

KINETICS OF THE GLYCOLYSIS OF AROMATIC CARBOXAMIDES CATALYSED IN SOLUTION BY METAL IONS*..**

J. MÁLEK and E. ZELENÁ

*Institute of Chemical Process Fundamentals,
Czechoslovak Academy of Sciences, 165 02 Prague 6 - Suchbát*

Received January 28th, 1975

The metal ion-catalysed reaction of benzamide with excess ethylene glycol at elevated temperatures is first-order in benzamide, 0.25-order in Cd^{2+} and Mn^{2+} ions and half-order in Pb^{2+} , Sn^{2+} , Mg^{2+} , Na^+ , Ti^{4+} and Sn^{4+} ions. The activation energy of the reaction catalysed with Cd^{2+} and Na^+ ions is 14.6 and 14.9 kcal mol⁻¹, respectively. The activation entropy was found to be -50 e.u. for reactions catalysed by Cd^{2+} as well as Na^+ ions. The catalytic effectiveness of the metal ions decreases in the order $\text{Cd}^{2+} > \text{Pb}^{2+} > \text{Mn}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{Ca}^{2+} > \text{Sn}^{2+} > \text{Ti}^{4+} > \text{Sn}^{4+} > \text{Zn}^{2+} > \text{Sb}^{3+} \approx \text{Co}^{2+}$; Hg^{2+} and Cu^{2+} ions were catalytically inactive. The correlation of the reaction rate constants with the metal electronegativities or the acid ionisation (hydrolysis) constants of their aquo ions is presented.

Formation of the amides from carboxylic acid esters by the action of amines or ammonia is a well examined reaction and its kinetics and mechanism have been treated in monographies^{1,2}. Relatively little attention has been paid to the reverse reaction, *i.e.* the direct formation of the esters from the amides. The recent increased interest in this reaction has been initiated by the study of peptides^{3,4} and by the fact that the amides are now more easily available, *e.g.* by partial alkaline hydrolysis of nitriles⁵ or by nitrile hydrolysis in the absence of alkalies or inorganic acids^{6,7}. Because of the exothermic character of the aminolytic and ammonolytic reactions, the esters are formed in appreciable amounts by direct alcoholysis or glycolysis of the amides only at higher temperatures^{1,8}; aliphatic amides are generally more reactive than aromatic ones⁹. Satisfactory reaction rates and high conversions of aromatic amides can be therefore achieved only in the presence of catalysts and at elevated temperatures. Sodium alkoxides and magnesium oxide have been recommended earlier as catalysts¹⁰ for the glycolysis of aromatic amides. Our preliminary experiments have proved that some transition metal compounds could be more efficient catalysts for this reaction^{11,12}.

In this communication we report on the kinetics of the glycolysis of amides catalysed in solution by metal ions; the glycolysis of benzamide by ethylene glycol was chosen as a model reaction to determine the catalytic activity of metal ions in the glycolytic reaction; transformation of some aromatic and heterocyclic amides with

* Presented in part on the XIV. Int. Conference on Coordination Chemistry, Toronto, June 1972.

** Part II in the series Metal Ion-Catalysed Conversion of Amides and Imides into Esters; Part I: Proc. XIV. Int. Conf. Coord. Chem., p. 629, Toronto 1972.

aliphatic α,ω -diols leading to the corresponding ω -hydroxyalkyl esters is also reported.

EXPERIMENTAL

Chemicals. Benzamide obtained from benzoyl chloride and ammonium carbonate in acetic acid¹³ was freed of benzoic acid by recrystallisation from water and according to the nitrogen content it was of 99.89% purity. M.p. 128.0—128.5°C (ref.¹⁴ m.p. $127.1 \pm 0.5^\circ\text{C}$). For $\text{C}_7\text{H}_7\text{NO}$ (121.1) calculated: 11.6% N; found: 11.6% N. Terephthalamide was prepared by allowing terephthaloyl dichloride¹⁵ (12 g) to react with gaseous ammonia in dioxane (200 ml) under stirring at 10—15°C; as soon as further addition of the ammonia did not increase the temperature, the reaction mixture was warmed up to ambient temperature and the ammonia was introduced for another 1 h. The crystalline amide was filtered off, washed with cold water until a negative test on the chloride ions, recrystallised from formic acid and dried over potassium hydroxide *in vacuo* (81% yield). M.p. 331°C (dec.) (ref.⁶ m.p. 300°C (dec.)); according to the nitrogen content, the product was of 99.98% purity. For $\text{C}_8\text{H}_8\text{N}_2\text{O}_2$ (164.2) calculated: 17.07% N; found: 17.07% N. Phenylacetamide (*purum*, Fluka, Basel) was recrystallised successively from water, ethanol and benzene; the product was of 99.19% purity (according to the nitrogen content). M.p. 156.0 to 157.5°C (ref.¹⁶ m.p. 154—155°C). For $\text{C}_8\text{H}_9\text{NO}$ (132.2) calculated: 10.36% N; found: 10.27% N. Nicotinamide (*purum*, Koch-Light Ltd.), 98.5% purity (according to the nitrogen content), was used without further purification; m.p. 128—131°C (ref.¹⁷ m.p. 128.5—129.5°C). For $\text{C}_6\text{H}_6\text{NO}$ (108.1) calculated: 12.95% N; found: 12.76% N. Ethylene glycol, commercial product (Slovnaft, Bratislava) was distilled through a 30 TP column and the fraction boiling at 96°C/12 Torr has been collected which contained 0.07% water and 0.02% diethylene glycol (by gas chromatography). 1,6-Hexanediol, 98% purity (Koch-Light Ltd.), was used without further purification; m.p. 40—42°C (ref.¹⁸ m.p. 43°C).

