Imidazoline Hydrolysis in Alkaline and Acidic Media—A Review

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The literature was reviewed for information on imidazoline hydrolysis. Conflicts involving structures and mechanisms of hydrolysis have been found. Researchers also disagree as to the role of water and whether a protonated form of the imidazoline exists. However, there is agreement that the rate of hydrolysis is dependent on pH and temperature.

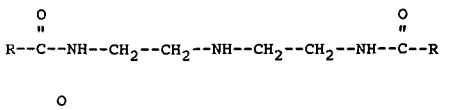
KEY WORDS: **Imidazoline hydrolysis, kinetics of imidazoline hydrolysis, review of imidazoline hydrolysis.**

Imidazolines and their derivatives are useful surfactants as laundry products, corrosion inhibitors, personal care products, textile processing aids, and other surfactant uses. Imidazolines belong to the five-membered heterocyclic family and can be considered the dehydrated versions of an ethylene polyamine amidoamine. Commercial materials are made from diethylenetriamine (DETA), aminoethylethanolamine (AEEA), ethylenediamine (EDA), or triethylenetetraamine (TETA) and fatty acids or esters. Imidazolines are unstable in the presence of water, reverting to the precursor amidoamine or an isomer. The literature was surveyed for references on the alkaline and acidic hydrolysis of imidazolines.

DISCUSSION A: ALKALINE HYDROLYSIS

Two schools of thought exist on the alkaline hydrolysis of imidazolines. They are: attack of the OH^- on the protonated imidazoline (Theory 1); and, attack of OH^- on the imidazoline itself (Theory 2).

Much work has been done on the alkaline hydrolysis of DETA-, AEEA-, and EDA-based imidazolines. Some agreement is found among researchers as to what the structure is of the hydrolyzed DETA imidazoline. Depending on the starting materials, the amidoamine found can be either the 1,2 diamide or the 1,3 diamide. When the 1,3 diamide (**1**) is converted to the imidazoline and then gently hydrolyzed, two products are formed: 1,2 diamide (**2**, the kinetic product of hydrolysis) and the 1,3 diamide (the thermodynamic product of hydrolysis).



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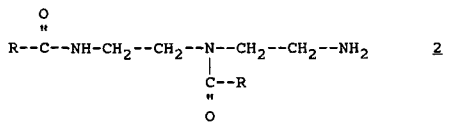

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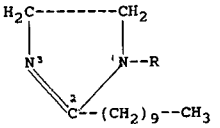
Past laboratory work on alkaline hydrolysis of imidazolines has reached the following conclusions: i) The hydrolysis rate is increased with an increase in temperature whereby 90+% of the imidazoline has been hydrolyzed within 4-6 hr at 100°C and 48-72 hr at ambient temperature. ii) Increased temperature favored the formation of the secondary amine isomer (1,3 diamide) as the major hydrolysis product. iii) Initial hydrolysis yields two equivalent products: the 1,2 and the 1,3 diamides. iv) With time, the 1,3 diamide increases relative to the other product, the 1,2 diamide. v) The higher the pH, the faster the rate of hydrolysis.

De Savignac and co-workers (1) describe the alkaline hydrolysis reaction. When the authors discuss this topic, they use two different models (**3** and **4**):

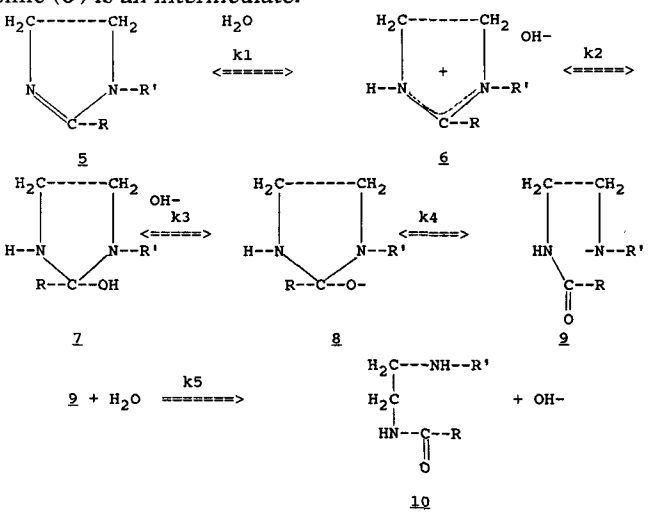


3 R = CH_2-CH_2-NH_2

4 R = H

The opening of the ring by hydrolysis can be at the 1-2 bond or the 2-3 bond. For compound **4**, the product is the same. For compound **3**, two different products are possible depending on where the rupture takes place. Nuclear magnetic resonance (NMR) analysis verifies that the rupture takes place at the 1-2 bond.

