Proceedings IRF2020: 7th International Conference Integrity-Reliability-Failure.
J.F. Silva Gomes and S.A. Meguid (editors), INEGI-FEUP (2020), pp.571-582.
https://paginas.fe.up.pt/~irf/Proceedings_IRF2020/

PAPER REF: 17395

THE IMPACT OF CATALYST WASTE ON PHYSICAL AND MECHANICAL PROPERTIES OF CEMENT MATERIALS

Marija Vaiciene[1(*)], Jurgita Malaiskiene[2], Carla Costa[3], Dmitrij Letenko[4]
[1]VTDK, Civil Engineering Faculty, Vilnius College of Technologies and Design, Vilnius, Lithuania
[2]VGTU, Laboratory of Composite Materials, Vilnius Gediminas Technical University, Vilnius, Lithuania
[3]ISEL, Faculty at Civil Engineering Department, Instituto Superior de Engenharia de Lisboa, Lisbon, Portugal
[4]SPbGASU, Faculty of Civil Engineering, Saint Petersburg State University of Architecture and Civil Engineering, Saint Petersburg, Russia
[(*)]*Email:* m.vaiciene@vtdko.lt

ABSTRACT

This paper presents a research on viability of using a waste catalyst (FCCCw) generated in Lithuanian oil-refinery as a pozzolanic cement surrogate in cement-based materials. One prepared mortars and concretes with 0, 5, 10, 15 and 25% (by mass) of cement replacement with FCCCw. The pozzolanic activity was assessed both using a direct method (Chapelle test) and an indirect method i.e, computing the Index Activity and assuming, as reference, the requirement laid down in the EN 450-1. Physical and mechanical hardened state properties - density, mechanical strength and ultrasound pulse velocity - of the mortars and concretes were determined. Results reveal that FCCCw presents pozzolanic activity. The mortar and concrete with 10% of cement replacement with FCCCw present improved properties than those with plain cement binders. The use of FCCCw until 25% as cement surrogate do not affect negatively the quality class of the concretes. The concretes microstructures were imaging using SEM/ES mode.

Keywords: concrete, cement mortars, waste catalyst, oil refinery, pozzolanic activity.

INTRODUCTION

Cement based materials have a significant environmental impact namely, it has a considerable energy consumption during the cement production and in the products transportation. In addition, cement production also is a massive source of CO_2 to the atmosphere. At present, reduction of CO_2 emission in cement industry is one of the priority areas in the European Union and worldwide. Cement production alone represents about 85% of the CO_2 emissions from concrete manufacturing (Miller *et al.* 2016) and contributes around 7% of global CO_2 emissions (International Energy Agency 2018) today.

Currently, oil-refineries worldwide generate more than 800 thousand tons/year of catalyst waste (Letzsch 2014) of which around 20% in Europe (ECCPA 2006). In Lithuania, it is generated 200 ton/year. However, since this catalyst is not a commodity being specifically manufactured for each oil-refinery (Pavol *et al.* 2011) based on its typical oil feed composition and desired products spectra, its use and the incorporation content in the cement-based materials must be previously evaluated for each FCCCw source.

The FCCCw constituents are an aluminosilicate faujasite-type zeolite, an essentially amorphous alumina active matrix, clay and a binder. It possesses a high content of $Al_2O_3 \cdot SiO_2$ of c.a 90%

(w/w) (Pacewska *et al.* 2013). The crystalline structure of the zeolite is the main compound responsible for this waste catalyst very high specific surface (> 100 m^2/g) (Sadeghbeigi 2012). The FCCCw has a chemical composition similar to some other pozzolanic materials (i.e, materials that undergoes a chemical reaction with calcium hydroxide ($Ca(OH)_2$)) which used in construction materials industry is already consolidated such as, fly ashes and metakaolin (Pacewska *et al.* 2002). FCCCw was found to increase the amount of hydrated calcium silicates in cement materials (Paya *et al.* 2003).

Previous investigation revealed that FCCCw can be both used as a pozzolanic material incorporated in the binder and in this case the smaller particle size are more suitable (range 20–80 µm) as well as it can be used as micro-aggregate being more suitable the bigger particle size samples (Pacewska *et al.* 2002).

A study (Garcia *et al.* 2007) analyzed the pozzolanic activity of FCCCw using direct test method, which follows the reaction between the material and a saturated lime solution with time: a specimen was placed in a saturated lime solution at 40°C for 2 h, 1, 7 and 28 days, and afterwards the CaO concentration in the solution was measured. This study showed that FCCCw produced by the Company Repsol YPF is an active pozzolanic material. Moreover, this waste catalyst revealed its highest indirect pozzolanic activity when it is partially replacing 10% of cement since it presents the highest compressive strength.

The pozzolanic activity of FCCCw produced by the Brazilian refinery was tested using thermo gravimetric analysis after 28 days of curing age. In specimens modified with 15–25% of cement replacement with FCCCw, the amount of $Ca(OH)_2$ dropped and the amount of tobermorite increased. These specimens, however, demonstrated lower compressive strength (Dweck *et al.* 2008) than the plain cement specimens.

