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# Kinetics of acid reactions: making sense of associated concepts

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In chemical kinetics, in addition to the concepts related to kinetics, stoichiometry, chemical equilibrium and the characteristics of the reactants are often involved when comparing the rates of different reactions, making such comparisons very challenging for students at all levels, as well as for pre-service science teachers. Consequently, four multiple-choice items were developed to determine the understanding of 217 pre-service science teachers of the kinetics of acid reactions that are taught at the Grade 9 to 10 levels in Singapore schools. Each of four items compared two different acid reactions under similar conditions, and respondents were required to select the best graphical representation for the two reactions. Respondents were also required to provide reasons to explain their particular selection for each item. In addition, one item on the dissociation of sulfuric acid and two items involving excess/limiting reagents were also included to provide additional data on the pre-service teachers' understanding of these concepts that were assessed in the four items on kinetics of acid reactions. The results showed that the pre-service teachers had difficulties in explaining the properties of different common acids, including the dissociation of the acids and how these affect the rates of the different acid reactions. This study highlights the importance of determining pre-service teachers' understanding of the concepts that they will be teaching with a view to addressing areas of difficulty, as these will have consequences on their future students' learning.

**Keywords:** acid-base chemistry, alternative conceptions, kinetics of acid reactions, stoichiometry, chemical equilibrium, graphical representations of reaction rates

## Introduction

Learners' existing knowledge has significant effects on new learning (Driver, 1995; Duit, 1995, 2009; Johnstone, 1999; Anderson, 2007) as it influences the selection of, and the attention given to the various aspects of the learning task. Learners try to make sense of the new material based on their existing knowledge, test the validity of their constructions, and subsume them into their depository of knowledge. When learners try to link the new material with existing knowledge but cannot make the appropriate connections, they may try to 'bend' the knowledge to fit somewhere, and this may give rise to erroneous ideas (Johnstone, 2000). Erroneous ideas which differ from those commonly accepted in the disciplines are referred to as alternative conceptions (Wandersee *et al.*, 1994).

Thus, teachers must be aware that they "cannot assume that what is taught is what is learned" (Driver and Scott, 1996, p. 106) and that alternative conceptions can arise when students are presented with concepts in too few contexts or when the concepts presented are beyond their developmental level (Gabel, 1989). In addition, McDermott (1988) suggested that some alternative conceptions may arise from failure to integrate knowledge from different topics, and from concept

interference, which comprises "situations where the correct application of a conception by students is hindered by their misuse of another concept that they have learned" (p. 539). Students respond this way when they do not have an adequate conceptual framework to know which concepts to apply in a situation.

Studies have also shown that pre-service teachers have alternative conceptions similar to those of other students (Abell, 2007), for example, in the areas of chemical equilibrium (Quilez-Pardo and Solaz-Portoles, 1995), redox reactions (de Jong *et al.*, 1995), chemical kinetics (Justi, 1997) and inorganic qualitative analysis (Tan, 2005). Thus, it is important to determine teachers' curriculum content knowledge in order to help them address the alternative conceptions that they may have, as how they think will influence the way they teach (de Jong *et al.*, 2002; Crawford, 2007) and hence, what their students learn.

## Studies of students' understanding of stoichiometry, chemical equilibrium, acids and bases, and kinetics

As this study required pre-service teachers to apply their knowledge of stoichiometry, chemical equilibrium and characteristics of acids to compare rates of acid reactions, research on learning difficulties in these areas are briefly described. Stoichiometry is a difficult topic to understand, and students from Grade 7 to undergraduate levels have been shown to have difficulty solving conceptual problems that

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require understanding of the concepts at the macroscopic and sub-microscopic levels, even though they were proficient in solving traditional problems by rote learning (Nurrenbern and Pickering, 1987; Gabel *et al.*, 1992). The difficult concepts in stoichiometry include balanced equations, the subscripts and coefficients in an equation, mole-mass relationship and ratios to be used in calculations, excess and limiting reagents, and conservation of mass/matter (Koch, 1995; De Astudillo and Niaz, 1996; Olmsted, 1999; Mulford and Robinson, 2002; Sanger, 2005; Gauchon and Meheut, 2007; Chandrasegaran *et al.*, 2009). For example, Sanger (2005) found that undergraduates included excess reagents in a balanced equation as they did not understand that a chemical equation described the reaction that occurred rather than the actual reaction system with the spectator species present. Gauchon and Meheut (2007) examined Grade 10 students' explanations of reactions involving limiting reagents where the reactants are in the same physical state, as well as in different states, and found that there was a stronger belief that both the limiting and excess reagents were used up when they were in the same physical state compared to when they were in different states. Other studies found that students were using algorithms to perform stoichiometric computations with limited understanding of the concepts involved, and many students were unable to solve novel problems (Schmidt, 1997; BouJaoude and Barakat, 2000; Fach *et al.*, 2007; Cracolone *et al.*, 2008).

Studies have shown that students find the concepts in chemical equilibrium difficult, and that they have many alternative conceptions on chemical equilibrium (Garnett *et al.*, 1995; Quilez-Pardo and Solaz-Portoles, 1995; Tyson *et al.*, 1999; Voska and Heikkinen, 2000; Grayson *et al.*, 2001; Chiu *et al.*, 2002; Kousathana and Tsaparlis, 2002). Some alternative conceptions that students have are: (1) one or all of the reactants must be used up when equilibrium is reached, (2) chemical equilibrium is static in nature or involves oscillating behaviour, (3) reversible reactions go to completion, (4) the forward reaction rate increases with time, and (5) the forward reaction rate always equals the reverse reaction rate. Pedrosa and Dias (2000) noted that textbooks systematically describe the reversible reactions in an equilibrium system as 'the reaction' rather than 'the reactions', and this "language inaccuracy contradicts the essential idea that two reactions are occurring" (p. 233). Van Driel (2002) proposed that students often perceive the state of chemical equilibrium as static because they may believe that a chemical reaction must be observable. He also noted that students cannot reconcile why "in the case of reversibility or incomplete conversion, some particles of the same species seem to behave differently from other particles of the same species" (p. 209).

Students in Singapore start learning about acids and bases in Grade 7, though simple references to acids, bases and indicators may be made in Grades 1 to 6. Studies have found that Grade 7-12 students' knowledge of acids and bases, often mistaken, centred on the macroscopic properties and reactions of acids and bases, and on the students' experiences with these substances in daily life (Hand and Treagust, 1988; Griffiths, 1994; Garnett *et al.*, 1995; Lin and Chiu, 2007).

