

Efficient and Reusable Pb(II) Metal–Organic Framework for Knoevenagel Condensation

Miroslav Almáši¹ · Vladimír Zeleňák¹ · Maksym V. Opanasenko² · Jiří Čejka²

Received: 1 February 2018 / Accepted: 24 June 2018 © Springer Science+Business Media, LLC, part of Springer Nature 2018

Abstract

A microporous lead–organic framework { $[Pb_4(\mu_8-MTB)_2(H_2O)_4]$ ·5DMF·H₂O}_n (MTB = methanetetrabenzoate, DMF = *N*,*N*'-dimethylformamide) was synthesized and studied as a catalyst in Knoevenagel condensation reactions. The framework is built from tetranuclear [$Pb_4(\mu_3$ -COO)(μ_2 -COO)_6(COO)(H₂O)_4] clusters and exhibits a 3D structure, with repeated 1D jar-like cavities with sizes about 14.98 × 7.88 and 14.98 × 13.17 Å² and BET specific surface area of 980 m² g⁻¹. To obtain open framework with unsaturated Pb(II) sites needed for catalysis, the thermal activation of the solvent exchanged sample was performed (DMF was exchanged by EtOH). The activated compound was tested in Knoevenagel condensation of bulky aldehydes and active methylene compounds at different temperatures. Excellent catalytic conversion and selectivity in condensation of small-sized aldehydes with malononitrile was observed, which indicates that the opened Pb(II) sites play a significant role in the heterogeneous catalytic process. Leaching test confirmed the stability of the catalyst in catalytic reactions. Moreover, the compound displayed good recyclability after several reuses without significant decrease in the original catalytic activity.

Graphical Abstract

Novel Pb(II) metal–organic framework was tested in Knoevenagel condensation. The catalyst showed excellent catalytic conversion, selectivity and recyclability. Aldehydes with lower kinetic diameter demonstrated high conversions and yields. Catalyst is less efficient for condensation of larger aromatic aldehydes.



Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10562-018-2471-8) contains supplementary material, which is available to authorized users.

Extended author information available on the last page of the article

Keywords $Lead(II) \cdot Methanetetrabenzoate \cdot Metal-organic framework \cdot Sorption properties \cdot Knoevenagel condensation$

1 Introduction

The Knoevenagel condensation is one of the most important C–C forming condensation reactions in organic chemistry [1]. Products of this reaction are α,β -unsaturated compounds, which have been widely used as final substances or intermediates in the synthesis of fine chemicals [2], pharmaceuticals [3], natural products [4], perfumes [5], agrochemicals [6] and functional polymers [7]. Knoevenagel condensation can be performed under homogeneous conditions in the presence of catalysts such as organic amines [8], alkali salts [9], ionic liquids [10, 11], self-assembled solids [12], polyoxometalates [13], and others. In recent years, Knoevenagel condensations promoted by microwave irradiation have been developed [14]. Unfortunately, reactions under these conditions often need high power microwaves and are not applicable for large-scale synthesis.

Nowadays there is an urgent need to develop green chemistry processes, where the generation of waste can be avoided, but considering both environmental and economic points of view. Therefore, the current research is focused on the development of new heterogeneous catalysts, which can help to overcome these tasks. To catalyse Knoevenagel condensation, amines [15], metal nanoparticles [16] or metal oxides [17] immobilized on mesoporous silica [18], alumina [19], polyacrylamide [20] and polyacrylonitrile fiber [21], mesoporous carbon nitride [22] or zeolites were tested [23, 24].

Among potential catalysts, metal–organic frameworks (MOFs) have attracted tremendous interest in the last decade [24]. MOFs represent crystalline porous solids resembling zeolites, having metal ions/clusters and organic ligands to build a final framework with large surface area, predictable, controllable and post-synthetic modifiable pores and cavities. Due to their fascinating diversity, MOFs are intensively studied in the different practical areas including gas storage [25, 26] and separation [27], drug delivery [28], sensing [29], magnetism [30] and heterogeneous catalysis [31–40].

As for catalysis, MOFs have been investigated as solid catalysts or catalysts support for organic transformations. The coordinatively unsaturated metal sites within MOF framework can serve as catalytic centres acting as Lewis acid catalysts for various organic reactions, such as Beckmann rearrangement [31], Henry [32] and Prins [33] reactions, Friedel–Crafts alkylation [34] and of course Knoevenagel condensation [35–40]. In the case of different porous coordination polymers, Knoevenagel condensation is usually catalysed by basic sites (e.g. amine group located on linker in the polymeric framework, imidazole in ZIFs, M–O pairs) or acid sites such as coordinatively unsaturated

sites on metal ions [41–45]. To date different MOFs such as UMCM-1 and IRMOF-3 [35, 43], MIL-101 [36, 43], Ni-MTB [38], UIO-66 [39], HKUST-1 [2], PCN-100 [46] and PCN-101 [46] were investigated as catalysts in Knoevenagel condensation. In the case of PCN-100 and PCN-101 a size-selective catalytic activity was studied by varying the size and shape of the substrates [46].

In our research we are interested in the preparation of the new MOFs using methanetetrabenzoate linker (MTB). Based on our knowledge and experience this linker prefers coordination with central atoms in oxidation state +2. To date we have prepared and studied MOF compounds containing Zn(II) [25, 49] and Ni(II) [38] ions as metal nodes. As a continuation of these works, in the subsequent study, we selected lead atom, which also prefers oxidation state +2 and moreover the stereochemistry of lead(II) ions is due to presence of lone electron pair in the valence sphere very interesting for the chemists working in the field of coordination chemistry. Using lead(II) ion and MTB linker we have prepared and investigated the compound {[$Pb_4(\mu_8-MTB)_2($ H_2O_4]·5DMF· H_2O_1 (1). The properties of this compound, like crystal structure, low and high-pressure gas adsorption and preliminary catalytic properties were described in detail in our recent work [40]. The catalytic properties of 1 seemed us so interesting, that we studied them more in detail. The obtained results we describe in the present study dealing with the Knoevenagel condensation reaction over MOF with composition $\{[Pb_4(\mu_8-MTB)_2(H_2O)_4]\cdot 5DMF\cdot H_2O\}_n$. The tested catalytic reaction was selected based on our previous results when we explored and compared the effect of zeolites versus MOF activity in Knoevenagel condensation [2]. Moreover, the Knoevenagel condensation was selected also based on the literary review showing, that the Knoevenagel reactions are one of the most frequent reactions used for tests of new prepared catalysts today. It is to note, based on searches in different databases, there are no studies in the literature dealing with the application of lead-based MOFs in the Knoevenagel condensation reaction.

