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Size Control of Catalytic Reaction Space by Intercalation of Alkylcarboxylate Anions into Ni–Zn Mixed Basic Salt Interlayer: Application for Knoevenagel Reaction in Water

Takayoshi Hara, Jun Kurihara, Nobuyuki Ichikuni, and Shogo Shimazu*
Graduate School of Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522

(Received January 5, 2010; CL-100012; E-mail: shimazu@faculty.chiba-u.jp)

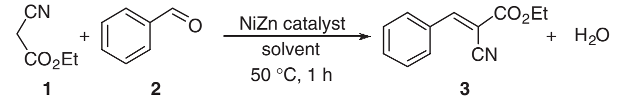
The interlayer space of layered Ni–Zn mixed basic salt (NiZn) can be controlled precisely by the intercalation of various carboxylate anions with long alkyl chains via simple anion exchange. Expansion of interlayer space in the anion-exchanged NiZn depends on the alkyl chain lengths of pillar molecules. The butyrate anion-exchanged NiZn ($C_3H_7COO^-$/NiZn) catalyst promoted effectively various base-catalyzed Knoevenagel reactions in water with remarkably high yield. This $C_3H_7COO^-$/NiZn catalyst was reusable without any loss of catalytic activity or selectivity.

It is well known that Knoevenagel condensation of aldehydes with active methylene compounds in organic solvent is a useful tool for the stereoselective synthesis of α,β-unsaturated carbonyls or nitriles with *E*-geometry.[1] Although alkali metal hydroxides, alkoxides, amines, or ammonia are conventionally applied for these reactions in organic solvent, they are harmful and furthermore bring about large amounts of wastes after neutralization.[2] To achieve green organic transformation, it is necessary to establish a catalyst design for high-performance recyclable solid base catalysts, which work even in water solvent.

Hydroxy double salts (HDSs) and layered double hydroxides (LDHs) have received considerable interest as anion-exchangeable layered compounds due to their potential applications as catalyst supports.[3] The Ni–Zn mixed basic salt (NiZn), considered a HDSs, has a typical chemical composition of $Ni_{1-x}Zn_{2x}(CH_3COO)_{2x}(OH)_2{\cdot}nH_2O$ ($0.15 < x < 0.25$).[4] We have recently reported a novel strategy for catalyst design via anion exchange by use of NiZn as a catalyst support. For example, the introduction of anionic Pd hydroxide species into the NiZn interlayer can generate monomeric $[Pd(OH)_4]^{2-}$ species stabilized by strong electrostatic interaction with Zn(II) cation, which acts as efficient heterogeneous catalyst for aerobic alcohol oxidation in air.[5] In this sort of catalysts, the active species are metal complexes but not host supports. Considering the use of NiZn itself as a catalyst, the size control of interlayer space is a key issue to create an effective catalytic reaction field.[6] Herein, we will report the synthesis of novel nanostructured NiZn by the intercalation of various carboxylate anions with long alkyl chains as a pillar molecule. The interlayer space of NiZn can be controlled precisely by changing alkyl chain length of pillars. In this paper, the Knoevenagel reaction in water catalyzed by synthesized NiZn is also presented.

The acetate-intercalated Ni–Zn mixed basic salt (CH_3COO^-/NiZn), was synthesized by a previously reported procedure.[7] Based on characterization by XRF, and TG-DTA, the chemical formula and anion-exchange capacity of CH_3COO^-/NiZn were found to be $Ni_{0.78}Zn_{0.44}(OAc)_{0.44}(OH)_2{\cdot}0.86H_2O$ (Ni/Zn = 1.77) and 2.93 mmol g^{-1}, respectively. The anion exchange in the NiZn interlayer was achieved by a simple anion-exchange process in water. Treatment of CH_3COO^-/NiZn with various sodium alkyl carboxylates yielded the anion-exchanged NiZn catalysts (X/NiZn, X was exchanged alkylcarboxylate anion) as a green powder.[8] In the case of $HCOO^-$/NiZn catalyst, the d_{001} peak shifted to a large angle from that of CH_3COO^-/NiZn catalyst, and the calculated C. S. (clearance space = basal spacing (d_{001}) − thickness of layer (0.46 nm)) was 0.45 nm. On the contrary, the C. S. increased with increasing alkyl chain length: the $C_9H_{19}COO^-$ anion extended the NiZn interlayer up to 2.11 nm. The C. S. calculated from XRD is proportional to the length of alkyl groups (slope: 0.17 nm/CH_2). It can be said that the C. S. as a catalytic reaction field can be controlled precisely by simple intercalation with alkylcarboxylate anions. To explore the catalytic abilities of various anion-exchanged NiZn, the Knoevenagel reaction between ethyl cyanoacetate (**1**) and benzaldehyde (**2**) was carried out. The results and the C. S. of the X/NiZn catalysts is also shown in Table 1.[9]

Table 1. Knoevenagel condensation under various conditions[a]