Most of the reactions in specimens containing FCCCw take place during the first 14 hours of curing. The highest amounts of CSH, CASH and CAH are formed during this time (Silva *el al.* 2015). Higher amounts of CSH were found (Lemos *et al.*, 2017) after 28 days of curing in specimens where a higher (20–30%) portion of cement was replaced by FCCCw. The content of $Ca(OH)_2$ after 24 h curing decrease from 14.8% (control specimen) till 11.4% (replacement of cement with FCCCw 30%).

Other authors report (Antonovič *et al.* 2019) that 9% of FCCCw replacement of cement in the mixture accelerates cement hydration and increases the strength of the light composite with glass beads.

FCCCw from the Portuguese oil refinery also possess a very high pozzolanic activity. This spent catalyst has already been tested in cement pastes, mortars and concretes for different applications (Costa *el al.* 2014; Nunes and Costa 2017; Costa and Marques 2018). The results showed that typically it is able to be used as a cement surrogate up to 15-20% (by mass) enhancing both early and long-term mechanical properties, with no adverse effect on volume stability and improving durability parameters in terms of water absorption resistance, chloride migration resistance and ASR expansion.

Similar results have been obtained by other researchers (Gomez 2007), chloride ingress attack (Zornoza *et al.* 2009).

The aim of the current study is to assess the viability of partially replace the cement with the catalytic cracking catalyst waste (FCCCw) generated in Lithuanian oil refinery. For this purpose, FCCCw pozzolanic reactivity was evaluate the using different test methods as well as the it was evaluated effect of different incorporation level of FCCCw on the physical and mechanical properties mortars and concretes.

MATERIALS AND METHODS

The raw materials used for mortars preparation were: cement CEM I 42.5 R (conforms the standard EN 197-1), FCCCw generated by AB Orlen Lietuva oil refinery (Lithuania), natural siliceous sand (fraction 0/4, conforming to standard EN 12620 requirements, particles density 2.500, bulk density 1.575, water absorption 0.57%). Besides these materials concretes were prepared using also two crushed granite aggregates (fraction 5/8, bulk density 1.300 and 11/16, bulk density 1.410) and a new generation of superplasticizer (Sp) based on polycarboxylic ether polymers (supplied in liquid form, density of 1.04, $pH_{(20\%\ solution,\ 20°C)}=6.5$). All specimens were prepared with drinking water, conforming the requirements of European standard EN 1008.

Table 1 lists the chemical composition of cement and FCCCw obtained by X-ray fluorescence spectrometry (ZSX PRIMUS IV) and the loss on ignition (LOI) evaluated following the standard EN 196-2. The mineral composition of the cement determined by XRD (DRON 7) is: C_3S - 56.6%, C_2S - 16.7%, C_3A - 9.0%, C_4AF - 10.6 % and 7.1 % others (alkaline sulphates and CaO). Particle density 3.100, compressive strength after 28 days 55 MPa, initial time 180 min.

Table 1 - Chemical composition of the cement and FCCCw used (%, by mass)

Compound	Chemical composition (%, by mass)	
	Cement	FCCCw
SiO_2	20.4	50.1
Al_2O_3	4.0	39.4
Fe_2O_3	3.6	1.3
CaO	63.2	0.5
MgO	2.4	0.49
SO_3	3.1	2.3
K_2O	0.9	0.07
Na_2O	0.2	0.2
Mn_2O_3	-	0.03
Cl	0.05	0.008
Loss by ignition	2.15	3.5

Figure 1 shows the particle size distributions (PSD) of the cement and FCCCw catalyst obtained by laser diffraction (CILAS 1090).

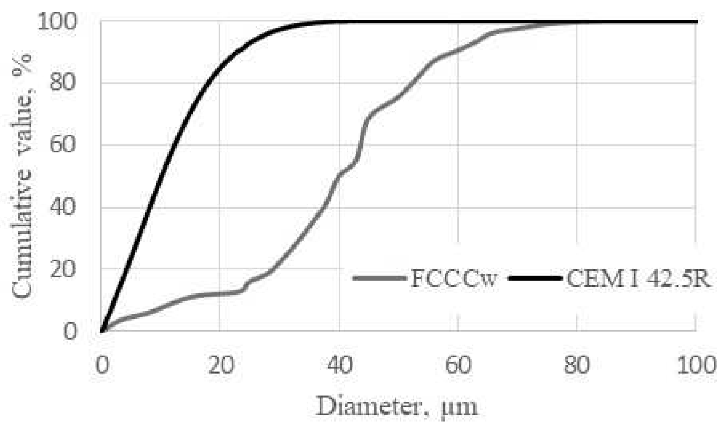

Fig. 1 - Particle size distributions of cement and FCCCw

The d_{50} of cement and FCCCw particles are 10.25 µm and, 43.06 µm respectively and the d_{90} of cement and FCCCw particles are 22.92 µm and 62.54 µm, respectively. The average diameter of cement particles 11.65 µm.

