Ferrate As an Advance Oxidator Materials (AOM) for Removing the Congo Red Dyes: Study of Optimization and Kinetics Degradation

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Abstract. Ferrate (VI) as an alternative oxidizing material that has a multifunction. This species is able to degrade Congo Red (CR) dyes. The performance of ferrates in degrading CR are by free up of hydroxyl ions from the active group then initiating active groups on the CR species. This initiation will cause the CR oxidation reaction to become a simpler compound that is easily biodegradable. The stages of this study were ferrate synthesis, characterization, optimization of the volume of Fe(NO₃)₃, optimization of pH, and optimization of ferrate(VI) molar ratio with CR. Ferrate synthesis is carried out by reacting a solution of Fe(NO₃)₃ and oxidizing NaOCl in alkaline conditions. This synthesis produces crystals which formed to sodium ferrate (Na₂FeO₄) then tested using XRD. The XRD test showed that a good results at a value of 2θ = 32°. Dyestuff oxidation reactions carried out by batch systems and non-oxidized dyes were analyzed using spectrophotometric methods. The results showed that sodium ferrate can effectively oxidize CR dyes with the percentage of degradation of 98.2% at the optimum pH conditions of 9.2, the ratio of the concentration of CR to ferrate was 1:5 and the oxidation time was 20 minutes. The CR oxidation reaction using ferrate (VI) in this study is a first-order reaction with an R² value of 0.979 and a reaction rate constant of 8.95 x 10⁻² mol/sec.

1. Introduction
The textile industry is still the backbone of national exports, but the rise of the textile industry also has a negative impact on the quality of the environment. This impact is well aware that every production process of the industry will definitely produce waste. In general, dyes from the textile industry wastewater are an organic compound that has an aromatic structure so that it is difficult to be degraded naturally and certainly not environmentally friendly [1]. The textile industry produces wastewater with relatively high levels of BOD, COD, suspended solids and colors. Textile liquid waste also contains remnants of dyes such as phenols or aromatic compounds and also heavy metals such as Cr, Br, Fe, Mn, Cu and Cd [2].

Color matter or dyes is one of the important components in the textile industry because the presence of color will support the aesthetics of textile products. Synthetic coloring substances have recently been widely used in various industries. Waste that contains a lot of textile dyes is toxic, carcinogens and can cause mutagens in aquatic biota [3]. The compound CR has a general structure \( R-N-N = R' \), with \( R \) and \( R' \) is the same or different organic chains. This compound has a group \( -N = N- \) which is called the azo structure. The measurement of CR is shown...
in Figure 1. The presence of CR dyes in the aquatic environment can damage various species of living things because of the high toxicity of CR. Several methods are used to treat textile industry waste such as adsorption, coagulation and flocculation, and chemical oxidation [4].

There has not been a single treatment system that is sufficient to degrade CR, so it is necessary to develop other methods that are expected to be more effective and efficient, namely by using Advance Oxidator Materials (AOM). One of the AOM that meets these criteria is ferrate or Fe(VI). The spesi of Fe(VI) in its ionic form (FeO$_4^{2-}$) has the role of oxidizing hazardous pollutant compounds in a more environmentally friendly form. Ferrate compounds have a strong oxidizing ability and can be easily synthesized [5]. Potential reduction potassium ferrate (FeO$_4^{2-}$) in solution is the highest among all oxidants commonly used in water and liquid waste treatment, such as chlorine (C$_{20}$H$_{16}$N$_4$), hypochlorite (ClO$^-$), chlorine dioxide (ClO$_2$), ozone (O$_3$), hydrogen peroxide (H$_2$O$_2$), and permanganate (KMnO$_4$) [6]. As an oxidizer in water, Fe(VI) is reduced to Fe(III) or the final product which is not soluble in water (Fe(OH)$_3$), is a conventional coagulant. Therefore, ferrate(VI) is said to have a dual function that has the potential to carry out oxidation and coagulation at once in one stage [7]. The expected benefit of this dual combination of functions is the process of water and liquid waste treatment can produce clean water products with better quality (hazardous byproduct risk is smaller) and smaller operational costs.

