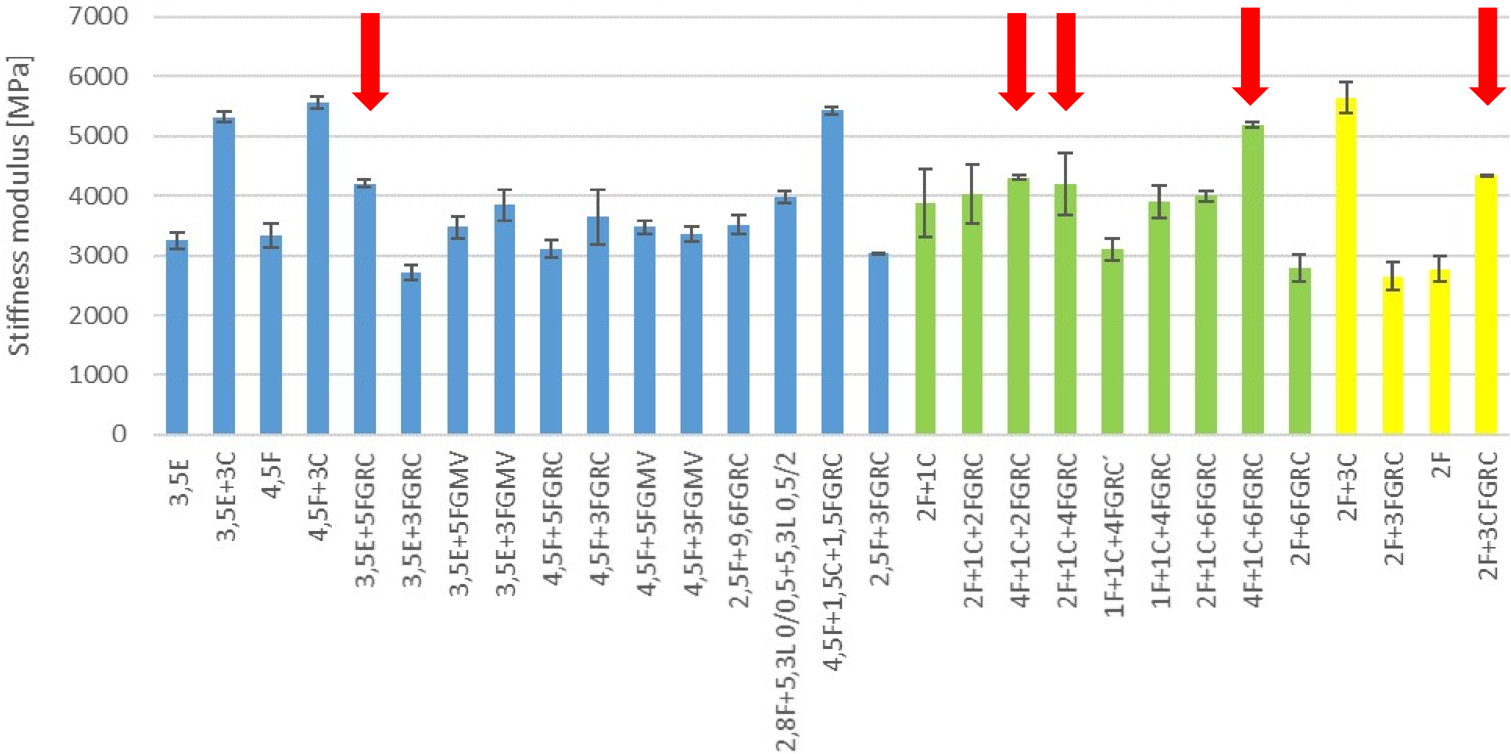



Fine ground recycled concrete (FGRC) – case study

	3.5E+3C	4.5F+3C	3.5E	4.5F	3.5E+ 5FGRC	3.5E+ 3FGRC	3.5E+ 5FGML	3.5E+ 3FGML
RAP 0/22	91.5	90.5	94.5	93.4	89.0	91.5	89.0	91.5
Water	2.0	2.0	2.0	2.0	2.5	2.0	2.5	2.0
Bituminous emulsion	3.5	-	3.5	-	3.5	3.5	3.5	3.5
Foamed bitumen	-	4.5	-	4.5	-	-	-	-
Cement	3.0	3.0	-	-	-	-	-	-
FGRC	-	-	-	-	5.0	3.0	-	-
FGML	-	-	-	-	-	-	5.0	3.0