FCCCw particles are spherical, particle density 2.750. The FCCCw pozzolanic reactivity of was assessed by different test methods. One of which was the evaluation of its ability to react directly with lime through a classic titration method namely the Chapelle test (following the standard NF P18-513).

Mortars preparation and testing

Blended binders were formulated by partially replacing the cement with FCCCw within the range 5 to 25%, by mass. Table 2 presents the mortars compositions and the notation adopted for each mixture mortar.

Mortars mixing procedure was performed in accordance with Standard EN 196-1. Prismatic steel moulds of dimensions 160×40×40 mm size were cast and cured so that compressive strength were able to be evaluated at 7 and 28 days of ages (average of 6 specimens results) in accordance with standard EN 196-1.

Table 2 - The compositions of mortars and corresponding notation

Constituents (%, by mass)		M0	M5	M10	M15	M25
Binder (FCCCw+Cement)		25	25	25	25	25
(% in the binder)	FCCCw	0	5	10	15	25
	Cement	100	95	90	85	75
Fine aggregate		75	75	75	75	75
Water (W)		12.5	12.5	12.5	12.5	12.5
Proportion						
W/B		0.5	0.5	0.5	0.5	0.5

The activity Index (AI) is the ratio (in %) of the compressive strength of the mortars produced with a certain percentage of cement replacement with a test pozzolan material - in this case FCCCw - and the compressive strength of the plain cement mortars, at the same age, produced in exactly the same conditions. The determination of AI is a consolidated indirect test method to evaluate the pozzolanic activity of the test material i.e., its ability to react with $Ca(OH)_2$ in a cement matrix.

In this regard, the standard EN 450-1 was used as reference: for the material to be pozzolanic, the mortar produced with 25% (by mass) of test pozzolan material incorporation have to present AI ≥ 75% at 28 days of curing age.

Ultrasound propagation time was measured using the equipment "Pundit 7" with two 54 kHz transducers. The ultrasonic pulse velocity (UPV) was computed using equation (1):

$$UPV = \frac{l}{\tau} \text{ (m/s)} \tag{1}$$

where: l - the ultrasonic pulse path length through the sample i.e., the distance between the two transducers that in this case is the length of the specimen, m (0.16 m for mortar specimens and 0.10 m for concrete specimens) and τ - signal propagation time provided by the test equipment, s.

Concretes preparation and testing

Five concrete mixtures with a designation codes C0, C5, C10, C15 and C25 was mixed. Five concrete mixtures were formulated using the same blended binders of those used in the mortars mixtures. Table 3 presents the concrete mixtures compositions and the notation adopted for each mixture. Sp corresponds to 0.6 % of the binder content.

Table 3 - Compositions of concrete mixtures (kg/m^3) and corresponding notation

Notation	Binder (Cement +FCCCw)		Sand	Granite crushed stone 5/16	Water	Plasticizer	W/B
	Cement	FCCCw					
C0	300	0	980	1000	165	1.8	0.55
C5	285	15	980	1000	165	1.8	0.55
C10	270	30	980	1000	165	1.8	0.55
C15	255	45	980	1000	165	1.8	0.55
C25	225	75	980	1000	165	1.8	0.55

Note: 50% - 5/8 fraction and 50% - 11/16 fraction of granite crushed stone

Cubic steel moulds of dimensions 100×100×100 mm-sized were cast and stored for 1 day under normal conditions, then for 27 days in water at 20°C±2°C so that compressive strength were able to be evaluated (average of three replicate specimens results) in accordance with standard EN 12390-2. Density of concrete mixtures was determined according with standard EN 12390-7. The UPV testing was performed following the same procedure of that used on mortars test specimens.

Microstructure imaging

Fracture surfaces of hardened concretes were analyzed by scanning electron microscopy (SEM) using secondary electron (SE) mode using a TESCAN VEGA3 SEM microscope (Czech Republic). Prior to the test, the specimen surface was covered with a thin golden layer by gold electron vacuum evaporation.

RESULTS

Assessment of pozzolanic activity by a direct test method

The direct ability for FCCCw to react with $Ca(OH)_2$ was assessed using the modified Chapelle test following the procedure described in the standard NF P 18-513. Test result showed that each gram of FCCCw consumes 1017 mg of $Ca(OH)_2$. Since this value is significantly higher than 630 mg/g, the FCCCw presents pozzolanic reactivity according to this standard.

Mortars testing results

Figure 2 shows the compressive strength of the mortars with 0, 5, 10, 15 and 25% of cement replacement with FCCCw catalyst at 7 and 28 days of curing age.

Results presented in Figure 2 shows that, on the 7th curing day, mortars with FCCCw incorporation up to 10% exhibit already strength-enhanced which is similar with that of the plain cement mortar. Moreover, incorporation of 15% of FCCCw catalyst delay the strength development during the first 7 curing days. However, at 28 days of age the compressive strength of M15 also reached that of the mortar without waste incorporation. The 10% of FCCCw incorporation led to the highest compressive strength value achieved (M10=51.8 MPa, at 28 days) what is in good accordance with other results find in literature with spent catalysts from other oil refineries.