In the present study an interesting size-selectivity screen has been observed revealing the relationship between the size of the substrates and the catalytic activity of **1** in the Knoevenagel condensation of different bulky aldehydes (*n*-heptanal, cyclohexane carbaldehyde, benzaldehyde, 4-*tert*-butylbenzaldehyde, 3,5-*ditert*-butylbenzaldehyde, 2-naphthaldehyde) with active methylene compounds (malononitrile, methyl cyanoacetate and ethyl acetoacetate) at different temperatures (70–130 °C).

2 Experimental

2.1 Materials

All chemicals used in the synthesis of the complex and reagents for catalytic reactions were obtained from Sigma-Aldrich or Acros Organics companies and used without further purification. The catalyst was prepared according to the literature procedure [40]. *n*-heptanal (95%), cyclohexane carbaldehyde (97%), benzaldehyde ($\geq 99\%$), 4-*tert*-butylbenzaldehyde (97%), 3,5-*ditert*-butylbenzaldehyde (97%), 2-naphthaldehyde (98%), malononitrile ($\geq 99\%$), methyl cyanoacetate (99%), ethyl acetoacetate ($\geq 99\%$), *n*-dodecane ($\geq 99\%$, internal standard) and *p*-xylene ($\geq 99\%$, solvent) used in the catalytic experiments were obtained from Sigma-Aldrich and Across Organics.

2.2 Characterization

The catalyst was analysed by an Avatar FT-IR 6700 spectrometer using KBr and ATR techniques to identify the organic ligands of the catalyst, to monitor the desolvation process and immobilization of the substrates/products after catalysis. The crystallinity of the samples was monitored by powder X-ray diffraction (Bruker AXS D8 Advance). Thermogravimetric analysis of **1**, solvent exchanged sample and reused catalyst was performed in the temperature range of 30–900 °C under dynamic atmosphere of air with heating rate 9 °C min⁻¹ (STA Netzsch 409-PC). The surface area and pore volume of the samples after different activation procedures were analysed and determined from nitrogen physisorption at – 197 °C (Quantachrome Nova 1200e). The details of analysis procedures are described in [40].

2.3 Knoevenagel Condensation Reactions

The Knoevenagel condensation of aldehydes and active methylene compounds was performed in a liquid phase under atmospheric pressure and temperature of 130, 100 and 70 °C on a multi-experiment work station StarFish. Before catalytic experiments the single crystals of the catalyst **1**, after solvent exchange with ethanol, were gently grinded with aim to decrease the size of grains and increase their active sites for catalytic experiments. After this procedure, the catalyst was activated at 200 °C for 90 min with a temperature heating rate 10 °C min⁻¹ in a stream of air (50 cm³ min⁻¹). The *p*-xylene was used as a solvent for Knoevenagel condensation. We have performed condensation reaction in different solvents such as benzene, toluene and *p*-xylene, but best results were obtained for *p*-xylene. Moreover, the *p*-xylene as nonpolar

solvent was necessary for dissolution of substrates. Methyl groups on phenyl ring in *p*-xylene are in positions 1 and 4 and therefore less steric limitation for diffusion of these molecules into channel system compared to *o*- and *m*-xylene. Finally, in comparison to benzene (b.p. 80.1 °C) and toluene (b.p. 110.6 °C), *p*-xylene (b.p. 138.4 °C) has higher boiling point and we can reach reaction temperature 130 °C, used in our study.

Typically, 4 mmol of aldehyde, 0.4 g of dodecane (internal standard), 50 mg of catalyst and 10 cm³ of *p*-xylene (solvent) were added to the 25 cm³ three-necked vessel, equipped with condenser and thermometer, stirred and heated. Then 6 mmol of methylene compound was added into the reaction vessel through syringe with needle when the desired reaction temperature was reached.

0.1 cm³ of the reaction mixture was sampled after 10, 30, 60, 120, 240, 360 and 1440 min. After the sampling, the reaction suspension was immediately centrifuged for 5 min at 4000 rpm. After this procedure, the reaction products were analysed by gas chromatography (GC) using an Agilent 6850 with FID detector equipped with a nonpolar HP1 column (diameter 0.25 mm, thickness 0.2 μ m and length 30 m). The reaction products were identified using GC–MS analysis (ThermoFinnigan, FOCUS DSQ II Single Quadrupole GC/MS). The identity of the reaction products was also confirmed using ¹H NMR spectroscopy measurements carried out on a Varian Unity 400 spectrometer. ¹H chemical shifts in CDCl₃ were given with tetramethylsilane (TMS) as the internal standard. The observed spectra corresponded to the previously published data [47].

To evaluate the potential influence of leaching of the active species from the heterogeneous catalysts, a part of the reaction mixture was taken away, immediately centrifuged and the obtained liquid phase was again investigated in the Knoevenagel condensation under the same reaction conditions. The reaction mixture was sampled after 5, 10, 20, 30, 40 and 60 min. Leaching test was also performed using ICP-MS measurement on ICP-MS 7700 instrument (Agilent Technologies). Before measurement, reaction suspension composed from the catalyst, malononitrile and *n*-heptanal was heated at 130 °C for 24 h. After this time the catalyst was separated by filtration and liquid phase evacuated in vacuum. Final residue was mineralized with aqua regia and solution was analysed by ICP-MS.