The authors suggest a reaction scheme for the hydrolysis. They are advocating Theory 1 where the protonated imidazoline (**6**) is an intermediate.



5 **6** **7** **8** **9** **10**

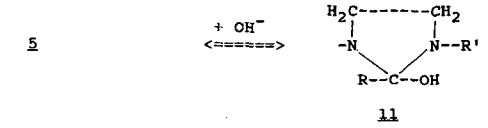
According to De Savignac *et al.* (1), key points to this mechanism are: i) Since water does not play a role in the hydrolysis of the imidazoline, the concentration of water is not a factor. ii) Hydrolysis rate is a function of pH. iii) The findings are in agreement with other researchers (2-4) who hydrolyzed compounds possessing the C=N bond. The ring opening mechanism in aqueous solutions confirms reports of these authors. iv) In most basic media, the rate determining step (k2) is the attack of hydroxide ion on the protonated form of the substrate. v) In less basic media, the rate determining step (k4) is the breaking of the intermediate.

De Savignac and co-workers' conclusions (1) are in contradiction with the mechanism proposed by Harnsberger and Riebsomer (5,6). De Savignac and Harnsberger and Riebsomer both have seen a nonlinear variation of the rate constant with pH. The interpretation of this data is the problem. Harnsberger and Riebsomer interpret this as a rapid addition of the hydroxyl ion to the neutral form of the imidazoline (**5**) followed by the slow decomposition of the formed intermediate. Harnsberger and Riebsomer have calculated a negative entropy which would indicate a very stable intermediate. But De Savignac claims that this reac-

tion should be accompanied by a change of positive or zero entropy (unstable intermediate) which was calculated from Harnsberger's and Riebsomer's experimental data.

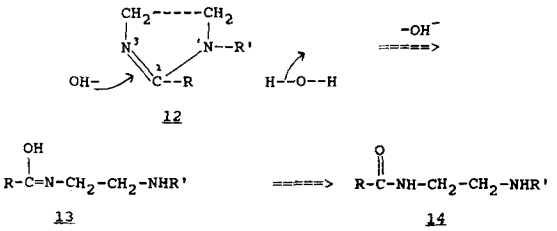
Harnsberger and Riebsomer have examined alkaline catalyzed imidazoline hydrolysis that leads to the opening of the ring between positions one and two. The reaction is influenced by the various ring substitutes and by pH. In aqueous solutions, the imidazolines are normally hydrogen bonded to water molecules. An equilibrium exists between the ionized (**6**) and unionized species (**5**). In their opinion, the salt (reaction of imidazoline and OH^-) of the imidazoline takes little, if any, part in hydrolysis (Theory 2).

Hydrolysis is catalyzed by the hydroxide ion. An initial attack by the hydroxide ion occurs on the number two carbon which is slightly positive (Reaction 2). Any substituent that reduces this positive charge should also reduce the probability of attack by the hydroxide ion which would lead to a slower reaction.



The reaction between the imidazoline and the hydroxide ion is fast and reversible. But the reaction between the intermediate (**11**) with the water is rate-controlling and irreversible. An equilibrium may form between the imidazoline and the hydroxide ion which would react with the water to give the hydrolyzed products.

It is possible the hydroxide ion is attracted to the imidazoline molecule by strong electrostatic forces and reaction occurs when this species is approached by a water molecule:



Steric hindrance by straight-chain substituents in the 1-position does not greatly affect the rate of hydrolysis. Steric hindrance occurs when the 1-position is a branched-chain alkyl group.