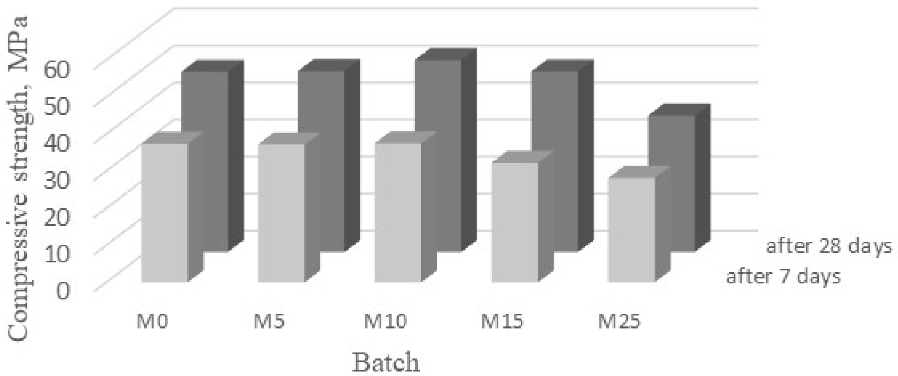

Fig. 2 - Compressive strength of mortars with 0, 5, 10, 15 and 25% (w/w) of cement replacement with FCCCw catalyst at 7 and 28 days of age

Table 4 presents the results of the pozzolanic activity index for the mortars with different FCCCw content incorporation. Due to the dilution effect, the theoretical AI value of a blended binder mortar is its cement content in the binder. Compressive strength development beyond this value is provided by the replacer material, meaning that it presents pozzolanic activity. In case of the present study, AI values higher than those presented in the 2nd row of Table 4 reveal that the FCCCw was pozzolanically active in the corresponding mortar. As such, results show that the FCCCw present pozzolanic activity in all mortars with catalyst incorporation up to 15%, already after 7 days of curing and at 28 days. Actually, with this age none of the mortars present loss in strength regarding the plain cement mortar thus the FCCCw provide a relevant contribute to the mechanical properties.

Table 4 - Pozzolanic activity index values for mortars mixtures with 0, 5, 10, 15 and 25% (by mass) of FCCCw incorporation at 7 and 28 days of age

Notation	Cement content in the binder, %	Compressive strength after 7 days, MPa	Activity index after 7 days, %	Compressive strength after 28 days, MPa	Activity index after 28 days, %
M0	100	37.4	–	48.6	–
M5	95	37.2	99.5	48.8	100.4
M10	80	37.5	100.3	51.8	106.6
M15	85	32.2	86.1	48.7	100.2
M25	75	28.1	75.1	36.8	75.8

Higher catalyst waste content tends to decrease the mechanical properties of the specimens. The AI value for mortar M25, at 28 days, is 75.8% thus complying with the specification laid down in standard EN 450-1 to be classified as a pozzolanic material, as referred above. Water requirement of FCCCw determined according EN 450-1 is 10%.

Figure 3 shows the density results of the mortars with 0, 5, 10, 15 and 25% of cement replacement with FCCCw catalyst at 7 and 28 days of curing age.

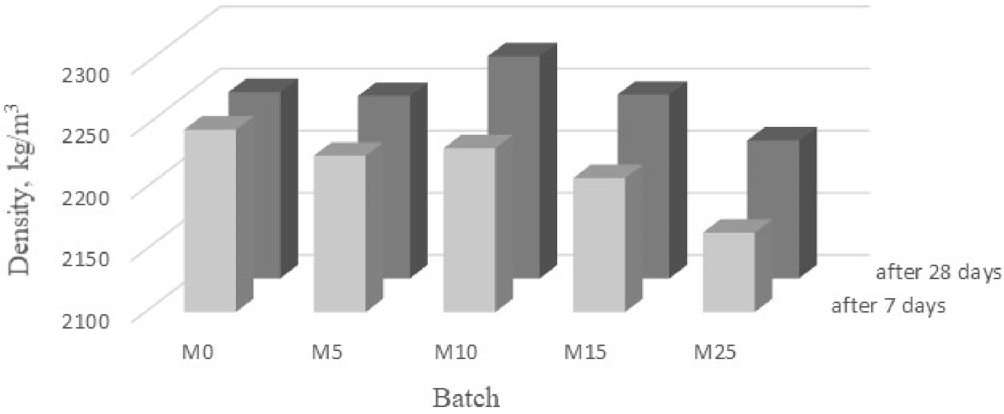

Fig. 3 - Density of cement mortars with 0, 5, 10, 15 and 25% (w/w) of cement replacement with FCCCw catalyst after 7 and 28 days curing

The highest density (2279 kg/m^3) of cement mortar after 28 days of curing was observed in mixture with 10% of cement replacement with FCCCw. In fact, since the mechanical properties of cement-based materials are highly influenced by its density so that denser materials generally provides higher strength, as expected the trend in both compressive strength in the mortars with different FCCCw incorporation (Figure 2) is the same as that of density (Figure 3). The similar trends were determined in some research articles (Garcia *et al.* 2007, Antonovic *et al.* 2019 etc).