Analytical methods. The ammonia released by the reaction was absorbed in 0.3N- H_2SO_4 ; at fixed time intervals aliquot portions of the solution (10 ml) were analysed for the ammonium sulphate content by amperometric oxidimetry using the hypochlorite method¹⁹ (0.05M-NaOCl). The concentration of the unreacted amide in the final reaction mixtures was determined in the following way: A sample of the mixture was hydrolysed with concentrated potassium hydroxide solution, the ammonia released was steam-distilled and absorbed in 0.3N- H_2SO_4 and the content of ammonium sulphate was determined by titration with 0.05M-NaOCl according to the above described method. The sum of the equivalents of ammonia released during the reaction and of the unreacted amide differed from the amount of the initially charged amide within $\pm 1.5\%$. The contents of bis(2-hydroxyethyl)terephthalate and its dimer, *i.e.* the products of the reaction of terephthalamide with ethylene glycol, were determined by polarographic analysis²⁰. The content of diethylene glycol in the unreacted ethylene glycol was determined by gas chromatographic analysis²¹ of the samples of the final reaction mixtures. The same method was used to determine the content of diethylene glycol bound in the ester form, after the preceding hydrazinolysis²¹ of the samples of the reaction mixture. The absence of the carboxylic ion in reaction mixtures resulting from the catalysed reaction of benzamide and of terephthalamide with ethylene glycol was checked by alkalimetric titration of samples with 0.1M-KOH on phenolphthalein as an indicator. Melting points were determined with a Kofler hot stage microscope and were not corrected.

Catalysts. Manganese(II) acetate tetrahydrate was prepared by precipitation of an aqueous solution of manganese(II) chloride (30 g) with hot 20% aqueous ammonium carbonate (30 g) solution. The precipitate so formed was washed with ammonium carbonate until negative test on the presence of chloride ions, suspended in water, mixed with acethanhydride (40 g) and heated

on a water bath for 2 h. The crystals separating on evaporation of the solution were dried at 105°C. For $C_4H_{14}MnO_8$ (245.1) calculated: 22.4% Mn; found: 22.3% Mn. Cobalt(II) acetate tetrahydrate was prepared similarly from cobalt(II) chloride. For $C_4H_{14}CoO_8$ (249.1) calculated: 23.7% Co; found: 23.7% Co. Amorphous titanium(IV) oxide monohydrate was prepared from titanium(IV) chloride by the reported procedure²². For TiH_2O_3 (97.9) calculated: 48.9% Ti; found: 48.9% Ti. Tin(II) oxide (black modification) prepared from tin(II) chloride by the reported procedure²³ was free of chloride ions and Sn^{4+} compounds; tin(II) oxalate was prepared by the procedure reported earlier²⁴; for C_2O_4Sn (206.7) calculated: 57.4% Sn; found: 57.3% Sn. Tetra-(n-butyl)tin of analytical grade purity (Výzkumný ústav organických syntes-Rybitví) was used without further purification. Zinc(II) acetate dihydrate, analytical grade purity (Lachema Brno); for $C_4H_{10}O_6Zn$ (219.5) calculated: 29.8% Zn; found: 29.8% Zn. Lead(II) acetate trihydrate, analytical grade purity (Lachema Brno); for $C_4H_{12}O_7Pb$ (379.3) calculated: 54.6% Pb; found: 54.8% Pb. Di(n-butyl)tin oxide (Výzkumný ústav organických syntes, Rybitví); for $C_8H_{18}OSn$ (248.9) calculated: 47.7% Sn; found: 47.6% Sn. Sodium methoxide was prepared by dissolving metallic sodium in methanol under nitrogen and evaporating the solution *in vacuo*; for CH_3ONa (54.0) calculated: 42.4% Na; found: 42.3% Na. Copper(II) acetate monohydrate (purum, Koch-Light Ltd.) was recrystallised from water. For $C_4H_8CuO_5$ (199.7) calculated: 31.8% Cu; found: 31.7% Cu. Mercury(II) acetate (purum, Koch-Light Ltd.) was used without further purification, similarly as antimony(III) oxide (99.99%, Koch-Light Ltd.), magnesium(II) oxide (99.99%, Koch-Light Ltd.) and calcium(II) acetate (p.a., Lachema, Brno). Cadmium(II) acetate dihydrate (purum, Koch-Light Ltd.) was recrystallised from water; for $C_4H_{10}CdO_6$ (266.5) calculated: 42.2% Cd; found: 42.1% Cd.

Kinetic measurements. The rate measurements of the glycolysis of benzamide, the measurements of the activity of the catalysts in this reaction and the preparation of some 2-hydroxyethyl esters were carried out in a 200 ml glass tubular reactor equipped with a mercury seal, a thermometer, a nitrogen inlet tube reaching above the level of the reaction mixture, a sampling tube, and with a 30 cm reflux condenser. The measurements were carried out at 167–197°C at the amide-diol initial molar ratio 1 : 30. The ammonia formed during the reaction and nitrogen were removed from the reaction system by a tube connected to the top of the reflux condenser and reaching below the level of the 0.3N- H_2SO_4 solution placed in an 1 l-absorption flask. A sealed thin-walled glass ball containing the weighed amounts of the amide and the catalyst was introduced into the reactor containing known amounts of ethylene glycol; the reactor was placed into a thermostat with a methyl phenyl silicone oil bath, glycol was warmed up to the reaction temperature (167–197°C) and the glass ball was shattered by starting the stirrer. A 5–7°C decrease in the temperature of glycol was offset in 1–3 min and this moment was taken as the very beginning of the reaction. In all cases the amide and the catalyst dissolved completely during this period. The reaction temperature was maintained with an accuracy of $\pm 0.5^\circ C$. At 0.025 to 0.050 mol of the amides, a 5 l/h nitrogen flow rate through the reactor and at a stirring intensity of 500 rev./min, the reactions took place in the kinetic region. The rates of ammonia and 2-hydroxyethyl ester formation as well as the rates of the amide consumption, determined by parallel experiments, were practically identical; in further experiments the course of the reactions was therefore followed by determining analytically the amount of ammonia released during the glycolysis. The rate law for the catalysed reaction of benzamide with ethylene glycol was determined for the initial molar ratio of both components equal to 1 : 30; under these conditions the volume changes of the reaction mixture due to evolution of ammonia were negligible and were not considered in deriving kinetic equations.

