Permeable Reactive Barrier Technology for Contaminated Remediation: Review

Akash Nade[1], Saloni Badgujar[2], Priyanka Hiwale[3], S. D. Shinde[4], A. S. Pathan[5]
[1,2,3]*B.Tech –Civil student, Deogiri Institute of Engineering and Management studies, Aurangabad, M.S., India*
[4,5]*Assistant Professor, DIEMS, Aurangabad, M.S., India*

***Abstract* - The pollution of groundwater by organic or inorganic pollutants, originating from either soil leaching or anthropogenic activities, is one of the major environmental issues. Remediation of this water source is of highest priority because many countries use it for drinking purpose. Pump-and-treat method is represented for many decades the major technique to treat groundwater infected with organic/inorganic pollutants. In last two decades, this technique becomes to be in lack with the sense of modern concepts of sustainability and renewable energy. Permeable reactive barriers (PRBs) technology was introduced as an alternative method for traditional pump-and-treat systems to remediate contaminated groundwater that was achieving these concepts. Within this issue, this technology has been proven to be a successful and most efficient promising method used by many researchers and in several projects due to its direct and simple techniques to remediate groundwater. A rapid progress from bench scale to field scale implementation in the PRB technique is recognized through the last few years. In addition, this technique was modeled theoretically for characterizing the migration of contaminants spatially and temporally through the barrier and, consequently, these models can be used for estimating the longevity of this barrier. An overview of this technique and the promising horizons for scientific research that integrates this method with sustainability and green technology practices are presented in the present study.**

***Index Terms* - Polyhouse Automation, Communication.**

INTRODUCTION

Perhaps no recent remedial technology has generated as much interest as the use of subsurface permeable reactive barriers (PRBs). This is due to the perceived PRB cost/benefit ratio and the potential of PRBs to mitigate the spread of contaminants that have proven difficult and expensive to manage with other cleanup methods. The concept of a PRB is relatively simple. Reactive material is placed in the subsurface where a plume of contaminated ground water must move through it as it flows, typically under its natural gradient (creating a passive treatment system) and treated water comes out the other side. The PRB is not a barrier to the water, but it is a barrier to the contaminant. When properly designed and implemented, PRBs are capable of remediating a number of contaminants to regulatory concentration goals. It is currently believed that these systems, once installed, will have extremely low, if any, maintenance costs for at least five to ten years. There should be no operational costs other than routine compliance and performance monitoring.

The majority of installed PRBs use iron metal, Fe (0), as the reactive media for converting contaminants to nontoxic or immobile species. Iron metal has the ability to reductively DE halogenate hydrocarbons, such as converting trichloroethene (TCE) to ethane. It can also reductively precipitate anions and oxyanions, such as converting soluble Cr (VI) oxides to insoluble Cr (III) hydroxides. Organic materials are being used as reactive media in some PRBs to biologically remediate certain other contaminants, such as nitrate and sulfate. Both laboratory and field results have shown that the rate of transformation of these and many other contaminants is sufficiently rapid for PRBs to be successfully used as full-scale remediation systems. Numerous other reactive materials are being investigated, as are means to enhance both the iron and biological reactions.

Commercial PRBs are currently built in two basic configurations (although others are being evaluated), the funnel and-gate and the continuous PRB. Both have required some degree of excavation and been limited to fairly shallow depths of fifty to seventy feet or less. Newer techniques for emplacing reactive media, such as the injection of slurries, hydro fracturing, driving mandrels, etc., may serve to overcome some of these emplacement limitations. The funnel-and-gate design PRB uses impermeable walls (sheet pilings, slurry walls, etc.) as a "funnel" to direct the contaminant plume to a "gate(s)" containing the reactive media, whereas the continuous PRB completely transects the plume flow path with reactive media. Due to the funnels, the funnel-and-gate design has a greater impact on altering the ground-water flow than does the continuous PRB. In both designs it is necessary to keep the reactive zone permeability equal to or greater than the permeability of the aquifer to avoid diversion of the flowing waters around the reactive zone.

