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Alkylation of Phenols on Fe_2O_3 and Cr_2O_3

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Ferric oxide and chromium oxide, were found as new alkylation catalysts of phenols. The activity and the selectivity of these oxide catalysts were examined by liquid-phase reaction. Methylation of phenol, cresol, xylenol, and α-naphthol was carried out in an autoclave at 400°, using methanol as an alkylating agent. The selective methylation of phenols to their *ortho*-position took place, and *o*-cresol and 2,6-xylenol were obtained selectively from phenol. Their yield reached 70% after 5 hr. Ferric oxide was effective only in methanol, whereas chromium oxide was available for C_1 to C_4 alcohols. From the distribution of methylated products on various oxides, an outline of oxide-catalyzed alkylation was presented.

Introduction

Although proton acids and Friedel-Crafts catalysts have been reported for the alkylation of phenols by alcohols, methylation of phenols on their aromatic carbon atom has remained unsuccessful. For example, in the alkylation of phenol with methanol using anhydrous aluminum chloride, methylated phenol was not obtained.[2] In the presence of boron trifluoride, anisole is formed from phenol and methanol at 170°.[3] In 1925, Ipatieff, *et al.*[4] first obtained anisole, *o*-cresol, and a small amount of xanthene from phenol and methanol in the presence of aluminum hydroxide at 440°.

Recently, catalysts for methylation of phenol in vapor-phase reaction were published in patents and reports.[5] These catalysts are not always applicable to liquid-phase methylation because of their poor activity and selectivity. In the present work, alkylation catalysts, especially for methylation of phenols in liquid-phase, were investigated using oxide catalysts. Among the catalysts examined, two oxides, ferric oxide and chromium oxide, showed good conversion rate and selectivity for the methylation to the *ortho*-position of phenols. Further, cresols, xylenols, and even α-naphthol were methylated successfully with methanol.

The catalytic activity and selectivity of these oxides are also an interesting problem. From the nature of these oxides and the distribution of products, the reaction mechanism was examined.

Experimental

Alkylation of Phenols——Phenol (10 g), methanol (15 g), and a catalyst (1 g) were charged in an autoclave (100 ml) equipped with a magnetic stirrer (800 rpm). After air in the autoclave was substituted with H_2, the temperature was raised to 400° in 45—50 min. The pressure reached 100 atm at this temperature.

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1) Location: *3190, Gofuku, Toyama.*
2) I.P. Tsukervanik and Z.N. Nagarova, *J. Gen. Chem. U. S. S. R.*, **7**, 623 (1937) [*Chem. Abstr.*, **31**, 5778 (1937)].
3) F.J. Sowa, G.F. Hennion, and J.A. Niewland, *J. Am. Chem. Soc.*, **57**, 709 (1935).
4) V.N. Ipatieff, J. Orlof, and G. Razoubaief, *Bull. Soc. Chim. Fr.*, **37**, 1576 (1925).
5) Oxides of Al, Th, Zn, Fe, Mn, Mg, Ca, and Ba: W. Kunz, Brit. Patent 717588 (1954) [*Chem. Abstr.*, **49**, 15962 (1955)]; MgO: S.B. Hamilton, Jr., U.S. Patent 3479410 (1967) [*Chem. Abstr.*, **72**, 43132 (1970)]; CeO_2, J.A. Sharp and R.E. Dean, Brit. Patent 1124839 (1966) [*Chem. Abstr.*, **70**, 19793 (1969)]; Ce_2O_3–MgO–MnO_2: S. Enomoto and M. Inoue, Ger. Offen. Patent 1948607 (1970) [*Chem. Abstr.*, **73**, 25097 (1970)]; UO_3–MgO–B_2O_3: Ruetgenswerke und Toerverwertung A.-G., Netherland Patent Appl., 6516774 (1967) [*Chem. Abstr.*, **67**, 73341 (1967)]; Fe_2O_3–ZnO: T. Kotanigawa, M. Yamamoto, K. Shimokawa, and Y. Yoshida, *Bull. Chem. Soc. Japan*, **44**, 1961 (1971). Modified catalysts of these oxides are summarized by A. Tasaka, *Shokubai*, **15**, 155 (1973).

