Coke Degradation by Surface Breakage in a Modified Tumble Drum*

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Synopsis

The surface breakage rate constant for three Australian battery cokes was measured in a specially modified tumble drum using a previously developed technique. The effect of experimental test parameters—coke size, sample mass, drum speed, lifter height and lifter number—on the surface breakage rate constant was examined. The motion of coke particles within a tumble drum was filmed in a simulation experiment with a 0.31 m diameter drum. Particles were raised on the lifters, fell and collided with the bottom of the drum. These collisions were the main source of fines (minus 1 mm) production rather than true abrasion as depicted by a rubbing, rolling action. Hence the term ‘surface breakage’ is more appropriate than ‘abrasion’ to describe the breakage process. By measuring the volume of coke carried by each lifter and the height of fall of the coke, the effect of drum speed, sample mass, lifter height and number on the rate of surface breakage was successfully explained. The surface breakage rate constant was found to be proportional to particle size to the power 0.33 for the three cokes studied. A normalized surface breakage rate constant was derived which allowed comparison of cokes with different size distributions. This parameter characterises the coke surface breakage resistance.

Key words: metallurgical coke; breakage; abrasion; tumble drum; coke size.

1. Introduction

Coke strength is traditionally measured by empirical tumble indices. It is common to measure a “strength” index related to degradation by volume breakage, e.g., I_{20} , ASTM stability, and an “abrasion” index, e.g., I_{10} , ASTM hardness. (Henceforth, abrasion will be described by the more general term ‘surface breakage’.) These indices cannot be directly related to fundamental coke properties. In a previous paper¹⁾ the problems associated with these indices were discussed. An alternative approach to the degradation of coke in tumble drums was proposed in which coke degradation was considered as a rate process. By first stabilizing the coke and then removing the minus 1 mm material at regular intervals, the degradation of coke by surface breakage could be described by the equation:

$$\frac{dm_1}{dN} = -k_a \cdot m_1 \dots\dots\dots(1)$$

where, k_a : surface breakage rate constant
 m_1 : mass of coke lumps remaining
 N : no. of revolutions.

Integrating Eq. (1):

$$\ln (m_1/m_0) = -k_a \cdot N \dots\dots\dots(2)$$

where, m_0 : initial coke mass.

The surface breakage rate constant can be calcu-

lated as the slope of a plot of $\ln(m_1/m_0)$ against N . The rate constant, k_a , was proposed as a measure of coke surface breakage resistance and an index of coke strength.

In the present work, a modified tumble drum is described which allows the surface breakage rate constant to be easily measured. The effect of drum parameters and coke size on the surface breakage rate constant is studied, leading to an understanding of the mechanism of fines generation and the measurement of a rate constant normalized for the effect of coke size.

II. Experimental System

Experiments were performed in a specially constructed drum (see Fig. 1). The dimensions of the drum were the same as those of the standard MICUM drum,²⁾ i.e., a diameter of 1 m and a length of 0.5 m. An important feature of the drum was the provision of a section of 1 mm slotted screen as used extensively for sieve bends in the mineral processing industry.³⁾ This screen allowed continuous removal of fines without the tedious process of stopping the drum at short intervals to screen the drum contents. Lifters of heights 50 and 100 mm were tested in the drum. All lifters were attached to the inside of the drum by bolts and were easily removed so that the drum could be operated with 0, 2, or 4 lifters. A variable speed motor allowed the drum speed to be varied between 16 and 70 rpm.

Three samples of battery coke were used. Cokes

Fig. 1. Modified tumble drum with removable slotted screen. (Arrow indicates position of slotted screen).

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A and B were sampled from the same battery during different periods of operation. Coke C was from a second battery. The samples were first stabilized by tumbling 25 kg lots in the drum for 500 revolutions. This was done to remove the effects of volume break-age.¹⁾ It has been found that for weak cokes a longer stabilization time is required. A stabilization period of 1 500 revolutions is recommended. After stabilization, the coke was removed and screened using 63, 50.8, 45, 31.5, and 22.4 mm square hole sieves and a 20 mm round hole sieve. All experiments were performed using coke stabilized in this fashion. The experimental procedure was as follows. A single size fraction sample was placed in the drum and the drum rotated. Fines produced by surface breakage (abrasion) were continuously removed from the drum through the 1 mm wedge wire screen. It had been established previously¹⁾ that the surface breakage product was less than 1 mm in size. After 200 revolutions, the coke lumps were removed from the drum and their mass measured. The coke was then returned to the drum. This procedure was repeated until the stabilized coke had undergone a total of 1 400 revolutions in the drum. The surface breakage rate constant was calculated from the experimental data as described in *Chap. I*. Full details of the range of process variables covered are given in *Sec. III. 1*. Except where otherwise stated, the standard conditions used were 10 kg sample mass, 25 rpm drum speed and two 100 mm high lifters.