The sub-microscopic and symbolic representations of acids and bases make understanding of acids and bases challenging for students at all levels. Smith and Metz (1996) found that even undergraduates had difficulty with the concepts of weak and strong acids in that they could not identify the sub-microscopic representations of strong and weak acids, and Demircioğlu *et al.* (2005) reported that Grade 10 students believed that acidity increases as the number of hydrogen atoms in the formula of an acid increases. Students also struggle with the various models of acids and bases, as the use of the different models is seldom clarified by teachers or textbooks (Carr, 1984; Drechsler and Schmidt, 2005). In addition, other equally difficult chemical concepts, such as chemical equilibrium and hydrolysis, and the ability to differentiate between dissociation and dissolution are essential for a deeper understanding of acids and bases, especially at higher levels of chemical education (Garnett *et al.*, 1995; Smith and Metz, 1996; Lin and Chiu, 2007). For example, students have difficulty determining the pH of polyprotic acids such as sulfuric acid, as they have to consider and understand successive dissociations of such acids, and how their impact on pH calculations (Demerouti *et al.*, 2004). Thus, it is no surprise that Nakhleh and Krajcik (1994) deemed the concepts: acids, bases and pH particularly demanding because "the student must possess a deep understanding of atoms, molecules, ions and chemical reactions" (p. 1078).

Chemical kinetics at the Grade 9-12 levels generally involves a qualitative understanding of the effects of several factors, such as concentration, temperature, state of subdivision of solid reactants and catalysts, on the rates of reactions. Students are expected to make use of the collision theory of particles to explain the effects of these factors and to use and/or interpret simple graphical representations that illustrate the influence of these factors. Studies regarding students' understanding of chemical kinetics concepts, especially at the high school level, are not extensively reported in the science education literature (Justi, 2002). In one study involving 16 year-old Brazilian students, Justi and Ruas (1997) found that 59% of the 42 students involved did not use the particulate nature of matter when explaining why chemical reactions occurred at different rates. These students tended to hold a continuous view of matter, did not display understanding of particle interaction in chemical reactions and lacked understanding of the dynamic nature of the particles. Van Driel and De Vos (1989) investigated how 15-16 year-old students used the colliding particle model to explain the effects of temperature and concentration on kinetics experiments that they had performed. Most students attributed the increased rate at higher temperatures to faster moving particles producing more collisions. However, others reasoned that when fast moving particles collided with each other they would bounce back without producing any change, contradicting the view presented in their textbook that suggested that there would be more 'effective' collisions at higher temperatures. The researchers attributed this opposing view held by the students as a result of limitations in the textbook that lacked reference to the idea of activation energy

and spatial orientation of the colliding particles. Cakmakci *et al.* (2006) found that Grade 10 students could not accept volume or pressure as factors affecting the rate of reaction of gases, and had difficulties differentiating between the number of reactant particles and concentration when solving a problem involving the same amount of reactants in closed containers of different volumes.

Representations are crucial to help students understand, think about and discuss topics that are abstract and dynamic in nature, such as kinetics, equilibrium and solution chemistry (Burke *et al.*, 1998; Schank and Kozma, 2002; Orgill and Sutherland, 2008). Thus, the understanding of the effects of various factors on the rates of chemical reactions may be further enhanced if students are able to represent the accompanying observable macroscopic changes that take place during chemical reactions using particle diagrams and graphical representations. Cakmakci *et al.* (2006) found that students were able to provide written and oral explanations for the rates of specific reactions, but were unable to provide correct graphical representations for their explanations. The students could not differentiate graphs representing changes in the amounts of reactants/products over time from changes of reaction rate over time. This is similar to students' difficulties with displacement-time and velocity-time graphs (Testa *et al.*, 2002). The students also had mistaken beliefs that reaction rates were lowest at the beginning of the reaction and highest at the end, and lacked understanding of instantaneous and average rates of reactions.

## Purpose of the study

The purpose of the study was to determine pre-service teachers' understanding of the concepts involved in the kinetics of acid reactions that also involves understanding of stoichiometry, chemical equilibrium and graphical representations. The content framework, described by the propositional knowledge statements for graphical representations of reaction rates of dilute acids, is given in the Appendix. Understanding of these concepts is essential because the majority of the pre-service teachers will be assigned to teach chemistry in secondary schools (Grade 7-10) or junior colleges (Grade 11-12), and most of the concepts involved are included in the respective chemistry curricula.

## Methods and procedures

### Participants

The study involved twenty-seven Final (Fourth) Year undergraduate and 123 graduate pre-service teachers who enrolled in chemistry pedagogy courses in the August 2008 semester, and sixty-seven graduate pre-service teachers who were enrolled in similar chemistry pedagogy courses in the January 2009 semester in a teacher education institution in Singapore. There were 217 participants in total. Ten undergraduates were chemistry majors and had to complete thirteen chemistry content modules and four chemistry pedagogy modules, while seventeen undergraduates were taking chemistry as a minor, and had to complete eight chemistry content modules and the same four chemistry

pedagogy courses as the chemistry majors; the chemistry majors and minors attended the chemistry pedagogy classes together. Undergraduates majoring in chemistry are assigned to teach Grade 7-10 or Grade 11-12 chemistry, while those with a minor in chemistry could be deployed to teach Grade 7-10 chemistry only. All pre-service teachers in the Grade 7-12 programme are required to have two teaching subjects.

Similarly, the graduate pre-service teachers who were enrolled in a one-year Postgraduate Diploma in Education programme were divided into two groups; seventy-one were assigned chemistry as their first (major) teaching subject (CS1) and fifty-two were assigned chemistry as their second (minor) teaching subject (CS2) in the August 2008 semester, while forty-six and twenty-one were assigned to the CS1 and CS2 groups, respectively, in the January 2009 semester. The majority of the pre-service teachers taking CS1 chemistry had science degrees, majoring in chemistry or material science, or had material engineering or chemical engineering degrees. The majority of those assigned chemistry as a second teaching subject had at least Grade 12 chemistry, if not a minor in chemistry at the tertiary level, and were mainly science graduates who majored in mathematics or the life sciences. Both groups of graduate pre-service teachers had to take three chemistry pedagogy courses. The content of the courses and the way they were conducted were mostly similar for the CS1 and CS2 groups except that there were discussions of student difficulties in Grade 11-12 chemistry with the CS1 groups only.

The pre-service teachers were required to answer seven items in the Acid Reactions Instrument (see Supplementary data) that was posted on the institution's e-learning portal. They were informed in advance about the quiz and were requested to read up the requisite Grade 10 material on chemical kinetics before answering the questions. Before the administration of the quiz, in a lesson on using demonstrations and the predict-observe-explain strategy to teach chemistry, the pre-service teachers were shown the reactions of the same volumes of excess 1M and 0.5M hydrochloric acid, 1M sulfuric acid and 1M ethanoic acid with equal lengths of magnesium ribbon. The reactions were carried out in Petri dishes using an overhead projector to cast shadows (a more dramatic effect) of the interactions of the different reactants to illustrate and compare the reaction rates. The rate of effervescence and disappearance of similar lengths of magnesium ribbon highlighted that 1M sulfuric acid reacted most rapidly with the magnesium ribbon, followed by 1M hydrochloric acid, 0.5M hydrochloric acid and 1M ethanoic acid. The pre-service teachers were requested not to refer to any material when they were answering the questions, and to submit their answers within a week. Four undergraduate and eight graduate pre-service teachers volunteered to be interviewed using the Acid Reactions Instrument as the interview protocol. The interviews were transcribed verbatim, but sections of the interviews that are presented in this paper were lightly edited to improve their readability.