Figure 4 shows the results of the UPV obtained on mortar with different FCCCw incorporation level.

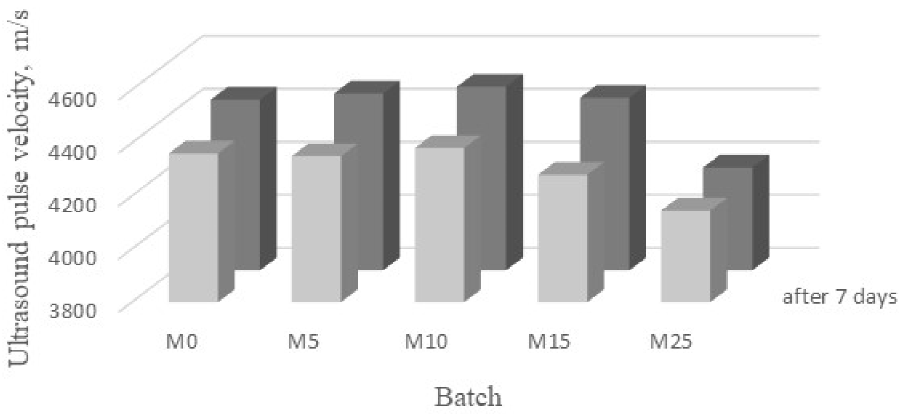

Fig. 4 - The results of cement mortar ultrasound pulse velocity after 7 and 28 days curing

As expected, the results of ultrasonic pulse velocity in mortars presents the same trend (Figure 4) of those of compressive strength and density tests (Figures 2 and 3 respectively). Namely, he highest UPV was recorded on mortar M10. The highest pozzolanic activity was also observed when this amount of FCCCw was used: more CSH and CASH products formed in hardened cement paste. Active pozzolanic additions are recommended for reducing the content of free CH (Slamečka and Škvára, 2002).

Concretes testing results

Figures 5 to 7 shows, respectively, the results of the compressive strength, density and ultrasound pulse velocity obtained on the concrete mixtures with different FCCCw incorporation level after 28 days of curing age.

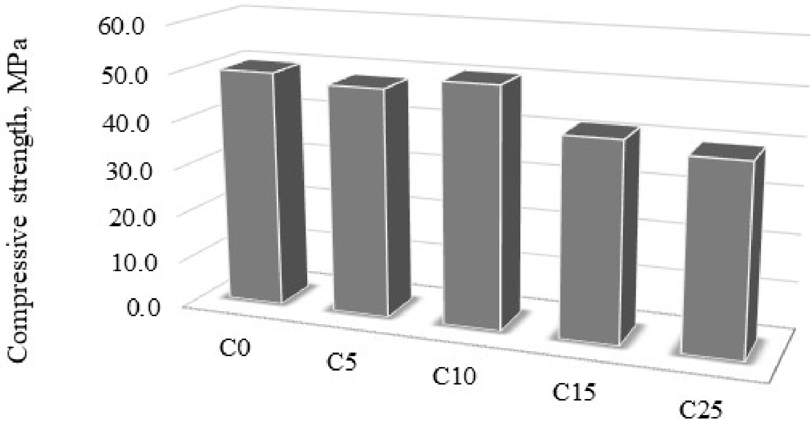

Fig. 5 - Compressive strength of concrete with 0, 5, 10, 15 and 25% (w/w) of cement replacement with FCCCw catalyst at 28 days of age

In brief, the results obtained on concrete mixtures with different FCCCw content incorporation follow the same trend of those obtained with mortars. In fact, these results confirmed that 10% of cement replacement with FCCCw, C10, leads the highest pozzolanic activity improving the cement matrix density (Figure 6) and, thus, the performance assessed through the compressive strength (Figure 5) and UPV (Figure 7). Moreover, the results also confirmed that higher incorporation level of the spent catalyst beyond 10% (C15 and C25) lead to a progressive decrease of the cement matrix density, strength and UPV values. These findings might be attributed that to the fact that, exceeding 10% of FCCCw incorporation, the dilution effect prevails over the catalyst pozzolanic ability or the system might be run out of $Ca(OH)_2$ (cement hydration product) before the pozzolanic reaction be able to be completed.