In order to develop a mechanistic understanding of coke degradation in a tumble drum, the motion of particles within a tumbling drum was filmed using a 0.31 m diameter rotating drum with transparent plastic ends. The drum rotated on a set of rollers and the drum speed could be varied between 5 and 50 rpm. Particle motion was filmed using a 16 mm camera. A full discussion of the technique and the range of process variables covered is given in *Sec. III. 2*.

III. Experimental Results

1. Effect of Experimental Parameters on Surface Breakage Rate Constant

Using three battery cokes, the effects of the number of lifters, lifter height, drum speed, particle size and sample mass on the coke surface breakage rate constant were studied. This examination provided a sensitivity analysis for the experimental procedure and enabled an understanding of the size degradation process to be developed. Results are presented below and are discussed further in *Chap. IV*.

Results of experiments at different drum speeds are given in Fig. 2. The surface breakage rate constant was a maximum at 25 rpm. Above 25 rpm, the rate constant decreased sharply with increasing drum speed. A drum speed of 25 rpm was therefore chosen for all further experiments.

The dependence of the value of the surface breakage rate constant on sample mass is shown in Fig. 3. Over the range 5 to 25 kg, the rate constant was invariant. Thus, the sample mass chosen for the

Fig. 2. Variation of surface breakage rate constant with drum speed.

Fig. 3. Effect of sample mass on surface breakage rate constant.

Table 1. Values of surface breakage rate constant for different lifter combinations.

Coke	Lifter height (mm)	No. of lifters	k_a (rev ⁻¹)
A	—	0	0.18×10^{-4}
A	100	2	2.73×10^{-4}
A	100	4	2.84×10^{-4}
A	50	2	2.72×10^{-4}
B	100	2	2.50×10^{-4}
B	100	4	2.60×10^{-4}
B	50	2	2.56×10^{-4}

Coke Size: -31.5 mm, +22.4 mm

experiment is not critical, provided a representative sample can be achieved. A standard sample mass of 10 kg was used in all other experiments.

Results of experiments using various combinations of lifters are given in Table 1. Experiments were performed with 0, 2 and 4 lifters and lifter height was varied from 50 to 100 mm. The difference in the

surface breakage rate constant between experiments using 2 and 4 lifters was small and not significant when compared to the experimental error in measuring the rate constant ($\pm 3\%$). Similarly, there was no significant difference in the rate constant when the lifter size was changed from 100 to 50 mm. However, when all the lifters were removed, the surface breakage rate constant was reduced to only 5 % of the value with lifters present. Clearly, the mechanism of size degradation requires the presence of lifters in the drum.

These results indicate that although the surface breakage rate constant is dependent on the presence of lifters in the drum, it is insensitive to sample mass and the number and size of lifters. The rate constant is dependent on drum speed which can be standardized. A mechanism for coke degradation by surface breakage which will account for these observations is presented in *Chap. IV*.

The effect of particle size on the surface breakage rate constant is shown in Fig. 4 for the three battery cokes. All three cokes showed a similar increase in rate constant with increasing particle size. In each case, the gradient of the log-log plot of rate constant against particle size was in the range 0.32~0.34. The effect of particle size could therefore be represented by the empirical equation:

$$k_i = \left[\frac{d_i}{d^*} \right]^{0.33} \cdot k^* \dots\dots\dots(3)$$

- where, d_i : geometric mean size for size fraction i
- d^* : reference size
- k_i : surface breakage rate constant for size fraction i
- k^* : surface breakage rate constant of reference size d^* .

