

Effects of Alkali and Alkaline Earth Metals on the Kolbe–Schmitt Reaction

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It was found that the carboxylations of magnesium, calcium, and barium phenoxides with carbon dioxide at 260 °C produced salicylic acid and dicarboxylic acids (4-hydroxyisophthalic acid and 2-hydroxyisophthalic acid) in very high yields (80–100%), exceeding that of the ordinary Kolbe–Schmitt reaction. The orientation (*ortho/para* ratio) was controlled not only by chelations of the intermediate with alkaline earth metal (Mg, Ca, Ba) ions, resulting in salicylic acid, but also by the sizes of metal ions (Rb, Cs), giving *p*-hydroxybenzoic acid in a much higher ratio than the widely used method with potassium or sodium phenoxide. These alkaline earth metals worked to produce 3-hydroxy-2-naphthoic acid by the reaction of 2-naphthoxide with carbon dioxide, but the yield of 6-hydroxy-2-naphthoic acid was comparable to that of 3-hydroxy-2-naphthoic acid when cesium or rubidium 2-naphthoxide was employed. Considerably high yields (~60%) of 6-hydroxy-2-naphthoic acid, a monomer of one of the best liquid-crystal polymers, was attained by the carboxylation of cesium or rubidium 2-naphthoxide in the presence of potassium or sodium carbonate, where the alkali metal ion was supposed to increase the reactivity of the substrate. The formation of “binol” was observed in the preparation of 2-naphthoxides with metal hydroxides, especially with copper(II) ion.

The Kolbe–Schmitt reaction is known to be one of the typical and efficient methods to use carbon dioxide in organic reactions.^{1,2} The reaction has been used for over 100 years for preparing aromatic hydroxy acids for pharmaceuticals, pesticides, pigments, and preservatives of foods, cosmetics etc. Special demanded productions today for totally aromatic liquid-crystal polymers are both *p*-hydroxybenzoic acid, prepared from phenol, and 6-hydroxy-2-naphthoic acid from 2-naphthol.

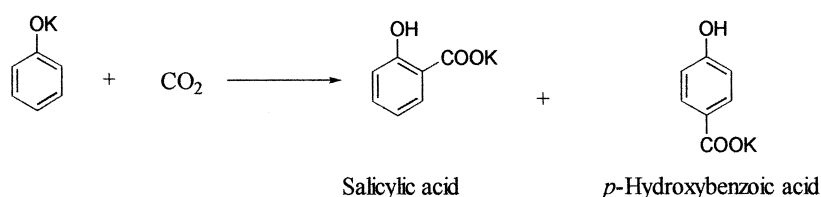
The reaction is carried out with alkali metal phenoxide and CO₂ of high pressure at high temperatures, and is greatly affected by metal ions of phenoxides.³ For example, the carboxylation of sodium phenoxide gives salicylic acid (SA), while potassium phenoxide yields a mixture of salicylic acid and *p*-hydroxybenzoic acid (*p*HBA) (Scheme 1). Although the Kolbe–Schmitt reaction is usually limited to potassium and sodium phenoxides, various metals would be applicable to the reaction with CO₂. Other metals have not been scrutinized, probably because of (i) difficulties in preparing their phenoxides, (ii) unreactivity of their carbonates in the Marasse method or a modification of the Kolbe–Schmitt reaction,⁴ and (iii)

fewer practical applications to industrial manufacturing. In this paper, a number of alkali metals and alkaline earth metals are considered, and the nature of the carboxylating reaction is discussed.

Experimental

Reagents. Phenol, 2-naphthol, alkali metal hydroxides (NaOH, KOH, RbOH·H₂O, and CsOH·H₂O), alkaline earth metal hydroxides (Ca(OH)₂, Ba(OH)₂·8H₂O, Cu(OH)₂, and Cu(OH)₂·CuCO₃·H₂O), and Mg turning were of guaranteed grade. Solvents (diethyl ether, ethyl acetate, hexane, methanol, and toluene) were purchased and used without further purification. Kerosene was distilled, and the fraction at the boiling point (200–215 °C) was collected. Carbon dioxide of more than 99.9% purity and nitrogen were purchased from Sanin Sanso Ltd. Co.

