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DIFFERENT REACTIVE MATERIALS OF GROUNDWATER TREATMENT WELLS - A MINIREVIEW

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ABSTRACT: The treatment of contaminated groundwater is among the most difficult and expensive environmental problems and often the primary factor limiting closure of contaminated sites. The most common technology used historically for remediation of groundwater has been ex-situ pump-and-treat systems. Over the past decade, permeable reactive barriers (PRBs) have provided an increasingly important role in the passive interception and in situ treatment of groundwater as a component of remedial action programs. PRBs have been used to remove a wide range of organic and inorganic contaminants from groundwater including petroleum hydrocarbons, chlorinated solvents, nutrients, metals and radionuclides. The concept of PRBs is relatively simple. A reactive material is placed in the subsurface at a location that intercepts a groundwater contaminant plume, such as a deep backfilled trench installed across the plume. The contaminants pass through the PRB with the flow of groundwater, typically under its natural gradient, thereby creating a passive treatment system. As the contaminants move through the material, reactions occur that transform it to less harmful or immobile species. Many reactive media types have been tested or are currently being investigated for treatment of a variety of contaminants by PRBs. Iron metal, otherwise known as Fe (0) or zero-valent iron (ZVI), is the most common reactive media used in the majority of PRB installations. This paper focuses on reactive materials in use in the PRB technology and will provide site-specific examples.

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1.INTRODUCTION

The technology termed as Permeable Reactive Barriers (PRB) is defined [1] as: "An emplacement of reactive media in the subsurface designed to intercept a contaminated plume, provide a flow path through the reactive media, and transform the contaminant(s) into environmentally acceptable forms to attain remediation concentration goals down-gradient of the barrier". The concept of PRBs is relatively simple. A permeable reactive barrier material consisting of permanent, semi-permanent or replaceable reactive media is placed in the subsurface across the flow of path of a plume of contaminated groundwater, which must move through it as it flows, typically under its natural gradient, thereby creating a passive treatment system. As the contaminant moves through the material, reactions occur that transform the contaminants into less harmful (non-toxic) or immobile species. The PRB is not a barrier to the groundwater, but it is a barrier to the contaminants. PRBs are designed to be more permeable than the surrounding aquifer materials so that contaminants are treated as groundwater readily flows through without significantly altering groundwater hydrogeology. PRBs potentially have several advantages over conventional pump-and-treat methods for groundwater remediation.

1. PRBs can degrade or immobilize contaminants in situ without any need to bring them up to the surface. Hence no need for expensive above ground facilities for storage, treatment, transport, or disposal other than monitoring wells. After the installation the above ground can be re-used for other purposes. Also, as the contaminants are not brought to the surface; there is no potential cross media contamination.

2. They also do not require continuous input of energy, because a natural gradient of groundwater flow is used to carry contaminants through the reactive zone. Only periodic replacement or rejuvenation of the reaction medium might be required after its reactive capacity is exhausted or it is clogged by precipitants and/or microorganisms. However, the drastically reduced operating costs offsets the higher construction cost that are typical for PRBs, which results in an overall reduction in the life cycle cost of this technology.

3. Degradation of most of the contaminants is achieved rather than mere change of phase of contaminants. The barrier provides effective contaminant remediation, much more than simple migration control of the pollutants.

4. Technical and regulatory problems related to ultimate discharge requirements of effluent from pump-and-treat systems are avoided with the PRB technology.

However, so far, limited data are available on the performances of reactive barriers with different materials and their comparative performances. Limited long-term field testing data are available and field monitoring is in its infancy [2]. This Minireview focuses on the different reactive materials used in PRBs and their consequences.

2. BODY OF PAPER

Sources and types of groundwater contamination

Broadly, groundwater contaminants come from two categories of sources:

(a) Point Sources and

(b) Distributed, or Non-Point Sources.