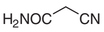
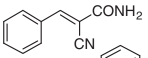
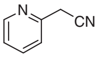
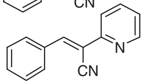
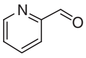
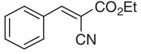
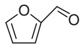
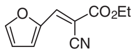
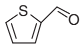
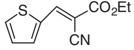
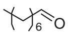
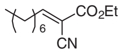
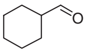
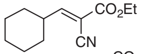
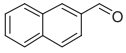
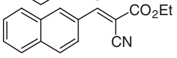


Entry	Catalyst	C. S. /nm[b]	Solvent	Convn /%[c]	Yield /%[c]
1	$HCOO^-$/NiZn	0.45	toluene	18	18
2	CH_3COO^-/NiZn	0.85	toluene	29	24
3	$C_2H_5COO^-$/NiZn	0.95	toluene	49	42
4	$C_3H_7COO^-$/NiZn	1.06	toluene	69	69
5	$C_3H_7COO^-$/NiZn	1.06	H_2O	>99	98 (93)[e]
6[d]	$C_3H_7COO^-$/NiZn	1.06	H_2O	>99	98
7	$C_3H_7COO^-$/NiZn	1.06	*n*-hexane	>99	97
8	$C_3H_7COO^-$/NiZn	1.06	DMF	87	87
9	$C_3H_7COO^-$/NiZn	1.06	1,2-DCE	86	86
10	$C_3H_7COO^-$/NiZn	1.06	CH_3OH	82	81
11	$C_3H_7COO^-$/NiZn	1.06	CH_3CN	74	73
12	$C_5H_{11}COO^-$/NiZn	1.49	toluene	33	30
13	$C_7H_{15}COO^-$/NiZn	1.74	toluene	39	39
14	$C_9H_{19}COO^-$/NiZn	2.11	toluene	36	34

[a]Ethyl cyanoacetate (1.5 mmol), benzaldehyde (1 mmol), NiZn catalyst (0.1 g), solvent (5 mL), 50 °C, 1 h. [b]Clearance space was calculated by XRD pattern. C.S = d_{001} − thickness of layer (0.46 nm). [c]Determined by GC using an internal standard. [d]Reuse experiment. [e]The value in a parenthesis was an isolated yield.

The parent CH_3COO^-/NiZn did not catalyze this condensation efficiently, yielding only 24% of (2*E*)-2-cyano-3-phenyl-2-propenoic acid ethyl ester (**3**) after 1 h (Entry 2). In the case of

Table 2. Aqueous Knoevenagel reaction using $C_3H_7COO^-$/NiZn catalyst[a]

Entry	Donor	Acceptor	D/A ratio (mmol/mmol)	Time/h	Product	Yield/%[b]
1		**2**	1.5/1	6		91
2[c]		**2**	1.5/1	24		81
3[c]	**1**		1/1.5	1		86
4	**1**		1.5/1	6		97
5	**1**		1.5/1	6		99
6	**1**		1/1.5	24		>99
7	**1**		1.5/1	6		98
8[c]	**1**		1.5/1	12		97

[a] $C_3H_7COO^-$/NiZn catalyst (0.1 g), H_2O (3 mL), 50 °C. [b] Determined by GC using an internal standard. [c] Under N_2 atmosphere.

$HCOO^-$/NiZn, CH_3COO^-/NiZn, and $C_2H_5COO^-$/NiZn catalyst, the reaction rate was slow (Entries 1–3), probably due to the mass-transfer limitation in the narrow interlayer space. It is noteworthy that the $C_3H_7COO^-$/NiZn showed the highest catalytic activity for the Knoevenagel reaction, giving only **3** in 69% yield after 1 h (Entry 4).[10] The catalysts which have more extended interlayer space such as $C_5H_{11}COO^-$/NiZn, $C_7H_{15}COO^-$/NiZn, and $C_9H_{19}COO^-$/NiZn did not promote this reaction efficiently (Entries 12–14). It is likely that the substrate cannot diffuse smoothly since the interlayer space fills up with alkyl chain. The screening of solvents showed that water was superior to organic solvents, giving only **3** in a quantitative yield within 1 h (Entries 4, 5, and 7–11). The spent $C_3H_7COO^-$/NiZn catalyst was easily separated after the reaction by either simple centrifugation or filtration. The catalyst was found to be reusable without any reduction in activity (Entry 6). The scope of the present $C_3H_7COO^-$/NiZn catalyst system toward aqueous Knoevenagel reactions with various active methylene compounds and aldehydes were examined, and the results are summarized in Table 2.

The condensation of 2-cyanoacetamide or 2-pyridineacetonitrile with **2** proceeded efficiently under aqueous conditions (Entries 1 and 2). Unfortunately, the reaction of phenylacetonitrile, which has a large pK_a value of 21.9, did not proceed at all in the presence of the $C_3H_7COO^-$/NiZn catalyst. Heterocyclic aldehydes such as 2-pyridinecarbaldehyde, 2-furancarbaldehyde, and 2-thiophencarbaldehyde also underwent the condensation (Entries 3–5). The $C_3H_7COO^-$/NiZn catalyst was able to catalyze the condensation of aliphatic and cycloaliphatic aldehyde such as *n*-octanal and cyclohexanecarbaldehyde (Entries 6 and 7). It is notable that sterically bulky aldehyde such as 2-naphthalenecarbaldehyde with **1**, and the corresponding products were formed in high yield (Entry 8).