	4.5F+ 1.5C+ 1.5FGRC	4.5F+ 5FGRC	4.5F+ 3FGRC	4.5F+ 5FGML	4.5F+ 3FGML	2.5F+ 9.6FGRC	2.8F+ 10.6L 0/2	2.5F+ 3FGRC
RAP 0/22	90.5	88.0	90.5	88.0	90.5	-	-	92.5
RAP 0/11	-	-	-	-	86.0	81.1	-	-
Water	2.0	2.5	2.0	2.5	2.0	2.0	5.5	2.0
Foamed bitumen	4.5	4.5	4.5	4.5	4.5	2.5	2.8	2.5
FGRC	1.5	5.0	3.0	-	-	9.6	-	3.0
FGML	-	-	-	5.0	3.0	-	-	-
Crushed limestone 0/2	-	-	-	-	-	-	10.6	-
Cement	1.5	-	-	-	-	-	-	-

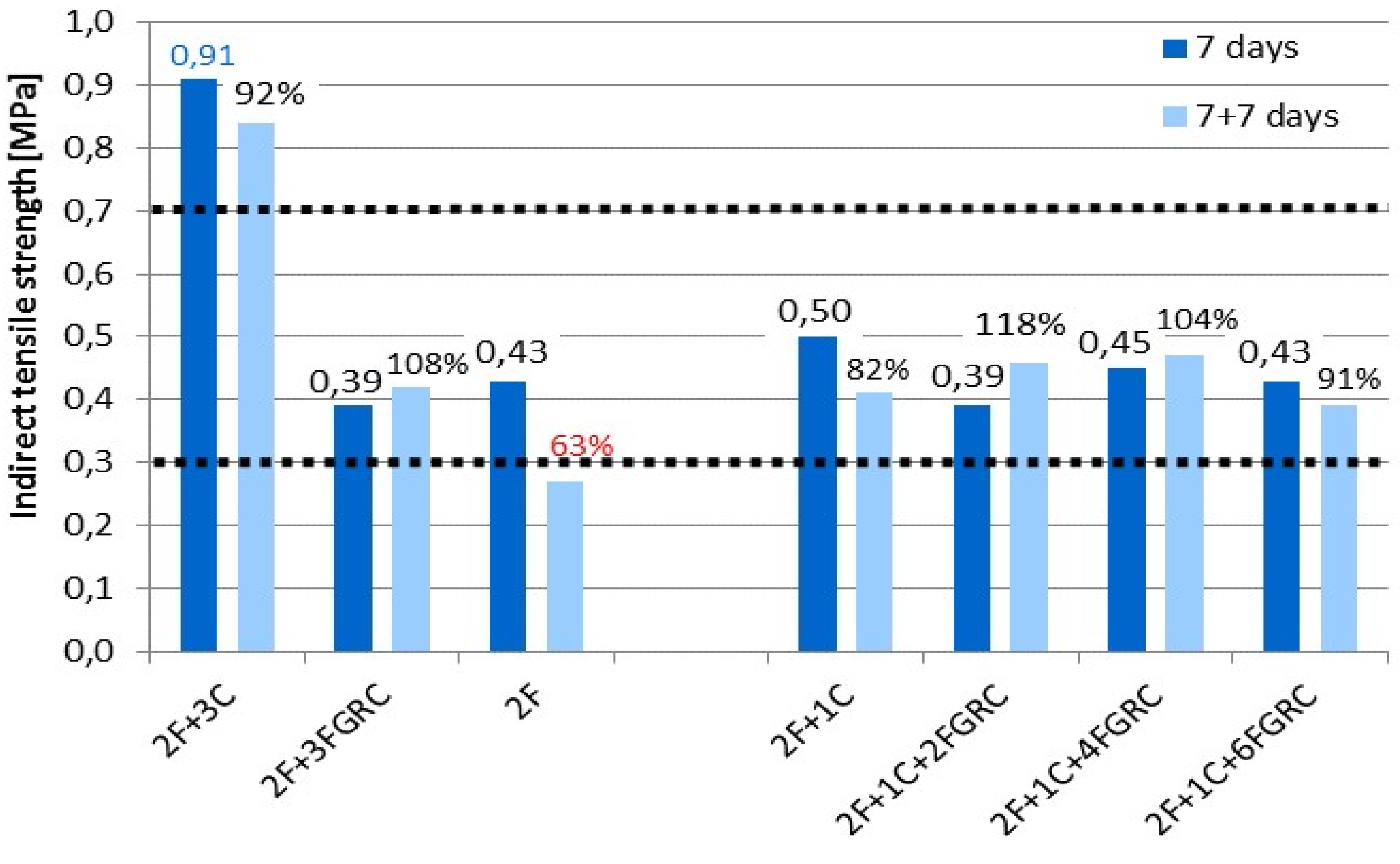
Fine ground recycled concrete (FGRC) – case study



- slightly higher stiffness and comparable or slightly lower tensile strength.
- most important influence of FGRC in moisture susceptibility.
- the addition of micro-milled limestone showed any significant advantages.