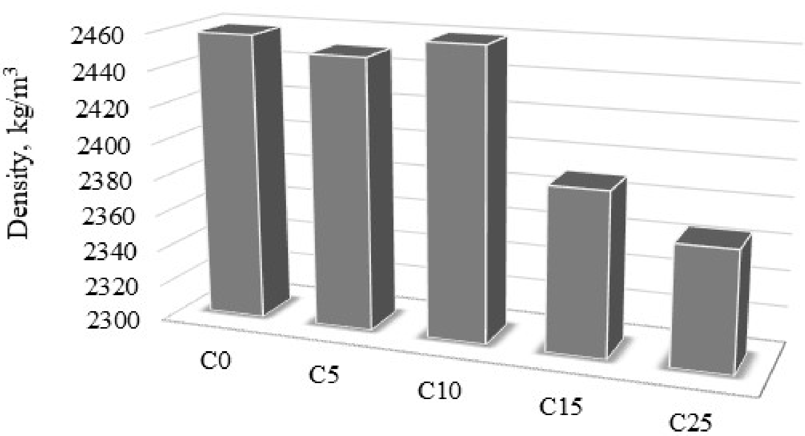

Fig. 6 - Density of concrete with 0, 5, 10, 15 and 25% (w/w) of cement replacement with FCCCw catalyst after 28 days curing

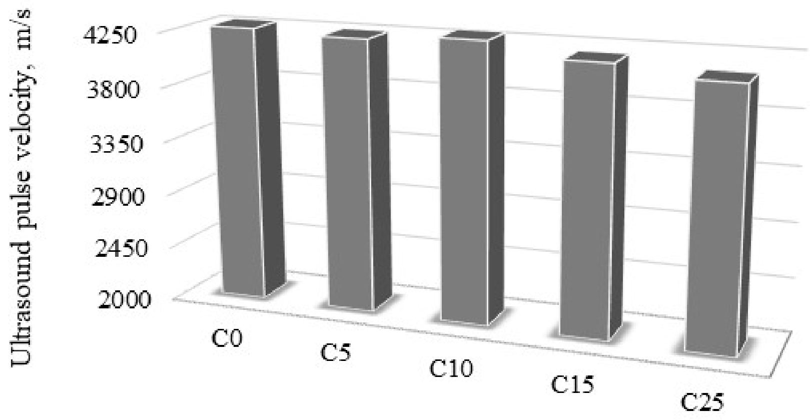

Fig. 7 - The results of concrete ultrasound pulse velocity after 28 days curing

The UPV is the most consensual in-situ and non-destructive test to evaluate the quality of concretes. Table 5 presents a classification available in the literature to correlate the concrete quality based on UPV values (Costa and Marques, 2018 and references herein). The results revealed that, besides the strength of C15 and C25 concretes decrease in relation to the concretes with smaller FCCCw incorporation level (Figure 7), all concrete mixtures with up to 25% of FCCCw fell within the range of 'Good' quality which is the same class of the plain cement concrete. This is a very promising finding since it demonstrate that it is possible that FCCCw generated in Lithuania can be used in significant amount, at least until 25%, as cement surrogate without negatively affect the quality class of the concretes.

Table 5 - Concrete quality classification based on UPV values

Concrete Quality	UPV (m/s)
Excellent	4500
Good	3600-4500
Questionable	3000-3600
Poor	2100-3000
Very poor	< 2100

Microstructure analysis

Figure 8 shows images of the microstructure of both the plain cement concretes samples, C0, and from those with 5% of using FCCCw incorporation, C5, obtained on fractured surfaces after 28 days of curing. Figure 8 shows the corresponding images of the microstructure of C10 at same age.

The images reveal the dendritic (plate-like snow) crystal typical of crystallization morphology of portlandite (CH), the acicular crystals of calcium sulfoaluminates hydrated phases, such as ettringite (E) dispersed in a fibrous matrix of calcium silicates hydrated (C-S-H) (Costa, 2015).