Localised sources are known as point sources of contamination. The contaminant interacts with the moving groundwater and the soil and spreads out to form a plume moving in the same direction as the groundwater. The resulting groundwater contamination plume may extend several hundred metres or even further away from the source of pollution. Groundwater can also be contaminated by diffuse sources over a wide area, for instance widespread use of fertilisers on gardens and fields. Diffuse contamination may have greater environmental impacts than contamination from point sources because a much larger volume of water is affected. Pollutants from point sources are generally related to urban development, while diffuse sources are generally rural in nature. Some of the examples of point and diffuse pollutions are given in Table 1.

Table 1: Examples of point and diffuse pollutions

Point source	Non-point or diffuse pollution
Municipal landfills, industrial waste disposal sites, leaking gasoline storage tanks, leaking septic tanks, and accidental spills and leaks of petroleum products and of dense industrial organics	Atmospheric deposition, contaminated sediments, and many land activities that generate polluted runoff, such as agriculture (pesticides and fertilisers), logging, and onsite sewage disposal

Analysts estimate that there are between 300,000 and 400,000 sites in the USA contaminated with a wide variety of toxic chemicals, representing clean-up cost in the range of $500 billion to $1 trillion [3]. Many of these sites experience groundwater contamination by complex mixtures of chlorinated solvents, fuels, metals, and/or radioactive materials. Europe's groundwater is polluted in several ways: nitrates, pesticides, hydrocarbons, chlorinated hydrocarbons, sulphate, phosphate and bacteria. Some of the most serious problems are pollution by nitrates and pesticides.

Configuration of PRBs

A. Conventional systems

Two installation schemes are more frequently used in field applications [4, 5]; Continuous and Funnel-and-Gate PRB. The continuous PRB configuration consists of a single reactive zone installed across the contaminant plume, while the funnel-and-grate system consist of a permeable

gate (reactive zone) placed between two impermeable walls that direct the contaminated plume towards the reactive zone. The choice between the two configurations depends on both the hydrogeological characteristics of the site and the reactive material cost [4]. When a high cost reactive material is used, funnel-and gate configuration is preferred since the reactive zone requires less material. However, construction cost of continuous type barrier is much cheaper than funnel and- gate system. Hence a balance must be struck between the cost of reactive material and the construction cost of the barrier, in accordance with the target pollutant and level of removal to be achieved. Multiple reactive medium in succession or in series can be installed in the funnel-and gate setup [5]. Alternatively, a relatively less expensive method using multiple caisson gates can also be installed [5]. A caisson is a shallow, load-bearing (usually cylindrical) enclosure generally used as an alternative method for excavation. For the purpose of emplacing a reactive cell, a prefabricated, steel caisson (normally 8-ft-dia or smaller) is pushed or vibrated down into the subsurface. Once the caisson has reached the intended depth, the soil within the caisson can be augered out and replaced with the reactive medium. Upon emplacement of the reactive cell/medium, the caisson can be pulled straight out. The caisson can be installed from the ground surface and completed without requiring personnel to enter the excavation. Usually, the conventional PRB installation techniques require some degree of excavation, which limits the PRB to fairly shallow depths of 20 m [6]. However, use of new construction techniques, such as slurry injection and hydro fracturing are able to overcome this depth limitation.

B. Advanced systems

(i) Injection system: Injection system involves creating a treatment zone within the contaminant boundary by drilling series of bore holes or injection wells and injecting the reactive material (chemical/particulate mixture) into the treatment zone. Potential advantages of this approach are that there is no need to construct a trench and possible aquifer access at greater depths. Usually, two or three rows of overlapping, interlocking columns can offer effective barrier [7]. Nevertheless, it has to be made sure that the contaminant plume is efficiently taken care of and no by-passing or fingering occurs, which may impair the remediation effect.