In solution, Fe(IV) has various species which are influenced by the pH of the solution. The species is H$_3$FeO$_4^+$, H$_2$FeO$_4^-$, HFeO$_4^-$, FeO$_4^{2-}$ [8]. At pH 1 to pH 2, Fe (VI) is more dominant as H$_3$FeO$_4^+$ ion, but also exists as H$_2$FeO$_4$ in a lower fraction to pH 6. At pH 4 to pH 8, Fe (VI) is dominant as HFeO$_4^-$. At pH 9 to pH 10, Fe(VI) is dominant as FeO$_4^{2-}$. The condition that pH greater than 10, Fe(VI) will follow a different reduction pathway through the formation of anionic species such as Fe(OH)$_3^-$ and Fe(OH)$_6^{3-}$ in lieu of Fe(OH)$_3$. Unfortunately, in several studies on the use of Fe(VI), it has not provided a more detailed description of ferrate(VI) synthesis. In ferrate (VI) synthesis several treatment parameters are needed to produce ferrate (VI) material with greater oxidation ability. This larger oxidation process will, of course, provide maximum performance degradation. In this study, the study of ferrate (VI) synthesis as a CR oxidizing agent was carried out by varying the solution Fe(NO$_3^-$)$_3$ and NaOCl under alkaline conditions. The study of solution variations Fe(NO$_3^-$)$_3$ and NaOCl was aimed at obtaining ferrate(VI) material with high purity. High levels of purity can provide a maximum percentage of degradation.

2. Experimental
2.1. Materials
The materials used in this study were iron (III) nitrate (Fe(NO$_3^-$)$_3$), potassium hydroxide (KOH), sodium hypochlorite (NaOCl) 5.25%, Congo Red, sodium dihydrogen phosphate (NaH$_2$PO$_4$), sodium tetraborate (Na$_2$B$_4$O$_7$), methanol, potassium chloride (KCl), sodium hydroxide (NaOH). Congo Red has the molecular formula C$_{32}$H$_{22}$N$_6$Na$_2$O$_6$S$_2$. The IUPAC name of congo red is sodium benzidindiazo-bis-1-naphthylamine-4-sulfonate. This compound has a molecular weight
of 696.67 g / mol. The materials used in this study are all analytical grades and purchase from Sigma Aldrich-Ltd., Hungary.

2.2. Procedure
Ferrate synthesis was carried out by reacting 40 mL of a bleach solution containing 5.25% NaOCl with 12 grams of NaOH. The solution is stirred until NaOH dissolves completely, by varying the addition of Fe(NO$_3$)$_3$ which is 1 mL, 3 mL, 5 mL, 7 mL. The solution is stirred again until the solution turns purple-black, then closed and left for a day. The ferrate solution which has been left alone for one day in the previous preparation is filtered with glasswool and reacted with a 0.3 M NaCl solution in a 50 mL Erlenmeyer flask. Erlenmeyer was closed and the solution was left to rest for as long as the experiment time was 3 and 6 days. Then the mixture was centrifuged for 10 minutes at a speed of 2000 rpm to produce black deposits and dried under incandescent lamps to reduce the water content, then characterized by XRD. The XRD specification used is to use a current of 40 kV 30 mA.