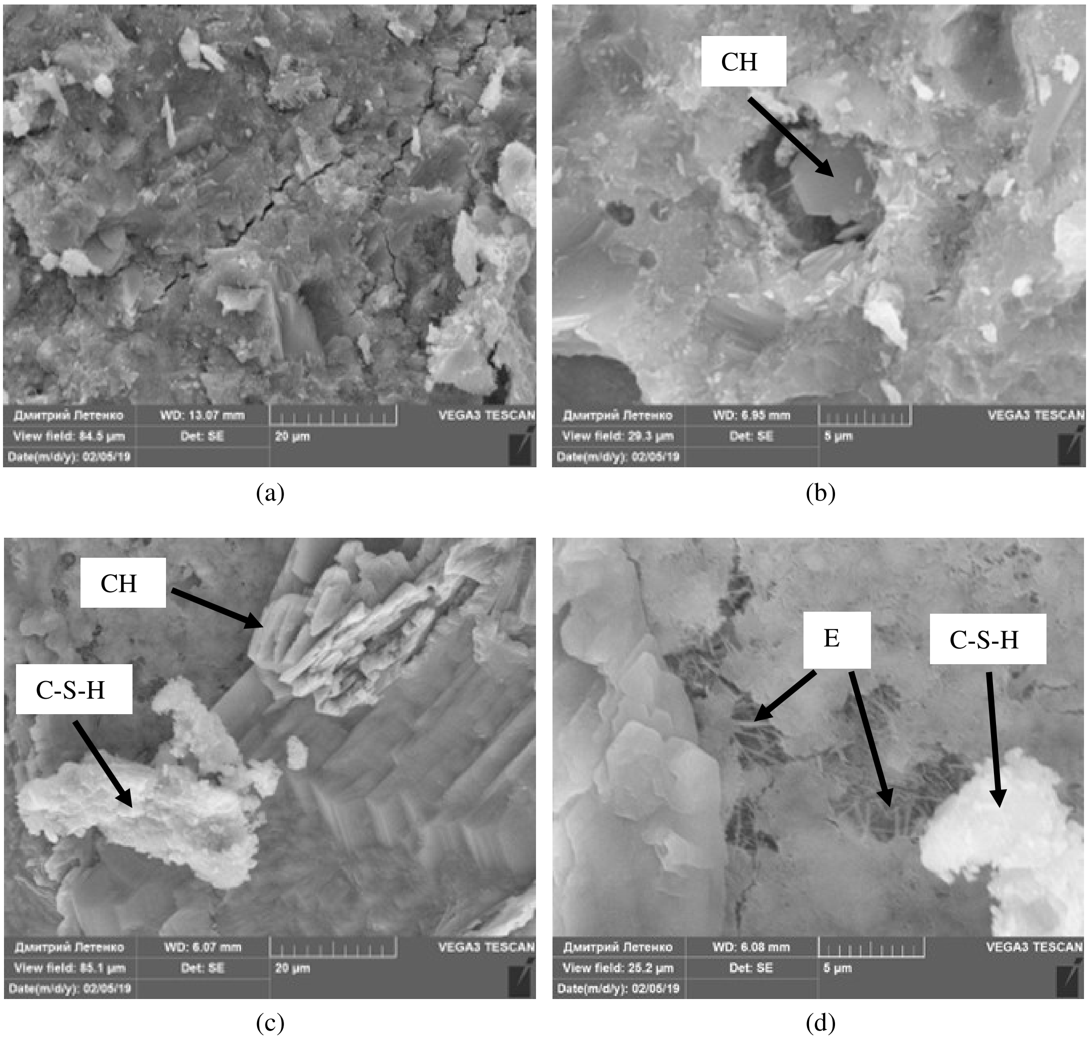

Fig. 8 - Images of the microstructure of concretes without and with 5% of FCCCw incorporation obtained on a fractured surfaces: (a), (b) C0; (c), (d) C5 (Note: CH-portlandite; E-ettringite; C-S-H - calcium silicate hydrate)

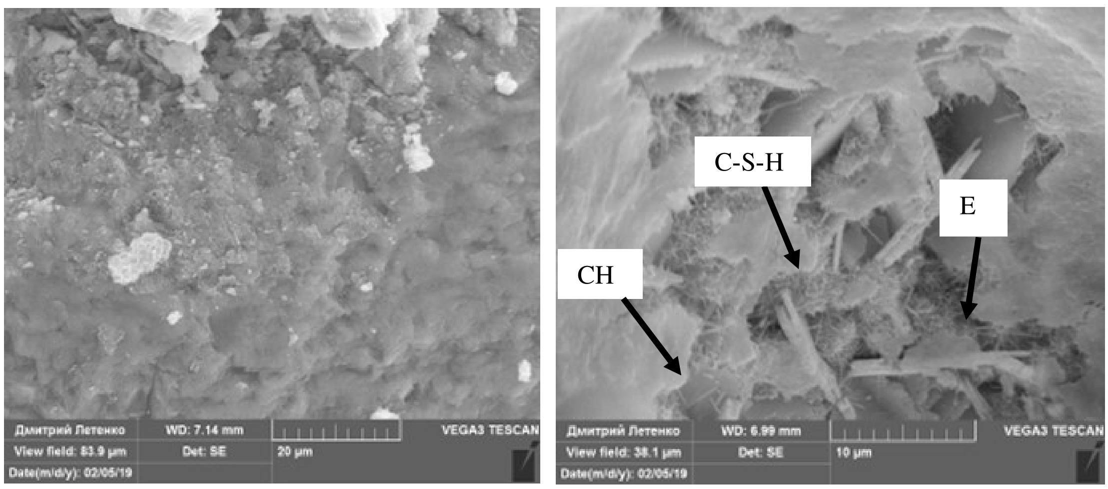

Fig. 9 - Images of microstructure C10 after 28 days (Note: CH-portlandite; E-ettringite; C-S-H-calcium silicate hydrate)

CONCLUSIONS

The following conclusions can be drawn from the study:

- FCCCw is pozzolanicly active i., it is able to react with $Ca(OH)_2$ both directly as in the cement matrix, as revealed respectively the modified Chapelle test and the Activity Index results.
- The pozzolanic activity comply with the requirements laid down in:
  - Standard NF P 18-513 i.e FCCCw consume 1017 mg $Ca(OH)_2$/g which is higher than 630 mg/g;
  - Standard EN 450-1 i.e AI of mortar with 25% of cement replacement with FCCCw is 75.8% is higher than 75%;
- Mortar and concrete mixtures with 10% of cement replacement with FCCCw present best physical and mechanical properties;
- Replacement of up to 25% of cement replacement with FCCCw do not affect the optimal quality class of concretes.