### The Acid Reactions Instrument

The first version of the instrument was developed in 2007 and trialled in the January 2008 semester with 101 graduate pre-

**Table 1** Distribution of students' answers (in percentages) for each item in the Acid Reactions Instrument (N = 217)

Reason	Item						
	1	2	3	4	5	6	7
A	-	<b>5.5</b>	<b>4.6</b>	1.4	1.4	<b>83.4*</b>	-
B	<b>19.4</b>	0.5	1.4	2.8	<b>67.3</b>	-	-
C	1.4	<b>82.5*</b>	0.5	<b>12.9</b>	4.1	2.3	0.9
D	<b>4.6</b>	0.9	0.5	<b>68.2*</b>	<b>20.7*</b>	-	<b>20.3</b>
E	3.2	0.5	<b>6.5</b>	2.8	<b>5.1</b>	0.5	1.4
F	<b>71.0*</b>	2.8	1.4	3.7	<b>7.8</b>	-	-
G	-	<b>6.9</b>	<b>78.8*</b>	2.8	3.2	0.5	0.5
H	0.5	0.5	1.4	4.1	0.5	0.5	0.5
I			2.3	0.9	-	-	0.5
J			2.3	-	-	0.5	0.5
K						-	<b>67.3*</b>
L						1.8	6.0

Note: \* denotes the correct answer

- denotes that no pre-service teacher chose this option.

Figures in bold and italics denote significant alternative conceptions

Blank spaces denote that the reasons are not available for the items.

service teachers in Phase 1 of the study (Tan *et al.*, 2008). There were four items in that version that involved two chemical reactions that were performed under similar conditions (see the first four items in Supplementary data).

Respondents were required to select the graph (from the ten graphs that were provided) that best described the two reactions in each item, and explain why they had made the particular selection in each item. The results showed that pre-service teachers generally did not explicitly relate the features of the graphs to the specific reactions, and their ambivalence regarding the stoichiometric concept of excess/limiting reagent and dissociation of acids interfered with their reasoning of the reactions (Tan *et al.*, 2008). In Phase 2 of the study, three additional items were added to assess students' understanding of the dissociation of sulfuric acid and excess/limiting reagents, as these concepts were involved in the four original items. These three additional items were included because it was difficult to decide if the pre-service teachers who gave incorrect answers misread the questions or actually had difficulties with these concepts, as well as to confirm what they meant in their reasons for selecting particular responses in the four items. Graphical representations in items 1 to 4 that were not chosen by any pre-service teachers were removed from the items in the second version of the instrument, but with every item there was an option included that allowed respondents to supply their own graphs if they disagreed with the given ones. The items in the second version of the Acid Reactions Instrument are given in Supplementary data. The Acid Reactions Instrument was validated by three experienced chemistry teachers and one university chemistry professor for accuracy and relevance.

## Results

A summary of the answers that were selected by the pre-service teachers for each item is presented in Table 1. Incorrect choices were considered significant if they attracted 5% or more of pre-service teachers. The pre-service teachers were expected to select the correct answer because they had

**Table 2** Distribution of percentage of correct responses to items 1 to 7 (N = 217)

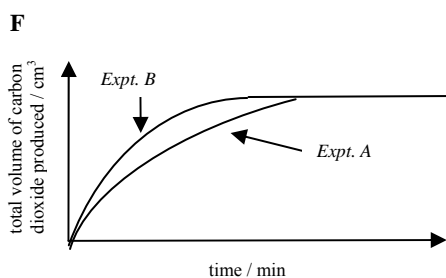
Item	Multiple-choice item selection [a]	Multiple-choice item selection and justification [b]	Difference [a] – [b]
1	71	13	58
2	83	74	9
3	79	68	11
4	68	4	64
5	21	14	7
6	83	76	7
7	67	29	38

studied chemistry at university and had chosen to teach chemistry. In addition, there were eight or more options in each item (except item 5 which had five), so the responses were expected to spread over more options than the usual multiple choice questions with four to five options. Consequently, there was a lower probability of pre-service teachers selecting a particular option and application of a more stringent cut-off percentage, say 10% or more, could result in the elimination of valid alternative conceptions. The data from items 1-4 suggest that 17-32% of pre-service teachers possess limited ability to translate the phenomenological attributes of the pairs of chemical reactions (from the demonstrations that they had earlier viewed in a previous lesson and their knowledge of stoichiometry, chemical equilibrium, acid reactions and general kinetics) to abstract graphical representations.

The pre-service teachers' justifications for selecting the correct graphical representation in each item were analysed and the results showed that for each item, the percentage of students who provided a correct answer and an acceptable justification was lower than the percentage of students who selected only the correct response to the multiple-choice items (see Table 2). The large differences between the numbers of those giving the correct answers and those giving the correct reasons for them in item 1 (58%) and item 4 (64%) are indications of the lack of understanding of the properties of dilute acids in the items.

As mentioned in the previous section, it was difficult to decide if the pre-service teachers who gave incorrect answers to items 1 to 4 misread the questions or actually had difficulty understanding the dissociation of sulfuric acid and/or the concept of excess/limiting reagents. Thus, the pre-service teachers' responses to items 5-7 focussing on the dissociation of sulfuric acid and excess/limiting reagents were used to clarify the reasons they provided in items 1-4. Accordingly, less emphasis is placed on the items 5-7 for their own sake, so they will not be discussed in great detail.

Cronbach's alpha values for the first tier (multiple choice answers) of the first four items (1-4) and all seven items in the Acid Reactions Instrument are 0.64 and 0.55, respectively. The higher value for the first four items is to be expected as the foci of the items are similar – graphical representations of two different acid reactions in each item. The last three items (5-7) are markedly different from the first four items, as they are designed to determine the pre-service teachers' understanding of the dissociation of sulfuric acid and



The total volume of carbon dioxide produced was the same in both experiments, indicated by the horizontal overlapping of the two graphs at the end of the reactions, because copper(II) carbonate was the limiting reagent.

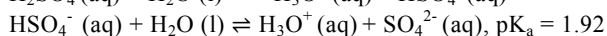
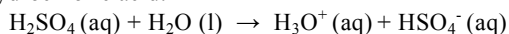
The initial rate of reaction was greater in Experiment B, indicated by the steeper initial gradient, because 1M H<sub>2</sub>SO<sub>4</sub> contains a higher concentration of H<sup>+</sup> ions than 1M HCl.

**Fig. 1** The correct answer and appropriate justification for item 1.

excess/limiting reagents. As there is a wide range of 'correctness' and 'completeness' of the reasons given by the pre-service teachers to support their first tier answers, the second tier answers are not included in the calculation of Cronbach's alpha values for the instrument.