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Analysis of Products——Oxide catalyst was separated by filtration from the liquid products. A portion of the filtrate (0.1—0.2 ml) was acetylated with acetic anhydride and pyridine (10: 1) at 90° for 1 hr. The mixture was poured into 1% HCl solution, and then extracted with hexane. After the solvent was evaporated from the extract, acetylated phenols were analyzed by a gas-liquid chromatograph (GLC) (Hitachi Ltd., type 063); column packings, 20% tricresyl phosphate+diisodecyl phthalate (7: 3) on Chamelite (80—100 mesh) (2 m) or 30% silicone DC-550 on Chamelite (80—100 mesh) (4 m); detector, frame ionization detector (FID). The decomposed products in gas phase were also analyzed by GLC (Yanaco G-800T), with active charcoal as a column packing (1 m).

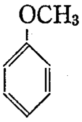
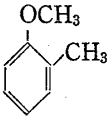
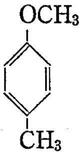
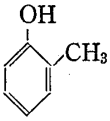
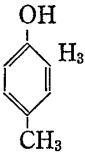
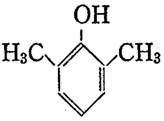
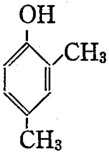
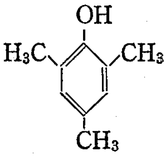
Preparation of Catalysts——MgO, Cr_2O_3, and Al_2O_3 were prepared from their nitrates by thermal decomposition at 500° for 3 hr. ZnO and Fe_2O_3 were prepared by the calcination of carbonates, which were precipitated from 10% aqueous solution of their nitrates and sodium carbonate. A binary catalyst, Fe_2O_3–MgO, was obtained by co-precipitation from their nitrates with 10% NaOH at pH 9. TiO_2 was prepared from $TiCl_4$ and 5 N ammonia at pH 9. SiO_2–Al_2O_3 (90: 10) was co-precipitated from Na_2SiO_3 (water glass) solution and $AlCl_3$ by 10% HCl at pH 9.

Results and Discussion

Methylation of Phenol on Various Oxide Catalysts

Methylation of phenol was carried out in methanol, in the presence of some typical oxides at 400° for 3 hr. The yield and composition of methylated phenol isomers varied with the kind of acidic and basic oxide catalysts. The results are summarized in Table I. In the methylation of phenol with WO_3, MoO_3, and SiO_2–Al_2O_3, known as acidic oxides, a mixture of anisoles and methylated phenols were obtained. Amphoteric oxides such as ZnO, TiO_2,⁽⁶⁾ Cr_2O_3, and Al_2O_3 also gave anisoles and cresols. Even basic oxides, MgO and Fe_2O_3,⁽⁶⁾ catalyzed the methylation to *ortho* position of phenol. Considering conversion and selectivity to *ortho*-methylated phenols, Cr_2O_3 and Fe_2O_3 were excellent catalysts.

TABLE I. Methylation of Phenol with Methanol on Various Oxides at 400° for 3 hr

Expt. No.	Catalyst[a]	Conversion (mol %)	Methylated products (mol %)							
										
1	MgO	8.0	37.6	0	0	62.4	0	0	0	0
2	ZnO	29.4	12.8	0	0	74.4	6.1	6.7	0	0
3	Fe_2O_3	25.5	2.6	0	0	90.3	2.2	4.9	0	0
4	Cr_2O_3	34.5	5.7	0	0	75.8	4.1	10.9	3.5	0
5	TiO_2	64.8	10.3	1.9	trace	59.2	5.3	12.5	10.8	trace
6	Al_2O_3	67.8	51.6	10.2	trace	28.6	trace	9.6	0	0
7	WO_3	14.1	46.7	0	0	53.3	0	0	0	0
8	MoO_3	88.2	3.7	2.1	0.6	21.6	trace	37.9	11.7	22.4
9	SiO_2–Al_2O_3 (9:1)	44.7	70.8	4.0	2.3	16.8	6.1	0	0	0
10	α-Fe[b]	4.3	0	9.5	0	0	0	90.5	0	0
11	Fe_2O_3–MgO (8:2)	59.5	21.0	0	0	70.2	0	8.8	0	0

catalyst 1 g, methanol 15 g, phenol 10 g

a) Expt. No. 1—7 are arranged in the order of dehydrogenating properties of oxides by Szabó [*J. Catalysis*, 6, 458 (1966)].

b) *o*-Cresol was used in stead of phenol.

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6) From the reactivity to mineral acids and bases, TiO_2 was classified as amphoteric oxide[a] and Fe_2O_3[b] as basic oxide in this paper. Amphoteric character was also noted with $Fe(OH)_3$.[c] *a*) J.W. Mellor, "A Comprehensive Treaties on Inorganic and Theoretical Chemistry," Vol. VII, Longmans, Green & Co. Ltd., London, 1930, p. 27; *b*) *Idem, ibid.*, Vol. XIII, 1934, p. 809, p. 816; *c*) T. Chitani, "Muki-Kagaku," (Inorganic Chemistry), Sangyo-Tosho Co. Ltd., Tokyo, 1960, p. 1188.