(ii) Hydraulic/pneumatic fracturing: Hydraulic/pneumatic fracturing is intentional fracturing (cracking) of a subsurface using pumped water and/or air under high pressure. As the confining pressures are exerted in the borehole, fractures will open and propagate out laterally from an initiation point. A fracture fill slurry composed of the reactive medium, can then be injected into the fracture to form a reactive treatment zone. More than one fracture may be required within the treatment zones. Fractures have a preferred direction of propagation, they are therefore asymmetric with respect to the borehole and they climb in the preferred direction of propagation. Fractures can be controlled to happen either horizontally or vertically [8, 9]. Some advantage to this technique includes the ability to emplace a barrier to a depth greater than 80

ft. Also, fracturing causes minimal disturbance, does not generate contaminated soils, and is inexpensive. Fractured zones may also be applied to direct groundwater flow towards the gates in funnel-and-gate system [10]. Some drawbacks of emplacement by hydraulic fracturing include difficulty in controlling the fracture direction and the limited soil conditions in which it can be used effectively.

(iii) <u>Passive groundwater capture and treatment by reactor cells</u>: This technique involves emplacement of reactor cell(s) in the subsurface consisting of reactive medium and capturing the contaminated plume into the reactor for treatment [11]. This system does not involve any pumping equipment and the plume is directed into the reactor by siphoning or by natural gradient. Because of the passive mode of operation, the operating and maintenance requirements are relatively minor.

The selection of the construction technique to be used depends upon the site characteristics [9] such as depth of PRB, geotechnical consideration, soil excavation: space for handling and disposal of soil (contaminated), health and safety of personnel.

Reactive materials

A. Limestone

Limestone, a raw natural cheap material, was the first type of reactive materials used in the PRB technology [12; 13]. In 1999, a contaminated groundwater produced from a coal pile at the US Department of Energy (DOE) Savannah River Site in South Carolina was treated by installation of limestone PRB [14]. Although this material is effective in remediation process, satisfied treatment was difficult because it cannot produce the required pH for the direct precipitation of wider range of metal hydroxides or create conditions necessary to promote sulfate reduction. Many studies have suggested improving limestone according to the contaminant type and condition by either adding another type of reactive material with limestone as a mixture to overcome the limitations in limestone action and work together in an integrated manner or using sequence process as multiple reactive barriers and creating integrated action. Lee et al. [15] combined calcium carbonate (limestone chemical base) with hydrated lime in continuous column experiments fed with artificially contaminated groundwater to improve the As, Zn, and Ni removal efficiencies. They found that the uptake capacity of this mixture for mentioned metals was very high. Furthermore, Komnitsas et al. [16] used multiple permeable reactive barriers of limestone and red mud in a sequence manner.

B. Zero Valent Iron (ZVI)

A conventional reactive material that is most commonly used with PRBs is the ZVI. ZVI was first used in groundwater treatment by the University of Waterloo (UW), Ontario, Canada, in 1992, and has been shown to destroy chlorinated compounds and immobilize several hazardous inorganics by means of redox (reduction–oxidation) and precipitation reactions of anion and cations [17; 18]. Based on column tests, Mackenzie et al. [19] studied the plugging of the treatment zone and

