PERFORMANCE EVALUATION OF BLAST FURNACE SLAG AS FILTER MEDIA FOR WATER TREATMENT

Thesis

Submitted in partial fulfilment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

by

ANJALI M S

(Register No. 165115CV16F03)

DEPARTMENT OF CIVIL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA
SURATHKAL, MANGALORE – 575025
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Prof. S Shrihari and **Dr. Sunil B M**

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DECLARATION

by the Ph.D. Research Scholar

I hereby declare that the Research Thesis entitled "**Performance Evaluation of Blast Furnace Slag as Filter Media for Drinking Water Treatment**" which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Civil Engineering** is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Date: 9th June 2021

CERTIFICATE

This is to *certify* that the Research Thesis entitled "**Performance Evaluation of Blast Furnace Slag as Filter Media for Drinking Water Treatment**" submitted by **Anjali M S (Register Number: 165115CV16F03)** as the record of the research work carried out by her, is *accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of Doctor of philosophy.

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अन्नदानं महादानं विद्यादानमतः परम् ।
अन्नेन क्षणिका तृप्तिः यावज्जीवञ्च विद्यया ॥

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ANJALI M S

ABSTRACT

Owing to the degree of contamination, treatment of water has been practised from ancient periods using various naturally available materials. It was initially carried out with a general idea of using a readily available resource material as the filter medium. The commonly used filter media worldwide for drinking water treatment is river sand. But it will not be a reliable resource because of its increased demand and multifarious application. There are several naturally existing materials similar to sand. As per the available literature, the by-products from various industries are promising source of materials that could be used as filter media. Since the discarding of these stuffs poses a threat to the environment, their wise usage in waste water treatment may be helpful to reduce the impact.

Blast furnace slag is an industrial by-product of the iron and steel industry. The slags contain a significant portion of silica, calcium, aluminium and magnesium compounds with a little amount of iron. Besides their manifold use in construction practices, their use in environmental engineering is highly valuable. Ferrous slag has been used in the treatment of waste water enriched with nutrients, heavy metals and treatment of acidic mine drainage. In addition, the characteristics showed its usage as a landfill liner material. Very little literature is available on their effective use in drinking water treatment, even though some works dealt with certain specific biological parameters. In view of these, the utilisation of slag as a replacement for sand is considered both sustainable as well as economical.

The present research aims at the application of ferrous slag in drinking water treatments. Bench-scale filter proved the ability of slag as a potential alternative material to sand. In the present work, the performance evaluation of slag filter with sand as a control, a filter with partial replacement of slag with charcoal and the variation of head loss in the slag filter and its comparison with the Carman-Cozeny model were studied.

The performance of a slag filter with intermittent washing was evaluated for various filtration rates such as 0.32 m^{3}hr^{-1}m^{-2}, 0.64 m^{3}hr^{-1}m^{-2}, 0.96 m^{3}hr^{-1}m^{-2} and 1.28 m^{3}hr^{-1}m^{-2} and different concentration ranges. Slag filter media of 40 cm height was found to be sufficient for removing 99.9 % of turbidity, total suspended solids and colour. The slag filter performed similarly to the sand filter in removing *E.coli*. The dual media filter of slag with charcoal was not as good in removing suspended impurities from the water. The maximum head loss observed in a slag filter was lesser than the sand filter. The scatter plots of measured and simulated heads based on the Carman-Kozeny equation show that the model fits the observed heads.

Considering the effluent values of various water quality parameters such as hardness, sulphate, chloride and nitrate, both the flow type and concentrations are significant at 1% level of significance (p-value <.01). But for iron, only the concentration is significant at 5% level of significance (p-value <.05). The type of filter material is not significant for all the parameters except iron, where it is significant at a 1% level of significance (p-value <.01). Thus iron is the only parameter whose removal efficiency is dependent on the type of media. The treated water pH from the slag filter showed fairly consistent pH in the normal range of drinking water. These results showed that the slag would be useful in the locations where there is a scarcity of sand and no further alternative technique for drinking water treatment exists. It would be practically beneficial for the surface as well as groundwater treatment.

Key words: Blast furnace slag, water quality parameters, headloss, slag filter, dual media.

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NOMENCLATURE

SiO_2	Silica
Al_2O_3	Alumina
CaO	Calcium Oxide
MgO	Magnesium Oxide
FeO	Iron oxide
Fe_2O_3	Ferric Oxide
γ	Unit weight
n	Porosity
k	Permeability
EC	Electrical Conductivity
TDS	Total Dissolved Solids
TSS	Total Suspended Solids

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The granulated blast furnace slag, an industrial by-product, was considered earlier as a solid waste produced from iron industries. Iron and steel industries generate several million tonnes of blast furnace slag every year all over the world (Proctor *et al*., 2000; Johansson, 2010; Isawa, 2013; IBM, 2014; Li and Guo, 2014; Lim *et al*., 2016). The waste dumps of slag can be seen in and around the iron industry occupying large areas of land (Lim *et al*., 2016). The disposal of massive quantities of slag results in the degradation of land, surface and groundwater besides the aesthetic appearance of the nearby areas of the industries. It needs to be cleared off from the locality as the effect is long-term and is a major challenge facing such industries and the surrounding environment. Nowadays, ferrous slag has found potential use as a source of fine aggregate in place of natural river sand, cement manufacturing and the making of autoclaved and calcium silicate bricks (Asish *et al*. 2016; Goel and Kalamdhad, 2017; Patra and Mukharjee, 2017; Patra and Mukharjee 2018). In India, granulated blast furnace slag is mainly utilised for the manufacture of cement (IBM, 2014). But slag lost market in the last few years because of the restrictions on cement industries and less demand for cement itself. Recently the demand for cement has picked up again.