Recyclability of the catalyst was tested in the reactions of *n*-heptanal/cyclohexane carbaldehyde with malononitrile in a three repetition cycles. After each test, the catalyst was separated by centrifugation, stirred in solvents with different polarity (ethanol, acetone, *n*-hexane), filtered off, reactivated at 200 °C for 90 min and then reused in the next run. Moreover, the catalyst recycled after 3rd run in the reaction of *n*-heptanal and malononitrile was analysed by a combination of infrared spectroscopy and TG/DTG–DTA in order to demonstrate the immobilization of reactants/products in the pores of the material.



Fig. 1 a Building blocks used in the synthesis of **1** and its tetranuclear lead(II) cluster $[Pb_4(\mu_3 \text{-}COO)(\mu_2 \text{-}COO)_6(COO)(H_2O)_4]$ with marked catalytic active sites on Pb2 and Pb4 ions (blue ellipsoids). **b** View of the final 3D polymeric framework with 1D channels propagating along *a* axis

3 Results and Discussion

3.1 Description of the Crystal Structure

The crystal structure of 1 is formed by tetrahedral methanetetrabenzoate linkers and lead(II) ions (see Fig. 1a). Pb(II) cations are bridged by carboxylate groups under formation of asymmetrical tetranuclear clusters with composition $[Pb_4(\mu_3\text{-}COO)(\mu_2\text{-}COO)_6(COO)(H_2O)_4]$ in which the μ_3 -carboxylato functional group is coordinated in chelate-anti-anti fashion and connected to three lead(II) ions Pb1, Pb3 and Pb4 (Fig. 1a). The other six carboxylates are bonded to Pb(II) ions in μ_2 -coordination mode and connect lead ions into the final cluster. Cluster is strongly distorted because of the presence of the stereochemically active $6s^2$ lone-pair electrons on the Pb(II) central atoms. An interesting feature of the cluster is presence of four coordinated water molecules, which could be easily removed by thermal treatment (see Sect. 3.2 below) and this way four unsaturated centers as Lewis acid metal sites for catalysis could be obtained.

As depicted Fig. 1b, lead–organic framework contains open channels propagating along crystallographic axis *a*, which are formed by repeated jar-like cavities with narrow entrances (14.98×7.88 Å²) and wider inside pockets (14.98×13.17 Å²). Each channel is constructed by the methanebenzoate subunit of MTB^{4–} with [Pb₄(μ_3 -COO) (μ_2 -COO)₆(COO)(H₂O)₄] and is further connected with five neighboring MTB^{4–} molecules, forming a 3D open framework, with 50.3% solvent accessible voids. The detailed description of crystal structure can be found in [40].

3.2 Study of Activation Process and Characterization of the Catalyst

The activation process of the compound was studied by the combination of thermal analysis (TG/DTG–DTA) and infrared spectroscopy measured at different temperatures (see Sect. 2.2). The framework stability was monitored by powder X-ray diffraction (PXRD) and nitrogen adsorption/ desorption measurements.

As it is evident from TG/DTG–DTA curves (Fig. S1 in Supplementary information), compound **1** is thermally stable after heating up to 110 °C. The desolvation processes take place in the temperature range 100–240 °C in one decomposition step. The observed weight loss of 19.8% in this region corresponds to release of five water and five clathrated DMF molecules (calcd. 20.1%). The desolvation process is characterized by two endothermic effects on DTA at 105 and 210 °C, corresponding to the release of water and DMF, respectively. The desolvated form of 1, {[Pb₄(μ_8 -MTB)₂]}_n (denoted as 1' in the further text), is thermally stable in the temperature range 240–340 °C, as evidenced by a plateau on the TG curve. In the range 340–750 °C, decomposition of the polymeric framework takes place with the observed mass change of 38.5% (calcd. 37.8%) on TG curve. Decomposition process was accompanied by three exothermic effects on DTA at 375, 510 and 620 °C. The final product of the decomposition was PbO₂ (obs. 41.7%, calcd. 42.2%).

In addition to the as synthesised sample, the sample after solvent exchange process (DMF was exchanged by ethanol), was also studied by TGA (see Fig. S2 in the Supplementary information). As it can be seen from TG curve, in the ethanol exchanged sample, molecules of solvents (EtOH and H_2O) are evolved in temperature range 50–150 °C and after this process framework of the compound is stable in region 150–300 °C. At higher temperatures, the decomposition of the polymeric framework is similar as for as-synthesized sample described in the paragraph above.

IR spectra of compound 1 (see Fig. 2, black curve) show characteristic bands of the antisymmetric vibrations, (ν (COO)_{as}), of methanetetrabenzoate ligands at 1588, 1532 cm⁻¹, symmetric vibrations, (ν (COO)_s), at 1389 cm⁻¹ and absorption band at 777 cm⁻¹ corresponding to δ (COO⁻) vibration. The absence of characteristic absorption bands of protonated carboxylic groups in the range 1730–1690 cm⁻¹ indicates the complete deprotonation of H₄MTB. The broad band at 3440 cm⁻¹ confirms the presence of coordinated water molecules. Very strong and sharp band at 1659 cm⁻¹ corresponds to stretching vibration ν (C=O), which could be attributed to DMF molecules. The presence of DMF molecules is also evident from weak aliphatic stretching vibrations of C–H bonds, (ν (CH)_{aliph}), at 2975 and 2928 cm⁻¹.