As coke is heterogeneous, it was possible that the dependence of k_i on coke size was due to a change in coke strength properties with size rather than a true size effect. To test this hypothesis, a sample of minus 45 mm plus 31.5 mm stabilized coke A was tumbled and the rate constant determined. The

sample was then tumbled for a further 2 600 revolutions until most of the remaining sample was in the size range minus 31.5 mm plus 22.4 mm. The rate constant for this size fraction was then measured. The size of the lumps in the sample was reduced by further tumbling and the rate constant of the minus 22.4 plus 16 mm size fraction was measured. As the coke used was all from the original minus 45 mm plus 31.5 mm sample, no change in strength properties with size would be expected. However, the surface breakage rate constant still showed similar particle size dependence (see Fig. 5). It is therefore concluded that the rate of surface breakage for coke is inherently size dependent.

2. Small Drum Results

The small drum experiments were used to observe the motion of particles within the tumble drum and were scaled so as to be geometrically and kinematically similar to the full scale tumble drum, thus ensuring the particle trajectories in the small drum would match those in the large drum. The ratio of lifter and particle size to drum diameter was held constant and the ratio of sample mass to drum volume was maintained. To preserve kinematic similarity,

Fig. 5. Variation of surface breakage rate constant with particle size. (Samples produced by surface breakage of minus 45 mm plus 31.5 mm size fraction).

Fig. 4. Effect of particle size on surface breakage rate constant.

the drum speed was changed to ensure the Froude number for the small and large drums were the same. Thus, the small drum was operating at the same fraction of its critical speed as the full scale tumble drum.

Figure 6 shows a schematic representation of particle motion in the tumble drum as observed in the small drum experiments. As a lifter sweeps around, it picks up a portion of the coke. Some of the coke rolls off the lifter before it reaches the horizontal plane. The coke that is not picked up slips and rolls against the bottom of the drum (Fig. 6(a)). The coke that is lifted past the horizontal is dropped over a fairly narrow angular range as the lifter approaches the vertical plane (Fig. 6(b)). This coke collides with the bottom of the drum. The second lifter engages the coke remaining in the bottom of the drum and some of the coke that has dropped from the first lifter (Fig. 6(c)). For each experiment, the volume of material supported on the lifter as it passed the horizontal plane and the height of fall of the particles were measured from frames of 16 mm film taken during the experiment. Estimated errors in lifted volume and height of fall were $\pm 15\%$ and $\pm 5\%$, respectively. Results are given in Table 2. A mechanistic interpretation of these results is discussed in *Chap. IV*.

IV. Discussion

1. The Mechanism of Coke Surface Breakage

There are three possible mechanisms for fines production:

- 1) Particle–particle abrasion as the particles roll in the drum and rub against each other.
- 2) Abrasion of particles as they slide/roll against the surface of the drum.
- 3) Fines produced on collision as particles drop from lifters and impact the rotating drum.

Observations in the small drum experiments showed that the predominant motion of the particles in the drum was that of being lifted and dropped, rather than a cascading action. In the full scale drum, when the lifters were removed a very low surface breakage rate was observed. It is therefore concluded that the third mechanism is the main cause of fines production in the drum. The fines are not produced by a true abrasion process, but by the combination of crushing and shear forces that occur when a coke particle is dropped from a lifter onto the rotating drum. This result is significant as it is different from the accepted view of fines production by “abrasion” in tumble drums.^{4,5)}

For a particular coke, the surface breakage rate will depend on the mass of material lifted and dropped per revolution and the kinetic energy of the particle at the collision point. This energy will depend on the height of fall of the particle. It should be possible, therefore, to explain the effect of drum parameters on the surface breakage rate constant, at least qualitatively, from the results of the small drum simulations.

Figure 7 shows schematically the effect of process variables on the amount of coke picked up on each lifter. Over the range covered, the amount of coke lifted by each lifter was proportional to the sample

Fig. 6.
Schematic representation of particle motion in a tumble drum.

Table 2. Results of small drum experiments.