precipitation in the iron media for characterizing the performance of ZVI barrier. The reactive media in these tests were investigated for periods reaching 1400 min with the aid of SEM, energy-dispersive X-ray spectroscopy (EDS), and WDS. The authors proved that there were small effects of precipitates on porosity, hydraulic conductivity and iron reactivity with respect to chlorinated solvent reduction. However, dissolved oxygen in the influent groundwater control porosity changed within the iron and this can cause the plugging at the entrance of barrier. In the same direction, Li et al. [20] prepared a model to simulate performance of ZVI barrier. A series of simulations were introduced using MODFLOW (groundwater flow model) and RT3D (reactive transport model) to evaluate the fouling effects on the hydraulic behaviour of barrier in carbonate-rich alluvial soils. The authors found no significant change in the hydraulic behaviour within first 10 years of barrier life. However, considerable change was recognized after 30 years and after 50 years, the barrier was expected to exhibit failure in hydraulic function. In another direction, many researches were directed to improve the efficiency of ZVI barrier by mixing different proportions of ZVI with other porous medium such as sand [21], lignite [22], limestone [23], and pumice [24]. Ruı́z et al. [25] used ZVI reactive barrier with electroremotion technology depending upon a set of columns for removing contaminants from the soil in addition to water. Geiger et al. [26] applied the ultrasonic energy on the field scale PRB to enhance the degradation of trichloroethylene (TCE). The authors presented a wide range of laboratory and field analyses data for two PRBs: the first located at NASA Kennedy Space Center, FL, USA, and the other in the western USA. The results indicated that 30-min sonication period had a positive impact on the degradation of the contaminant. Zhao and Reardon [27] studied the de-halogenation and improvement in the ZVI degradation efficiency due to the possible role of hydrogen gas bound in its lattice. Many works done attempt to use nZVI particles in PRB technology. Hosseini et al. [28] evaluated the injection process of the nZVI to the funnel and gate PRB configuration for nitrate removal using a series of batch and column test to support a design of PBR. In this study, the results of PRB indicate that, however, increasing the initial nitrate concentration and pore velocity has inhibitor effect against the effect of nZVI concentration on the process of nitrate removal; the proposed PRB can solve the low permeability of medium in down-gradient.

C. Activated carbon or Granular Activated Carbon (GAC)

GAC is one of the conventional reactive materials that are used in ex situ pump-and-treat techniques for groundwater treatment as well as in general treatment plants of water and wastewater. The treatment potential of activated carbon is presented by adsorption of contaminant particles in a physical manner on its high lattice surface area. However, in passive groundwater remediation technology, the use of GAC as a reactive material is somewhat limited because it is a fabricated material and is expensive. Accordingly, Suthersan [29] recommended using a certain configuration of funnel and gate such as bioreactor wells, air stripping gate for shallow water table and air stripping

well for deeper water table. The virgin carbon can be slurred into the reactor and the exhausted carbon can be vacuum-slurried out of the reactor. Also, replaceable cassettes filled with carbon can be retrofitted into the reactor. Subsequently, an attempt was made to use activated carbon in a limited manner as a mixture with other reactive materials to reduce the cost of a variety of its action, especially with ZVI [17]. Ko¨ber et al. [30] investigated the efficiency of the Fe^0 and GAC mixtures as fillings for PRBs in the remediation of TCE and monochlorbenzene (MCB). Column tests proved that the durability of GAC was increased by a factor of 4 when mixed with Fe^0 and no substantial limitations in the use of activated carbon by Fe^0. Fronczyk et al. [31] examined the feasibility of using selected activated carbon with ZVI, zeolite, and geza rock for the removal of chlorides in road runoffs. The results signified that the activated carbon and ZVI seemed to be reasonable materials for the reduction of chlorides in PRB technology. Furthermore, Suponik [32] studied the mechanisms used for benzene and phenol (spilled from the dumping site located somewhere in Upper Silesia, Poland) removal from contaminated groundwater using GAC or mixture of coarse sand and granulated peat as reactive medium in PRB. GAC utilization in PRB was confirmed as an efficient technology to various contaminant remediation policies. Mumford et al. [33] and Statham et al. [34] proved that the GAC permeable barrier installed during 2005/2006 at the Main Power House, Casey Station, Antarctica, was able to remediate a fuel spill for operation time equal to 10 years. The performance efficiency of the PRB is conducted via interpretation of total petroleum hydrocarbon (TPH) concentrations, degradation indices and most probable number(MPN) counts of total heterotroph and fuel-degrading microbial populations. They reach through the results to conclude that the PRB with GAC is the most appropriate groundwater remediation technology used in cold and nutrient-limited environments with fuel and TPH polluted sites. By mean of combined interactive role between low reactive materials ZVI and GAC associated with the concepts of nanotechnology, Hu et al. [35] introduced a composite combination of nZVI and GAC to obtain a complete nitrate transformation into nitrogen with minimum by-products via chemical reduction which represent a promising technique can be used with PRB in the future. They showed that there is an excellent cooperative role in activity between these two reactive materials in releasing nitrate pollution without any obvious bad interaction between them. Instead of that both the dispersion and long term reactivity of nZVI were improved with minimizing the by-products of nitrite and ammonium formation in reduction process that reach below 0.008 and 0.04 mg/L, respectively. X-ray photoelectron spectroscopy analysis achieved that the nitrogen was the main end product. They found that these techniques are very beneficial to develop an efficient and low-cost chemical remediation method for nitrate-contaminated groundwater.