To study the liberation of guest molecules from {[Pb₄(μ_8 - $MTB_{2}(H_{2}O)_{4}$]·5DMF·H₂O}_n, the infrared spectra at different temperatures 100, 200, 300 and 400 °C were measured (see Fig. 2). IR spectra at the respective temperatures illustrate the decrease of the intensity of the bands corresponding to water and DMF molecules and thus indicate release of these solvents from the framework of 1. In the concrete, after heating to 100 °C a decrease of the intensity of the broad band around 3400 cm⁻¹, corresponding to the $\nu(OH)$ stretching vibration in water molecules, was observed. The spectrum measured at 200 °C showed diminishment of the intensity of this band due to complete release of water molecules. On the other hand, stretching vibration of aliphatic C–H bonds in the region under 3000 cm^{-1} and strong adsorption band of the carbonyl ν (C=O) vibration at 1659 cm⁻¹ of DMF were still observed in the spectrum. Further heating to 300 °C leads to the complete removal of N,N'-dimethylformamide molecules. After the desolvation (removal of water and DMF molecules), the framework is stable and keeps its structure integrity as confirmed by powder X-ray diffraction. The details about PXRD can be found in [40]. Finally, heating to 400 °C led to the decomposition of the framework. It should be noted, that the presented conclusions observed from IR spectra measured at different temperatures are in good agreement with the results obtained from TG/DTG-DTA analysis.

Relatively large accessible volume in **1** (50.3% of the cell volume 17 704 Å^3) led us to investigate the textural properties of the compound using nitrogen adsorption



Fig.2 IR spectra of compound 1 measured at room temperature (black line), and after heating to 100 °C (red line), 200 °C (green line), 300 °C (wine line) and 400 °C (orange line)



Fig. 3 Nitrogen adsorption isotherms of as-synthesized/solvent exchanged samples subsequently activated at different temperatures (100, 150 and 200 $^{\circ}$ C)

measurements under different activation conditions. The solvent molecules in the cavities of as-synthesized sample 1 were removed using different thermal treatment procedures or solvent exchange processes with the aim to find the activation conditions leading to the best textural properties. Freshly prepared sample was first activated at 100, 150 and 200 °C for 24 h under vacuum, but according to nitrogen adsorption measurements the compound adsorbed only a limited amount of nitrogen (see Fig. 3). Therefore, we have tried to activate the compound by solvent exchange with ethanol (5 days, while ethanol was changed every day), followed by outgassing at 100, 150 and 200 °C under vacuum for 24 h. Measured adsorption isotherms are illustrated in Fig. 3.

The highest nitrogen uptake was observed for ethanol exchanged sample after evacuation at 200 °C for 24 h (denoted as 1'). Nitrogen adsorption measurement of 1' at - 196 °C revealed a type I isotherm classified by IUPAC typical for microporous materials (see Fig. 3, the isotherm with orange colour). At the relative pressure $(p/p_0 = 0.95)$, the N₂ uptake capacity reaches 278 cm³ g⁻¹, which corresponds to a total microporous volume of 0.666 cm³ g⁻¹ calculated by density functional theory (DTF) method. Evaluation of the nitrogen adsorption isotherm in the $p/p_0 = 0.05-0.2$ range using the Brunauer-Emmett-Teller (BET) equation gave the specific surface area (S_{BET}) of 980 m² g⁻¹. It is to note, that the observed S_{RET} surface area is the highest, when compared to the other reported MOFs constructed by the methanetetrabenzoate linker (see Table 1).

3.3 Knoevenagel Condensation Reactions

According to Lewis acid/base theory, Lewis acids and bases are atoms, molecules or ions that tend to act as an electron acceptor or donor, respectively. Lewis acid sites, i.e., coordinatively unsaturated sites (CUSs) can be formed by different ways, such as defect engineering in MOFs, the removal of labile water molecules or coordinating solvent molecules from the metal centre. In compound 1, there are four terminal water molecules per each $[Pb_4(\mu_3 \text{-}COO)(\mu_2 \text{-}$ $COO_{6}(COO)(H_{2}O)_{4}$] cluster in the asymmetric unit, which could be eliminated by thermal treatment to provide CUSs as Lewis acid sites for catalysis.

On the other side, the nature of basic sites of MOFs is unclear. However, we can speculate, that their basic sites arise from the oxygen atoms of carboxylate groups of organic linkers connected to metal ions of SBUs (M-O bond) from benzene rings or from basic functional groups in linkers [41]. So, in the sense of our suggestion, the possible basic sites in 1' could came from carboxylate oxygen atoms bonded to lead(II) ions (Pb-O), or from inert electron pairs on the valence sphere of central atoms.

In this work, Knoevenagel condensation reactions of different aromatic and non-aromatic aldehydes with active methylene compounds at different temperatures were chosen as catalytic test reactions. A size-selectivity screening has been studied to reveal the relationship between the size of the aldehyde substrate and the catalytic activity of 1'. Knoevenagel condensation proceeds according to the reaction shown in Fig. 4, the summary of conversion and selectivity to the targeted products are presented in Table 2 and the size of the substrates used in catalytic reactions are shown in Fig. S3 in the Supporting information.



Fig. 4 Scheme of Knoevenagel condensation with experimental conditions and used substrates

D (

Table 1	Textural properties	
of up to	date prepared MOFs	
containi	ng MTB ^{4–} linker	

Compound	Adsorbate	Surface $(m^2 g^{-1})$	Pore volume $(cm^3 g^{-1})$	References
{ $[Ni_2(\mu_4-MTB)(\kappa^4-CYC)_2]\cdot 4DMF\cdot 8H_2O$ } _n	CO ₂	141	0.055	[48]
$\{[Zn_2(\mu_8-MTB)(H_2O)_2]\cdot 3DMF\cdot 3H_2O\}_n$	N ₂	248	0.089	[49]
$\{[Co_4(\mu_6-MTB)_2(\mu_2-H_2O)_4(H_2O)_4]\cdot 13DMF\cdot 11H_2O\}_n$	CO_2	356	0.165	[50]
$\{[Cu_2(\mu_8-MTB)(H_2O)_2]\cdot 6DEF\cdot 2H_2O\}_n$	N_2	526	-	[51]
$\{[Zn_2(\mu_4-MTB)(\kappa^4-CYC)_2]\cdot 2DMF\cdot 7H_2O\}_n$	Ar	644	0.246	[25]
$\{[Ni_4(\mu_6-MTB)_2(\mu_2-H_2O)_4(H_2O)_4]\cdot 10DMF\cdot 11H_2O\}_n$	N ₂	700	0.291	[38]
$\{[Pb_4(\mu_8 - MTB)_2(H_2O)_4] \cdot 5DMF \cdot H_2O\}_n$	N_2	980	0.666	This work