The standard solution of CR with a concentration of 5.1 x 10$^{-4}$ M was made by dissolving 0.0355 grams of CR with distilled water and being diluted to the limit mark in a 100 mL volumetric flask. The solution of NaOCl with a concentration of 5.25% was made by diluting 43.75 mL of 12% NaOCl with distilled water and diluted to the limit mark in a 100 mL volumetric flask. The solution of Fe(NO$_3$)$_3$ with a concentration of 0.3 M was made by dissolving 6.0601 grams of Fe(NO$_3$)$_3$.9H$_2$O with distilled water and diluted to a 50 mL volumetric flask. The condition of pH 10 buffer solution from Na$_2$B$_4$O$_7$ solution and NaOH solution. The na$_2$b$_4$o$_7$ solution with a concentration of 0.025 M was made by dissolving 2.3875 grams of Na$_2$B$_4$O$_7$ with distilled water and diluted to the limit mark on a 250 mL volumetric flask. NaOH solution with a concentration of 0.2 M was made by dissolving 0.4 grams of NaOH with distilled water and diluted to the limit mark on a 50 mL volumetric flask.

Determination of the molar ratio is carried out by making a molar ratio of Ferrate: CR dye with a ratio of 1: 1; 2: 1; 3: 1; 4: 1; 5: 1; 6: 1; 7: and 1: 8. The ferrate solution with the different ratio in a vortex for 30 minutes with optimum pH is pH 9.6. Then shake it. The absorbance of the solution was measured by a UV-Vis spectrophotometer at the maximum wavelength of the red congo solution at intervals of 2 minutes to 20 minutes. Determination of optimum pH degradation is carried out by making ferrate molar ratios: CR was 1:1. As much as 1 mL of the solution is set pH from 6-10 by using CH$_3$COONa buffer, then the solution is measured at its wavelength congo red dye. Determination of CR degradation percentage is calculated using formula 1.

$$
\text{Percentage of CR degradation} = \frac{[CR]_{\text{initial}} - [CR]_{\text{final}}}{[CR]_{\text{initial}}} \times 100% \tag{1}
$$

In general, the determination of the kinetics of the CR degradation process by Fe(VI) is carried out by using the first reaction order model estimation, the second reaction order, and the double exponential reaction order. In the first order reaction model and the second reaction model, models of equations 2 and 3 are used. The research conducted by Dong, et al. have used this equation to study the study of oxidation kinetics of iopamidol [9].

$$
[k_{\text{potassium ferrate(VI)}}]_t = [k_{\text{potassium ferrate(VI)}}]_0 \times \exp^{-k_1t} \tag{2}
$$

$$
[k_{\text{potassium ferrate(VI)}}]_t = \frac{[k_{\text{potassium ferrate(VI)}}]_0}{1 + k_2 \times [k_{\text{potassium ferrate(VI)}}]_t \times t} \tag{3}
$$

where $[k_{\text{potassium ferrate (VI)}}]_t$ is the concentration of potassium ferrate(VI) at t. For potassium ferrate (VI)$_0$ is the concentration of potassium ferrate (VI) first, $k_1$ is the average constant per minute on first order reaction in min$^{-1}$, $k_2$ is the average constant per minute.
on the second order reaction in mM$^{-1}$ min$^{-1}$, and it is the time in minute. The process of kinetics study of CR degradation reaction is carried out by mixing 1 mL of ferrate solution with a solution of CR at the optimum molar ratio conditioned at optimum pH conditions. The solution is shaken so that it is homogeneous then the absorbance is measured by using a UV-Vis spectrophotometer at a wavelength of 510 nm. Every 2-minute interval is measured to get the absorbance value. Measurements were carried out for 60 minutes, at room temperature of 250 ±1°C at a pressure of 1 atm.

Figure 2: (a) XRD results in a variation of the volume of Fe(NO$_3$)$_3$ 1 ml at 3 days. (b) XRD results in variations in the volume of Fe(NO$_3$)$_3$ 1 ml at 6 days. (c) XRD results in variations in the volume of Fe(NO$_3$)$_3$ 3 ml at 3 days. (d) XRD results in a variation of the volume of Fe(NO$_3$)$_3$ 3 ml at 6 days

