A systematic mapping study on the development of permeable reactive barrier for acid mine drainage treatment

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Abstract. Acid mine drainage is a result of exposure of sulfide ore and minerals to water and oxygen. This environmental pollutant has been considered the second biggest environmental problem after global warming. On the other hand, permeable reactive barrier is an emerging remediation technology which can be used to treat acid mine drainage. However, the effectiveness of this proposed remediation technology greatly depends on the reactive media. Also, treatment of acid mine drainage using permeable reactive barrier is still in the infancy stage, and long-term performance is still unknown. Hence, this study was conducted to identify what have been studied, addressed and what are currently the biggest challenges and limitations on the use of permeable reactive barrier for acid mine drainage treatment. Through systematic mapping approach, the results have shown that the reactive media used in permeable reactive barrier can be categorized into five namely iron-based, organic-based, inorganic-minerals-based, industrial waste-based, and combined media. The data revealed that majority of the papers which is about 40% use combined media as the reactive substrate. The future direction is toward the use of combined media as a reactive material for AMD treatment, for instance, use of geopolymer with mine tailings and silts as reactive media in combination with organic-based media.

1 Introduction

Acid mine drainage (AMD), also known as acid rock drainage (ARD), is a result of the reaction of oxygen and water with sulfide minerals commonly in the form of pyrite. It has a low pH, high salinity, and high heavy metal toxicity [1]. The resulting waste is an environmental pollutant associated with mining activities which can contaminate both ground and surface water [2]. AMD normally contains ferrous, ferrous, sulfate ions, and other cationic metallic elements such as Mn, Al, Ni, Cu, and Zn in various concentration. These solutes can be detrimental to the environment. In fact, the United Nations has considered AMD as the second biggest environmental problem after global warming [3]. In addition, the generation of AMD starts from the mining operation and continues even after mine closure and/or abandonment. The reaction mechanism involved in AMD generation in the form of pyrite as sulfide mineral is shown in Reactions R1-R5.

Oxidation of Pyrite forms ferrous iron and sulfate:
\[
\text{FeS}_2 + \text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + 2\text{SO}_4^{2-} + 2\text{H}^+ \quad (R1)
\]

Ferrous iron is further oxidized to ferric iron in the presence of iron-oxidizing bacteria:
\[
\text{Fe}^{2+} + 0.25\text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}^{3+} + 0.25\text{H}_2\text{O} \quad (R2)
\]

Spontaneous reaction of ferric iron with water to form ferric hydroxide (orange-red precipitate):
\[
\text{Fe}^{3+} + 3\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 3\text{H}^+ \quad (R3)
\]

Excess Fe\(^{3+}\) serves as an additional and secondary reducing agent for pyrite:
\[
\text{FeS}_2 + 14\text{Fe}^{3+} + 8\text{H}_2\text{O} \rightarrow 15\text{Fe}^{2+} + 2\text{SO}_4^{2-} + 16\text{H}^+ \quad (R4)
\]

The resulting overall reaction produces sulfuric acid and ferric hydroxide:
\[
\text{FeS}_2 + 3.75\text{O}_2 + 3.5\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 2\text{SO}_4^{2-} + 4\text{H}^+ \quad (R5)
\]

AMD treatment can be classified into two: active and passive technique. The active treatment involves continuous addition of alkali to increase the pH and subsequent removal of metals. The passive treatment, on the other hand, uses natural and biological processes. Various prevention and treatment techniques include lime neutralization, passivation, in-situ biological remediation, backfilling, waste heap-covers, constructed wet lands, and permeable reactive barrier. Among these techniques, the most promising is the use of permeable reactive barrier for AMD treatment.

The treatment of AMD can either be physical, chemical, or biological using this technique. PRB is an emerging remediation technology for AMD treatment which is a low-cost in-situ treatment, prevents cross-contamination with surface waters, prevents loss of large amounts of groundwater, has no land space required, and doesn’t require any waste disposal [1]. However, the performance of PRB on AMD treatment is dependent on
the substrate used. In addition, PRB is still in the infancy stage for AMD treatment, and long-term performance is still unknown.

Hence, this study aims to identify the biggest challenges and limitations encountered on the use of PRB to treat AMD through systematic mapping approach.

2 Materials and methods

Systematic mapping study aims to provide an overview of a research area, to establish existence of research evidence, and quantify the amount of evidence [4]. In this study, the researcher follows the systematic mapping process [5]. The systematic mapping process was chosen as research methodology because the aim was to explore the existing studies related to PRB for AMD treatment. The results of the mapping study would help us to identify and map research areas related to PRB for AMD treatment and possible research gaps. The process for the systematic mapping study is illustrated in Error! Reference source not found..

2.1 Definition of research question

The first step in systematic process is definition of research question. In this study, the three defined questions are as follows:

2.1.1 What topics have been addressed in current research on PRB for AMD treatment?
2.1.2 What approaches/techniques have been developed on PRB for AMD treatment?