Isolation of products: benzoic acid esters. Benzamide (6.06 g, 0.05 mol) was heated with ethylene glycol (93.1 g, 1.5 mol) in the presence of $Cd(CH_3CO_2)_2 \cdot 2 H_2O$ (0.536 g, $4 \cdot 10^{-2}$ mol Cd/mol)

as a catalyst for 6.5 h at 197°C (the amide conversion 92.5%); the reaction mixture was freed of the excess ethylene glycol *in vacuo* (10 Torr) and distilled to give 2-hydroxyethyl benzoate (63%), b.p. 149–150°C/10 Torr (ref.²⁵ b.p. 160–162°C/14 Torr); for C₉H₁₀O₃ (116.2) calculated: 65.05% C, 6.06% H; found: 65.35% C, 6.15% H. Crystallisation of the distillation residue from an ethanol–light petroleum mixture yielded ethylene glycol dibenzoate (10%), m.p. 71–72°C (ref.²⁶ m.p. 73°C); for C₁₆H₁₄O₄ (270.3) calculated: 71.10% C, 5.22% H; found: 70.97% C, 5.25% H.

Isolation of products: bis(2-hydroxyethyl)terephthalate. Terephthalamide (8.2 g, 0.05 mol) was reacted with ethylene glycol (93.1 g, 1.5 mol) in the presence of TiO₂·H₂O (0.096 g, 1.2% wt. : mol) as the catalyst at 197°C up to 98.2% conversion (10 h). A pale yellow, transparent reaction mixture was condensed to c. one third of the initial volume by distilling-off the excess ethylene glycol *in vacuo* (10 Torr), the residue was cooled to 0°C and set aside. The crystalline bis(2-hydroxyethyl) terephthalate (79%) so separated was washed with 10 ml of ice water and dried *in vacuo* over P₂O₅, m.p. 109°C (ref.²⁷ m.p. 110.0–110.5°C). The product contained 0.68% of ester-bound diethylene glycol and did not show melting point depression when mixed with an authentic sample.

Isolation of products: 2-hydroxyethyl phenylacetate. The reaction of phenylacetamide (5.846 g, 0.044 mol) with ethylene glycol (82.66 g, 1.32 mol) catalysed by Cd(CH₃CO₂)₂·2 H₂O (0.2374 g, 2.026 · 10⁻² mol Cd/mol) at 197°C gave a reaction mixture (6 h, the amide conversion 97%) which was freed of the excess ethylene glycol *in vacuo* (10 Torr); a distillation of the residue gave 71% of 2-hydroxyethyl phenylacetate, b.p. 170–171°C/12 Torr (ref.²⁵ b.p. 171–172°C/13 Torr); for C₁₀H₂₃O₃ (180.2) calculated: 66.65% C, 6.72% H; found: 66.30% C, 6.69% H.

Isolation of products: nicotinic acid esters. Nicotinamide (5.93 g, 0.05 mol) was allowed to react with ethylene glycol (93.1 g, 1.5 mol) in the presence of Cd(CH₃CO₂)₂·2 H₂O (0.0863 g, 6.669 · 10⁻³ mol Cd/mol) as the catalyst at 197°C up to 94.4% conversion (7 h) and the excess ethylene glycol was distilled off *in vacuo* (10 Torr); a distillation gave 63% of 2-hydroxyethyl nicotinate, b.p. 145–147°C/3 Torr (ref.²⁸ b.p. 142–144°C/2 Torr). For C₈H₆NO₃ (167.2) calculated: 57.48% C, 5.43% H; found: 57.70% C, 5.40% H. The distillation residue was crystallised to give ethylene glycol dinicotinate (9%), m.p. 128°C (ref.²⁹ m.p. 128°C); for C₁₄H₁₂N₂O₄ (272.2) calculated: 61.76% C, 4.44% H; found: 61.50% C, 4.41% H.

RESULTS AND DISCUSSION

The reaction of benzamide with ethylene glycol at 197°C or with 1,6-hexanediol at 250°C (both used in excess) proceeds in the absence of a catalyst at a very slow rate (Fig. 1); the amide is converted to the 2-hydroxyethyl ester or to the 6-hydroxyhexyl ester only in 12 or 21% after 7 h. The uncatalysed reaction is first-order in benzamide and its activation energy has a value of 14.9 kcal/mol. Terephthalamide exhibits similarly low reactivity toward ethylene glycol; nicotinamide is the more reactive compound. In agreement with the known facile conversion of aliphatic carboxamides by glycols into the corresponding esters⁹, phenylacetamide was the most reactive of the amide series studied (Fig. 2). We have found that the formation of the esters depicted by Eq. (A)



where $R = C_6H_5$, $C_6H_5CH_2$, C_5H_4N and $n = 1$ or $R = 1,4-C_6H_4$, $1,3-C_6H_4$ and $n = 2$ and $m = 2-6$, can be significantly accelerated (Figs 1 and 2) by the addition of catalytic amounts of some transition metal compounds which are soluble in the amide-diol mixture. Their catalytic activity was measured in the reaction of benzamide with ethylene glycol carried out at $197^\circ C$ and was compared with the activity of the known catalysts for the amide glycolysis, *i.e.* sodium and magnesium compounds. The glycol esters of carboxylic acids are known to condense easily at elevated temperatures (Eq. (B)); in order to suppress this condensation reaction as effectively as

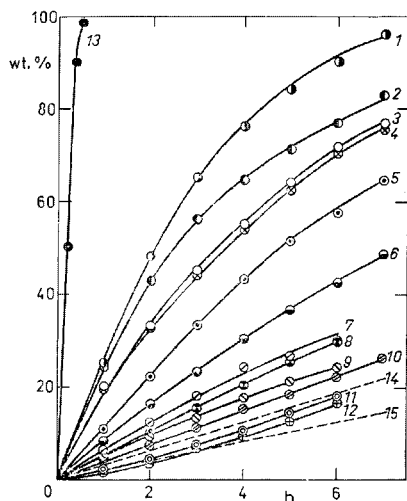


FIG. 1

Time Dependence of Benzamide Conversion for the Reaction with Ethylene Glycol (1-12) and with 1,6-Hexanediol (13) Catalysed by Metal Compounds ($1-4 \cdot 10^{-2}$ mol/mol Amide; $2-13 \cdot 5 \cdot 10^{-3}$ mol/mol Amide; $14-5 \cdot 10^{-2}$ mol/mol Amide) at $197^\circ C$ (1-12) and $250^\circ C$ (13)