3. Results and Discussion
3.1. Characterization of Ferrate
Synthesis of sodium ferrate was carried out by mixing 12 grams of NaOH solids with 40 mL of 5.25% NaOCl. A drop of Fe(NO$_3$)$_3$ solution that the Fe(III) oxidation reaction becomes Fe(VI) and will be oxidized by NaOCl in an alkaline atmosphere. This reaction produces a blackish purple solution which shows that Fe(III) has been oxidized to Fe(VI). The ferrate formation reaction is shown by the reaction equation 4.

\[ 2Fe^{3+} + 3ClO^- + 10OH^- \rightarrow 2FeO_4^{2-} + 3Cl^- + 5H_2O \]  \hspace{1cm} (4)
Then the solution is left to stand for 1 day so that the resulting ferrate is stable which is marked by no change in the color of the solution formed. Then the NaCl solution is added to form the precipitate, then it is closed again for 3 days. This solution was analyzed by a UV-Vis spectrometer to determine the maximum wavelength of ferrate. Wavelength measurements are carried out in the range of 480 nm to 580 nm. From the measurement results, the maximum wavelength is 500 nm. This is in accordance with research by Talaiekhozani which states that the wavelength of ferrates is between 500 nm to 510 nm [8].

Solids of sodium ferrate (Na$_2$FeO$_4$) formed purple then characterized by using XRD by varying the addition of Fe(NO$_3$)$_3$ which is 1 mL and 3 mL at 3 days and 6 days. Characterization using XRD is done to provide information about the characteristics of ferrate crystals formed. A material containing certain crystals if analyzed using XRD, specific peaks will appear. In this study, data was obtained as shown in Figure 2.

Table 1: Optimization of Ferrate

| Peak number | $\nu_1$ | $\nu_2$ | $\nu_3$ |
|-------------|---------|---------|---------|
|             | 2$\theta$ | RI   | 2$\theta$ | RI   | 2$\theta$ | RI   |
| 1           | 31.83(8) | 3.7(9) | 30.115(14) | 20.0(11) | 30.135(13) | 9.7(8) |
| 2           | 45.574(15) | 5.3(7) | 31.689(2) | 31.2(11) | 30.317(3) | 4.2(5) |
| 3           | -       | -      | 32.20(4) | 20.5(16) | 31.720(3) | 33.6(15) |
| 4           | -       | -      | 34.501(17) | 7.7(8) | 32.31(5) | 12.9(15) |
| 5           | -       | -      | 37.904(9) | 13.1(9) | 34.52(2) | 5.0(7) |
| 6           | -       | -      | 41.085(4) | 3.9(6) | 35.210(19) | 3.7(7) |
| 7           | -       | -      | 41.410(9) | 6.7(7) | 37.899(5) | 17.4(9) |
| 8           | -       | -      | 45.216(9) | 2.3(5) | 39.908(12) | 5.7(8) |
| 9           | -       | -      | 45.386(6) | 3.6(6) | 41.28(9) | 5.1(8) |
| 10          | -       | -      | 56.365(7) | 14.9(10) | 45.459(13) | 8.6(9) |
| 11          | -       | -      | -       | -      | 56.455(9) | 16.1(10) |
| The purity of Ferrate (%) | 70.23 | 72.16 | 72.80 |