Exp. No.	Coke size (mm)		Drum speed (rpm)		Lifter height (mm)		No. of lifters	Sample Mass (kg)		ϕ	H
	S	L	S	L	S	L		S	L		
1	-11.2 + 8	-36 +26	45	25	30	100	2	0.53	10	0.028	0.87
2	- 8 + 5.6	-26 +18	45	25	30	100	2	0.53	10	0.029	0.86
3	-16 +11.2	-52 +36	45	25	30	100	2	0.53	10	0.032	0.87
4	-11.2 + 8	-36 +26	45	25	30	100	2	0.27	5	0.014	0.87
5	-11.2 + 8	-36 +26	45	25	30	100	2	0.93	17.5	0.053	0.86
6	-11.2 + 8	-36 +26	45	25	30	100	2	1.33	25	0.071	0.87
7	-11.2 + 8	-36 +26	29	16	30	100	2	0.53	10	0.030	0.81
8	-11.2 + 8	-36 +26	45	25	—	—	0	0.53	10	—	—
9	-11.2 + 8	-36 +26	45	25	30	100	4	0.53	10	0.016	0.87
10	-11.2 + 8	-36 +26	45	25	15	50	2	0.53	10	0.032	0.83

S : Actual small drum dimension

L : Corresponding dimension in full scale drum

 ϕ : Volume of material picked up per lifter/volume of drum

H : Height of particle drop/drum diameter

mass. The mass of coke lifted by each lifter is not constant as has been previously assumed in analysing drum tests.⁶⁾ Thus, the fraction of the sample lifted and dropped each revolution was the same, irrespective of sample mass (see Fig. 8). As the height the coke dropped did not change with sample mass, it would be predicted that the surface breakage rate constant is independent of sample mass. This is confirmed by measurements in the large drum.

Similarly, small drum observations can be used to explain the effect of lifter height and number on the rate of fines production in the large drum. Reducing the lifter height from 100 to 50 mm did not affect the amount of material picked up by each lifter (see Fig. 7). When four lifters were used, the volume of material carried by each lifter was, within experimental error, half that carried when two lifters were used (see Fig. 7). Thus, the amount of material lifted and dropped per revolution was the same irrespective of the number of lifters. In summary, results of the small drum simulations have shown that for the range of variables covered, the fraction of the sample mass lifted and dropped per revolution and the height of fall are independent of sample mass, lifter size and lifter number. These results are consistent with full

scale drum experiments which show no relationship between the surface breakage rate constant and these parameters.

A limit on the maximum speed of the small drum allowed only the experiments at 16 and 25 rpm to be simulated. At 16 rpm, the coke was dropped approximately 50° from the vertical, while at 25 rpm the coke was dropped 25° from the vertical, resulting in a greater height of fall. On this basis, the surface breakage rate constant would be slightly higher at 25 rpm than at 16 rpm. At drum speeds higher than 25 rpm, the coke would be carried past the vertical before dropping and would be thrown towards the side of the drum. This would significantly decrease the height of fall of the particle before it hit the drum. In fact, for a 1 m diameter drum, the critical speed is 44.2 rpm. Therefore, at 50 rpm, the coke lumps will not be dropped at all and degradation would be due to rolling/rubbing only. This would explain why the surface breakage rate constant falls away very sharply as the drum speed approaches the critical speed.

These small drum observations are consistent with the proposed mechanism of fines production in the full scale drum and therefore further support the hypothesis that this is the true mechanism of fines production.

Within the limits of experimental error and coke sizes used, particle size did not affect the motion of particles in the drum (see Table 2). The dependence of surface breakage rate constant on particle size is therefore not due to differences in particle motion in the drum. Coke behaves differently to brick like materials which show no dependence of rate constant on size.¹⁾

The reason for this size dependence cannot be simply explained by the greater kinetic energy of the larger lumps. Although the kinetic energy of collision is proportional to the mass of a coke particle, the total number of particles (and hence collisions) is inversely proportional to the mass of a single particle. On this basis, the surface breakage rate should be independent

Fig. 7. Schematic diagram showing the effect of process variables on the amount of coke held on each lifter.

Fig. 8. Variation of volume of coke lifted per lifter with sample mass.

of coke size. However, for the larger particles, a greater proportion of collisions may lead to breakage. For breakage to occur, the applied local stress from the collision must exceed the local yield stress.¹⁾ The probability of this occurring would be higher for the larger lumps because of the higher collision energy. Thus, the surface breakage rate would increase with size. For weak materials with very high surface breakage rates, such as the brick like material previously tested,¹⁾ the yield stress would be very low. The proportion of successful collisions would be high for all size fractions and hence the effect of particle size would be negligible.