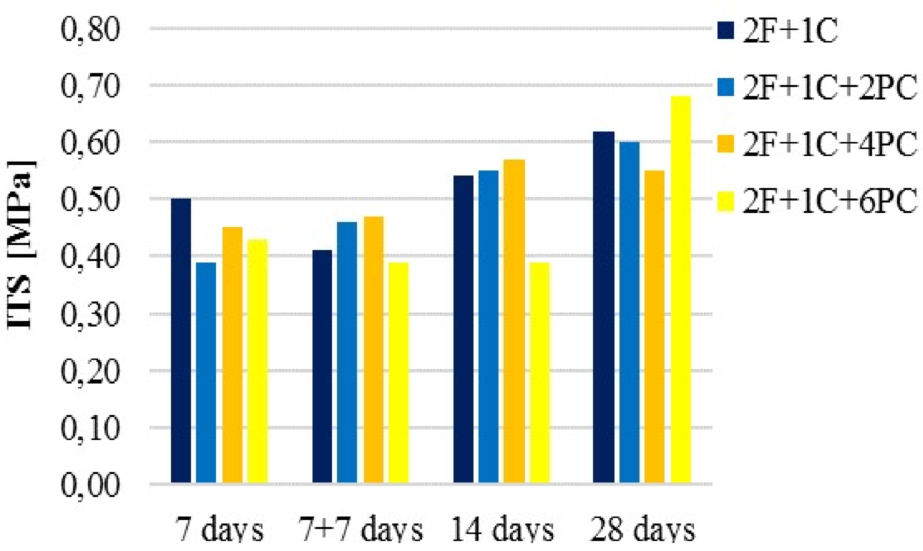
Fine ground recycled concrete (FGRC) – case study

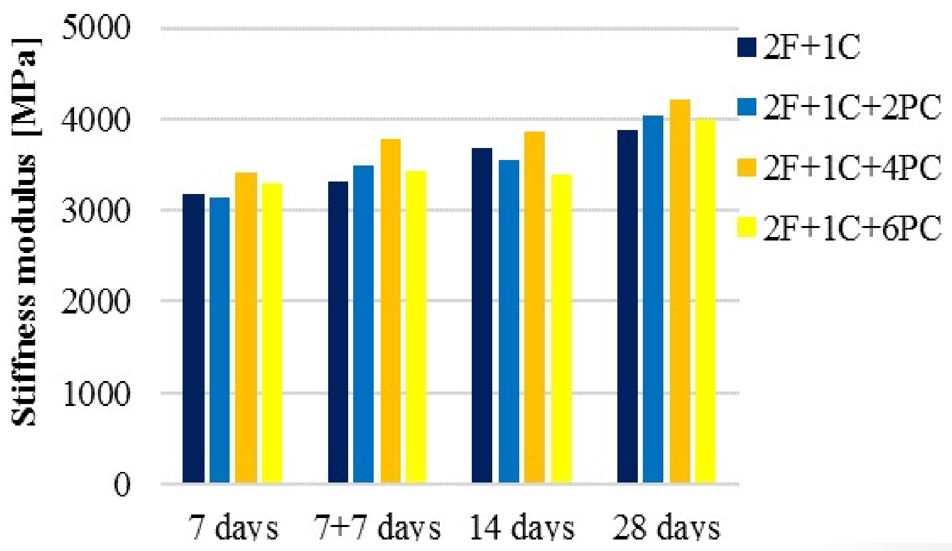
Cold recycling mixture – moisture susceptibility