Preparation of Alkali Metal Phenoxides and 2-Naphthoxides. Phenol (5.00 g, 53.2 mmol) or 2-naphthol (5.00 g, 34.7 mmol) was dissolved in 100 mL of an aqueous solution of hydroxides. Water was evaporated on a rotary evaporator at 80 °C and further dried in vacuo at 180 °C for 3 h. The prepared phenoxides or 2-naphthoxides were ground to a fine powder in a dry box un-



Scheme 1.

der a dry nitrogen stream.

Preparation of Alkaline Earth Metal Phenoxides and 2-Naphthoxides. Calcium and barium phenoxides or 2-naphthoxides were prepared in a similar manner as described above. Magnesium phenoxide was prepared as follows: a mixture of phenol (5.00 g, 53.2 mmol) and magnesium turning (0.62 g, 25.6 mmol) was refluxed in 80 mL of toluene with stirring for 24 h. The mixture was cooled to room temperature and the solid portion was dried in a vacuo for 2 h at 110 °C. The same method did not work for the preparing magnesium 2-naphthoxide.

General Reactions and Analyses. The prepared metal phenoxide (1.0 g) or 2-naphthoxide (1.0 g) was placed in an autoclave (200 mL), and CO₂ was introduced after flushing with N₂. The vessel was heated quickly to the reaction temperatures and kept for a certain reaction time. The reaction mixture in the autoclave was cooled in an ice bath, and then washed out with a small amount of aqueous methanol. The solution was neutralized with dilute HCl and analyzed using a high-performance liquid chromatograph (HPLC) with a Shimadzu LC-10AD chromatograph and a column (ODS column 150 × 4.6 mm); the peak areas were obtained with a Shimadzu chromatopack C-R3A.

Spectral Identifications. The products were isolated by extraction with ether from the aqueous reaction mixture after adjusting the pH value. The isomeric isophthalic acids were separated from each other by column chromatography (Wakogel C-300) and eluted with hexane/ethyl acetate (2/1). Binol was also isolated from 2-naphthol on the same column and eluted with hexane/ethyl acetate (1/1). ¹H NMR and IR spectra were obtained on a JNM-GX-270, FT-NMR spectrometer (JEOL) and a FT/IR-620 (JASCO), respectively. **2-Hydroxyisophthalic acid.** ¹H NMR (acetone-*d*₆) δ 8.09 (d, *J* = 7.5 Hz, 2H, 4,6-H), 6.98 (t, *J* = 7.5 Hz,

1H, 5-H); IR (KBr) 3400, 3200–2500, 1700, 1610 cm^{−1}; **4-Hydroxyisophthalic acid.** ¹H NMR (acetone-*d*₆) δ 8.60 (d, *J* = 2.2 Hz, 1H, 2-H), 8.16 (dd, *J* = 2.2, 8.79 Hz, 1H, 6-H), 7.06 (d, *J* = 8.79 Hz, 1H, 5-H); IR (KBr) 3420, 3000–2500, 1660 cm^{−1}; **2-Hydroxy-1-naphthoic acid.** ¹H NMR (D₂O/KOH + H₂O) δ 7.75 (d, *J* = 7.8 Hz, 1H, 8-H), 7.65 (d, *J* = 9.0 Hz, 1H, 5-H), 7.56 (d, *J* = 8.5 Hz, 1H, 4-H), 7.42 (t, *J* = 6.5 Hz, 1H, 7-H), 7.18 (t, *J* = 7.8 Hz, 1H, 6-H), 7.01 (d, *J* = 9.0 Hz, 1H, 3-H); **3-Hydroxy-2-naphthoic acid.** ¹H NMR (D₂O/KOH + H₂O) δ 7.74 (d, *J* = 8.3 Hz, 1H, 8-H), 7.72 (d, *J* = 1.4 Hz, 1H, 9-H), 7.59 (d, *J* = 8.3 Hz, 1H, 5-H), 7.38 (tt *J* = 0.9, 6.8 Hz, 1H, 6-H), 7.18 (tt, *J* = 1.2, 7.0 Hz, 1H, 7-H), 6.89 (s, 1H, 4-H); **6-Hydroxy-2-naphthoic acid.** ¹H NMR (D₂O/KOH + H₂O) δ 8.40 (s, 1H, 1-H), 7.94–7.89 (d, 2H, 3,8-H), 7.69 (d, *J* = 8.7 Hz, 1H, 4-H), 7.18 (dd, *J* = 2.4, 9.0 Hz, 1H, 7-H), 7.06 (d, *J* = 2.4 Hz, 1H, 5-H); **1,1'-Bi-2-naphthol.** ¹H NMR (CDCl₃) δ 7.98 (d, *J* = 8.7 Hz, 2H, 3,3'-H), 7.89 (d, *J* = 7.8 Hz, 2H, 5,5'-H), 7.38 (d, *J* = 9.0 Hz, 2H, 4,4'-H), 7.28–7.39 (m, 4H, 6,6',7,7'-H), 7.15 (d, *J* = 8.7 Hz, 2H, 8,8'-H); IR (KBr) 3480, 3400, 1620, 1600 cm^{−1}; MS *m/z* 286 (M⁺), 257, 239, 226, 119. Found: C, 82.25; H, 5.27%. Calcd for C₂₀H₁₄O₂: C, 83.91; H, 4.89%.