1 $Cd(CH_3CO_2)_2 \cdot 2 H_2O$, 2 $Pb(CH_3CO_2)_2 \cdot 3 H_2O$, 3 $Mn(CH_3CO_2)_2 \cdot 4 H_2O$, 4 MgO , 5, 13 SnO , 6 $TiO_2 \cdot H_2O$, 7 $Zn(CH_3CO_2)_2 \cdot 2 H_2O$, 8 $(n-C_4H_9)_2SnO$, 9 $Co(CH_3CO_2)_2 \cdot 4 H_2O$, 10 Sb_2O_3 , 11 $Hg(CH_3CO_2)_2$, 12 $Cu(CH_3CO_2)_2 \cdot H_2O$; 14 uncatalysed reaction of the amide at $250^\circ C$, 15 uncatalysed reaction of the amide at $197^\circ C$; the amide to diol initial molar ratio 1 : 30.

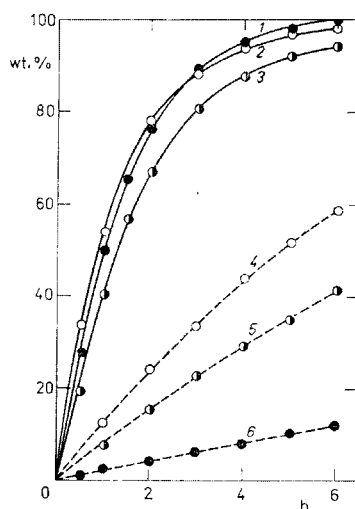
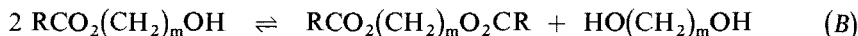


FIG. 2

Time Dependence of the Conversion of Terephthalamide (1), Phenylacetamide (2) and Nicotinamide (3) for the Reaction with Ethylene Glycol Catalysed by Cadmium(II) Acetate Dihydrate (1 and 2 $2 \cdot 10^{-2}$ mol/mol Amide, 3 $6 \cdot 10^{-3}$ mol/mol Amide) and the Uncatalysed Reaction of Phenylacetamide (4), Nicotinamide (5) and Terephthalamide (6)

The amide to diol initial molar ratio 1 : 30, temperature $197^\circ C$.

possible, the measurements were carried out with ethylene glycol in excess, *i.e.* at an initial molar ratio of the amide to ethylene glycol equaling to 1 : 30.



The rate of formation of the ω -hydroxyalkyl esters according to Eq. (A) was practically identical with the rate of ammonia evolution up to high amide conversions. Under the given experimental conditions the glycolysis rate is not influenced by desorption of the released ammonia, the ammonia is practically immediately removed from the reaction system and the reverse formation of the amide from the ester can be therefore neglected. The direct conversion of benzamide to 2-hydroxyethyl benzoate in the presence of metal catalysts is first-order in benzamide and at the molar ratio of the reactants used it is zero-order in ethylene glycol. As the volume changes due to ammonia evolution are also negligible under these conditions, the glycolytic reaction proceeding at a constant catalyst concentration can be described

TABLE I

Rate Constants k_c (h^{-1}) for the Reaction of Benzamide with Ethylene Glycol Catalysed by Metal Ions and Relative Activities of the Catalysts (C)

$[\text{C}_6\text{H}_5\text{CONH}_2]_0 = 0.025 \text{ mol/kg}$, $[\text{C}_2\text{H}_6\text{O}_2]_0 = 0.75 \text{ mol/kg}$, $[\text{C}] = 1.3 \cdot 10^{-3} \text{ mol/kg}$, temperature = $197 \pm 0.5^\circ\text{C}$.

Catalyst	k_c	Relative activity of the catalyst ^a
$\text{Cd}(\text{CH}_3\text{CO}_2)_2 \cdot 2 \text{H}_2\text{O}$	0.182	9.6
PbO	0.166	8.7
$\text{Pb}(\text{CH}_3\text{CO}_2)_2 \cdot 3 \text{H}_2\text{O}$	0.163	8.6
$\text{Mn}(\text{CH}_3\text{CO}_2)_2 \cdot 4 \text{H}_2\text{O}$	0.152	8.0
MgO	0.150	7.9
$\text{Ca}(\text{CH}_3\text{CO}_2)_2$	0.123	6.5
NaOCH_3	0.110	5.8
SnO	0.089	4.7
$\text{Sn}(\text{CO}_2)_2$	0.090	4.7
$\text{TiO}_2 \cdot \text{H}_2\text{O}$	0.052	2.7
$(n\text{-C}_4\text{H}_9)_2\text{SnO}$	0.034	1.8
$(n\text{-C}_4\text{H}_9)_4\text{Sn}^b$	0.003	—
— ^c	0.019 ^d	1.0

^a Calculated with respect to the value of the constant k_0 ; ^b the tetra(*n*-butyl)tin concentration $1.0 \cdot 10^{-2} \text{ mol/kg}$; ^c the reaction in the absence of a metal catalyst; ^d the value of the rate constant k_0 for the uncatalysed reaction.

by the kinetic equation (1)

$$-d[A]/dt = k_{\text{obs}}[A], \quad (1)$$

where A is benzamide and k_{obs} the experimental pseudo-first order rate constant. The zero order of the reaction in ethylene glycol holds for the ethylene glycol to benzamide initial molar ratios equal to or higher than 15. The reaction rate does not depend on the concentration of 2-hydroxyethyl benzoate and the reaction is not thus inhibited by the product. The glycolysis of aromatic amides catalysed by metal compounds differs therefore significantly from the metal ion-catalysed glycolysis of aromatic nitriles whose rate decreases with increasing ester concentration³⁰.