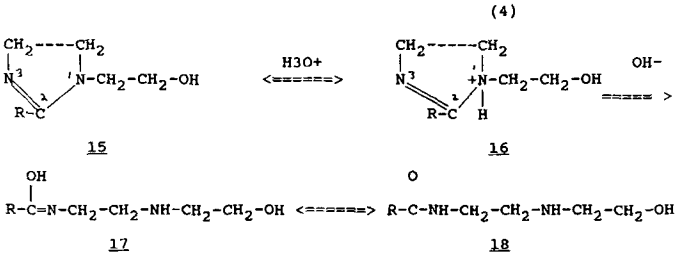
The hydroxyethyl group in an AEEA-based imidazoline is a less effective electron donor than a methyl group. However, atomic models show that the hydroxyl group may be in excellent position to attack the number two carbon on the ring.

Kolomiets and various co-workers (7) have done extensive work on aqueous alkaline hydrolysis of these imidazolines. They support Theory 1, attack of the OH^- on the protonated imidazoline, and conclude that: i) At pH > 9, decrease of the relative rate of hydrolysis is due to a change in the disassociation of the protonated form of the molecule. ii) Addition of inorganic salts or of nonaqueous solvents will lower the hydrolysis rate. iii) Length of the alkyl group (R = 9-17) has no influence on the rate. iv) The rate-limiting step is the nucleophilic attack by OH^- on the protonated form of the molecule.

The hydrolysis of AEEA-based imidazolines is examined in two other papers by Kolomiets and co-workers (8,9). As was found in works by other researchers, hydrolysis is a gradual process at all temperatures, although the rate increases with temperature. After thirty minutes of treatment, the hydrolysis conversion was 22.7% at 40°C and 90.7% at 90°C. The pH of the system was not taken into consideration.

When the conversion to the monoamide is between 0 and 50%, the hydrolysis rate constant fits a first-order equation. Lowering the water content in the reaction mixture will slow the hydrolysis. "Variation of the molar ratio of water to the main component from 11 to 55, and presence of up to 10% of amide compounds in the original substance, have virtually no effect on the hydrolysis rate. The process slows sharply at lower ratios."

In their continuing study of AEEA-based imidazolines, Kolomiets and co-workers (8,9) examine the pH factor in relationship to hydrolysis. The pH varied from 8.05 to 12.50 at a temperature of 50°C. They determine that the imidazoline concentration falls slowly with time. As the pH increases, the rate of hydrolysis increases. The rate-determining step is the attack of the OH^- on the protonated form of imidazoline (Theory 1). The rate, a linear function of the OH^- concentration, is first order with respect to the hydroxide ion. The rate is also linear in respect to imidazoline concentration, another first-order reaction. The overall alkaline hydrolysis of imidazoline is a bimolecular second-order reaction.

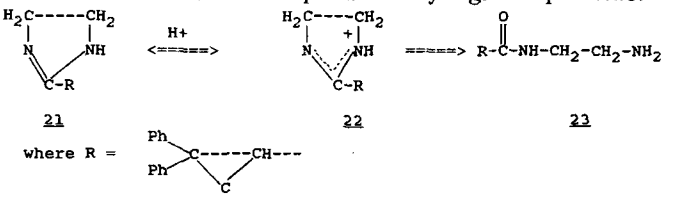


"The first state is rapid formation of the protonated form; according to literature data, such reactions have rate constants of 10^{10}-10^{11}. . . . the controlling second stage is nucleophilic attack of the OH^- on the protonated form, resulting in formation of an unstable compound of imidol structure (**19**). According to literature data and our analytical results, the imidol structure passes rapidly into the amide form."

Medical researchers, Ross *et al.* (10), examined cibenzoline, (**21**) [2-(2,2-diphenylcyclopropyl)-4,5-dihydro-1H-imidazol]. "The reaction is subjected to specific base catalysis which proceeds via the protonated cibenzolium ion. No evidence for the existence of a "pseudobase"-type intermediate could be found. The results support only one of two different mechanisms which have been proposed previously for the hydrolysis of this class of compounds."

The work done by Ross and co-workers centers on temperature and pH variations. The pH range varies from 7 to 13; temperature from 25° to 80°C. From the data, the reaction was determined to follow a pseudo first-order kinetics.

The data are consistent with the mechanism involving reaction of the protonated form of the imidazoline with water and hydroxide ion (Theory 1). The contribution of the water was detected at low pH and very high temperature.