#### Item 1: Comparing the reactions of copper(II) carbonate with excess 1M HCl(aq) and excess 1M H<sub>2</sub>SO<sub>4</sub>(aq)

One hundred and fifty-four pre-service teachers (71%) selected the correct graphical representation (F) but only twenty-nine (13%) were able to provide an acceptable explanation (see Fig. 1). Ninety-five pre-service teachers (44%) indicated in their reasons that sulfuric acid dissociated completely such that the concentration of hydrogen ions in 1M sulfuric was twice that in 1M hydrochloric acid. In actual fact, though the first dissociation of sulfuric acid is said to be complete, its second dissociation is incomplete (Russo and Silver, 2007), so the concentration of hydrogen ions in 1M sulfuric acid will be only slightly more than that in 1M hydrochloric acid.



It has to be stated that the term 'hydrogen ions' is used in Grade 7-10 chemistry instead of the more accepted 'hydroxonium ions', so the term, 'hydrogen ions', as well as diagrams depicting such ions, will be used in this paper.

The rate of reaction for sulfuric acid will still be faster than that of hydrochloric acid because the hydrogensulfate ions will dissociate further to generate more hydrogen ions as they are used up, unlike hydrochloric acid where the hydrogen ions cannot be replenished. Examples of pre-service teachers' answers indicating the complete dissociation of sulfuric acid were:

*Since 1 mol of HCl gives 1 mol of H<sup>+</sup> and 1 mol of H<sub>2</sub>SO<sub>4</sub> gives 2 mol of H<sup>+</sup>, in experiment A, the concentration of H<sup>+</sup> ions is 1 mol/dm<sup>3</sup> whereas that of experiment B is 2 mol/dm<sup>3</sup>. A higher concentration of H<sup>+</sup> in experiment B means that there is a higher frequency of effective collisions between the reacting particles and hence a faster rate of reaction. Hence, the gradient of the graph for*

*experiment B will be steeper. (Written reason of pre-service teacher D2)*

*Volume of CO<sub>2</sub> produced remains the same as the acid is in excess. However, the concentration of H<sup>+</sup> ions is double because a diprotic acid is used instead of a monoprotic acid. Thus, reaction rate increases and the reaction takes a shorter time to reach completion. (E22)*

As indicated in Table 1, the most frequently selected incorrect graphical representation was (B) (19%) followed by (D) (5%) (see Fig. 2). The pre-service teachers who chose option (B) generally indicated that the rates of reaction of the two acids were the same because both acids were of the same concentration (12%) or because both acids were in excess (3%), as illustrated by the following two answers:

*Rate of reaction can be affected by concentration of reactant. In this case, since the concentration for both acids used in both Experiments A and B are the same (1 mol dm<sup>-3</sup>), the rate of reaction for both Experiments are the same. (B6)*

*The rate of reaction, measured by the rate at which carbon dioxide is produced, will be the same for both cases. This is because excess amount of acids are added in both cases. Though experiment A uses a monobasic acid (HCl) and experiment B uses a dibasic acid (H<sub>2</sub>SO<sub>4</sub>), the excess amount of acids added in both cases would have allowed the experimental rate to be similar in both experiments, thus explaining for the same rate of carbon dioxide produced in both situations. (D42)*

In an interview, pre-service teacher B6 expressed uncertainty whether the concentration of the acids or the concentration of the hydrogen ions was the determining factor but decided on the concentration of the acids as B6 could not recall if textbooks or his teachers mentioned anything about the concentration of hydrogen ions affecting the rate of reaction as shown in the following interview excerpt:

B6: *...the only doubt that I had was...because this is a...sulfuric acid is a dibasic acid but HCl is a monobasic acid...so I was wondering whether it would affect the rate at all but later I dismiss(ed) the idea because I thought that only concentration will affect rate ...so it was something whether it is concentration of a solution or concentration of H<sup>+</sup> ions...so I took the concentration of solution...so I thought that my answer will be B because both rates are the same because both concentration of solution is the same.*

I: *What made you dismiss the concentration of H<sup>+</sup>?*

B6: *Because textbook never mentioned...and I have forgotten...about what I have learned in my secondary school days...whether the teacher mentioned anything about...concentration of H<sup>+</sup> affecting the rate of reaction at all.*

Out of the ten pre-service teachers who selected option (D) (5%), six (3%) seemed to have ignored the information given that the acids were in excess (even though the word, 'excess', was in bold print) and focussed on the fact that 1 mole of sulfuric acid would produce 1 mole of carbon dioxide while 2 moles of hydrochloric was required to produce the same amount of carbon dioxide. So, for the same amount and concentration of both acids, sulfuric acid will react to produce

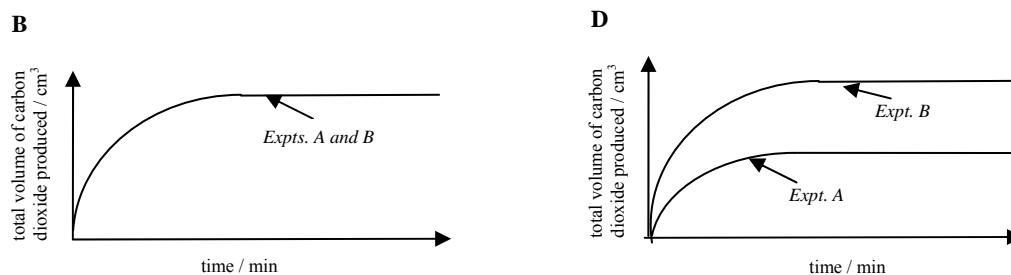
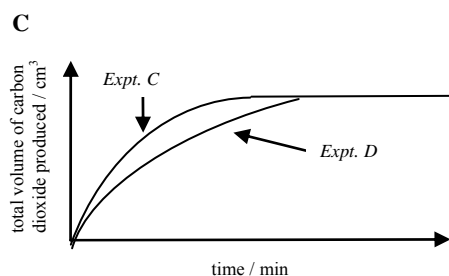


Fig. 2 The most frequently selected incorrect graphical representations in item 1.

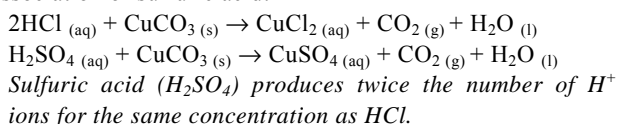


The total volume of carbon dioxide produced was the same in both experiments, indicated by the horizontal overlapping of the two graphs at the end of the reactions, because calcium carbonate was the limiting reagent.

The initial rate of reaction was greater in Experiment C, indicated by the steeper initial gradient, because of the higher concentration of  $H^+$  ions in 1M HCl compared to 0.5 M HCl.

Fig. 3 The correct answer and appropriate justification for item 2.

more carbon dioxide. The following pre-service teacher's reason illustrates this thinking as well as the complete dissociation of sulfuric acid:



Hence, the initial rate of reaction of Experiment B is faster than that of Experiment A.

By Stoichiometry,

2 moles of HCl produce 1 mole of  $CO_2$

1 mole of  $H_2SO_4$  produces 1 mole of  $CO_2$

Hence, Experiment A produces a lower volume of  $CO_2$  than Experiment B. (B7)

### Item 2: Comparing the reactions of powdered marble (calcium carbonate) with excess 1M HCl(aq) and excess 0.5M HCl(aq)

One hundred and seventy-nine pre-service teachers (83%) chose the correct graphical representation (C) in item 2 (see Fig. 3) and 160 (74%) were able to provide acceptable justifications for making the selection. As indicated in Table 1, the two most frequently selected incorrect graphical representations were (A) (6%) and (G) (7%) (see Fig. 4).