As the amide is converted by two parallel (the uncatalysed and catalysed) reactions, the pseudo-first order rate constant k_{obs} is the sum of the independently determined pseudo-first order rate constant k_0 for the uncatalysed reaction and the pseudo-first order rate constant k_c for the metal ion-catalysed reaction. Eq. (1) can be therefore re-written as follows

$$-d[A]/dt = (k_0 + k_c)[A]. \quad (2)$$

The course of the time dependence of the conversion of benzamide in the presence of the most active catalysts computed with the use of the integrated Eq. (2) was compared with experimental data. As it is evident from the inspection of Fig. 3, a satisfactory agreement was obtained, which confirms that under the above-mentioned reaction conditions the kinetic equation (2) is valid up to high benzamide conversions for the reactions catalysed by Cd^{2+} , Pb^{2+} , Mn^{2+} and Na^+ ions. The experimental and computed data for the benzamide conversion in reactions catalysed by Sn^{2+} and Sn^{4+} ions differ from one another in an average by 1.7 and 1.5%, respectively.

From comparison of the values of the rate constant k_c , which were obtained by subtracting the rate constant k_0 from the rate constant k_{obs} , it follows (Table I) that the catalytic effectiveness of the metal ions used at the same concentration ($1.3 \cdot 10^{-3}$ mol metal/kg) decreases in the order $\text{Cd}^{2+} > \text{Pb}^{2+} > \text{Mn}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{Ca}^{2+} > \text{Sn}^{2+} > \text{Ti}^{4+} > \text{Sn}^{4+}$. Nearly the same activity as for Sn^{4+} ions was found for Zn^{2+} ions; Co^{2+} and Sb^{3+} ions were even less effective (Fig. 1). The reactions catalysed by the above metal compounds do not show any induction period, in contrast to copper(II) and mercury(II) compounds which form insoluble precipitates and are essentially inactive (Figs 1 and 2). The efficiency of the catalysts does not depend on the nature of the anion. This is indicated by practically identical values of the rate constant k_c for the reactions catalysed by lead(II) oxalate and lead(II) oxide (Table I). It seems likely, however, that in addition to their solubility in the reaction medium, the ability to form a metal glycolate is a prerequisite for the efficiency

of the catalysts; in contrast to tin(II) oxide, tin(II) oxalate or di(*n*-butyl)tin oxide, tetra(*n*-butyl)tin, which is soluble in the reaction mixture within a broad concentration region but inert toward ethylene glycol, did not show any catalytic activity even when used at high concentrations (Table I). In the case of a homogeneous catalysed reaction the rate constant k_c includes also the effect of the catalyst on the rate of the catalytic reaction. The order of the glycolysis of benzamide with respect to the catalysts (C) was determined from the linear dependence of $\log k_c$ on $\log [C]$. As follows from Fig. 4 the conversion of benzamide into its ester is 0.25-order in Cd^{2+} and Mn^{2+} ions, 0.5-order in Pb^{2+} , Sn^{2+} , Mg^{2+} and Na^+ ions and approximately 0.5-order also in Ti^{4+} and Sn^{4+} ions. The linear dependence of $\log k_c$ on $\log [C]$ in the above regions of metal ion concentrations speaks for the homogeneous catalysed conversion of benzamide into the ester according to Eq. (A); this dependence defines also the limits of the validity of the kinetic equation (4) derived from Eq. (2)

$$k = k_c/[C]^n, \quad (3)$$

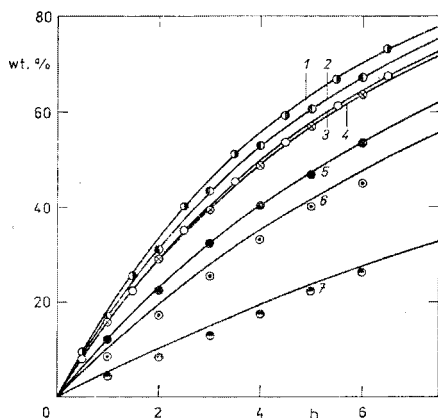


FIG. 3

Experimental (Points) and Calculated (Eq. (2)) (Curves) Time Dependence of Benzamide Conversion for the Reaction with Ethylene Glycol Catalysed by Metal Compounds ($1.3 \cdot 10^{-3}$ mol/kg)

1 $\text{Cd}(\text{CH}_3\text{CO}_2)_2 \cdot 2 \text{H}_2\text{O}$, 2 $\text{Pb}(\text{CH}_3\text{CO}_2)_2 \cdot 3 \text{H}_2\text{O}$, 3 $\text{Mn}(\text{CH}_3\text{CO}_2)_2 \cdot 4 \text{H}_2\text{O}$, 4 MgO , 5 NaOCH_3 , 6 SnO , 7 $(n\text{-C}_4\text{H}_9)_2\text{SnO}$; the amide to diol initial molar ratio 1 : 30, temperature 197°C .

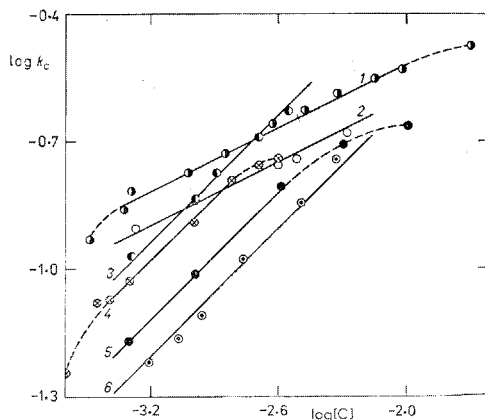


FIG. 4

Dependence of Logarithms of the Pseudo-First Order Rate Constants k_c on Logarithms of Catalyst Concentrations

1 $\text{Cd}(\text{CH}_3\text{CO}_2)_2 \cdot 2 \text{H}_2\text{O}$, 2 $\text{Mn}(\text{CH}_3\text{CO}_2)_2 \cdot 4 \text{H}_2\text{O}$, 3 $\text{Pb}(\text{CH}_3\text{CO}_2)_2 \cdot 3 \text{H}_2\text{O}$, 4 MgO , 5 NaOCH_3 , 6 SnO .

$$-d[A]/dt = k_0[A] + k[A][C]^n, \quad (4)$$

where k is the rate constant for the catalysed reaction of the pseudo-1.25-order (for $C = \text{Cd}^{2+}$ and Mn^{2+} ions) or of the pseudo-1.5-order (for $C = \text{Pb}^{2+}$, Sn^{2+} , Mg^{2+} , Na^+ , Ti^{4+} and Sn^{4+} ions), which in turn was calculated from Eq. (3) where n is the order of the catalysed reaction in the catalyst.