Results and Discussion

The Carboxylation of Phenoxides. Three kinds of alkaline earth metal phenoxides were subjected to carboxylation with carbon dioxide (Table 1, run nos. 1–10). It is a surprised to see that the Kolbe–Schmitt reaction using metals other than potassium and sodium gives carboxylic acids in high yields. In most cases, a yield of more than 80% was attained in 1 h when the reaction temperature was 260 °C; further carboxylation

Table 1. Carboxylation of Various Alkali and Alkaline Earth Metal Phenoxides with Carbon Dioxide

Run no.	Metal	Reaction condition			Recovered phenol %	Yield/ % ^{a)}				
		CO ₂ MPa	Temp. °C	Time h		SA	<i>p</i> HBA	4HIPA	2HIPA	Total yield ^{b)}
1	Mg	5.0	150	1.0	96.0	4.0	0	0	0	4.0
2	Mg	5.0	200	1.0	83.0	16.0	0.5	0	0	16.5
3	Mg	5.0	230	1.0	56.5	40.5	1.8	0	1.0	44.3
4	Mg	5.0	260	1.0	21.0	72.0	2.5	0	4.4	83.3
5	Mg	5.0	260	5.0	14.7	74.0	3.0	0	8.0	93.0
6	Ca	5.0	150	1.0	70.0	26.7	2.8	0	0	29.5
7	Ca	5.0	200	1.0	54.4	42.7	2.8	trace	trace	45.5
8	Ba	5.0	150	1.0	20.0	76.0	3.0	0.6	0	80.2
9	Ba	5.0	260	1.0	8.4	77.0	2.0	3.0	9.5	104.0
10	Ba	5.0	260	5.0	16.0	64.8	2.0	5.5	11	99.8
11	Rb	5.0	150	0.25	29.3	30.6	39.0	0.9	0	71.4
12	Rb	5.0	150	1.0	6.5	39.8	51.5	1.8	0	94.9
13	Rb	5.0	150	1.0	19.6	36.1	42.8	1.3	0	81.5
14	Rb	5.0	200	1.0	1.4	37.0	51.6	7.8	1.8	107.8
15	Cs	5.0	150	1.0	29.5	20.7	48.0	1.6	0	71.9
16	Cs	5.0	150	5.0	7.5	29.0	57.0	5.5	0	97.0
17	Cs	5.0	200	1.0	17.0	26.0	35.0	16.0	4.5	102.0
18	Cs	5.0	260	1.0	6.0	26.5	19.0	35.0	12.5	140.5

a) Determined by HPLC. An unidentified peak was observed in run nos. 17 (ca. 1.0%) and 18 (ca. 3.9%) of retention time at 8.5 min. SA, *p*HBA, 4HIPA, and 2HIPA denote salicylic acid, 4-hydroxybenzoic acid, 4-hydroxyisophthalic acid, and 2-hydroxyisophthalic acid, respectively.

b) Total yield of the carboxylation based on the amount of phenol used.

proceeded with an increase in the reaction time to give dicarboxylic acids, such as 4-hydroxyisophthalic acid (4HIPA) and 2-hydroxyisophthalic acid (2HIPA). There is a single report on the carboxylation of barium and calcium phenoxides in DMF, but the yields were less than 50%.⁵ The mechanism of the Kolbe-Schmitt reaction has recently been checked in this laboratory:⁶ the $[\text{PhOM}\cdot\text{CO}_2]$ complex^{2,3,7} is not an intermediate of the reaction, but a direct carboxylation on the benzene ring by carbon dioxide; that is, an electrophilic substitution reaction takes place. Thus, the reaction would be affected by not only the electron density on the benzene ring, but also by the stabilization energy of the intermediate to produce final products. The present results well reflect the stability of the intermediate forming a chelate⁸ between SA and the bivalent metal ion. Thus, the ratio of SA to *p*HBA is 10–40, which is very different from the ratio of 2–7 in the case of potassium or sodium phenoxides.