Table 2Results of Knoevenagelcondensation performed atdifferent temperatures

Aldehyde	Methylene comp.	Repetition	130 °C		100 °C		70 °C	
			Conv. ^b	Sel. ^a	Conv. ^b	Sel. ^a	Conv. ^b	Sel. ^a
п-НСНО	MNT	1st	100	100	100	79	83	57
		2nd	100	96	-	_	-	_
		3rd	100	97	-	_	_	-
	MCA		100	96	95	28		
	EAA		97	42	88	26	-	-
ChCHO	MNT	1st	100	100	100	85	91	87
		2nd	100	97	-	_	_	_
		3rd	100	98	-	_	-	-
	MCA		61	100	95	92	-	-
	EAA		57	55	68	25	-	-
PhCHO	MNT		100	100	72	93	35	66
	MCA		100	100	62	92	-	-
	EAA		68	87	63	55	-	-
4T-PhCHO	MNT		56	98	38	85	24	45
	MCA		45	61	30	28	-	-
	EAA		39	48	12	6	-	-
3,5T-PhCHO	MNT		45	98	26	93	30	84
	MCA		26	65	19	23	-	-
	EAA		21	100	18	n	-	-
2-NaphCHO	MNT		83	99	56	76	38	n
	MCA		40	69	38	18	_	-
	EAA		31	55	26	3	-	_

The yield is calculated by GC using n-dodecane as the internal standard

n not detected, – not performed, *n*-HCHO *n*-heptanal, *ChCHO* cyclohexane carbaldehyde, *PhCHO* benzaldehyde, *4T-PhCHO* 4-*tert*-butylbenzaldehyde, *3,5T-PhCHO* 3,5-*ditert*-butylbenzaldehyde, *2-NaphCHO* 2-naphthaldehyde, *MNT* malononitrile, *MCA* methyl cyanoacetate, *EAA* ethyl acetoacetate

^aSelectivity after 360 min of reaction

^bConversion after 360 min of reaction

In addition to the main product, the reaction mixture may contain some by-products from the consecutive reactions of primary product. According to the results of GS–MS, carboxylic acids from the corresponding aldehydes, formed via an oxidation, were found as by-products. Other identified side products were cyanoacetic acid formed during deesterification reaction of methyl cyanoacetate, or compounds created by hydrolysis of cyano group of malononitrile or methyl cyanoacetate (or its deesterification form).

The test reaction, Knoevenagel condensation of malononitrile with aldehydes at 130 °C, resulted in the condensation product with excellent selectivity about 100% (*n*-HCHO), 100% (ChCHO), 100% (PhCHO), 98% (4T-PhCHO), 98% (3,5T-PhCHO) and 99% (2-NaphCHO) yielding the desired product after 360 min of reaction. Our obtained results for reaction PhCHO with malononitrile over **1'** (see Table 2) are comparable to conversion and selectivity for compounds CAU-1–NH₂ (conv. 98%, sel. 100%, 40 °C, 420 min), Fe–MIL-101–NH₂ (conv. 90%, sel. 100%, 80 °C, 180 min) or Zn–MOF–NH₂ (conv. 98%, sel. 100%, 80 °C, 270 min),



Fig. 5 Conversion curves of different bulky aldehydes in the reaction with malononitrile (130 $^{\circ}\text{C})$

which in contrast to our sample, contain basic Lewis sites in their frameworks [52]. As it can be seen from the Table 2 and Fig. 5, the conversions for n-heptanal and benzaldehyde are similar and are faster in comparison with the other aldehydes, giving the condensation product with 100% yield in 240 min, in contrast to 480 min in the case of 2-naphthaldehyde. On the other hand, the catalytic activity for cyclohexane carbaldehyde lies between those of n-heptanal/ benzaldehyde and 2-naphthaldehyde as it takes 360 min to reach 100% conversion. Although we extended the time of reaction to 24 h, bulkier aldehydes such as 4T-PhCHO and 3,5T-PhCHO did not reach 100% conversion. For the bulkier aldehydes, their conversions (selectivities) under the same conditions were 45% (100%), 56% (95%), and 83% (95%) for 3,5-ditert-butylbenzaldehyde, 4-tert-butylbenzaldehyde, and 2-naphthaldehyde, respectively. Since the conversions of aldehydes with similar accessibility and polarity of the carbonyl group significantly depend on the size of the substrate, we assume that the Knoevenagel condensation proceeds inside the pore system of 1' under the applied conditions.

The 100% conversions in the reactions of methyl cyanoacetate with selected aldehydes after 360 min was observed only for *n*-heptanal and benzaldehyde. The size effect was also observed in the case of bulkier aldehydes (see Fig. S3 in the Supporting information) and the conversions decreases with increasing size of substrate as follows, NaphCHO (83%), ChCHO (61%), 4T-PhCHO (56%), and 3,5T-PhCHO (45%). The observed selectivities were lower compared with malononitrile and the values are in the range 60–100%.

In addition, ethyl acetoacetate has been proven as not efficient active methylene compound for Knoevenagel condensation, because of low conversions and selectivities were observed in the catalytic tests (see Table 2). Similar low conversion for reaction PhCHO with ethyl acetoacetate were also observed for compound IRMOF-3, where different solvents and reaction temperatures were applied: 65% (DMSO, 80 °C), 54% (DMF, 80 °C), 54% (MeOH, 60 °C) or 39% (DMF, 60 °C) [35].