In XRD the diffraction pattern is expressed by the magnitude of the angles formed as a result of diffraction of the beam of light by the crystal in the material. The angle value is expressed in 2$\theta$, where $\theta$ indicates the angle of incidence of light. While the value of 2$\theta$ is the angle of incidence with the diffraction angle detected by the detector. One characteristic of the formation of ferrate crystals is that there are sharp peaks in each theta. Characteristics of sodium ferrate compounds using XRD make it possible to verify the presence of ferrate crystal structures. X-ray diffraction is one way to verify the presence of crystals in ferrate. The XRD spectra produced has the highest peak at an angle of 2$\theta = 32^\circ$. The resulting spectra also show a large intensity at a price of 2$\theta$ around 25$^\circ$ to 35$^\circ$. The presence of a large intensity at 2$\theta$ indicates that the resulting deposits are crystalline. Table 1 shows the results of the relative intensity of the peaks generated from this study. Based on Table 1, it can be seen that in the condition of the volume variation of Fe(NO$_3$)$_3$ as much as 3 mL and at 6 days of treatment, it produced the best peak relative intensity compared to other conditions. This is because that when the volume of Fe(NO$_3$)$_3$ is 3 mL and the treatment time for 6 days will produce the optimum ferrate ion. This condition is interpreted that at that time the reaction process between Fe(NO$_3$)$_3$ and the other reactants in ferrate synthesis is in the best condition. Molecular interactions produce perfect crystalline solids which produce peaks that have the highest relative height. Synthesis of crystals or sodium ferrate solids that produce a relatively high peak intensity used in the degradation of CR. Based on Table 1 that ferrate with the maximum level is equal to 72.80%. In addition, the results of
this synthesis produce a very small diffractogram so that the resulting crystals are good to be applied, one of which is the degradation process of Congo red Research by Fu et al. resulted in the purity of ferrate(VI) equal to 52.85% [10]. The notation accompanying Table 1 is $V_1$ for (Fe(NO$_3$)$_3$ 1 ml 3 days), $V_2$ for (Fe(NO$_3$)$_3$ 3 ml 3 days), $V_3$ for (Fe(NO$_3$)$_3$ 3 ml 6 days), and $RI$ for Relative Intensity.

3.2. Effect of Ferrate(VI) Concentration on Effectiveness of CR Oxidation

The effect of sodium ferrate concentration on oxidizing dyes needs to be studied to obtain information about the maximum ferrate concentration that can oxidize CR. To determine the effect of ferrate concentration the oxidation process has been carried out on 1 ml of CR solution at the CR molar ratio: ferrate which is 1: 1; 1: 2; 1: 3; 1: 4; 1: 5; 1: 6; 1: 7; 1: 8. The results can be seen in Figure 3.

Figure 3: CR degradation percentage based on the comparison of molar ratio. The solution condition in this treatment is $[\text{ferrate}]$ of $1.275 \times 10^{-4}$M, $[\text{CR}]$ of $5.1 \times 10^{-4}$M, and pH of 9.6 is oxidized for 20 minutes

Figure 3 shows that for the CR solution the addition of concentration to the 1:2 molar ratio decreases degradation. This indicates that at this concentration the oxidation process is less effective. But the addition of concentration to a molar ratio of 1: 5 has increased absorbance so that the oxidation process is more effective. The increase in ferrate -4 concentration can increase the number of ferrate molecules that can interact with the CR so that the amount of CR oxidized is increasing. However, for a higher concentration of ferrate solution the amount of Fe(OH)$_3$ deposition products as a result of reducing ferrates become more numerous so that it will disrupt the process of electron capture by the next ferrate. Besides that, the oxidation compounds from the dyes have also been formed. This condition can reduce the effectiveness of the oxidation process. The oxidation process of CR with ferrate is done by mixing ferrate solutions with CR dyes. In the Fe(III) oxidation reaction to Fe(VI), Fe(NO$_3$)$_3$ is added drops. This reaction produces a dark purple solution in which this indicates that Fe(III) has been oxidized to Fe(VI). This is possible due to the molecular structure of the dye. Congo red has a chromophore group -N=N- so it is difficult to oxidize. This is because the electrons in the -N=N- group are more so that the attraction between the two is getting stronger. This strong pulling force will make the electrons more difficult to remove and cause electrons to become more difficult to oxidize. In the structure of CR, the more substituents that are bound to the chromophore group will hinder the process of releasing electrons which will affect the speed of oxidation of the dye.
3.3. Effect of Time on the Effectiveness of CR Color Oxidation

The effect of time on the effectiveness of dyestuff oxidation was studied by doing the oxidation process with time variations, namely 5, 10, 15, 20, 25 and 30 minutes. The time study was carried out under conditions of the dyestuff molar ratio: ferrate which is 1: 5 with pH 9.6. The results data obtained are presented in Figure 4.