The empirical relationship between surface breakage rate and coke size has been determined experimentally for three Australian battery cokes only. This relationship would need to be verified before being used for other cokes.

2. A Normalized Surface Breakage Rate Constant

It has been shown above that the surface breakage rate constant is dependent on stabilized coke size. Because of the heterogeneous nature of coke, it is preferable to use a sample for the tumble drum test which has a size distribution representative of the whole coke sample, rather than use a particular size fraction. Thus, to compare the resistance to surface breakage of cokes with different size distributions it is desirable to normalize the value of the surface breakage rate constant to remove the size distribution effect.

Although k_a is a function of size, the change in k_a with the decrease in lump size due to surface breakage over the course of an experiment is small enough to use an average value of k_a for the whole experiment (see Appendix). For a single size fraction feed, Eq. (1) is rewritten:

$$\frac{dm_i}{dN} = -k_i \cdot m_i \dots\dots\dots(4)$$

where, m_i : mass of material remaining that was originally in size fraction i at the start of the test

k_i : surface breakage rate constant for material of size fraction i .

Assuming that, for a wide size range feed, each size fraction degrades independently of the others, the total rate of fines production from all size fractions is given by:

$$\frac{dm_T}{dN} = -k_T \cdot m_T = -\sum_{i=1}^n k_i \cdot m_i \dots\dots\dots(5)$$

where, m_T : total remaining sample mass
 k_T : overall surface breakage rate constant
 n : no. of size fractions.

Substituting from Eq. (3) into Eq. (5) and rearranging:

$$k^* = \frac{k_T}{\sum_{i=1}^n \left(\frac{d_i}{d^*} \right)^{0.33} \cdot x_i} \dots\dots\dots(6)$$

where, x_i : mass fraction of the remaining material that was originally in size fraction i .

It can be shown that the values of x_i will only change very slightly over an experiment. Thus Eq. (6) becomes:

$$k^* = \frac{k_T}{\sum_{i=1}^n \left(\frac{d_i}{d^*} \right)^{0.33} \cdot x_{i0}} \dots\dots\dots(7)$$

where, x_{i0} : initial mass fraction in size i .

The assumption that, for a wide size range feed, each size fraction degrades independently of the other was tested in two experiments using coke A. In the first experiment, a feed of 50 % minus 22.4 mm plus 20 mm (round hole) and 50 % minus 50.8 mm plus 45 mm coke was used. In the second experiment, a size distribution representative of the whole coke sample was used. The measured rate constant (k_T) was compared to that predicted from the rate constants for the individual size fractions and Eq. (5). Results are shown in Table 3. It can be seen that the difference between the measured and predicted rate constants was less than 3 %. This difference was within experimental error, thus validating the assumption.

Thus, by measuring the initial size distribution of the stabilized coke and measuring k_T , the normalized surface breakage rate constant, k^* , can be calculated.

The normalized surface breakage rate constant was measured for two new samples of battery cokes (D and E). A 25 kg sample of each coke was stabilized for 500 revolutions. The minus 20 mm (round hole) material was discarded and the size distribution of the stabilized feed was recorded. The surface breakage rate constant was measured for each of the two stabilized samples. Although the stabilized sample mass was slightly different for each experiment it has been demonstrated that sample mass does not affect surface breakage rate constant over this range. The normalized rate constant was calculated using Eq. (7) and a value of 37.6 mm for d^* (the geometric mean size of the minus 45 mm fraction plus 31.5 mm). A duplicate of each experiment was performed.

Results are shown in Table 4 and compared to the

Table 3. Comparison of predicted and measured values of k_T for different size distributions using Coke B.

Mass (%)	Size fraction (mm)	k_T (measured) (rev ⁻¹)	k_T (predicted)* (rev ⁻¹)
100	—63 +50.8	3.54×10^{-4}	—
100	—50.8 +45	3.13×10^{-4}	—
100	—45 +31.5	2.82×10^{-4}	—
100	—31.5 +22.4	2.50×10^{-4}	—
100	—22.4 +20 (r.h.)	2.31×10^{-4}	—
50	—50.8 +45	2.83×10^{-4}	2.82×10^{-4}
50	—31.5 +22.4		
6.9	—63 +50.8		
8.2	—50.8 +45		
37.8	—45 +31.5	2.66×10^{-4}	2.72×10^{-4}
36.7	—31.5 +22.4		
10.4	—22.4 +20 (r.h.)		