The dependence of the rate of the benzamide glycolysis on temperature was measured in the presence of the metal ions which differed in their coordinating ability. The activation energy determined from the dependence of $\log k_c$ on $1/T$ in the region from 167 to 197°C for the Cd^{2+} ion catalysed reaction had a value of 14.6 kcal/mol and did not differ significantly from the activation energy (14.9 kcal/mol) determined similarly for the reaction catalysed by Na^+ ions. The entropy of activation was found to be -50 e.u. for reactions catalysed by Cd^{2+} as well as Na^+ ions. The rate constants k can be expressed by the following equations

$$k_{\text{Cd}} = 6.2 \cdot 10^6 \exp(-14\,600/RT) \text{ kg}^{0.25} \text{ mol}^{-0.25} \text{ h}^{-1}. \quad (5)$$

$$k_{\text{Na}} = 2.5 \cdot 10^7 \exp(-14\,900/RT) \text{ kg}^{0.5} \text{ mol}^{-0.5} \text{ h}^{-1}. \quad (6)$$

We observed that in the reactions catalysed by cadmium(II) acetate, magnesium oxide and sodium methoxide the rate increases to a certain extent even when the concentration of the catalysts exceeds their solubility in the benzamide-ethylene glycol system (Fig. 4). Parallel experiments showed that this phenomenon is not caused by the diffusion-controlled reaction; the break on the linear dependence of $\log k_c$ on $\log [C]$ at the upper limit of the concentrations of these catalysts appears at different k_c values and depends thus only on the type of the metal catalyst. A similar successive, and not sudden, decrease in the reaction rate with increasing concentration of the catalysts has been observed by Tomita and Ido³¹ in the transesterification of dimethyl terephthalate with ethylene glycol catalysed in solution by zinc(II), manganese(II), magnesium(II) and tin(II) acetates and has not so far been satisfactorily explained. On the other hand, a sudden decrease in the reaction rate observed by us during the reaction of benzamide with ethylene glycol at low concentrations of cadmium(II) acetate or magnesium oxide (Fig. 4) could be due to the already insufficient concentration of the metal compound needed for the formation of a benzamide-ethylene glycol-metal compound complex which is likely formed in the transition state of the reaction.

We have found that the activity of the catalysts in the glycolysis of benzamide, expressed by the rate constant k_c can be correlated, with several exceptions, with the Pauling's electronegativity (x) of metal ions³² (Fig. 5) or with the acid ionisation (hydrolysis) constants ($\text{p}K_a$) for metal aquo ions^{33,34} (Fig. 6). In both cases plots of a "volcano" type were obtained. As follows from the relationship between the

catalytic effectiveness of the metal compounds and the electronegativity of the corresponding metal ions, the most effective (with the exception of zinc) are those ions the electronegativity of which lies between 1.2 to 1.6, *i.e.* magnesium(II) (1.2), manganese(II) (1.4), cadmium(II) (1.5) and lead(II) (1.6) ions; the metal ions whose electronegativity is lower than 1.2 or higher than 1.6 exhibit markedly decreasing catalytic activity. It is remarkable that Pb^{2+} , Cd^{2+} and Mn^{2+} ions (given in the order of their decreasing activity) have been found to be highly catalytically effective in the transesterification of dimethyl terephthalate with ethylene glycol³⁵, similarly as Pb^{2+} and Cd^{2+} ions in the transesterification of poly(ethylene terephthalate) with poly(ethylene isophthalate)³⁶ or Cd^{2+} , Pb^{2+} and Mn^{2+} ions in the transesterification of 1,2-bis(*p*-methoxycarbonyl)phenoxyethane with ethylene glycol³⁷. High activity showed Mn^{2+} ions also in the transesterification of benzoic acid esters with *n*-octadecyl alcohol³⁸ and Cd^{2+} ions in the transesterification

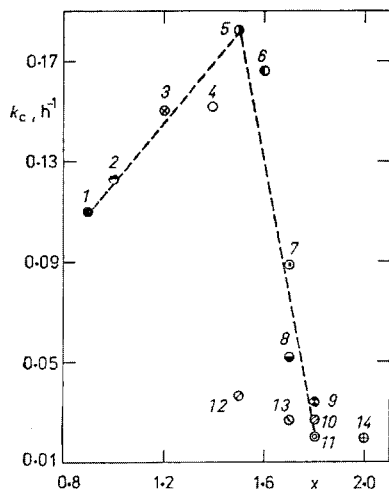


Fig. 5

Correlation of the Pseudo-First Order Rate Constants k_c with Metal Electronegativities (x) for the Metal Ion-Catalysed Reaction of Benzamide with Ethylene Glycol

1 NaOCH_3 , 2 $\text{Ca}(\text{CH}_3\text{CO}_2)_2$, 3 MgO , 4 $\text{Mn}(\text{CH}_3\text{CO}_2)_2 \cdot 4 \text{H}_2\text{O}$, 5 $\text{Cd}(\text{CH}_3\text{CO}_2)_2 \cdot 2 \text{H}_2\text{O}$, 6 $\text{Pb}(\text{CH}_3\text{CO}_2)_2 \cdot 3 \text{H}_2\text{O}$, 7 SnO , 8 $\text{TiO}_2 \cdot \text{H}_2\text{O}$, 9 $(n\text{-C}_4\text{H}_9)_2\text{SnO}$, 10 Sb_2O_3 , 11 $\text{Hg}(\text{CH}_3\text{CO}_2)_2$, 12 $\text{Zn}(\text{CH}_3\text{CO}_2)_2 \cdot 2 \text{H}_2\text{O}$, 13 $\text{Co}(\text{CH}_3\text{CO}_2)_2 \cdot 4 \text{H}_2\text{O}$, 14 $\text{Cu}(\text{CH}_3\text{CO}_2)_2 \cdot \text{H}_2\text{O}$.