Figure 4: Effect of Time on the oxidation of CR by ferrate

Figure 4 shows that for congo red dyes, the longer the oxidation reaction takes place the absorbance decreases. This shows that more and more oxidized dyes. In congo red dyes within 30 minutes give the lowest absorbance because all ferrate molecules have succeeded in oxidizing the molecule of congo red. The molecules of CR are aromatic compounds so that these molecules will be substituted by ferrate (VI) compounds. This will cause substance reactivity to decrease [11]. This decrease will impact on reducing electron density from the CR aromatic ring. At the beginning of the oxidation reaction, there will be an electron transfer process from the molecules ferrate (VI), water, and also CR. This process results in the transformation of CR into phenoxy radicals and other resonance forms due to the unpaired electrons. This electron radical has a high electron density.

3.4. Effect of pH values on the effectiveness of the oxidation of CR by ferrates

The effect of pH is carried out because speciation of ferrates and dyes is greatly influenced by the pH of the solution. Speciation determines the ease of dyes to be oxidized and release electrons, as well as ease for ferrates to be reduced and capture electrons. To assess the pH of the solution to the effectiveness of the oxidation of dyes with ferrate oxidizers, tests have been carried out on variations in pH 6.6.4, 6.8, 7.2, 7.6, 8, 8.4, 8.8, 9.2, 9.4, 9.6 and 10. The results obtained are presented in Figure 5.

Based on Figure 5 above shows that the degradation process of congo red at pH 6 to pH 10 decreases which indicate that the number of congo red decreases. Absorbance at pH 6 to pH 9.2 solution has decreased absorbance which indicates that the oxidation process is running more effectively. This is because in this condition Fe(VI) is already in the form of FeO$_4^{2-}$ ions which are very easy to reduce to Fe$^{3+}$.

At pH 9.6 to pH 10 there is an increase in absorbance which means there is a decrease in the oxidation process. This is because Fe (VI) ions follow different reduction pathways through the formation of anionic species such as Fe(OH)$_6^{3-}$ dan Fe(OH)$_4^{2-}$ as a substitute for Fe(OH)$_3$, and the presence of these anions will disrupt the release process electron by the congo red molecule [12]. With the presence of these anions, it can cause competition in the release and
capture of electrons from the -N=N- group, which results in ineffective oxidation processes. From the graph above, it can be seen that sodium ferrate works best at pH 9.2. This pH 9.2 is the optimum pH of sodium ferrate in degrading CR dyes. In the process of CR oxidation using ferrate, pH is a very important variable because of its stability and reactivity in order to maintain self-decomposition. The process of protonation or deprotonation of the active group in CR also depends on the condition of the pH of the solution. The CR oxidation process becomes a simpler compound which provides good performance at alkaline pH, namely pH 6 to 11. This can be stated that the highest removal efficiency occurs when the pH of the solution is 9.2. The process of attacking ferrate to CR molecules is very good when the position of the CR active group is in the ortho position [13]. The active group in CR includes sulfate groups. This group will be very easy to experience the oxidation process when the pH of the solution is in alkaline conditions. This is because the deprotonation process of CR will be very easy to occur when the presence of hydroxyl groups is very abundant [14]. The existence of this hydroxyl group, when the condition of the ferrate ion is in a stable species, it will experience a maximum oxidation process. An increase in the number of hydroxyl ions, one day will reduce the effectiveness of degradation or deprotonation of CR [15]. This is due to the process of ferrate formation, for pH greater than 10, then ferrate will follow different reduction pathways through the formation of anionic species such as Fe(OH)$_3^-$ dan Fe(OH)$_6^{3-}$ in lieu of Fe(OH)$_3$.