The background-substituted FT-IR spectrum of the $C_3H_7COO^-$/NiZn, upon treatment with **1**, showed a shift of the ν(C=O) band toward 1651 cm^{-1} in comparison to the free ν(C=O) band of ethyl cyanoacetate at 1747 cm^{-1}.[8] It is reasonable to suggest that the anionic enolate species is coordinated to Zn(II) in the interlayer of $C_3H_7COO^-$/NiZn.[11] The suggested mechanism of this $C_3H_7COO^-$/NiZn-catalyzed Knoevenagel reaction is as follows. The Zn(II)–enolate species is formed in the interlayer of $C_3H_7COO^-$/NiZn, and alkylation and anion exchange then take place, affording the Knoevenagel adduct.[12]

In conclusion, C. S.-controlled NiZn catalysts were prepared by simple anion exchange with alkylcarboxylate anions. Expansion of C. S. was proportional to the alkyl chain length of the pillar molecule. The $C_3H_7COO^-$/NiZn has been developed as a recyclable base catalyst for aqueous Knoevenagel condensation reactions. Further mechanistic studies and the evolvement toward the other base-catalyzed reactions are now in progress.

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References and Notes

1 a) C. H. Heathcock, in *Comprehensive Organic Synthesis*, ed. by B. M. Trost, Pergamon Press, Oxford, **1991**, Vol. 2, p. 341. b) G. Jones, *Org. React.* **1967**, *15*, 204.

2 a) S. Marcaccini, R. Pepino, M. C. Pozo, S. Basurto, M. García-Valverde, T. Torroba, *Tetrahedron Lett.* **2004**, *45*, 3999. b) M.-H. Shih, M.-Y. Yeh, *Tetrahedron* **2003**, *59*, 4103.

3 a) G. Poncelet, J. J. Fripiat, in *Handbook of Heterogeneous Catalysis*, 2nd ed., ed. by G. Ertl, Wiley-VCH, Weinheim, **2008**, Vol. 1, p. 219. b) C. Forano, T. Hibino, F. Leroux, C. Taviot-Guého, *Dev. Clay Sci.* **2006**, *1*, 1021. c) F. Figueras, M. L. Kantam, B. M. Choudary, *Curr. Org. Chem.* **2006**, *10*, 1627. d) D. Tichit, B. Coq, *CATTECH* **2003**, *7*, 206. e) G. Centi, S. Perathoner, *Microporous Mesoporous Mater.* **2008**, *107*, 3.

4 a) E. Kandare, J. M. Hossenlopp, *Inorg. Chem.* **2006**, *45*, 3766. b) H. Morioka, H. Tagaya, M. Karasu, J. Kadokawa, K. Chiba, *Inorg. Chem.* **1999**, *38*, 4211. c) M. Meyn, K. Beneke, G. Lagaly, *Inorg. Chem.* **1993**, *32*, 1209. d) R. Rojas, C. Barriga, M. A. Ulibarri, P. Malet, V. Rives, *J. Mater. Chem.* **2002**, *12*, 1071. e) J.-H. Choy, Y.-M. Kwon, K.-S. Han, S.-W. Song, S. H. Chang, *Mater. Lett.* **1998**, *34*, 356.

5 T. Hara, M. Ishikawa, J. Sawada, N. Ichikuni, S. Shimazu, *Green Chem.* **2009**, *11*, 2034.

6 N. Yamaguchi, S. Shimazu, N. Ichikuni, T. Uematsu, *Chem. Lett.* **2004**, *33*, 208.

7 S. Yamanaka, K. Ando, M. Ohashi, *Mater. Res. Soc. Symp. Proc.* **1995**, *371*, 131.

8 From the XRD results, the layered structure of NiZn was maintained in each case; however, the clearance space of the interlayer was changed after intercalation. See Supporting Information, which is available electronically on the CSJ-Journal Web site, http://www.csj.jp/journals/chem-lett/index.html.

9 The reaction did not proceed at all without the catalyst. $Ni(OAc)_2\cdot 4H_2O$, $Zn(OAc)_2\cdot 2H_2O$, $Ni(OH)_2$, and $Zn(OH)_2$, which are the precursors of NiZn and the partly components of brucite layer of NiZn did not show remarkable catalytic activity under this reaction conditions.

10 Taking account of the C. S. and the size of pillar molecule, a suitable conformation of the $C_3H_7COO^-$/NiZn can be a bilayer arrangement with a tilting angle of ca. 40 degree.

11 It can be speculated that the butyrate anion is exchanged in apparent to enolate anion.

12 After the reaction, the C.S. of the spent $C_3H_7COO^-$/NiZn catalyst was maintained its original one. See Supporting Information.