2.2 Conduct search

The second stage of mapping is to search for all relevant papers related to the study. A search protocol has been defined in the study in which it is limited to search papers containing the identified keywords in the abstract. The keywords used were acid mine drainage, AMD, mine drainage, mine drain*, permeable reactive barrier, permeable reactive treatment zone, and PRTZ as the search string. The asterisk (*) was used to broaden the search result. The researchers decided to use the Scopus as the database to search for all relevant papers related to the study.

2.3 Screening of relevant papers

The third stage of mapping is to screen all the relevant papers resulted using the search protocol since not all papers are relevant. The papers were screened based on the title.

2.4 Keywording

The next step in mapping process is to classify relevant papers by reading the abstract.

2.5 Data extraction and mapping

The last step in mapping process is to extract relevant information necessary to address the research questions. In addition, quantification was also performed the have an overview of the current research related to the study.

3 Results and discussion

3.1 Basic Information of the papers

The defined search protocol has returned a 78 papers search results as preview shown in Figure 2. Majority of the study were published as article paper (62.80%). There are 23% papers presented at conferences (Figure 3a and 3b). Other papers were published as review paper, book chapter, erratum, an article in press, and short survey.

Out of the 78 papers, 65 papers were found to be relevant. The papers were then classified based on the reactive media such as iron-based PRB, organic-based PRB, inorganic minerals-based PRB, industrial waste-based PRB, and combine media PRB as shown in Figure 4.
3.2 Synthesis

Permeable reactive barrier is a new remediating technology which can be used for acid mine drainage treatment. Based on the review of current state of the art, the reactive media used in permeable reactive barrier can be categorized into five namely iron-based, organic-based, inorganic minerals-based, industrial waste-based, and combined media.

The typical reactive media used for PRB that has been classified as iron-based is zero-valent iron [6–12]. It has been observed that in high pH environment, the oxidation of zero-valent iron proceeds slower, thereby could affect the overall performance of the PRB. The occurrence of mutual interactions of various contaminants was impossible to detect based on current methods. Furthermore, degradation of sulfates and nitrates should be improved if the reactive media to be used is zero-valent iron. The recommendation is to include other biotic processes or improve the reducing conditions.

New approaches have been introduced together with the use of organic substrate as reactive media in PRB [13–33]. The results showed that the use of membrane-free microbial fuel cell (MFC) for preconditioning has improved the performance of the PRB. The modification of the PRB design by using lattice-layout SRB-PRB has also shown improved efficiency. Understanding the microbiology and kinetics of sulfate-reducing bacteria can help improve the design and operation of the treatment system. This includes methods such as bioaugmentation, biostimulation, and gene profiling. Another notable finding is the use of spatial tracking which provides valuable insight for microbial activity monitoring. The total carbon analysis cannot be used as justification to explain the longevity of the PRB.

Commonly used media that is classified as inorganic minerals-based PRB are limestone, apatite, concrete, manganese, zeolite, and magnesite [34–38]. These materials are composed of calcium, sodium, magnesium, and manganese-based minerals which are responsible for the increase in the alkalinity. However, common concern encountered with the use of inorganic minerals is the accumulation of precipitates in the pore spaces which can cause clogging of the pores. It is also worthy to note that the use of concrete-based PRB can result in the formation of gypsum and ettringite. These are undesirable since presence of these compounds can cause cracks and damage in the structure. The use of
nano-sized inorganic minerals as reactive media can effectively remove the heavy metal such as arsenic [39]. The industrial wastes such as coal fly ash, slag, and bauxsol as reactive media are also a promising alternative [40-44]. These materials neutralize the pH and effectively remove metals from AMD. However, waste precipitation is a concern as it causes large reduction in hydraulic conductivity of the PRB thereby limiting the efficiency of the treatment system. Numerous studies have been exploring the use of combined media in PRB [1,39,45-66]. The potential of the combination of reactive media has been realized due to its promising performance in terms of removal of sulfates and reduction of toxic metals. For example, the result showed that the permeability coefficient of an iron-based limestone system is better than that of the pristine limestone system [55]. It also improves the retention of redox contaminants. The presence of compost in greatest concentration, presence of biosolids, and zero-valent iron has resulted to a higher sulfate reducing mechanism activity. With these findings, an improved performance and an increase in efficiency is anticipated.

4 Conclusion

This study has reviewed the state-of-the-art of the development of permeable reactive barrier for acid mine drainage treatment using systematic mapping approach. The following findings can be drawn:

1. Out of the 78 searched paper based on the defined search protocol, 65 were found to be related and relevant to the scope of the study.
2. The reactive media used in permeable reactive barrier can be categorized into five namely iron-based, organic-based, inorganic minerals-based, industrial waste-based, and combined media.
3. The data has shown that majority of the papers which is about 40% uses combined media as the reactive substrate. Published papers that use organic-based PRB is about 34%. Of the relevant papers, 11% are iron-based PRB. The remaining 16% is for both inorganic minerals (8%) and industrial waste-based PRB (8%).
4. The future direction is toward the use of combined media as a reactive material for AMD treatment due to the improved performance and efficiency of PRB, for instance, use of geopolymer with mine tailings and silts as reactive media in combination with organic-based media. To date, no studies have been reported yet on the use of geopolymer for AMD treatment.

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