Fine ground recycled concrete (FGRC) – case study

Cold recycling mixture – influence of FGRC content





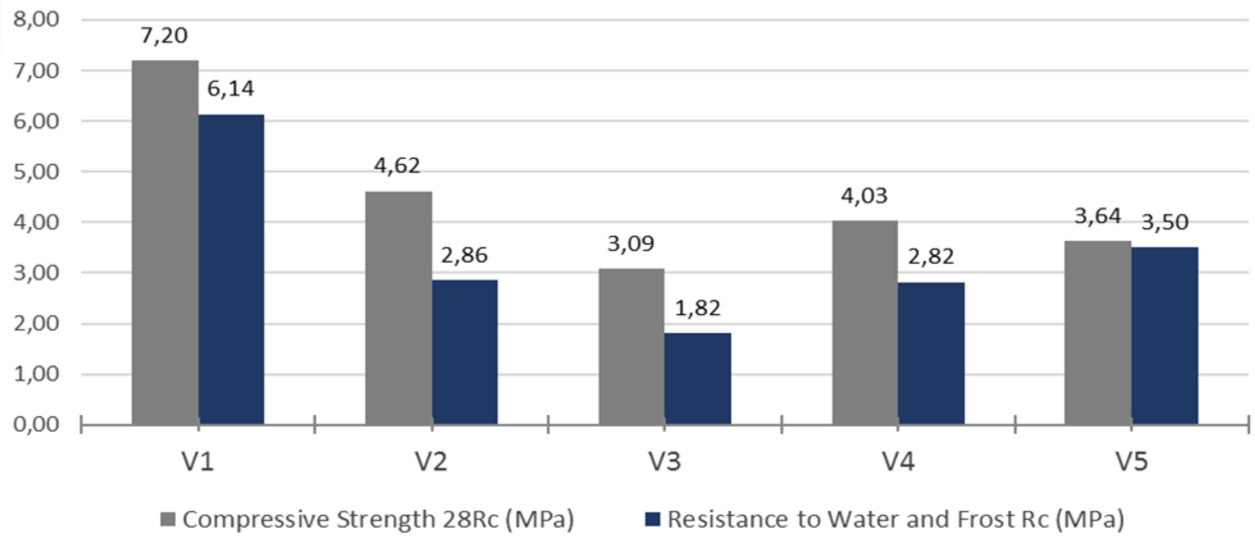
Fine ground recycled concrete (FGRC) – case study

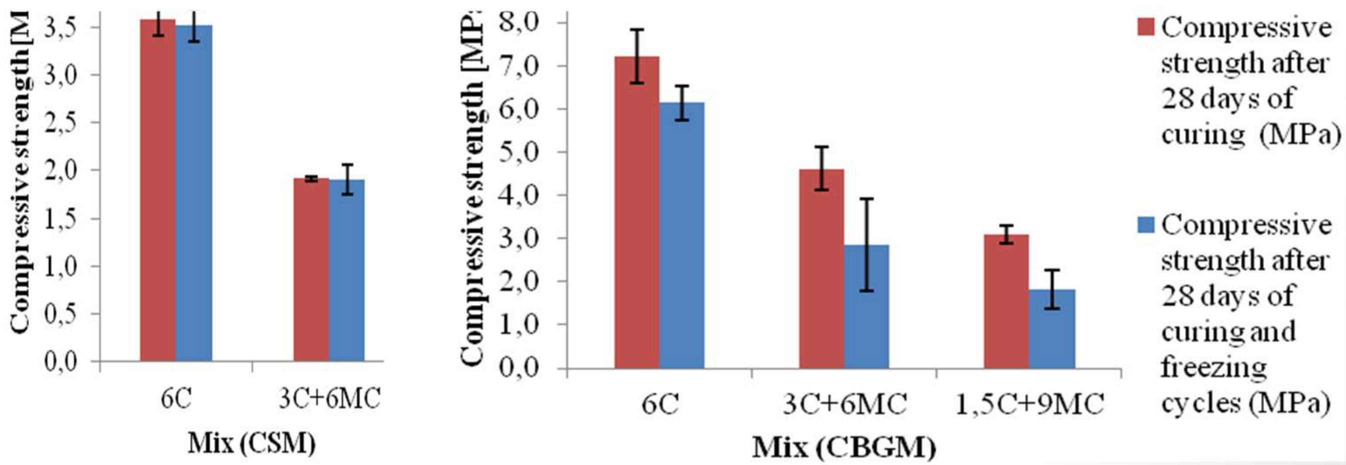
Cold recycling mixture – some concluding remarks

- FGRC when applied alone as substitute of cement, or in combination with cement it does not result in any improvement of strength characteristics.
- Some binding potential of FGRC in cold recycled mixtures – more interestning than bond granulare base layers
- Significant benefit could be the reduced risk of shrinkage micro-cracks.
- Substitution does not negatively affect resistance to water immersion and frost.
- Focusing on the cold recycling with foamed bitumen, it is obvious that there is a distinctive improvement of stability (lower water susceptibility) and the stiffness values increase to a certain degree – with bituminous emulsion it is not as significant.