On the other hand, for rubidium and cesium in the series of alkali metals, the ratio of SA to *p*HBA was less than 1.0 (Table 1, run nos. 11–18). The remarkable increase of dicarboxylic acid 4HIPA may be due to the carboxylation of *p*HBA at 260 °C (no. 18). The prominent selectivity of *para*-carboxylation is ascribable to their larger ionic radii (147 and 167 pm of Rb^+ and Cs^+ , respectively), which interfere with a direct attack of carbon dioxide at the *ortho* position. The order of $\text{Li} < \text{Na} < \text{K} < \text{Rb} < \text{Cs}$ agrees with the observed ratio (*o/p*) as 1.0/0,⁹ 6/1, 3/2, 4/5, 3/5, respectively. Alternatively, the size is important to stabilize the transition states of the chelation at the *ortho* position in a similar way of bivalent metal ions, as de-

scribed above.

The Carboxylation of 2-Naphthoxides. 2-Naphthol is another interesting phenol in the Kolbe-Schmitt reaction, because the reactivity at the 1-, 3-, and 6-positions is competitive with each other. Although sodium and potassium 2-naphthoxides easily produce 2-hydroxy-1-naphthoic acid (2H1NA) at room temperature, the corresponding 3- and 6-naphthoic acids (abbreviated as 2H3NA and 2H6NA, respectively) were obtained above 200 °C. The CO_2 complex of 2-naphthoxide is unreactive to produce 2H1NA, and is decomposed to naphthoxide at higher temperatures.

When the rubidium and cesium 2-naphthoxides were subjected to carboxylation with 2.0–5.0 MPa CO_2 , 2H3NA and 2H6NA were produced in almost equal amounts, but smaller amounts of 2H1NA remained at 200–230 °C (Table 2). On the other hand, when alkaline earth metals (Ca and Ba) were used, 2H6NA was not obtained, but 2H3NA was the single major product, which was ascribed to the chelate formation as observed in the case of phenoxides. Similar chelations at 1-COOH, especially with barium ion, increased the stability against the thermal decomposition, even at 260 °C. During studies on the carboxylation of 2-naphthoxides, the formation of 1,1'-bi-2-naphthol "binol" was observed. The preparation of copper 2-naphthoxide by the addition of copper(II) hydroxide to 2-naphthoxide was in vain. The oxidative dimerization of 2-naphthol catalyzed by copper(II) or iron(III) has been well studied.^{10–13} The present results may be explained by the process of the homolytic bond fission of 2-naphthoxy-metal, especially alkaline earth metal, at high temperatures, followed by

Table 2. Carboxylation of Various Kinds of Alkali and Alkaline Earth Metal 2-Naphthoxides with Carbon Dioxide.

Run no.	Metal	Reaction condition			Recovered 2-naphthol %	Yield/% ^{a)}			
		CO_2 MPa	Temp. °C	Time h		2H1NA	2H3NA	2H6NA	Binol
1	K	5.0	20	1.0	47.0	52.0	0	0	0
2	K	5.0	230	0.5	27.5	22.3	33.2	9.0	1.7
3	K	5.0	230	10	24.0	4.0	72.0	0	0
4	K	5.0	250	10	10.0	2.0	87.0	0	0
5	K	2.0	230	15	5.0	3.0	86.5	4.5	0
6	Na	5.0	230	10	11.0	14.5	71.5	2.5	0
7	Na	5.0	250	10	13.0	trace	84.5	2.0	0
8	Rb	5.0	230	1.0	53.0	10.0	24.6	11.8	0
9	Rb	2.0	230	5.0	55.0	3.0	21.0	20.6	0
10	Rb	2.0	260	5.0	49.0	6.4	22.4	22.0	0
11	Cs	5.0	230	0.5	36.8	14.8	16.4	18.7	1.0
12	Cs	5.0	230	0.5	33.4	12.3	16.1	19.3	1.6
13	Cs	5.0	230	1.0	55.7	9.4	15.0	19.7	0
14	Cs	5.0	230	5.0	48.5	4.0	19.0	28.0	0
15	Cs	5.0	230	5.0	43.7	3.8	24.0	28.0	0
16	Cs	5.0	230	10	36.8	3.4	21.2	37.2	1.0
17	Ca	5.0	230	3.0	37.9	7.8	28.0	0	25.9
18	Ca	5.0	230	10	65.0	2.5	15.5	0	16.5
19	Ba	5.0	230	3.0	52.0	21.0	10.0	0	16.7
20	Ba	5.0	230	5.0	38.0	33.0	14.0	0	14.0
21	Ba	5.0	260	3.0	32.5	52.5	8.5	0	6.0