From the results of catalytic measurements, it can be concluded, that the selectivity (more than 98% for all reactions) and conversion to the target product were in most cases higher for condensation of aldehydes with malononitrile compared to methyl cyanoacetate and ethyl acetoacetate (see Table 2). The sequence of substrate reactivity is in good agreement with our previous reports [2, 38].

An explanation of the catalytic results in terms of used active methylene compounds is that the reactivity trend depends on the strong accelerating influence of electron withdrawing groups bonded to active methylene centrum (-CN > -OMe > -OEt). The stronger electron withdrawing ability of the substituent, the easier activation of active methylene compound for electrophilic attack at the R-CH₂-R group and hence higher conversion. Furthermore,

the reactivity difference of the methylene compounds follows with their acidity scale, which increases in the order EAA ($pK_a = 13.1$) < MCA ($pK_a = 12.8$) < MNT ($pK_a = 11.1$) [53–55].

An explanation of the catalytic results in terms of used aldehyde is that *n*-heptanal, benzaldehyde and cyclohexane carbaldehyde have sizes of 2.1 × 8.1 Å, 4.0 × 6.0 Å and 2.6×6.3 Å (see Fig. S3 in the Supporting information), which allows them to enter and exit from 1' freely. As it was described above, in the framework of 1, there are 1D jar-like cavities with effective pore size about 14.98×7.88 Å and 14.98×13.17 Å. This is the main reason why catalyst demonstrated excellent yields towards the Knoevenagel condensation reaction of these aldehydes. While slightly larger aldehyde substrates, such as 4-tert-butylbenzaldehyde, 3,5-ditert-butylbenzaldehyde and 2-naphthaldehyde, showed significantly decreased conversions and yields. The sizes of 4T-PhCHO, 3,5T-PhCHO and 2-NaphCHO are 4.1×8.3 Å, 8.6×8.4 Å and 4.0×8.7 Å, respectively which are quite close to the pore size of 1. Moreover, these results also show on the size effect, the probability of bulkier aldehydes with methyl cyanoacetate or ethyl acetoacetate to form transition state complexes is significantly reduced due to the limited space in the pore system of the catalyst.

It was found that the activity and selectivity of **1'** in condensation reactions significantly decreased after decreasing of the reaction temperature from 130 to 70 °C. As an example, the reaction of benzaldehyde with malononitrile is presented. When the reaction temperature decreases from 130 to 100 °C and finally to 70 °C, conversion (selectivity) decreases in the order 100% (100%), 72% (93%) and 35% (66%), respectively. The results could reflect high energy barrier of transition state, which could not be achieved at lower reaction temperature.

Although conversion and selectivity over catalyst 1' gave satisfactory results, they were achieved at relatively high temperature. For comparison, MOF catalysts giving the best results in Knoevenagel condensation of aldehydes and active methylene compounds (especially containing basic sites) reached the comparable conversion and selectivity values at lower temperatures (25–40 °C) [2, 41, 42].

The key advantage of the use of heterogeneous catalysts is their easy recovery from the reaction mixtures and their reuse. We examined the recyclability of 1' in Knoevenagel condensation reactions of *n*-heptanal and cyclohexane carbaldehyde with malononitrile by reusing recovered catalysts for the 2nd and 3rd catalytic runs under the same conditions as the 1st run. In each test, the catalyst was separated by centrifugation, stirred in solvents with different polarity (ethanol, acetone, *n*-hexane), filtered off, reactivated at 200 °C and then reused in the next run. As shown in Fig. 6, the conversion curves of reused catalyst in the reaction of malononitrile with *n*-heptanal displayed steady acceleration,



Fig. 6 Conversion and selectivity (inset) curves using reused catalyst after 1st (black squares), 2nd (red ball) and 3rd (green triangle) catalytic run in the condensation reaction of *n*-heptanal and malononitrile at 130 °C

with slight decreasing of selectivity during three repetitions. A similar trend was observed in the repetition reactions with cyclohexane carbaldehyde and malononitrile (see Table 2). Results indicate, that **1'** possesses good recyclability without significant degradation in the original catalytic activity.

When a solid catalyst is employed for a liquid-phase organic transformation, an important problem, that should be seriously considered, is the possibility that some of the active species could release into the reaction solution. In some cases, these leached species could contribute significantly to the catalytic activity during the reaction. Therefore, we have performed a leaching test. The leaching test for



Fig.7 Leaching test of Pb(II) ions from the framework of 1' under heterogeneous and homogeneous (after centrifugation procedure) conditions in the Knoevenagel condensation of *n*-heptanal and malononitrile at 130 °C

Pb(II) ions from the framework of 1', performed under the Knoevenagel condensation of *n*-heptanal with malononitrile at 130 °C, provided that leaching of the active sites is not responsible for the high catalytic activity of 1'. After 10 min reaction, the solid catalyst was filtered off and the same reaction mixture was continued to react for further 60 min with aliquots being taken at regular time intervals and analysed by GC. As can be seen from Fig. 7, GC analysis proved stop of reaction at ~60% conversion, indicating absence of leaching of the active species from 1'. Negative leaching test of Pb(II) ions form 1' was also confirmed by ICP-MS measurement.

The possible incorporation or immobilization of substrates in the catalyst was investigated in the reaction of *n*-heptanal with malononitrile by the combination of thermogravimetry and infrared spectroscopy. Figure S4 in SI shows TG/DTG–DTA analysis of the used, refreshed and activated catalyst in the temperature range 30–900 °C. After heating of the sample to 300 °C no significant mass change on TG was observed indicating the absence of solvents in the pore system of **1'**. The thermal decomposition takes place in the temperature range 300–600 °C, which is in good agreement with pyrolysis of the framework (see Figs. S1 and S2 in the Supporting information). The observed mass change



Fig. 8 Infrared spectra of a malononitrile, b *n*-heptanal and c 1' after reaction of heptanal and malononitrile at 130 $^{\circ}$ C



Fig. 9 PXRD patterns of 1 before and after the Knoevenagel condensation (reactions with malononitrile at $130 \text{ }^{\circ}\text{C}$)

in reused catalyst was 70.0% and it is higher in comparison to that observed in the thermal decomposition of 1 (37.8%). The difference between mass changes corresponds to immobilization of four molecules of 2-heptylidenemalononitrile as condensation product per formula unit of 1'.