Eight (4%) of the twelve pre-service teachers (6%) who chose option (A) stated that the rate of reactions for the

Table 3: Cross-tabulation of pre-service teachers' answers

Pre-service teachers' answers and reasons	Cross-tabulation: Frequency (percentage)
The rates of reaction of both acids are the same because:	
a. the acids involved are in excess	Item 1 (B) and item 2 (A): 5 (2%)
b. the concentrations of the acids are the same	Item 1 (B) and item 3 (E): 3 (1%) Item 1 (B) and item 4 (C): 10 (5%) Item 3 (E) and item 4 (C): 1 (0%)
The volumes of gas evolved are different, because the excess/limiting reagents are ignored.	Item 1 (D) and item 2 (G): 3 (1%)
The rates of reactions involving sulfuric acid are faster than those of hydrochloric acid, because sulfuric acid dissociates completely such that the concentration of hydrogen ions in 1M sulfuric acid is twice that in 1M hydrochloric acid.	Item 1 (F) and Item 4 (D): 57 (26%) Item 1 (F) and item 5 (B): 72 (33%) Item 4 (D) and item 5 (B): 54 (25%) Item 1 (F), item 4 (D) and item 5 (B): 54 (25%)

different concentrations of hydrochloric acid were the same because both acids were in excess; five of them consistently chose a similar graphical representation (B) in item 1 and gave similar reasons (see Table 3). An excerpt of a pre-service teacher's answer is given below:

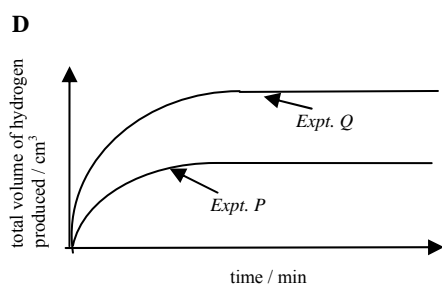
*Just like the previous answer, we have to assume even when the concentration of HCl is reduced by half, as long there is excess concentration of free  $H^+$ , the rate will be the same since (it) is only dependent on the free availability of  $H^+$  ions. (D21)*

Similarly, fifteen pre-service teachers (7%) seemed to have overlooked that the acids were in excess and ten of them (5%) indicated that the greater volume of carbon dioxide in experiment C was due to the higher concentration of hydrochloric acid in the experiment as illustrated below:

*The amount of gas, in this case carbon dioxide, formed is dependent on the number of reactants that have reacted. Clearly, the solution containing higher molar concentration would provide more moles of hydrochloric acid for reaction. Thus the hydrochloric acid of 1.0 M molarity will release twice as much carbon dioxide as that of 0.5 M molarity. (D51)*

It was found that only three pre-service teachers consistently chose a similar graphical representation in item 1





The acid was the limiting reagent in both experiments. As the total amount of  $H^+$  ions available in 1M  $H_2SO_4$  was double that in 1M HCl, the total volume of hydrogen produced in Experiment Q would be twice that in Experiment P.

The initial rate of reaction was greater in Experiment Q, indicated by the steeper initial gradient, because of the higher concentration of  $H^+$  ions in 1M  $H_2SO_4$  compared to 1M HCl.

**Fig. 7** The correct answer and appropriate justification for item 4.

*Since  $[H^+]$  is lower for experiment E, reaction rate will be slower as well. (C39)*

During an interview, pre-service teacher A4 expressed surprise when told that acetic acid would dissociate further to release more hydrogen ions for reaction when they are used up during the reaction.

*A4: ...acetic acid doesn't dissociate much in water...because it is a weak acid...so if it doesn't dissociate much there is lesser  $H^+$  in the aqueous solution to react with the calcium carbonate...whereas HCl dissociates completely...so there is an abundance of  $H^+$  compared with the acetic acid, so I feel...I didn't know that acetic acid...if let's say acetic acid  $H^+$  is being used up, it will dissociate some more...I didn't know that particular concept...so...I thought that it dissociates and then it is done...so I thought that the rate of reaction will be like...after that it will remain constant...but then when it remains constant, HCl will continue because it has abundant  $[H^+]$  so it will use up all the  $H^+$ .*

Fourteen pre-service teachers (7%) selected the incorrect option (E) (see Fig. 6), with six of them (3%) stating that the rates of reaction were the same because the concentrations of the two acids were the same. Three of them (1%) chose a similar graphical representation and gave similar reasons in item 1 (B) (see Table 3) as indicated below:

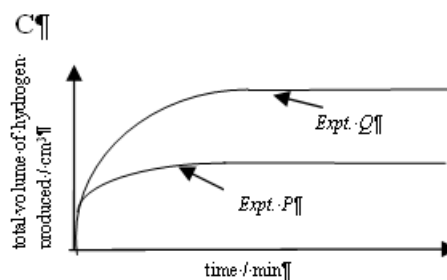
*Similar to Question 1.*

*In both experiments, the following factors were held constant:*

- (1) same amount of powdered calcium carbonate was used.*
- (2) same volume of acids used for each experiment.*
- (3) same concentration of acids used for each experiment.*

*The only difference in the experiments was the type of acids used, which does not affect the rate of reaction. As long as the acids have the same concentration, they would be able to dissociate the respective acids into equal amounts of  $H^+$  ions, as both their concentrations are at 1 mol  $dm^{-3}$ .*

*Thus the rate of reaction would be similar to each other. (B5)*



**Fig. 8** The most frequently selected incorrect graphical representation in item 4.

#### Item 4: Comparing the reactions of excess magnesium powder with the same volumes of 1M HCl(aq) and 1M $H_2SO_4$ (aq)

One hundred and forty-seven pre-service teachers (68%) selected the correct graphical representation (D) (see Fig. 7), while only nine (4%) were able to provide an acceptable explanation for selecting the correct graphical representation. The reasons from seventy pre-service teachers (32%) who chose the correct multiple choice option indicated that sulfuric acid dissociated completely such that the concentration of hydrogen ions in 1M sulfuric acid was twice that of 1M hydrochloric acid. Fifty-seven (26%) of them gave the same reason in item 1 (see Table 3), showing consistency in their answers. Two examples of pre-service teachers' answers indicating the complete dissociation of  $H_2SO_4$  were as follows:

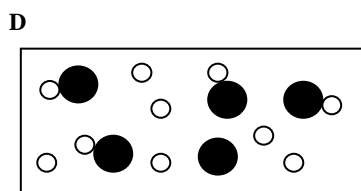
*Since 1 mol of HCl gives 1 mol of  $H^+$  and 1 mol of  $H_2SO_4$  gives 2 mol of  $H^+$ , in experiment P, the concentration of  $H^+$  ions is 1 mol/ $dm^3$  whereas that of experiment Q is 2 mol/ $dm^3$ . A higher concentration of  $H^+$  in experiment Q means that there is a higher frequency of effective collision(s) between the reacting particles and hence a faster rate of reaction. Hence, the gradient of the graph for experiment Q will be steeper. (D2)*