The mechanism, as stated by the authors, has the support of other researchers, such as Martin and Parell (11), DeWolfe (12), and Saam and Bank (13).

Ross and co-workers (10) continue with their analysis by discrediting the mechanisms of Harnsberger and Riebsomer (5,6) and Fernandez and co-workers (14)—"... our proposed mechanism and the Harnsberger mechanism differ in the dependence of observed rate constant on pH." The authors could not get their data to fit the Harnsberger rate equation.

Ross Equation:

$$Kobs = \frac{ko + kOH^- [OH^-]}{\frac{Ka[OH^-]}{Kw} + 1}$$

Harnsberger Equation:

$$Kobs = \frac{K^2\ Keq\ [OH^-]^2}{Ki\ fI + [OH^-]^*\ [Keq\ [OH^-] + 1]}{fOH^-\ fIH}$$

where

ko—water rate constant
Ka—equilibrium constant of acid
Kw—equilibrium constant of water
[OH⁻]—concentration of hydroxide ion
I—imidazoline
IH—imidazoline salt
f—activity coefficient of reactants
Ki—K ionization of imidazoline
Keq—K equilibrium
kOH—rate constant for hydroxyl ion
K2—reaction rate of the complex with water

Harnsberger and Riebsomer (5,6) believe the mechanism involves rapid and reversible reaction of free-base imidazoline with hydroxide ion (Theory 2) to form an intermediate which reacts with water in the rate-determining step to give products.

Fernandez *et al.* support the Harnsberger mechanism. But in all actuality, Ross feels that Fernandez is "in accord with a mechanism involving a rate-determining reaction between a protonated imidazoline and hydroxide ion (Theory 1) and does not support a mechanism in which free imidazoline reacts with either water or hydroxide ion."

Ross *et al.* (10) found the data of Fernandez revealed little variation in the observed rate constants for hydrolysis. The system studied by Fernandez is best described by their (Ross *et al.*) hydrolysis (5).

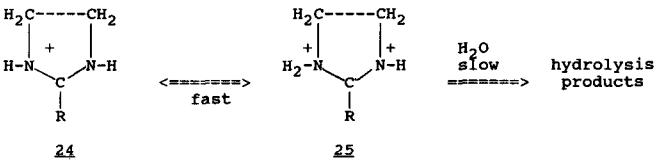
DISCUSSION B: ACID HYDROLYSIS

De Savignac *et al.* (1) describe the reaction of imidazolines in regard to acid hydrolysis. With acid hydrolysis, the mechanism is the breaking of the C – N bond by protonation. This occurs at high acid concentration and high temperatures.

Harnsberger and Riebsomer (5,6) have shown that acid hydrolysis of 2-imidazolines is very slow or nonexistent. The 1-unsubstituted imidazolines are resistant to acid-catalyzed hydrolysis. The 1,2-dialkyl-2-imidazolines are catalyzed by bases and inhibited by acids.

Acid hydrolysis of imidazolines is found in high temperature and extremely acidic environment. Limatibul and Watson (15) based their mechanism on earlier work by Haake and Watson (16). Hydrolysis of amidines is based on nucleophilic attack by water on the diprotonated amidines. The proposal is based on: i) rate of hydrolysis of the strong base being linearly dependent on acid concentration and ii) large downfield shift in the NMR signals of lysidinium ion in sulfuric acid more concentrated than 102% which suggest protonation of the lysidinium ion to a dication.

The proposed mechanism consists of the protonation of the lysidinium ion in a preequilibrium step to a strongly acidic dication which undergoes rate-determining nucleophilic attack by water. The dication then decomposes to the hydrolysis products.



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The electronic effects of the substituent (R) on the rate of hydrolysis should be small if step 2 involves nucleophilic addition of water to the dication at the 2-position. "It would seem quite unlikely that negligible electronic effects on the rate of hydrolysis would be obtained if step 2 consisted of a direct displacement reaction by water."

The hydrolysis reaction is faster in sulfuric and hydrochloric acids than perchloric acid. First-order reaction occurs in 102% sulfuric acid.

The purpose of this paper is not to make a determination as to which theory is correct, but to review the information on hand. Imidazoline hydrolysis is a reaction complicated by pH, temperature, and water. The various authors have tried to explain their positions by suggesting possible reaction schemes and kinetic equations.

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