a) Determined by HPLC. 2H1NA, 2H3NA, 2H6NA, and Binol denote 2-hydroxy-1-naphthoic acid, 3-hydroxy-2-naphthoic acid, 6-hydroxy-2-naphthoic acid, and 1,1'-bi-2-naphthol, respectively.

Table 3. Carboxylation of Cesium 2-Naphthoxide with Carbon Dioxide in the Presence of Alkali and Alkaline Earth Metal Carbonates

Run no.	Carbonate (mole ratio)	Reaction condition			Recovered 2-naphthol %	Yield/% ^{a)}		
		CO ₂ MPa	Temp. °C	Time h		2H1NA	2H3NA	2H6NA
1 ^{b)}	kerosene	—	0.3	265	6	80.0	1.0	5.0
2 ^{b)}	Cs ₂ CO ₃ /kerosene	0.1	0.3	265	6	50.0	2.0	9.0
3	Cs ₂ CO ₃	0.1	5.0	230	6	30.0	4.2	22.0
4	K ₂ CO ₃	1.0	5.0	230	24	14.6	2.1	13.7
5	K ₂ CO ₃	3.0	5.0	230	6	11.3	trace	29.3
6	Na ₂ CO ₃	1.0	5.0	230	6	16.5	6.5	15.0
7	Na ₂ CO ₃	1.0	5.0	230	24	6.5	2.4	7.8
8	CaCO ₃	1.0	5.0	230	6	28.4	5.3	20.5
9	BaCO ₃	1.0	5.0	230	6	13.4	6.5	22.5

a) Determined by HPLC.

b) The reactions were carried out as Ref. 14.

the formation of carbon radicals, which were stabilized by resonating forms, giving a coupling product, binol.

Production of 6-Hydroxy-2-naphthoic Acid (abbreviated as 2H6NA for convenience). A copolymerization of 2H6NA and *p*HBA gives an engineering plastic of high quality, and an efficient supply of 2H6NA has recently been expected to contribute to “information technology”. The carboxylation of cesium 2-naphthoxide gave 2H6NA in 37% yield, which was much better than those (20–30%) with potassium 2-naphthoxide. A US patent¹⁴ also claims 35–39% yield from cesium 2-naphthoxide with the addition of cesium carbonate in a solvent, such as isopropyl naphthalenes, trimethylphenylindanes, tetradecanes, and hexadecanes at 265 °C. In the present experiments, not only some modifications of the US patent, but also novel methods, were conducted (Table 3). Nearly a 40% yield of 2H6NA was obtained from the carboxylation of cesium 2-naphthoxide in kerosene, which could be recycled, if necessary, thus avoiding decomposition of the solvent at high temperature. When the reaction was carried out under a higher pressure of CO₂ with the addition of potassium carbonate, but without solvents, the yield was almost 60%, and the formation of 2H3NA was suppressed to 14–18%. Generally, the solvent has a role to homogenize the heat distribution in the reactor, but, at the same time, decreases the contact between the solid substrate and the reagent gas and slows down the reaction rate. The large size of cesium ion blocks the attack neighbor (*ortho*) position, and favors *para* carboxylation of phenoxide, as discussed in Table 1. However, their reactivity to carbon dioxide is inferior to those of potassium and sodium 2-naphthoxides. Since the bonding between cesium and oxygen of 2-naphthoxide is less polarized, the potassium ion of the carbonate would approach and coordinate weakly to the oxygen atom, resulting in an increased reactivity of the substrate. Sodium carbonate showed a similar effect to give 2H6NA in high yields. Calcium and barium carbonates behaved so as to increase the carboxylation, but might have replaced cesium during the reaction, resulting in the high yield of 2H3NA. The exchange between metal ions would occur in any case as the concentration

of the carbonate and the reaction time increase, even at a temperature (200–260 °C) lower than the melting or decomposing points of these carbonates (egs. 981 °C for K₂CO₃, 851 °C for Na₂CO₃).

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