*Since  $H_2SO_4$  is a stronger acid and will dissociate (into)  $2H^+$  ions as compared to HCl that will only dissociate (into)  $1H^+$  ion, given that the concentrations of acids are the same, the speed of reaction will be higher for the acid with more  $H^+$  ions due to higher frequency of collision(s) between reactants. (C9)*

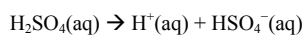
As indicated in Table 1, the most frequently selected incorrect graphical representation was (C) (13%) (see Fig. 8). Of the twenty-eight pre-service teachers (13%) who selected the graphical representation (C), thirteen respondents (6%) suggested that the initial rates of the two reactions were similar because the acids used were of the same concentration, as the answers of two respondents illustrate:

*The limiting factor here is the volume of acids. Since the acids are not in excess, having the same volume and concentration of HCl and  $H_2SO_4$  will result in more carbon dioxide [sic] being produced in Experiment Q due to the dibasic nature of sulfuric acid. As temperature and concentrations of acids are equal, the rate of reaction will be equal as well. (D9)*

*With excess magnesium powder added in both reactions, the rate limiting factor of the reactions would be the*

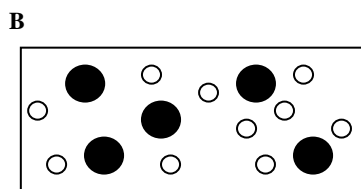


Sulfuric acid ( $\text{H}_2\text{SO}_4$ ) is a diprotic acid that undergoes dissociation in two steps:



$\text{H}_2\text{SO}_4$  dissociates readily to form  $\text{H}^+$  and  $\text{HSO}_4^-$  ( $K_{a1}$ ).  $\text{HSO}_4^-$  can further dissociate to form  $\text{H}^+$  and  $\text{SO}_4^{2-}$  ( $K_{a2}$ ). Dissociation constant  $K_{a1}$  is much greater than  $K_{a2}$ , thus anions mostly exist in the form of  $\text{HSO}_4^-$ .

**Fig. 9** The correct answers and most appropriate justifications for item 5.



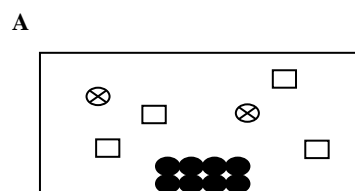
**Fig. 10** The most frequently selected incorrect representation in item 5.

*concentration of acids used. The rate of reactions of both experiments P and Q would therefore be the same since in both reactions, the concentration ( $1 \text{ mol dm}^{-3}$ ) of acids used was the same. Same rate of reactions (represented by the same gradient) in both experiments.* (D35)

Ten (5%) of the thirteen pre-service teachers consistently supplied the 'same concentration of acid, same rate of reaction' reason in items 1 (B) and 4 (C) (see Table 3).

#### Item 5: Dissociation of sulfuric acid

As previously mentioned, items 5-7 will not be discussed in great detail, as their main purpose is to clarify the pre-service teachers' reasons in items 1-4. Forty-five pre-service teachers (21%) chose the correct representation for the dissociation of sulfuric acid (D), but only thirty of them (14%) gave the correct reason (see Fig. 9). One hundred and forty-six (67%) chose option B, which illustrated the complete dissociation of sulfuric acid (see Fig. 10), with ninety-two of them (42%) stating that the complete dissociation of sulfuric acid was due to it being a strong acid. Cross-tabulation showed that seventy-two (33%) and fifty-four (25%) pre-service teachers indicated the same reasons in items 1 and 5, and items 4 and 5, respectively (see Table 3); the same fifty-four pre-service teachers who gave consistent reasons for items 4 and 5 also supplied the same reason for item 1, that is, they were consistent throughout items 1, 4 and 5. Eleven pre-service teachers (5%) drew their own representations of dilute sulfuric acid (E). A variety of drawings were obtained, for example, three drawings had undissociated hydrogen sulfate molecules only (1%) while two had undissociated and partially dissociated hydrogen sulfate molecules (1%).

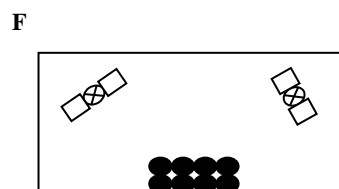


Magnesium is in excess for this particular reaction. Therefore, there will be magnesium particles left but no hydrogen ions after the reaction is completed. Since  $\text{MgY}_2$  is in aqueous solution, it will separate completely into its individual ions.

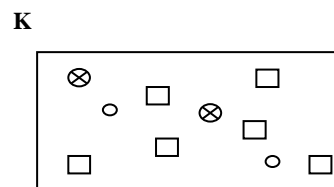


Therefore, for every  $\text{Mg}^{2+}$  ion there should be twice the number of  $\text{Y}^-$  ions in the aqueous solution.

**Fig. 11** The correct answer and appropriate justification for item 6.



**Fig. 12** The most frequently selected incorrect graphical representation in item 6



HY is in excess for this particular reaction. Therefore, there will be  $\text{H}^+$  and  $\text{Y}^-$  ions left, but no magnesium particles. Since  $\text{MgY}_2$  is in aqueous solution, it will, therefore, separate completely into its individual ions.



Therefore, for every  $\text{Mg}^{2+}$  ion there should be twice the number of  $\text{Y}^-$  ions in the aqueous solution. In addition, as HY is in excess, for every  $\text{H}^+$  ion there should be one  $\text{Y}^-$  ion present.

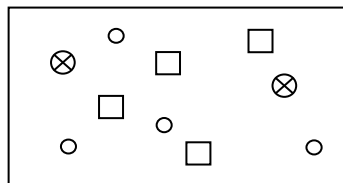
**Fig. 13** The correct answer and appropriate justification for item 7.

#### Items 6 and 7: Excess and limiting reagents

The pre-service teachers seemed to have little difficulty with item 6, as 181 of them (83%) chose the correct representation (A) (see Fig. 11) for the addition of excess magnesium in a dilute acid, HY. Interestingly, seventeen pre-service teachers (8%) chose the incorrect representation (F) (see Fig. 12), which showed the salt  $\text{MgY}_2$  as molecules.

In item 7, 146 pre-service teachers (67%) chose the correct representation (K) for the addition of magnesium into excess dilute acid, HY (see Fig. 13). Forty-four of them (20%) chose option (D) (see Fig. 14) with eighteen (8%) giving reasons that ignored the contribution of  $\text{Y}^-$  from the excess acid, HY;

D



**Fig. 14** The most frequently selected incorrect graphical representation in item 7.

they focussed only on the dissociation of  $MgY_2$  liberating  $2Y^-$  for every  $Mg^{2+}$  present. It was mentioned that in item 1, six pre-service teachers (3%) selected option (D) and in item 2, ten pre-service teachers selected option (G), giving reasons that seemed to indicate that they might have problems with the concept of excess/limiting reagent. As items 1 and 2 were similar to item 7 (excess acid with a solid being the limiting reagent), their answers to item 7 were examined; cross-tabulation showed that none of them chose options in item 7 in which magnesium particles were left at the end of the reaction; this indicated that they understood that the solid was the limiting reagent and the acid was in excess in item 7.