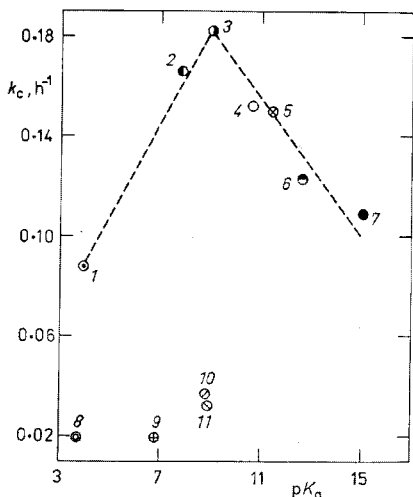


Fig. 6

Correlation of the Pseudo-First Order Rate Constants k_c with the Acid Ionisation Constants (pK_a) of the Metal Aquo Ions for the Metal Ion-Catalysed Reaction of Benzamide with Ethylene Glycol

1 SnO , 2 $\text{Pb}(\text{CH}_3\text{CO}_2)_2 \cdot 3 \text{H}_2\text{O}$, 3 $\text{Cd}(\text{CH}_3\text{CO}_2)_2 \cdot 2 \text{H}_2\text{O}$, 4 $\text{Mn}(\text{CH}_3\text{CO}_2)_2 \cdot 4 \text{H}_2\text{O}$, 5 MgO , 6 $\text{Ca}(\text{CH}_3\text{CO}_2)_2$, 7 NaOCH_3 , 8 $\text{Hg}(\text{CH}_3\text{CO}_2)_2$, 9 $\text{Cu}(\text{CH}_3\text{CO}_2)_2 \cdot \text{H}_2\text{O}$, 10 $\text{Zn}(\text{CH}_3\text{CO}_2)_2 \cdot 2 \text{H}_2\text{O}$, 11 $\text{Co}(\text{CH}_3\text{CO}_2)_2 \cdot 4 \text{H}_2\text{O}$.

of bornyl acetate with methanol³⁹; however, in the first two examples of transesterification reactions by far the highest catalytic activity was exhibited by the Zn^{2+} ion, in contrast to the benzamide glycolysis in which this ion shows one of the lowest activities. In other cases of the glycolysis of methyl esters Zn^{2+} ions were found to be significantly less effective, similarly as were Co^{2+} ions³⁷; the variable effectiveness of these ions leads to the assumption that the catalytic activity of zinc(II) and cobalt(II) compounds depends rather on the structure of the substrate than on the type of the reaction. On the other hand, a similar relationship between the electronegativity and catalytic activity of Na^+ , Ca^{2+} , Ti^{4+} , Sn^{4+} , Hg^{2+} and Cu^{2+} ions holds for the glycolysis of both the methyl esters and the amides. Glycolates of some divalent metals of the type³⁵ $\text{HOCH}_2\text{CH}_2\text{OMX}$ ($\text{X} = \text{OH}, \text{OCH}_2\text{CH}_2\text{OH}, \text{OR}, \text{RCO}_2$)

or their glycol oxides of the type $\text{O}-\text{CH}_2-\text{CH}_2-\text{O}-\text{M}$ (ref.⁴⁰), which are formed by fast interaction of some metal oxides, hydroxides, alcoholates or metal salts of carboxylic acids with ethylene glycol at elevated temperatures, are assumed to be the actual catalysts of transesterification reactions catalysed by metal ions^{35,41}; also known are glycolates of more complex structure derived from titanium(IV)^{42,43}, antimony(III)⁴⁴ and tin(IV)⁴⁵ and higher diols. Analogous correlation between the metal electronegativities and the rate constants for the metal ion-catalysed transesterification reactions and glycolysis of amides allows to assume that the glycolates or glycol oxides of the metals are the actual catalysts also for the glycolytic reactions of the amides. As follows from the correlation of the pK_a 's of the metal aquo ions (referring to the reaction $\text{M}(\text{H}_2\text{O})^{m+} \rightarrow \text{MOH}^{(m-1)+} + \text{H}^+$)³³ with the values of the rate constants k_c (Fig. 6), the most active ions are those with pK_a from 7 to 12, *i.e.* Cd^{2+} , Pb^{2+} , Mn^{2+} and Mg^{2+} ions. The correlation of pK_a with k_c is less unambiguous than that of k_c vs x ; the correlation of pK_a vs k_c is not obeyed by Zn^{2+} , Co^{2+} and Cu^{2+} ions which exhibit low or no catalytic activity in the glycolysis of the amides. The pK_a values for Ti^{4+} , Sn^{4+} and Sb^{3+} aquo ions are not known and their relation to the reaction rate is not therefore shown in the plot.

The low catalytic activity of Na^+ ions with the high charge density and, on the other hand, comparable activity of Mn^{2+} and Mg^{2+} ions indicate that the catalytic effect of the most active ions observed in the glycolysis of the amides is rather due to the chelate than electrostatic interactions. In majority of the reported, metal ion-catalysed nucleophilic substitution reactions the metal ion is coordinated to the carbonyl group oxygen^{42,43,46,47}. By analogy to these reactions and with regard to the known coordination of metal ions to the oxygen of the unprotonated amide group in aqueous solutions⁴⁸ one can presume that also in the glycolysis of amides with aliphatic diols the ions of catalytically active metals coordinate to the carbonyl oxygen of the unprotonated amide group facilitating thus the glycolytic reaction by polarisation of the carbonyl group. The complex formed in the transition state of the reaction is then easily attacked by a nucleophile, *i.e.* by ethylene glycol or by a higher

diol. The metal ion-catalysed glycolysis of aromatic amides proceeding according to this mechanism constitutes thus, similarly as the metal ion-catalysed transesterification of aromatic alkyl esters³⁸, a special case of "superacid" catalysis⁴⁹⁻⁵¹. The low catalytic activity of Cu^{2+} and Co^{2+} ions observed in the glycolysis of aromatic amides and, on the other hand, their high activity, *e.g.* in the glycolysis of aromatic nitriles, bearing upon the ability of these ions to coordinate readily to the nitrogen atom (in this case to the nitrogen of the intermediate iminoethers⁵²), is in accordance with the above interpretation.