D. Zeolites

Zeolites can be classified according to its source into:

i) Natural zeolites such as clinoptilolite, chabazite, analcime, erionite, faujasite, laumontite, phillipsite, ferrierite, mordenite, and heulandite.

ii) Synthetic zeolites such as those from natural materials, waste materials, coal fly ash (CFA), municipal solid waste incineration ash (MSWIA), oil shale ash (OSA), rice husk ash (RHA), or modified natural and synthetic zeolites (SMZ) [36]. The utilization of described zeolites as a reactive material in PRB is based on their characteristics such as mechanical strength, chemical stability, sorption capacity, plasticity, and thermal conductivity. Park et al. [37] performed batch and column tests to specify the possibility of using clinoptilolite in PRBs for remediating the groundwater contaminated with ammonium, copper, and lead cations. The results showed that the removal efficiencies in all cases were >80% with using 1 g of clinoptilolite, except in very high concentrations of ammonium and copper. However, the longevity characteristic of these PRBs was not investigated. Bowman and Sullivan [38] evaluated the use of surfactant-modified zeolite (SMZ) as a reactive material in PRB for the removal of chromate and PCE from subsurface water. In addition, SMZ was also used for treating the oilfield wastewaters contaminated with organics such as benzene, toluene, methylbenzene, and xylenes, and it was concluded that the main challenge for successful application of SMZ in environmental remediation is the maintenance and improvement in its long-term physical and chemical stability. Woinarski et al. [39] investigated the effects of low temperatures which ranged from 22 to 2°C on the exchange capacity of copper with clinoptilolite in natural and pre-treated sodium forms. The results showed that these temperatures decreased the copper uptake and appeared to slow the reaction kinetics. Furthermore, Woinarski et al. [40] studied the ion exchange characteristics of Cu^{2+} in the natural zeolite clinoptilolite at 2 and 22°C for development of a PRB to treat heavy metal polluted waters in Antarctica. A one dimensional mass transfer transport model describing nonequilibrium sorption of Cu^{2+} in fixed-bed flow revealed that the saturation capacities are independent of flow rate, but mass transfer coefficients increase with water velocity. Clinoptilolite capacity in fixed-beds was approximately 50% of the capacity in equivalent batch systems, and the mass transfer coefficients were between two and eight times the batch-estimated values. Moreover, fixed-bed performance was significantly reduced at cold temperature, with breakthrough points and saturation capacities at 2°C being between 60 and 65% lower than those at 22°C. For the nitrate contamination removal, Zeng et al. [41] proposed to use of nanoparticles Fe, Cu/Fe, and Mn/ Fe coated to NaY zeolite grains (F@Y, CF@Y, and MF@Y) that are prepared by two-step processes consisting of ion exchange and liquid-phase reduction. They showed that Fe, Cu/Fe, and Mn/Fe nanoparticles were successfully loaded onto NaY zeolite and exhibited larger BET surface area compared to nZVI by means of XRD, SEM-EDX, and BET-N2 adsorption tests. In addition, the experiments they have accomplished showed that nitrate removal

by metals@Y in unbuffered conditions reached nearly 100% at a dosage of 4 g/L after 6 h of reaction by not affecting the initial solution pH. However, at a high pH of 9.0, metals@Y nitrate reduction still not below 94%. CF@Y exhibit high N_2 selectivity, due to the high content of Cu (20 wt%) and Fe (41 wt%) in CF@Y and the highly active metallic sites on its surface with positive charge.