Several important issues must be addressed when considering contaminant remediation through the use of PRB technology. These include the nature of the contaminant and the availability of reactive media that can transform the contaminant yet remain reactive, in situ, for relatively long time periods. For contaminants of unknown treatability or media of unknown reactivity, addressing these issues will require laboratory studies using both batch and column techniques. The mobility, toxicity and stability of the transformation products resulting from the contaminant and media interactions must also be assessed. If these transformation products are regulated compounds, they must not exit the reactive zone of the PRB without themselves being immobilized or transformed to innocuous compounds. A thorough understanding of system hydrogeology and plume boundaries is needed prior to implementing a PRB, due to the need for the plume to passively flow through the reactive zone of the PRB. The hydrogeological characterization must also yield information suitable for determining the rate of ground-water flow through the reactive zone of the PRB. This is necessary to establish the ground-water/contaminant residence time per unit thickness of reactive media which, when combined with the contaminant transformation rate as it passes through the media, determines the total thickness of reactive media that is required. During PRB installation the reactive media must be made accessible to the contaminant by some emplacement method and, as with most remedial technologies, this becomes increasingly difficult at greater contaminant depth or for contaminants in fractured rock. Once installed, the PRB should be carefully monitored for both compliance and performance; compliance to ascertain that regulatory contamination goals are being met, and performance to assess whether the PRB emplacement is meeting its design criteria and longevity expectations.

As for any remedial technology, it is important to fully understand the factors that can result in either successful implementation and remediation or failure to achieve the remedial design goals. This document addresses the factors, such as those mentioned above, that have been found to be relevant for successfully implementing PRBs for contaminant remediation. Additionally, it provides sufficient background in the science of PRB technology to allow a basic understanding of the chemical reactions proposed for the contaminant transformations that have been witnessed both in the laboratory and in field settings. It contains sections on PRB-treatable contaminants and the treatment reaction mechanisms, feasibility studies for PRB implementation, site characterization for PRBs, PRB design, PRB emplacement, monitoring for both compliance and performance, and summaries of several field installations. The appendices supplement this information with a detailed table of information available in the literature through 1997, summarizing the significant findings of PRB research and field studies (Appendix A), a further examination of the physical and chemical processes important to PRBs, such as corrosion, adsorption, and precipitation (Appendix B), and a set of scoping calculations that can be used to estimate the amount of reactive media required and facilitate choosing among the possible means of emplacing the required amount of media (Appendix C). Appendix D provides a list of acronyms and Appendix E a glossary of terms that are used within this document.

The goal of this Issue Paper is to provide the most recent information available on PRB technologies and to do so in a format that is useful to stakeholders such as implementers, state and federal regulators, Native American tribes, consultants, contractors, and all other interested parties. Other documents are also available which address PRB topics that are not discussed in detail in this report to avoid duplicative effort, such as regulatory issues related to PRB technology and cost information. For example, the Interstate Technology and Regulatory Cooperation (ITRC) Workgroup

(Permeable Barrier Wall Subgroup) has prepared a document titled "Regulatory Guidance for Permeable Barrier Walls Designed to Remediate Chlorinated Solvents" (ITRC, 1997) and the Environs Directorate, U.S. Air Force, has published "Design Guidance for Application of Permeable Barriers to Remediate Dissolved Chlorinated Solvents" (Battelle, 1997). Documents on the costs of PRB technology are being prepared by U.S. EPA's Technology Innovation Office (TIO) and by its Office of Research and Development, National Risk Management Research Laboratory (ORD-NRMRL). Several web sites also provide information about PRB technology.