The methylation began at 300°, and conversion increased with the reaction temperature until 400°. At this temperature, conversion to phenol reached 45% after a 3 hr reaction. Above 400°, the selectivity to *ortho*-position decreased from 95% to 75% by thermal isomerization.

Methylation of phenol in the presence of Fe_2O_3 and methanol are shown in Fig. 1, where percentage of methylated phenol is plotted against the reaction time at 350° and 400°. After 6 hr, a constant conversion of 75% was attained. Longer reaction time did not improve the yield. The limiting value seemed to be brought by increasing water formation between phenol and methanol. In fact, catalytic activity of Fe_2O_3 was inhibited completely by the presence of 2 g of water in the reaction system.

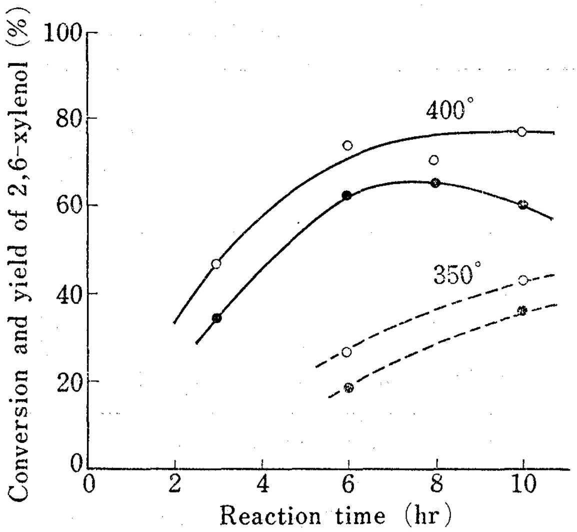


Fig. 1. Reaction Time *vs.* Conversion and Yield of 2,6-Xylenol in the Methylation of *o*-Cresol on Fe_2O_3

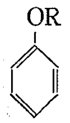
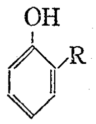
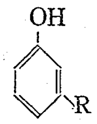
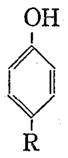
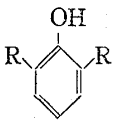
o-Cresol (10 g), methanol (15 g), and Fe_2O_3 (1 g) were used.
—○—: conversion —●—: yield of 2,6-xylenol

In the vapor-phase methylation over Fe_2O_3–ZnO catalyst, a violent decomposition of methanol to CH_4 (7.9%), CO_2 (18.2%), H_2 (64.2%), and CO (9.7%) has been reported.[7] Using the liquid phase methylation, in the presence of Fe_2O_3 at 400° for 5 hr, gaseous products of 25 kg/cm^2 were obtained. They were composed of 66.6% of CH_4, 28.3% of CO_2, 2.9% of H_2, and 2.2% of CO, due to the decomposition of methanol. Methanol contained in the liquid products was 75% of the theoretical value.

Methylation of Phenols by Alcohols

Although Fe_2O_3 is effective in methanol, alkylation of phenol over Cr_2O_3 occurs not only in methanol but also in ethanol, isopropanol, and *tert*-butanol, as shown in Table II. The best conversion was obtained in ethanol; the selectivity to *ortho* position of phenol reached 90%.

Table II. Alkylation of Phenol with C_1 to C_4 Alcohols on Cr_2O_3 at 400° for 3 hr

Alcohol	Conversion (mol %)	Alkylated products (mol %)				
						
Methanol	34.8	11.9	75.9	0	4.1	8.1
Ethanol	56.1	3.1	75.4	0	7.1	14.4
Isopropanol	13.8	4.1	46.9	0	12.9	24.5
tert-Butanol	10.3	0	17.3	20.0	62.7	0

alcohol 15 g, phenol 10 g, Cr_2O_3 1 g

Various phenolic compounds such as cresols, 3,5-xylenol, and α-naphthol were methylated in the presence of Fe_2O_3 (Table III). 2,3,5-Trimethylphenol, an important intermediate of α-tocopherol synthesis,[8] was obtained from 3,5-xylenol. An equimolecule of 3,5-xylenol

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[7] T. Kotanigawa, M. Yamamoto, K. Shimokawa, and Y. Yoshida, *Bull. Chem. Soc. Japan*, **44**, 1961 (1971).
[8] H.J. Teuber and W. Rar, *Chem. Ber.*, **86**, 1036 (1953).