## Discussion

It is common for Grade 7-10 students to think that since sulfuric acid is a strong acid, it will fully dissociate in solution to form hydrogen and sulfate ions as this is taught by their teachers and is also mentioned in textbooks (e.g., Tan *et al.*, 2007). In Grades 11-12 chemistry in Singapore, students are taught how to calculate  $K_a$  and  $pK_a$  of acids, but the focus is generally on monoprotic acids rather than diprotic or polyprotic acids such as sulfuric acid and phosphoric(V) acid. Therefore, the Grade 11-12 students may have difficulty understanding multi-stage dissociations of polyprotic acids and the associated chemical equilibria. This was highlighted by Demerouti *et al.* (2004) who found that Grade 12 students had difficulty determining the pH of 0.1M sulfuric acid when they were presented with the two-stage dissociation of the acid.

In Singapore, the incomplete second dissociation of sulfuric acid may only be discussed at the undergraduate level, so pre-service teachers who did not take undergraduate chemistry may not have any knowledge of the incomplete second dissociation of sulfuric acid. Therefore, based mainly on Grade 7-12 knowledge of chemistry, it is logical to think that the rate of reaction of sulfuric acid is twice as fast as that of the same concentration and volume of hydrochloric acid, because its hydrogen ion concentration is twice that of hydrochloric acid. Table 4 shows the numbers and percentages of the different categories of pre-service teachers who consistently supplied the 'complete dissociation of sulfuric acid' reason in items 1 and 4, and chose option B in item 5. Though lower percentages (30% undergraduates and 18% graduates) of the pre-service teachers taking chemistry as their major or first teaching subject stated this alternative

**Table 4** Numbers and percentages of the different categories of pre-service teachers who consistently supplied the 'complete dissociation of sulfuric acid' reason in items 1, 4 and 5 (N = 217)

Undergraduate		Postgraduate	
Chemistry major (n = 10)	Chemistry minor (n = 17)	CS1 Chemistry (n = 117)	CS2 Chemistry (n = 73)
3 (30%)	6 (35%)	21 (18%)	24 (33%)

conception compared to those taking chemistry as their minor or second teaching subject (35% and 33%), these percentages are still high, indicating that additional years of chemical education does not necessarily lead to greater understanding of chemistry concepts (Tan, 2005).

However, it has to be noted that this 'complete' dissociation of sulfuric acid alternative conception does not interfere with or limit the respondents' ability to compare the rates of reaction of the two acids and determine the *correct* graphical representation, supporting the argument by Hamza and Wickman (2008) that alternative conceptions do not "automatically interfere with learning the subject matter in other contexts" (p. 160). As students are usually taught in secondary school chemistry that sulfuric acid is a strong acid, and thus completely dissociates, the teaching of the dissociation of sulfuric acid at the secondary level needs to be elaborated. Chemical equilibrium is generally not taught at this level, and to discuss the first and second dissociation of sulfuric acid may not make sense to the students without the understanding of chemical equilibrium. In addition, not knowing how sulfuric acid dissociates does not affect the learning of the properties and reactions of sulfuric acid at the secondary level. Thus, the authors suggest that teachers focus on stoichiometry rather than equilibria; students should be taught that sulfuric acid has two hydrogen ions available to react but the extent of dissociation should be ignored until post-secondary levels. Students can learn about the first and second dissociations of sulfuric acid in Grade 11 or 12, as chemical, acid-base and ionic equilibria are included in the curriculum at this level. The data from item 5 indicate that 136 pre-service teachers (63%) thought that sulfuric acid completely dissociated in water. Among these pre-service teachers, 75 (32%) were taking chemistry as their first teaching subject and they would be expected to have a better understanding, as they had taken chemistry courses at university. Thus, it seems that for many pre-service teachers the learning that a strong acid completely dissociates in solution at the secondary level is not modified nor clarified by additional years of chemical education.

A related issue is the reaction of weak acids. Seven pre-service teachers (3%) who chose option (A) in item 3 thought that the reaction between excess powdered marble and acetic acid (a weak acid) would not go to completion because of the partial dissociation of the acid; the low percentage of pre-service teachers having this alternative conception indicates that it is a minor problem. Grade 7-10 chemistry textbooks (e.g. Tan *et al.*, 2007) only state that a weak acid does not dissociate fully in water and has a lower concentration of hydrogen ions compared to the same concentration of a strong

acid; there is no mention that the reactions of weak acids will proceed to completion. As previously stated, Grade 7-10 students do not learn about chemical equilibrium as do Grade 11-12 students, so the reactions of weak acids may cause problems for Grade 7-10 students. This means that Grade 7-10 chemistry teachers have to plan demonstrations or experiments involving reactions of strong and weak acids of the same concentration to help students acquire the knowledge that the extent of reaction of weak and strong acids of similar concentrations will be the same. The explanation for this can be left to the learning of chemistry at the Grade 11-12 level.

A number of pre-service teachers (12% in item 1, 3% in item 3 and 6% in item 4) seemed to think that there would be no difference in the rates of reaction of the two acids being compared, because they were of the same concentration; they seemed unable to differentiate between the two closely related concepts, the concentration of the reactants and that of the reacting species. Cross-tabulation indicated that only three pre-service teachers (1%) consistently gave similar reasons for items 1 and 3, ten pre-service teachers (5%) consistently gave similar reasons for items 1 and 4, and only one pre-service teacher (<1%) was consistent in items 3 and 4 (see Table 3). The higher percentage for items 1 and 4 is to be expected, as the two acids (strong acids and same concentration) used in both items are the same unlike in item 3 (where a weak and a strong acid are involved). Cakmakci *et al.* (2006) also found that students had difficulty differentiating between the closely related concepts of the number of moles and the concentration, and used these terms interchangeably. Thus, the function of the reacting species as well as the difference between the concentrations of the reactants and the reacting species needs to be emphasised by teachers when they discuss the factors affecting the rate of reaction; the use of ionic equations may help in this respect.

A related alternative conception is that the rates of reaction of the acids were the same because both acids were in excess (3% in item 1 and 4% in item 2). Cross-tabulation shows that only five pre-service teachers (2%) stated this in both items 1 and 2 (see Table 3). These pre-service teachers did not seem to realise that, even in excess, the concentration of hydrogen ions determined the frequency of collisions between the hydrogen ions and the powdered marble or magnesium, hence affecting the rates of reaction. The two findings indicate that they did not have a clear understanding of the processes at the sub-microscopic level. Thus, when teaching chemical kinetics, teachers have to explicitly translate between the symbolic, sub-microscopic and macroscopic levels for students (Orgill and Sutherland, 2008) by demonstrating the reactions, showing diagrams and animations to illustrate the sub-microscopic processes, and employing chemical and ionic equations as well as graphs to represent the species and processes taking place so that students can develop a better understanding of the topic.