In this study, the average dyestuff degradation data was calculated using the formula in equation 2. So that the percentage (%) of the average degradation was obtained as in Figure 5. From the results of the degradation, it can be seen that at pH 6.0 and pH 8.8, sodium ferrate cannot work optimally to degrade congo red dyes at that pH because the percentage of degradation is smaller than other pH values. Conversely, for pH 9.2; 9.4; 10 sodium ferrate can degrade dyes which can be seen from the higher percentage degradation value. Based on these data, sodium ferrate can degrade dyestuffs optimally at pH 9.6 which is proven by the highest decrease in absorbance and the highest percentage of degradation is 98.2%.

3.5. Kinetics Degradation
In general, the kinetic process of CR oxidation by Fe (VI) occurs at a relatively high pH. Species that have a dominant contribution to the degradation process have strong protonation power which will affect the degradation process of CR. An example is the Fe (VI) monoprotonated species having a potential of + 2.20V under acidic conditions, and 0.72V at alkaline conditions. Therefore, under relatively low pH conditions Fe (VI) will have a greater reduction potential [9, 16, 17].

Figure 5: Effect of pH values on CR oxidation by ferrate
Figure 6: Graph of Reaction Rate against Ferrate (VI). Graph A (order 1), Graph B (order 2), Graph C (order 3)\(^5\)

\[
\begin{align*}
H_3FeO_4^+ & \rightarrow H_2FeO_4 + H^+ \quad pK1 = 1.5 \\
H_2FeO_4 & \rightarrow HFeO_4^- + H^+ \quad pK2 = 3.5 \\
HFeO_4^- & \rightarrow FeO_4^{2-} + H^+ \quad pK3 = 7.2
\end{align*}
\]  \(5\)

The CR degradation process using Fe (VI) was carried out under conditions of pH 6-10. The kinetic reaction study of CR degradation using ferrate, the parameters specified include the reaction order of ferrate, CR, and the reaction rate constant \(k\). The graph for the determination of the reaction order is shown in Figure 6(A, B, and C). Based on Figure 6 the value of the reaction rate constant is interpreted from the plot slope value \(k\). In determining the reaction order of CR against ferrate (VI), the concentration of ferrate (VI) is considered constant and excessive during the process. From the data presented in Figure 6 shows that the reaction order of ferrate (VI) in this oxidation reaction follows the order of the pseudo 1. This is because the value of \(R^2\) of the three graphs, the highest value or close to 1 is the reaction order graph 1. That is equal to 0.9794. A pseudo 1 order reaction is a reaction where the concentration of one or more of a reactant far exceeds the concentration of other bonds. The reaction order for CR is shown in Figure 7, where the reaction order also shows a pseudo 1 reaction order with an \(R^2\) value of 0.867 with a reaction rate constant \(k\) of \(4.29 \times 10^{-2}\) mol / second. This rate of reaction interprets that there is more reaction between ferrate (VI) and the electrons released by CR. This indicates that one molecule of ferrate (VI) can oxidize several CR molecules. The electrons released by the CR molecule are sufficient to reduce ferrate (VI) ions to Fe\(^{3+}\) ions.

4. Conclusion

In this study ferrate (VI) crystals were produced with a purity level of 72.27%. The resulting ferrate is sodium ferrate (Na\(_2\)FeO\(_4\)). This Na\(_2\)FeO\(_4\) crystal was produced with a variation of
the volume of Fe(NO\textsubscript{3})\textsubscript{3} 7 ml for 6 days. Sodium ferrate can degrade CR dyes optimally at a 1: 5 molar ratio, at pH 9.2 within 20 minutes and produce a degradation percentage of 98.2%. Sodium ferrate can effectively degrade CR due to the presence of hydroxyl groups. The existence of a hydroxyl group, when the condition of the ferrate ion is in a stable species, it will experience a maximum oxidation process. The increase in the number of hydroxyl ions, one day will reduce the effectiveness of degradation or deprotonation of CR. This will provide an optimal oxidized effect on CR. The ferrate (VI) compound can effectively oxidize the CR optimally.

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