Santanu Maitra (2019) studied the new concepts related to sustainable (green) technology and use of waste (by-product) materials in the field of environmental remediation with the assistance of physical and numerical simulation provide considerable and wide horizons for scientific research. PRB is a promising technology, and studies about the possibility of using different reactive gates composed of strong chemicals, zeolites, surfactants, iron, adsorptive substances, organisms, and bioactive materials are still underway. In this study, several sorbents have been described, which are actually used for treating of water contaminated with inorganic and/or organic compounds. Accordingly, extensive studies and extra attempts are required for selecting new waste (by product) reactive materials, determining their properties and behavior in the removal of contaminants from groundwater and, consequently, identifying their appropriateness for use in PRBs.

Shuning Zhao (2019) proposed that electro kinetics is an in situ soil remediation technique by which the flow direction of the pollutants can be controlled and the soil with low permeability can be treated. In this study, the remediation of copper contaminated kaolin by electro kinetic process coupled with activated carbon permeable reactive barrier (PRB) was investigated. His experimental results showed that the integration of PRB with electro kinetics successfully removed copper from kaolin with pH control of the catholyte. The average removal rate reached the highest of 96.60% when the initial Cu^{2+} concentration was 2000 mg/kg. Compared to the electro kinetic process without PRB, the application of the coupled system could reduce the pollution of the electrolyte.

Michelle M. Scherer (2000) studied that the Sacre (1997) reviewed the state of permeable reactive barrier technology and identified 124 projects that are currently using or planning to install PRBs. He studied that sorption reaction removes contaminant from ground water plume via partitioning from the dissolved phase to solid medium. He also studied that the humic materials, particularly peat and activated carbon, have been used as effective sorbents in wastewater treatment for many years. Permeable Reactive Barrier are currently treating a host of groundwater contaminants. Indeed, numerous sites have been successfully remediated with PRB technologies (primarily iron metals PRBs).

R. Thiruvenkatachari (2007) Studies by identified increased demand for water in Australia and called for proper management of groundwater. The report also revealed that groundwater resource in Australia has been highly committed in some places, or of poor quality in others, and poorly investigated in others. He says that 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.

Ralph D. Ludwig (2002) studied the historical storage of ore concentrate containing sulfide minerals at an industrial site in British Columbia, Canada, has resulted in widespread contamination of the underlying soil and ground water. The oxidation of sulfide minerals has released significant quantities of heavy materials, including Cu, Cd, Co, Ni, and Zn, into the ground water. A pilot scale, compost-based, sulfate-reducing permeable reactive barrier was installed in the path of the dissolved heavy metal plume. The permeable reactive barrier uses sulfate-reducing bacteria to promote precipitation of heavy metals as insoluble metals sulfides. Monitoring over a 21 month period indicated significant removal of heavy metals within the barrier. He also studied metal contamination at the site, located in a coastal aquifer setting adjacent to a marine inlet in Vancouver, Canada, has resulted from historical ore concentrate storage and handling practices associated with the transfer of ore concentrate from railcars to ships destined for foreign ports. The oxidation of sulfide minerals entrained within the soils and subsequent liberation and downward movement of associated heavy metals (Cu, Cd, Co, Ni, and Zn) has resulted in extensive contamination of the shallow ground water in the underlying unconfined aquifer.

Arun Gavaskar (2000) proposed that the preliminary assessment is conducted to evaluate the technical and economic suitability of a given site for PRB applications. Once site is determined to be suitable, additional design steps are initiated. For contaminants, such as TCE, that are to be treated with common reactive media, namely iron, it may be possible if regulators agree, to forego treatability testing in favor of published contaminant half-lives and a design that includes appropriate safety factors. At several existing sites, PRB construction generally has involved installation of reactive media in an excavated space. Excavation using backhoes, continuous trenchers, augers, or caissons is a conventional way of ensuring that the desired thickness and continuity of the reactive cell is achieved. The increasing use of a biodegradable slurry, instead of sheet piles or cross-bracing, to stabilize the excavation has increased the convenience and safety of installing the reactive media in the ground. However, these excavation methods have varying depth limitations (generally between 30 to 50 ft. below ground surface). Innovative installation methods such as jetting, hydraulic fracturing, vibrating beam, deep soil mixing, and the use of mandrels, have been tested at some sites and offer potentially lower-cost alternatives for installing reactive media at greater depths.