r.h.: Round hole

* Predicted from Eq. (5)

Table 4. Normalized surface breakage rate constants for two battery cokes

	Coke D		Coke E	
	1	2	1	2
Size (mm)	Mass % on sieve			
−90 +75	1.5	3.4	1.7	0.0
−75 +63	6.7	3.5	0.0	0.0
−63 +50.8	14.8	12.0	4.1	6.1
−50.8 +45	10.2	11.2	8.4	6.0
−45 +31.5	41.3	40.8	39.3	38.2
−31.5 +22.4	20.9	24.0	36.2	38.8
−22.4 +20 (r.h.)	4.6	5.1	10.3	10.9
Stabilized sample mass (kg)	19.57	20.24	19.24	18.86
k_T (10^{-4} rev $^{-1}$)	2.66	2.67	2.74	2.75
k^* (10^{-4} rev $^{-1}$)	2.62	2.65	2.86	2.89
I_{10}	19.0	19.2	18.7	18.7
M_{10}	7.2	7.4	5.6	6.0
Tensile strength (MPa)	8.0		6.2	

r.h.: Round hole

measured I_{10} and M_{10} values for the same cokes. The measured values of surface breakage rate constant show good reproducibility ($\pm 1\%$). The I_{10} values appear to show that coke E has a higher surface breakage resistance than coke D. The M_{10} index indicates a greater difference in the same direction. However, the difference in rate constants show that coke D clearly has a higher surface breakage resistance than coke E, as the normalized rate constant for coke D was 9 % greater than that for coke E. The tensile strength of these two cokes was measured by a modified Brazilian test, and as shown in Table 4, coke D was stronger than coke E. This result further validates the fundamental nature of the surface breakage rate constant and demonstrates the problems with traditional indices, which are affected by the amount of volume breakage and the coke size distribution.¹⁾

In summary, the normalized surface breakage rate constant has been shown to effectively characterize the surface breakage resistance of coke in tumble drums. This parameter is not affected by volume breakage effects and hence coke fissuring. It allows comparison of cokes with different size distributions. The mechanism of fines production in the drum is well understood. This parameter should be able to be related closely to fundamental coke properties and hence allow easy measurement of these properties for a bulk sample.

Further work is continuing to characterize the surface breakage resistance for a wider range of cokes to:

- 1) Confirm the empirical relationship between surface breakage rate constant and particle size.
- 2) Establish the relationship between the normalized surface breakage rate constant and fundamental coke properties, especially tensile strength.

V. Conclusions

- (1) The surface breakage rate constant increases with increasing coke size and this relationship can be represented by a simple empirical equation.
- (2) Sample mass and lifter height had a negligible effect on the surface breakage rate constant over the range examined. There is no difference between the surface breakage rate with two lifters and that with four lifters. The rate of fines production without lifters is much lower than with lifters.
- (3) In a modified MICUM drum above 25 rpm, surface breakage rate constant decreases markedly with increasing drum speed.
- (4) The key mechanism of fines production in a tumble drum is not true abrasion, but rather the collision between particles dropped from lifters and the bottom of the rotating drum. In conjunction with observations of particle motion in the drum, this mechanism explains the effect of process variables on the surface breakage rate constant.
- (5) It is possible to normalize the surface breakage rate constant so as to allow comparison of cokes with different size distributions.

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Appendix

Change in Rate Constant During an Experiment

It is shown in Fig. 3 that

$k_a \alpha d^{0.33}$ (A-1)

Since the number of coke lumps is constant during an experiment,

$m_1 \alpha d^3$ (A-2)

Combining Eqs. (A-1) and (A-2):

$\frac{k_f}{k_0} \alpha \left(\frac{m_f}{m_0}\right)^{1/9}$ (A-3)

- where, k_0 : initial rate constant
 k_f : final rate constant
 m_0 : initial sample mass
 m_f : final sample mass.

In a typical experiment, the final mass of coke is about 65 % of the initial mass. Therefore

$k_f \simeq 0.95 k_i$ (A-4)

There is only a 5 % change in rate constant during the experiment, or a $\pm 2.5\%$ variation from the average rate constant measured for the experiment.