E. Mixed materials

Organic carbon-based barriers associated with sulfate reduction mechanism in releasing contaminants from groundwater were studied. These reactive barriers were investigated by Blowes et al. [42] who generated a reactive zone in the test cell from the growth of sulfate reducing bacteria (SRB) that resulted in metal precipitation in the presence of organic carbon. The barrier was built by providing organic carbon source (organic materials), source of SRB, and pH-neutralization agent. The SRB catalyzed the oxidation of organic carbon $((CH2O2)_x(-NH3)_y(H3PO4)_z)$ in combination with the reduction of sulfate to sulfide as follows:

$2 (CH_2O_2)_x (NH_3)_y (H_3PO_4)_z + xSO_4^{2-} \rightarrow 2xHCO_3^- + xH_2S + 2yNH_3 + 2zH_3PO_4$
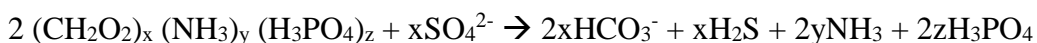
where x, y, and z are the stoichiometric coefficients. An increase in H_2S concentrations coupled with the low solubility of metal sulfides results in the removal of dissolved metals as follows [43]:

$Me^{2+} + S^{2-} \rightarrow MeS$
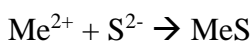
This technique appealed numerous researchers to study groundwater remediation due to its promising outcomes as a result of its use of waste material as a part of the remedy process. Benner et al. [44] evaluated one barrier of Nickel Rim mine site near Sudbury, Ontario, installed in August 1995, and used organic carbon-based SRB technology. The reactive mixture was composed of 20% wood chips, 40% leaf compost, and 40% municipal compost. It was designed to achieve bacterially mediated sulfate reduction and subsequent metal sulphide precipitation. The results of column tests proved that the reactive barrier remains effective for period not<15 years. Furthermore, Smyth et al. [45] used PRB technology as a promising sustainable application for the remediation of mine tailings impoundment. Three treatment cells (3 m x 3 m) within tens of meters of the perimeter drain installed in September 1999 at the Kidd Creek Metallurgical Site near Timmins, Ontario, were investigated. The tailings were deposited in a conical pile having depth of 15 m and diameter of several thousand meters within the 1200-ha impoundment. The results proved that these cells are efficient in the removal of high concentrations of sulfate, iron, and zinc from pore water within 1 m of the ground surface in this cell. Later, additional evaluation for this type of reactive material was performed by many researchers with different considerations [43;44;46]. Sulfate reduction geochemical approach as PRB was considered to be the most feasible approach in comparison with other classical reactive materials for treating of the groundwater plumes with low pH [47]. Liu et al. [48] improved the performance of PRB of bone char reactive material base by coatings its particles by nanosized manganese. Surface coating technology is used in the recent years to improve the adsorption performance of low-cost synthetic sorbents. Their pioneering work attempts to fix a

relationship between the coating and As(V) sorption performance by means of a series of batch and column experiments to investigate the adsorption and desorption of As(V). In addition, this study searches to introduce breakthrough curves by fitting the convection– diffusion equation (CDE), and retardation factors are used to quantify the effects of the Mn coatings on the retention of As(V). The results of this study suggest that using Mn coated bone char in permeable reactive barriers would be an effective method for remediating As(V)-bearing solutions such as acid mine drainage.