David H. Snow (1999) said many things must be known before a PRB can be successfully designed and implemented to remediate the groundwater. Such things are the contaminant concentration, the degradation rate with the proposed reactive media, the presence of daughter products of the original contaminant, groundwater velocities, preferential flow paths through the substrate, any natural groundwater sources and sinks, and plume depth and width. This important information allows designers to determine the contaminant's necessary residence time in the reactive zone and subsequently the barrier thickness as well as how long and deep it must be. Permeable reactive barriers are a relatively new technique for treating contaminated groundwater. There are two basic designs of barriers, continuous trench and the funnel and gate system. The continuous trench is the simplest and least expensive while the funnel and gate requires impermeable walls that funnel the water through the reactive media gate(s). These barriers can vary in length from less than 50 feet to well over 1000 feet. Extensive site characterization must be done before deciding on the location design, and reactive media of the barrier. Soil types and their respective permeability, groundwater velocities and general flow directions, hydraulic conductivities, fractured media, sources or sinks of groundwater flow, and any other possible preferential flow paths must be determined. Also, plume location, contaminant identification, concentration gradients, toxicity, and all possible daughter products must be known.

Qianfeng He (2019) discussed that PRB technology cannot guarantee the treatment effect of each pollutant, and has a certain randomness. Therefore, the selection of active materials, the types and components of pollutants should be considered comprehensively in future research and engineering application. With the accumulation of groundwater pollutants on the surface of the reactive barrier, the blockage of the reactive materials cause it to lose its activity gradually. Therefore, the periodicity of the replacement of the reactive materials should be considered comprehensively in the design of PRB to ensure its treatment efficiency. He said that it is difficult to ensure the effective time for the immobilization of heavy metals by active materials when heavy metal is remedied by PRB, and to determine which environmental conditions may lead to the reactivation of heavy metal contaminants. Therefore, the effective period of immobilization and which environmental condition may lead to the reactivation of heavy metals be considered comprehensively in depth research. The reaction between reactive materials and some substances in groundwater may produce toxic intermediate products, which may cause secondary pollution. Therefore, the mechanism of remediation should be fully considered to avoid secondary pollution when selecting reaction materials. The design process of PRB is greatly influenced by the characteristics of pollutants and the hydrogeological parameters on site. It is necessary to establish pollutant migration model and groundwater dynamic model, to accurately understand the hydrodynamic characteristics of groundwater, the migration and transformation of pollutants before the design of PRB. Therefore, the collection of preliminary data and experimental work are needed in the preliminary stage.

Gautam C. Ijoo (1999) focus of the present study was centered on the modeling analysis to support the PRB design. Prediction of the geometry and evaluation of different configurations is important in the design of a Permeable Reactive Barrier. While considerable modeling study had addressed the Funnel-and-Gate Configuration, limited modeling attention had been given to the Continuous Configuration. Studies on the continuous configuration were directed towards geo-chemical aspects of the configuration and the modeling support was directed towards prediction of the flow system in response to future events like the decrease in hydraulic conductivity over time or the effect of pumping in the vicinity of a PRB. No consensus had been reached on a uniform procedure to design a Continuous Configuration PRB. Therefore the overall objective of this study was to concoct modeling procedures and to formulate design curves to support the design of a Permeable Reactive Barrier to treat contaminated ground water economically. His study has arrived the following conclusions