The major finding is that the FCCCw generated in Lithuania is a promising steady supplier for cement-based materials industry as an alias both for more eco-friendly industry as well as for the circular economy implementation.

REFERENCES

[1] Antonovič V, Sikarskas D, Malaiškiene J, Boris R, Stonys R, Effect of pozzolanic waste materials on hydration peculiarities of Portland cement and granulated expanded glass-based plaster. Journal of Thermal Analysis and Calorimetry, 2019, 138, pp.4127-4137.

[2] Costa C, Ribeiro MS, Brito N, Effect of waste oil-cracking catalyst incorporation on durability of mortars. Materials Sciences and Applications, 2014, 5, pp.905-914.

[3] Costa C, Hydraulic Binders, in: Gonçalves M, Margarido F. (eds), Materials for Construction and Civil Engineering, Springer, 2015, pp.1-52.

[4] Costa C, Marques JC, Feasibility of eco-friendly binary and ternary blended binders made of fly-ash and oil-refinery spent catalyst in ready-mixed concrete production. Sustainability, 2018, 9, pp.31-36.

[5] Dweck J, Pinto CA, Büchler PM, Study of a Brazilian spent catalyst as cement aggregate by thermal and mechanical analysis. Journal of Thermal Analysis and Calorimetry, 2008, 1, pp.121-127.

[6] ECCPA, FCC Equilibrium Catalyst (Including FCC Catalyst Fines) Finds Safe Reuse/Rework Outlets in Europe. 2006. Available online: https://hnlkg4f5wdw34kx1a1e9ygem-wpengine.netdna-ssl.com/wp-content/uploads/2017/07/4_Fluid_catalytic_cracking_FCC_catalyst_reuse.pdf.

[7] García de Lomas M, Sánchez de Rojas MI, Frías M, Pozzolanic reaction of a spent fluid catalytic cracking catalyst in fcc-cement mortars. Journal of Thermal Analysis and Calorimetry, 2007, 2, pp.443-447.

[8] Gomez EMZ, El papel del catalizador usado de craqueo catalítico (FCC) como material puzolanico en el proceso de corrosion de armaduras de hormigon. Universitat Politecnica de Valencia, Spain. 2007.

[9] International Energy Agency. Technology Roadmap - Low Carbon Transition in the Cement Industry, 2018.

[10] Lemos MS, Lucas A, Cunha C, Dweck J, A study of cement Type II hydration partially substituted by Brazilian spent cracking catalyst fines Part I. Non-conventional differential thermal analysis. Journal of Thermal Analysis and Calorimetry, 2017, 130, pp.573-584.

[11] Letzsch W, Global demand for catalytic technology increases. Fuel Hart Energy Pub, 2014. Available online: http://www.hartfuel.com/f.catalyst.html.

[12] Miller SA, Horvath A, Monteiro PJM, Readily implementable techniques can cut annual CO2 emissions from the production of concrete by over 20%. Environmental Research Letters, 2016, 11, pp.1-7.

[13] Nunes S, Costa C, Numerical optimization of self-compacting mortar mixture containing spent equilibrium catalyst from oil refinery. Journal of Cleaner Production, 2017, 158, pp.109-121.

[14] Pacewska B, Nowacka M, Aleknevičius M, Antonovič V, Early Hydration of calcium aluminate cement blended with spent FCC catalyst at two temperatures. Procedia Engineering, 2013, 57, pp.844-850.

[15] Pacewska B, Bukowska M, Wilinska I, Swat M, Modification of the properties of concrete by a new pozzolan -a waste catalyst from the catalytic process in a fluidized bed. Cement and Concrete Research, 2002, 32, pp.145-152.

[16] Paya J, Monzo J, Borrachero MV, Velazquez S, Evaluation of the pozzolanic activity of fluid catalytic crackingcatalyst residue (FC3R). Thermogravimetric analysis studies onFC3R-Portland cement pastes. Cement and Concrete Research, 2003, 33, pp.603-609.

[17] Pavol H, FCC catalyst - key element in refinery technology. Proceedings of the 45th International Petroleum Conference, 2011.

[18] Sadeghbeigi R, Fluid Catalytic Cracking Handbook. An Expert Guide to the Practical Operation, Design, and Optimization of FCC Units, 3rd ed.; Elsevier Inc.: Oxford, UK, 2012.

[19] Silva FGS, Junior RA Fiuza, Silva JS, Pinto KW, Andrade HMC, Dweck J, Goncalves JP, Hydration of the equilibrium catalyst (Ecat) calcium hydroxide system. Thermogravimetric study of the formation of main hydrated phases. Journal of Thermal Analysis and Calorimetry, 2015, 120, pp.1089-1098.

[20] Slamečka T, Škvára F, The effect of water ratio on microstructure and composition of the hydration products of portland cement pastes. Ceramics - silikáty, 2002, 46, pp.152-158.

[21] Zornoza E, Garcés P, Monzó J, Borrachero MV, Payá J, Accelerated carbonation of cement pastes partially substituted with fluid catalytic cracking catalyst residue (FC3R). Cement and Concrete Composite, 2009, 31, pp.134-138.