Furthermore, immobilization of substrates/products was also studied by infrared spectroscopy. IR spectra of malononitrile, *n*-heptanal and 1' after the third catalytic run, are illustrated in Fig. 8. Malononitrile is characterized in the spectra by two absorption bands at 2966 and 2933 cm⁻¹ corresponding to $\nu(CH)_{aliph}$ of active methylene centrum $(-CH_2-)$ and one absorption band at 2272 cm⁻¹ of nitrile group (ν (CN)), Fig. 8a. In the IR spectrum of *n*-heptanal, ν (CH)_{aliph} and ν (C=O) vibrations in region 2980–2860 cm⁻¹ and at 1727 cm^{-1} , respectively are characteristic (Fig. 8b). IR spectrum of reused catalyst (Fig. 8c) exhibits some differences compared to that of freshly prepared sample (Fig. 2). As it can be seen from the Fig. 8c, new characteristic vibrations for aldehyde in the range 2980–2860 cm⁻¹ (ν (CH)_{alinh}) and nitrile bending vibration (ν (CN)) at 2272 cm⁻¹ for malononitrile were observed. The absence of $\nu(CH)_{aliph}$ originated from malononitrile and ν (C=O) of aldehyde in the spectrum of reused 1' confirm the immobilisation of condensation product, 2-heptylidenemalononitrile in the framework.

The stability of the catalyst after 24 h reaction of aldehydes with malononitrile at 130 °C was monitored by PXRD. As it follows from the PXRD patterns (see Fig. 9), small changes in the diffraction patterns of **1** and the patterns obtained from the sample after Knoevenagel condensation were observed. The observed changes of the intensity ratios of diffraction peaks and small shifts of the corresponding diffraction lines are related to the interaction of the framework of **1** with reaction products, as confirmed by the thermal analysis and IR measurements described above (Fig. S4 and Fig. 8).

4 Conclusions

Lead–organic framework with composition { $[Pb_4(\mu_8-MTB)_2]$ $(H_2O)_4$]·5DMF·H₂O}_n was prepared and tested as catalyst in Knoevenagel condensation. Compound properties and process of activation for catalysis was studied by different physicochemical techniques such as thermogravimetry, infrared spectroscopy measured at different temperatures, PXRD and nitrogen adsorption measurements. To obtain the best porosity and surface area characteristics, conditions of activation of compound at different temperatures and time intervals were investigated. The best textural characteristics with BET surface area of 980 m² g⁻¹ and micropore volume 0.666 cm³ g⁻¹ were obtained after ethanol exchange process and evacuation at 200 °C under dynamic vacuum. Activation procedure led to the formation of open framework and generation of unsaturated coordination sites on lead(II) ions as active centres for catalysis. The catalytic properties of activated compound (1') were tested in condensation reactions of different aldehydes with active methylene compounds at different temperatures (130-70 °C). Based on the results of the catalytic experiments it was shown, that catalyst is less efficient for Knoevenagel condensation of larger aromatic aldehydes such as 4-tert-butylbenzaldehyde, 3,5-ditert-butylbenzaldehyde and 2-naphthaldehyde with selected active methylene compounds and the conversion decreased when the aldehyde substrate became bulkier. On the other hand, aldehydes with lower kinetic diameter like, n-heptanal, cyclohexane carbaldehyde and benzaldehyde demonstrated high conversions and yields to desired products. It was demonstrated that the reaction proceeds mainly inside the pore system of the catalyst and the framework has reasonable stability under the used conditions. Moreover, 1' possesses good recyclability without significant decrease in the original catalytic activity.

Acknowledgements This work was supported by the Scientific Grant Agency of the Slovak Republic (VEGA) Project No. 1/0745/17, by the Slovak Research and Development Agency under the contracts APVV-0073-14 and APVV-15-520 and the project from P. J. Šafárik University No. VVGS-2016-249. V.Z. and M.A. thank the Ministry of Education, Science, Research and Sport of the Slovak Republic for the financial support of the TRIANGEL team in the frame of the scheme "Top Research Teams in Slovakia". J.Č. acknowledges the Czech Science Foundation for the support of the project P106/12/G015.

References

- Jones G (2004) The Knoevenagel condensation. In: Organic reactions, 2nd edn, vol 15. Wiley, New York, pp 204–599
- Dhakshinamoorthy A, Opanasenko M, Čejka J, Garcia H (2013) Catal Sci Technol 3:2509–2540