Binders in bond granular base layers and other solutions

FGRC in bond granular base layers – case study





FGRC in bond granular base layers – case study

Masonry Block

low cement content

recycled material up to 90 %

compr. strength 12 MPa

heat accumulation

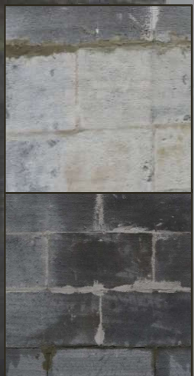
acoustic barrier

Exterior Plasters

stone micro-filler to 70 % compr. strength > 6 MPa

optimized for low shrinkage

good adhesion



Bed-Joint Mortar

stone dust up to 80 %

cement 20 %

compr. strength to 9 MPa

good adhesion

Interior Plasters

stone micro-filler up to 90 %

compr. strength > 4 MPa

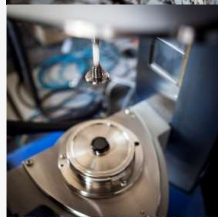
optimized for low shrinkage

good adhesion

Ground slags in granular base layers – case study

	D1	D2	D3	D4
DESTRO 0/32	88,0 %	91,0 %	88,0 %	–
DESTRO 0/4		–	–	25,2 %
DESTRO 16/32	–	–	–	16,8 %
ZEVO struska 0/32	–	–	–	42,0 %
Water content	6,0 %	6,0 %	6,0 %	10,0 %
BFS + fly-ash „50:50“	**5,0 %**	**–**	**–**	**5,0 %**
BFS + fly-ash „25:75“	**–**	**–**	**5,0 %**	**–**
Cement CEM I 42,5	**1,0 %**	**3,0 %**	**1,0 %**	**1,0 %**

Mix version	Compressive strength Rc [MPa]	Compressive strang after freeze cycles [MPa]	Strength ratio [%]
SC_D1	2,34	2,34	100,0
SC_D2	2,15	3,00	139,5
SC_D3	3,92	2,86	73,0
SC_D4	3,45	1,19	34,5


	D5	D6	D7	D8	D9	D10	TP1	D11	D12
DESTRO 0/32	90,0 %	90,0 %	90,0 %	70,0 %	70,0 %	90,0 %	85,0 %	89,0 %	89,0 %
RCA 8/16	–	–	–	20,0 %	20,0 %	–	–	–	–
Water content	4,0 %	4,0 %	4,0 %	4,0 %	4,0 %	4,0 %	9,0 %	5,0 %	5,0 %
BFS + fly-ash „50:50““	**3,0 %**	–	–	**3,0 %**	–	–	–	–	–
Granulated BFS	–	**4,0 %**	–	–	–	–	–	**5,0 %**	–
Cement CEM I 42,5	**3,0 %**	**2,0 %**	**2,0 %**	**3,0 %**	**3,0 %**	**3,0 %**	–	**1,0 %**	**2,0 %**
Sorfix (verze 2019)	–	–	–	–	–	–	–	–	**4,0 %**
TTA a $Ca(OH)_2$ (9:1 – HSM)	–	–	**4,0 %**	–	**3,0 %**	**3,0 %**	–	–	–
CEM 42,5:TAP milled (1:1)	–	–	–	–	–	–	**6,0 %**	–	–

Mix version	Compressive strength Rc [MPa]	Compressive strang after freeze cycles [MPa]	Strength ratio [%]
SC_D5	6,94	6,82	98,3
SC_D6	7,76	7,20	92,8
SC_D7	7,67	5,93	78,3
SC_D8	8,59	7,88	91,7
SC_D9	11,06	10,02	90,6
SC_D10	10,74	10,10	94,0
SC_D11	6,71	3,13	46,6
SC_D12	7,95	7,15	89,9
SC_TP1	2,39	2,00	83,7

Some conclusions

- fillers form alternative materials or by-products have plenty of use cases
- potentially very effective as substitutes to regular cement
- for asphalt mix adhesion properties more limited options

General comment:

If researching these materials always be practical. There are many theoretical approaches with various wastes which provide interesting results. They are just practically not feasible (often the reason is limited volume of these materials).

Reconmatic

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Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the HORIZON-RIA. Neither the European Union nor the granting authority can be held responsible for them.

There are always alternative ways….

Thank you for your kind attention.

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