The excess and limiting reagents seemed to be ignored by six pre-service teachers (3%) in item 1 and ten pre-service teachers (5%) in item 2; only three pre-service teachers (1%) ignored the excess limiting reagents in both items (see Table 3). Even though items 1 and 2 explicitly stated that the acids

were in excess, the pre-service teachers still indicated that sulfuric acid would liberate twice the volume of hydrogen gas as the same concentration and volume of hydrochloric acid, and similarly for 1M hydrochloric acid when compared to 0.5M hydrochloric acid. However, none of these teachers chose options (A, B, C, F, G and H) (see Supplementary data) that indicated the presence of metal particles at the end of the reaction in item 7, which, as mentioned in earlier sections, was developed to check the pre-service teachers' understanding of excess acid reacting with a solid limiting reagent. During separate interviews with pre-service teachers B2 and D33, both realised that they had overlooked that the two acids were in excess in item 2 and changed their answers to state that the volume of gas produced in both cases were similar. Thus, it can be concluded that these pre-service teachers did not have difficulty with the concept of excess/limiting reagents per se but it was likely that they had not read both items carefully. However, forty-four pre-service teachers (20%) might have had problems with the stoichiometry involved in reactions related to excess/limiting reagents, as indicated in their choice of the most popular distractor (D) (see Fig. 14).

In item 6, seventeen pre-service teachers (8%) indicated that the salt  $MgY_2$  existed as molecules (see Fig. 12). This is an indication that the pre-service teachers may have alternative conceptions of ionic bonding (Tan and Treagust, 1999). The first-named author regularly administers diagnostic instruments on chemical bonding (Taber, 1997; Tan and Treagust, 1999) to the intakes of pre-service teachers that he teaches, and the results obtained agree with the finding above that some of the pre-service teachers do have difficulty with chemical bonding. Thus, the auditing of pre-service teachers' curriculum content knowledge is important to ensure that they can clarify their own difficulties and alternative conceptions before teaching students in schools.

The results and discussion generated in this study refer specifically to the sample of pre-service teachers involved in the study. Generalisation of the findings to all chemistry teachers in Singapore and in other countries must be considered with caution due to the nature and the limited number of pre-service teachers involved. The pre-service teachers' familiarity with the acid reactions and whether they remember the stoichiometric, kinetic and chemical equilibrium concepts involved in the Acid Reactions Instrument may also affect their performance on the instrument. However, the authors believe that this should not be a problem as the acid reactions involved were demonstrated to the pre-service teachers before the instrument was administered to them, and there were discussions on how to use these demonstrations to teach chemical kinetics and acid reactions. In addition, the pre-service teachers were also advised in advance to review the relevant topics, and the examples of acid-metal and acid-carbonate reactions were often used in textbooks to illustrate ways to monitor the rate of reaction (see Tan *et al.*, 2007). The reading, interpretation and comprehension of the items in written tests have an impact on how the items are answered (Taber, 1999) as the respondents do not "always perceive and interpret test

statements in the way that test designers intend” (Hodson, 1993, p. 97). Interviews with students in this study suggest that this was not a major problem. A small number of pre-service teachers did seem to have problems with the excess and limiting reagents in items 1 and 2. However, through the interviews as well as the use of the additional items 6 and 7 to probe the reasons that the pre-service teachers gave in items 1-4, it was determined that they most likely had overlooked the excess and limiting reagents rather than have problems with the concepts.

## Conclusions

The data from the administration of the Acid Reactions Instrument to 217 pre-service teachers have shown that their incorrect selections of the relevant graphs in the items 1-4 were mainly the result of inadequate understanding of the properties of acids, especially sulfuric and acetic acids, that the concentration of acids mattered even if these were in excess and that hydrogen ion concentration rather than acid concentration determined the rates of reaction. These seemed to arise from the lack of understanding of the sub-microscopic processes involved in the properties and reaction of acids. This study is very relevant as the results show that several alternative conceptions are held by the pre-service teachers, and if these are not made known to them, they are likely to remain entrenched in their cognitive structures with serious consequences for their future students’ understanding. These findings will, therefore, be of value to academics who are involved in science teacher education programs at the tertiary level.

Finally, we believe that the findings of this study will make a significant contribution to the science education research literature as no similar studies have been documented to assess pre-service teachers’ ability to relate the kinetics of dilute acid reactions with relevant graphical representations.

## Supplementary data

The seven items the pre-service teachers were required to answer in the Acid Reactions Instrument can be found in the associated file labelled: ‘Supplementary data’.

## Appendix 1

### Propositional knowledge statements for graphical representations of reaction rates of dilute acids

1. A strong dibasic acid is a source of higher  $H^+$  ion concentration than a strong monobasic acid of the same concentration.
2. The initial rate of a reaction involving an acid increases as the concentration of  $H^+$  ions increases.
3. When an excess of any acid, regardless of its basicity, is added to the same amount of a carbonate or a reactive metal, the final volume of gas produced is the same.
4. When an excess of any acid, regardless of its concentration, is added to the same amount of a carbonate or a reactive metal, the final volume of gas produced is the same.

5. The higher the concentration of  $H^+$  ions in solution, the shorter the time taken for the reaction involving an acid to go to completion.
6. The initial rate in a reaction involving an acid is greater than that for the same acid of lower concentration.
7. A strong acid is a source of higher  $H^+$  ion concentration than a weak acid of the same basicity and concentration.
8. When an excess of a reactive metal is added separately to equal volumes of two different acids, the volume of gas produced is greater for the acid with higher  $H^+$  ion concentration.
9. In an aqueous solution of dilute sulfuric acid the first ionisation occurs completely, resulting in the formation of  $H^+$  and  $HSO_4^-$  ions.
10. In an aqueous solution of dilute sulfuric acid the second ionisation occurs only partially, resulting in the formation of  $H^+$ ,  $HSO_4^-$  and  $SO_4^{2-}$  ions
11. When an excess of a reactive metal is added to some dilute acid, metal cations and anions from the acid are the only ions present in solution, ignoring the ions produced by water.
12. When an excess of a reactive metal is added to some dilute acid, unreacted solid metal is present in the mixture.
13. When an excess of a reactive metal is added to some dilute acid, the resulting products are an ionic compound and hydrogen.
14. A balanced chemical equation represents the relative amounts of reactants that have reacted together and products that are formed.
15. The relative number of ions produced by a soluble ionic compound is represented by the chemical formula of the compound.
16. A balanced chemical equation obeys the law of conservation of mass.
17. A balanced chemical equation does not include quantities of unreacted substances in the reaction system.
18. The reactant that is completely used up in a reaction system is referred to as the limiting reagent.
19. The amount of products formed in a chemical reaction is limited by the amount of the limiting reagent.
20. The reactant that is not completely used up in a reaction system is referred to as the excess reagent.

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