- Walker SD, Borths CJ, DiVirgilio E, Huang L, Liu P, Morrison H, Sugi K, Tanaka M, Woo JCS, Faul MM (2011) Org Process Res Dev 15:570–580
- Jung JC, Lim E, Lee Y, Min D, Ricci J, Park OS, Jung M (2012) Molecules 17:2091–2102
- 5. Tietze LF, Rackelmann N (2004) Pure Appl Chem 76:1967–1983
- Gouda MA, Abu-Hashem AA (2012) Green Chem Lett Rev 5:203–209
- Liang F, Pu YJ, Kurata T, Kido J, Nishide H (2005) Polymer 46:3767–3775
- Bhat AR, Selokar RS, Meshram JS, Dongre RS (2014) J Mater Environ Sci 5:1653–1657
- 9. Pasha MA, Manjula K (2011) J Saudi Chem Soc 15:283–286
- Ma M, Li H, Yang W, Wu Q, Shi D, Zhao Y, Feng C, Jiao Q (2018) Catal Lett 148:134–143
- Priede E, Brica S, Bakis E, Udris N, Zicmanis A (2015) New J Chem 39:9132–9142
- 12. Zhu F, Sun X, Lou F. An L, Zhao P (2015) Catal Lett 145:1072–1107
- Wang H, Wang C, Yang Y, Zhao M, Wang Y (2017) Catal Sci Technol 7:405–417
- Maloo P, Roy TK, Sawant DM, Pardasani RT, Salunkhe MM (2016) RSC Adv 6:41897–41906
- Isobe K, Hoshi T, Suzuki T, Hagiwara H (2005) Mol Divers 9:317–320
- 16. Khurana JM, Vij K (2010) Catal Lett 138:104–110
- 17. Li JPH, Stockenhuber M (2015) Catal Today 245:108–115
- Ikeue K, Miyoshi N, Tanaka T, Machida M (2011) Catal Lett 141:877–881
- 19. Motokura K, Viswanadham N, Dhar GM, Iwasawa Y (2009) Catal Today 141:19–24
- 20. Tamami B, Fadavi A (2005) Catal Commun 6:747-751
- 21. Li G, Xiao J, Zhang W (2012) Green Chem 14:2234-2242
- 22. Xu J, Shen K, Xue B, Li YX, Cao Y (2013) Catal Lett 143:600–609
- 23. Srasra M, Delsarte S, Gaigneaux EM (2009) Catal Lett 52:1541–1548
- 24. Morris RE, Čejka J (2015) Nat Chem 7:381-388
- Almáši M, Zeleňák V, Zukal A, Kuchár J, Čejka J (2016) Dalton Trans 45:1233–1242
- 26. Qiu S, Xue M, Zhu G (2014) Chem Soc Rev 43:6116–6140
- Li JR, Kuppler RJ, Zhou HC (2009) Chem Soc Rev 38:1477–1504
 Ke F, Yuan YP, Qiu LG, Shen YH, Xie AJ, Zhu JF, Tian XY, Zhang LD (2001) J Mater Chem 21:3843–3848
- Qu XL, Gui D, Zheng XL, Li R, Han HL, Li X, Li PZ (2016) Dalton Trans 45:6983–6989

- 30. Kurmoo A (2009) Chem Soc Rev 38:1353-1379
- Opanasenko M, Shamzhy M, Lamač M, Čejka J (2013) Catal Today 204:94–100
- 32. Zhu L, Liu XQ, Jiang HL, Sun LB (2017) Chem Rev 117:8129-8176
- 33. Hu Z, Zhao D (2017) CrystEngComm 19:4066-4081
- Zhu NX, Zhao CW, Wang JC, Li YA, Dong YB (2016) Chem Commun 52:12702–12705
- 35. Burgoyne AR, Meijboom R (2013) Catal Lett 143:563-571
- Toyao T, Fujiwaki M, Horiuchi Y, Matsuoka M (2013) RSC Adv 3:21582–21587
- 37. Canivet J, Vandichela M, Farrusseng D (2016) Dalton Trans 43:4090–4099
- Almáši M, Zeleňák V, Opanasenko M, Čejka J (2014) Dalton Trans 43:3730–3738
- Luan Y, Qi Y, Gao H, Andriamitantsoa RS, Zheng N, Wang G (2015) J Mater Chem A 3:17320–17331
- Almáši M, Zeleňák V, Gyepes R, Bourrelly S, Opanasenko M, Llewellyn PL, Čejka J (2018) Inorg Chem 57:1774–1786
- Panchenko VN, Timofeeva MN, Jhung SH (2016) Catal Rev 58:209–307
- 42. Valvekens P, Vandichel M, Waroquier M, Van Speybroeck V, De Vos D (2014) J Catal 317:1–10
- Serra-Crespo P, Ramos-Fernandez EV, Gascon J, Kapteijn F (2011) Chem Mater 23:2565–2572
- 44. Tran UPN, Le KKA, Phan NTS (2011) ACS Catal 1:120-127
- Amarante SF, Freire MA, Mendes DTSL, Freitas LS, Ramos ALD (2017) Appl Catal A 548:47–51
- Fang QR, Yuan DQ, Sculley J, Li JR, Han ZB, Zhou HC (2010) Inorg Chem 49:11637–11642
- 47. Spectral database for organic compounds, National Institute of Advanced Industrial Science and Technology. http://riodb01.ibase .aist.go.jp/sdbs/
- 48. Cheon YE, Suh MP (2008) Chem Eur J 14:3961-3967
- Almáši M, Zeleňák V, Gyepes R, Zukal A, Čejka J (2013) Colloids Surf A 437:101–107
- Cheon YE, Suh MP (2009) Chem Commun 2296–2298. https:// doi.org/10.1039/B900085B
- 51. Ma L, Jin A, Xie Z, Li W (2009) Angew Chem Int Ed 48:9905–9908
- Dhakshinamoorthy A, Heidenreich N, Lenzen D, Stock N (2017) CrystEngComm 19:4187–4193
- 53. Olmstead WN, Margolin Z, Bordwell FG (1980) J Org Chem 45:3295–3299
- 54. Bordwell FG, Fried HE (1981) J Org Chem 46:4327-4331
- 55. Ugale B, Nagaraja CM (2016) RSC Adv 6:28854-28864

Affiliations

Miroslav Almáši¹ · Vladimír Zeleňák¹ · Maksym V. Opanasenko² · Jiří Čejka²

Vladimír Zeleňák vladimir.zelenak@upjs.sk

> Miroslav Almáši miroslav.almasi@upjs.sk

Maksym V. Opanasenko maksym.opanasenko@jh-inst.cas.cz

Jiří Čejka jiri.cejka@jh-inst.cas.cz

- ¹ Department of Inorganic Chemistry, Faculty of Science, P. J. Šafárik University, Moyzesova 11, 041 54 Košice, Slovak Republic
- ² Department of Synthesis and Catalysis, J. Heyrovský Institute of Physical Chemistry of the ASCR, v.v.i., Academy of Sciences of the Czech Republic, Dolejškova 2155/3, 182 23 Prague 8, Czech Republic