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TABLE III. Methylation of Phenols on Fe_2O_3 by Methanol

Phenols	Time (hr)	Reaction temp. (°C)	Conversion (mol %)	Product (mol %)				
				Phenol	2-Me-Ph	2,6-(Me)$_2$-Ph	6-Me-Ph	Other methylated phenols
o-Cresol	6	400	82.3	1.8	81.6	—	—	16.6a)
m-Cresol	3	400	69.3	0	34.0	15.3	49.5	1.2b)
p-Cresol	3	400	70.7	1.8	78.4	15.7	—	4.1c)
3,5-Xylenol	3	400	76.5	0	63.8	34.0	—	2.2d)
α-Naphthol	3	350	57.6	0	100	—	—	0

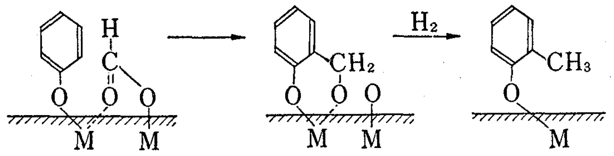
methanol 15 g, phenol 10 g, catalyst 1 g
a) 2,4,6-trimethylphenol 9.3%, 2,4-dimethylphenol 5.3%, 2-methylanisole 2.0%
b) 3-methylanisole
c) 2-methylphenol 3.7%, 4-methylanisole 0.4%
d) 3,5-dimethylanisole

and methanol yielded 2,3,5-trimethylphenol as a main product. By using three volumes of methanol to 3,5-xylenol, 2,3,5,6-tetramethylphenol was obtained as the only product. In the methylation of chlorophenol and aminophenol, only a resinous product was obtained.

Properties of the Catalysts and the Mechanism of Alkylation

To explain the mechanism of proposed methylation, the rearrangement of anisole to cresols in the presence of oxides was examined at 400° for 3 hr. The rearranged ratio was as follows: MgO 0%, Fe_2O_3 3.1%, Cr_2O_3 8.9%, Al_2O_3 54.2%, MoO_3 44.2%, and SiO_2–Al_2O_3 71.5%. From these result, a general tendency was that acidic oxides rearranges anisole easily. In contrast, basic oxides have no such ability. Anisole formation and rearrangement of methyl group to an aromatic C atom on acidic sites have already been reported in vapor-phase reaction.9) On basic sites, a new type alkylation seems to take place by direct methylation on *ortho*-position of phenols. An important role of basic oxides to methanol is dehydrogenation activity. After the methylation of phenol for 3 hr at 400°, Fe_2O_3 was reduced to α-Fe and Fe_3O_4, which were detected by X-ray analysis. Fe powder also showed a weak activity for methylation.10) As dehydrogenated stable species of methanol on basic oxides, formaldehyde and carbon monoxide are considered, in which formaldehyde is well known as active agent to phenol; 2-hydroxymethylated phenol is formed under alkaline conditions or in the presence of magnesium phenoxide.

In another experiment, *ortho*-cresol was obtained from phenol and paraformaldehyde in the presence of MgO, in hydrogen atmosphere. From this result, it is expected that the methylation proceeds between the dehydrogenated species of methanol and phenol. On metal oxides, such as MgO9,11) and Fe_2O_3–ZnO,12) phenoxides of metals have been observed spectroscopically by the contact of phenol vapor at 400° and 500°. On the other hand, chemisorbed species of methanol on MgO above 165° has been found as magnesium formate by Kagel and Greenler.13) The addition of a dehydrogenated methanol, *e.g.*, HCHO, to the phenoxide anion is considered to proceed by analogy with



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9) M. Inoue and S. Enomoto, *Chem. Pharm. Bull.* (Tokyo), **19**, 2518 (1971); *idem, ibid.*, **20**, 232 (1972).
10) M. Inoue and S. Enomoto, *Sekiyu Gakkaishi*, **15**, 372 (1972).
11) T. Nishizaki and K. Tanabe, *Shokubai*, **15**, 94 (1973).
12) T. Kotanigawa, *Sekiyu Gakkaishi*, **17**, 286 (1974).
13) R.O. Kagel and R.G. Greenler, *J. Chem. Phys.*, **49**, 1638 (1968).

liquid-phase hydroxymethylation. This step is illustrated below for the hydrogenolysis to methylated phenol. In contrast, Cr_2O_3 works as an amphoteric oxide, and the methylation proceeds both on basic and acidic sites. In this case, the presence of alkyl-cation on acidic sites is suggested as an intermediate species of alkylation by alcohols.

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