F. Waste and by-product materials

PRB technology requires little operational and maintenance costs, and, consequently, it can be considered a sustainable technology [49]. Use of high-duty green recycled waste, by product, or non-manufactured material for treatment process is the base of this consideration. As mentioned for organic carbon-based barriers, with the use of recycled or ''waste'' material as the reactive media, this technology confirms its rank as a sustainable technology and as a cornerstone for the green remediation movement [50]. In fact, this technology paved the road to wide exploration of alternate low-cost waste and recycled materials for utilization in PRBs to minimize its impact on the ecosystem by means of its contribution in waste disposal [45]. For instance, in cement industry, a large amount of a very fine powder by-product, cement kiln dust (CKD), is emitted. Every ton of produced cement will be accompanied with the generation of 41 kg CKD where the yearly production of cement around the world ranges from 2.5 to 4.0 billion tons. This means that the huge quantities of CKD will be banished to the ecosystem [51]. Sulaymon et al. [52] investigated in detail the possibility of using CKD in the PRB technology, especially the predominant mechanisms of removal process and the design criteria of the reactive bed. They attempt to improve the understanding of a complex behaviour of this material in releasing heavy metals during its utilization in PRB. They reported that the removal of heavy metals by CKD can be governed by adsorption and precipitation mechanisms which occurred simultaneously. Accordingly, using this waste as reactive medium in the PRB appears attractive in terms of sustainable development and green projects, as well as a means of cutting disposal costs [53]. Christophoridis et al. [54] proposed various reactive media for application in PRBs according to the range of contaminants, prevailing physicochemical conditions, and financial restrictions. Tests were conducted to assess the potential of natural clinoptilolite, Na-modified clinoptilolite, and ZVI to reduce the concentration of Cd(II) and Cr(III) from water solutions. Optimum pH conditions, metal selectivity, and maximum sorption capacities were determined for each material and metal. Batch tests showed that zeolite modification increased the efficiency of metal uptake dramatically, with respect to maximum sorption capacity and time of equilibrium. Furthermore, the use of ZVI reduced the metal concentration effectively, following reduction and precipitation mechanisms. Geranio and Elzinga [55] investigated the mechanisms controlling the removal of organic or inorganic compounds using apatite and ZVI as reactive materials. The results proved that the main mechanism for immobilization of metals on the

apatite is surface sorption and precipitation (for metals and lanthanides) on the ZVI. Yuncu et al. [56] studied the application of activated sludge as an alternative reactive material for treating heavy metals in the PRB. The removal of these metals could be achieved by biosorption process enhanced with functional groups such as carboxyl, hydroxyl, and phenolic of extracellular polymeric substance. Plamondon et al. [57] tested the following four reactive systems: (i) granular zeolite (clinoptilolite-GZ), (ii) granular organoclay (GO), (iii) 1:1 mixture of GZ and model sandy clayey soil, and (iv) 1:1:1 mixture of GZ, GO, and model soil for removal of Pb, Cu, Zn, Cd, and Ni from contaminated water. The results signified that the efficiency order of these materials was found to be GZ>GZ–soil mix>GZ–soil–GO mix>GO. Furthermore, Bazdanis et al. [58] studied the use of organic material and certain quantities of fly ash, ZVI, or red mud for remediating leachates contaminated with Cu, Zn, Ni, and Mn metals in up-flow packed columns. The experimental results showed adequate metal removal efficiency in most cases. Chalermyanont et al. [59] assessed the performance of activated sludge and ZVI as reactive materials for two configurations of PRB: continuous and funnel and gate. The simulation results showed that these materials have the same performance in remediation of groundwater contaminated with zinc metal. Considerable theoretical and experimental studies using different types of reactive medium such as red mud, peat, recycled concrete, shredded cast iron, steel fibres from tire, blast furnace slag, steel slag dust, basalt dust, paper ash, plant shell and weed, tree leaves, non-living biomass, and maize cob for the treatment of heavy metals in water have been achieved [60; 61]. However, using waste, recycled by product materials in PRB technology was adopted in response to sustainable (green) development concepts.

2. CONCLUSION

This paper tries to summarize the various array of reactive materials used in limited number of PRBs installed around the world and provide examples from collective knowledge and experience from several metal impacted sites. As more long-term performance data are being collected from the limited number of PRB's installed to-date, these data will provide a limited evidence to demonstrate the long-term effectiveness from a performance and cost perspective, relative to other available treatment technologies.

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CONFLICT OF INTEREST

Authors have no any conflict of interest.

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