REFERENCES

1. Ingold C. K.: *Structure and Mechanism in Organic Chemistry*, p. 1164, 2. Ed. Cornell University Press, 1969.
2. Beckwith A. L. J.: *The Chemistry of Amides* (J. Zabicky, Ed.), p. 96. Interscience, London 1970.
3. Fersht A. E., Jencks W. P.: *J. Amer. Chem. Soc.* **92**, 5442 (1970).
4. Fersht A. R.: *J. Amer. Chem. Soc.* **93**, 3504 (1971).
5. Hájek M., Šilhavý P., Málek J.: *This Journal* **39**, 2667 (1974).
6. Berther C.: *Chem. Ber.* **92**, 2616 (1959).
7. Asahi Chemical Industry Co.: *Japan.* **69** 05205 (1969); *Chem. Abstr.* **70**, 114 859 (1969).
8. Reid E. E., Hopkins J.: *J. Amer. Chem. Soc.* **45**, 38 (1911).
9. Courtaulds Ltd.: *Brit.* **592** 106 (1947); *Chem. Abstr.* **42**, 924 (1948).
10. Distillers Co.: *Brit.* **817** 372 (1959); *Chem. Abstr.* **54**, 5579 (1960).
11. Málek J., Hájek M., Dušková M.: *Czech.* **153** 864 (1974); *Chem. Abstr.* **81**, 169 320 (1974).
12. Málek J.: *Proc. XIV. Int. Conf. Coord. Chem.*, p. 629. Toronto 1972.
13. Kao C. H., Shao-Tuan Ma: *J. Chem. Soc.* **1930**, 2788.
14. Willard M. L., Maresh C.: *J. Amer. Chem. Soc.* **62**, 1253 (1940).
15. Zahn H., Seidel B.: *Makromol. Chem.* **29**, 70 (1959).
16. Wenner W.: *Org. Syn.* **32**, 92 (1952).
17. Galat A.: *J. Amer. Chem. Soc.* **70**, 3945 (1948).
18. *Handbook of Chemistry and Physics* (D. Hodgman, Ed.), 47. Ed., p. C-358. Chemical Rubber Publishing Co., Cleveland 1966-1967.
19. Čihalík J.: *Potenciometrie*, p. 468. Published by Nakladatelství ČSAV, Prague 1961.
20. Krumpolc M., Málek J.: *Makromol. Chem.* **171**, 69 (1973).
21. Hovenkamp S. C., Munting J. P.: *J. Polymer Sci., Part A-1*, **8**, 679 (1970).
22. Hájek M., Málek J.: *Chem. Prům.* **22**, 113 (1972).
23. Brauer G.: *Handbuch der Präparativen Anorganischen Chemie*, p. 553. Enke, Stuttgart 1954.
24. Málek J., Řeřichová M.: *Chem. Prům.* **25**, 437 (1975).
25. Robinson B.: *J. Chem. Soc.* **1963**, 2417.
26. Heim H. C., Poe C. F.: *H. Org. Chem.* **9**, 299 (1944).
27. Krumpolc M., Málek J.: *Makromol. Chem.* **168**, 119 (1973).
28. Vejdělek Z. J., Protiva M.: *Czech.* **84** 183 (1955); *Chem. Abstr.* **50**, 7149 (1956).
29. Löffler W.: *Ger. (GDR)* **36** 016 (1965); *Chem. Abstr.* **63**, 8323 (1965).
30. Ikeda T., Kitabatake M., Ito M., Noguchi J.: *Bull. Chem. Soc. Jap.* **41**, 1158 (1968).
31. Tomita K., Ida H.: *Polymer* **14**, 55 (1973).
32. Gordy W., Thomas W. J. O.: *J. Chem. Phys.* **24**, 439 (1956).

33. Basolo F., Pearson R. G.: *Mechanism of Inorganic Reactions. A Study of Metal Complexes in Solution*, p. 31, 2. Ed., Wiley, New York 1968.
34. Ringbom A.: *Complexation in Analytical Chemistry*, p. 298. Interscience, London 1963.
35. Yoda K., Kimoto K., Toda T.: *Kogyo Kagaku Zasshi* 67, 909 (1964).
36. Yoda K.: *Makromol. Chem.* 136, 311 (1970).
37. Kubo S., Suzuki K., Ishizuka O., Imamura R.: *Kogyo Kagaku Zasshi* 73, 195 (1970).
38. Zimmermann H., Schaaf E.: *J. Prakt. Chem.* 312, 660 (1970).
39. Berner E., Aaberg E.: *Suomen Kemistilehti B* 31, 53 (1958).
40. Torraca G., Turriziany R.: *Rass. Chim.* 14, 100 (1962); *Chem. Abstr.* 58, 9233 (1963).
41. Fontana C. M.: *J. Polym. Sci. A-1*, 6, 2313 (1968).
42. Reeves R. E., Mazzeno L. W. jr.: *J. Amer. Chem. Soc.* 76, 2533 (1954).
43. Puri D. M., Mehrotra R. C.: *Indian J. Chem.* 5, 448 (1967).
44. Mehrotra R. C., Bhatnagar D. D.: *J. Indian Chem. Soc.* 42, 327 (1965).
45. Gaur D. P., Srivastava G., Mehrotra R. C.: *J. Organometal. Chem.* 47, 95 (1973).
46. Bender M. L.: *Advan. Chem. Ser.* 37, 19 (1963).
47. Jones M. M.: *Ligand Reactivity and Catalysis*, p. 42. Academic Press, London 1968.
48. Kaden T., Zuberbühler A.: *Helv. Chim. Acta* 54, 1361 (1971).
49. Westheimer F. W.: *Trans. N. Y. Acad. Sci.* 18, 15 (1955).
50. Bender M. L.: *Mechanism of Homogeneous Catalysis from Protons to Proteins*, p. 212. Wiley-Interscience, New York 1971.
51. Ref. 33, p. 626.
52. Ikeda T., Kitabatake M., Ito M., Noguchi Y.: *Bull. Chem. Soc. Jap.* 41, 1154 (1968).

Translated by J. Hetflejš.