1. Comparison of the different simulation codes and interfaces resolved that Modflow with either of the two Graphic User Interfaces used in this study, namely, Visual Modflow and Ground Water Modeling System provide a versatile, user-friendly environment for GW simulations.
2. A conceptual model of a contaminated aquifer in association with the PRB system can be broadly considered to fall into six generic cases. These cases arise from having confined and unconfined aquifers, single and double trench barriers, and fully and partially penetrating configurations. In this PRB system design study all these cases have been addressed. Models of each case have been calibrated and executed.
3. The model was calibrated using the data ranges from available PRB installation sites and the specific case addressed in this study. This enabled the model to simulate as closely as possible the subsurface actualities. The basic set of assumptions was established prior to the model calibration to reflect as closely as possible the GW flow regime. The unconfined aquifer was considered to be deeper than reality to accommodate the ranges in hydraulic gradient at the different PRB installations and to vary the same. Models with impermeable boundaries at great depths were assumed to simulate within a reasonable range of error confined, unconfined and deep aquifer conditions. The number of barrier incident particles that the model incorporated were decided so as to reflect true contaminant concentrations.
4. The sensitivity analysis showed that the most critical parameter was barrier width followed by the length of 'less than aquifer' permeable barriers. The length of 'more than aquifer' permeable barrier is not sensitive. An important result of the sensitivity analysis is that the loss is not or only slightly sensitive to K a/Kb ratio. This can be 105 attributed to the 'water table mounding and subsequent inclined path' phenomenon. The hydraulic gradient does not affect the loss of contaminant.
5. During calibration of the model the average difference between the simulation and observed head expressed as mean error and the root mean square error was less than 5 %. Thus it can be concluded that the model was consistent with the ground water regime not only of the site considered in the case study but also with other instillation sites.
6. The most important result of this study is that the design curves were used to conceive a procedure for the design of a continuous barrier. The design procedure has been validated to include both barrier and aquifer properties and is with respect to all but one conceptual case. The mounding effect of the water table motivates the design rationale for a partially penetrating barrier (hanging wall) to include a site specific model execution.
7. When it is required to pre-treat the ground water a double trench barrier installation becomes necessary. Though the individual trenches can be designed similar to the single trench the loss of contaminant is sensitive to the distance between the barriers. In the case of the double trench barrier configuration the design agendum was hypothesized to include the distance between the trenches as a key parameter.
8. Residence time is sensitive to aquifer to barrier hydraulic conductivity, barrier length, barrier width and hydraulic gradient of the water table at the site. A barrier can be thus designed for minimum contaminant loss and then the

mentioned critical parameters can be worked with to achieve the desired residence time.

9. The three-step design procedure formulated in this study was used to design a Permeable Reactive Barrier at the site. The barrier system thus designed consists of two trenches 2m apart. Each trench is 200m long designed to a hydraulic conductivity to 9 x 10-7m/s. The width of the first and the second trench is 2m and 2.2m respectively.

Christopher C. Walkons (2016) proposed design of a sorption based pilot-scale permeable reactive barrier (PRB) for the removal of copper from groundwater. The reactive material for the barrier is the residual of coagulants used in drinking water treatment operations. Physical and chemical properties of these water treatment residuals (WTR) have been studied to optimize PRB design. Batch reactor tests have shown that equilibrium sorption of copper can be fit to a Langmuir type isotherm. Kinetic and column experiments have been conducted to understand the significance of chemical and physical mass transfer limitations. A leaching test indicated the concentrations of hazardous elements leached from the residuals do not exceed specified limits. Permeameter tests were performed with various mixtures of the WTR and an inert support material (pea gravel) to determine the ideal mix for matching the hydraulic conductivity of the field site. Additional work has been conducted at the site to determine groundwater flow direction, pore water velocity, and contaminant concentration for designing the optimal dimensions and placement of the PRB. He also proposed future work could entail barrier design based on a test site with hydrogeological characteristics better suited to the use of a PRB. Sorption at low concentrations could be predicted better if a method were developed that completely separated the copper sorbed to WTR from copper left in solution. Alternatively, a method of analysis which does not require filtration may be helpful. Future column studies could use a solution of lower copper concentration that may reduce the chance of precipitation at the natural groundwater ph. A sensitivity analysis considering the relationship between pH and 27 sorption could be run in either a batch or column set-up. Additionally, evaluating the effects of pH on copper precipitation, dominant species presence, and hydroxide complixation may be helpful in better understanding the factors affecting sorption of copper to the WTR.

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