The best waste management practice can prevent the problems of contamination of industrial wastes to a considerable extent. The reuse of industrial byproducts is one of the waste minimization processes. Resource recycling is generally promoted to effectively utilize or reuse the slag (Hizon-Fradejas *et al*., 2009; Gong *et al*., 2009).

The potential application of slag lies in its effective use in place of naturally available materials. Over-exploitation of natural river sand consequently led the Government to enforce more stringent rules and regulations on excessive sand mining. Otherwise, it subsequently leads to ecological imbalance and environmental discrepancy.

Extensive research has been carried out to found out a suitable natural or synthetic substitute for sand. The sand coated with metallic hydroxides is also used to treat water (Ahammed and Davra, 2011; Park *et al*., 2015). Koupai *et al.* (2016) conducted studies on porous concrete containing iron slag for storm water runoff treatment. Heavy metals could be visible in ground water (Garg *et al*., 2004) and according to Reddy *et al*. (2019), slags are helpful to prevent soil and groundwater contaminated with heavy metals. Studies have demonstrated its use as a media for eliminating nutrients, heavy metals and biological contaminants. Thus the waste material from industries could be used as a resource to improve and protect the quality of the environment. Isawa (2013) emphasized that ferrous slag cannot be considered as a waste material as far as it is utilized effectively and in an environmentally acceptable way.

The technology of treating wastewater with wastes has already been established. It is a good neutralizing agent against acidic soil (Isawa, 2013) and therefore finds its application in the treatment of acid mine drainage. Steel slag can be used as a barrier material against leachate containing heavy metals (IBM, 2014). It could be used for remineralization and conditioning of soil such as liming agent, fertilizer, etc. (Lewis, 1982; Johansson and Gustafsson, 2000; Proctor *et al*., 2000; Kalyoncu, 2001; Isawa, 2013). It is reported that marine block made of ferrous slag could be used as a decontaminant for both water and bottom sediment in the marine environment (Isawa, 2013). The slag has found applications in landfills (IBM, 2014) drainage works and as a soil conditioner for the growth of both plants and microbes (Lewis, 1982).

Most of the wastewater treatment studies relied upon adsorption using slag in combination with other naturally available or processed materials for treatment. Ferrous slag was capable of removing nutrients from wastewater either alone (Johansson, 2010; Oguz, 2004; Johansson and Gustafsson, 2000; Hedström and Rastas, 2006; Korkusuz *et al*., 2007; Ballantine and Tanner, 2010; Shilton *et al*., 2013) or in combination with limestone, Polonite, Opaka, gravel and sand (Johansson and Gustafsson, 2000; Hylander *et al*., 2006; Korkusuz *et al*., 2007; Gong *et al*., 2009; Nilsson *et al*., 2013) in laboratory and field trials. Slag could also be used as a sorbent for heavy metals like nickel, zinc, lead and chromium (Nehrenheim and Gustafsson, 2008). Column studies were conducted using crystalline and amorphous blast furnace slag along with sand and pine bark as media for eliminating copper, zinc and nickel (Nehrenheim *et al*. 2008). According to Hallberg and Renman (2008), slag could remove total and dissolved cadmium, zinc, copper, nickel and chromium from road runoff.

1.2 RESEARCH MOTIVATION

The increased demand for river sand for its multiple applications brought about large scale legal and illegal sand mining activity and its associated environmental impacts have imposed strict rules and regulations for its sustainable use and resulted in finding out a suitable substitute to it. Sand mining has been prohibited in most parts of India due to its over-exploitation resulting in the ecological imbalance of the environment. Research has been carried out with suitable alternative substitute to the sand where slag, an industrial resource, is considered in place of sand, a natural resource.

In water treatment, sand has often been in use as a media due to the abundance and acceptable pollutant removal efficiency. Since there is a growing demand for sand, it is required to provide a sustainable solution to the use of filter sand with an alternative material. The use of slag in place of sand is an effective way to reduce the menace caused by the dumping off of slag in the premises of the industry. Hence there is a promising use of slag as a filter media for water treatment.

1.3 OBJECTIVES OF THE STUDY

In this research, utilisation of slag as a complete replacement for sand has been studied. The main objectives were

1. Studies on slag as filter media for water treatment
2. Performance evaluation of ferrous slag filter with respect to the water quality parameters
3. Comparative studies of slag and sand media filters for operating and maintenance conditions
4. Evaluation of the performance of slag and charcoal dual media filter

5. Comparison of headloss of slag filter with mathematical model

1.4 ORGANISATION OF THE THESIS

The thesis has been organized into five chapters. A brief overview of chapters is presented below.

Chapter 1 introduces the relevance of blast furnace slag in environmental engineering, the scope and objectives of the research work.

Chapter 2 describes the literature review of previous and current research on ferrous slag, its valorisation and the filtration technology in general. It also presents the summary of the literature and the literature gap.

Chapter 3 describes the material used for the study and the methodology adopted in the study. It also discusses the experimental set-up, technical procedures. The details of the experimental study with changes in flow rates and concentration changes are also presented.

Chapter 4 presents the results of characterisation of blast furnace slag, the performance of slag filter in drinking water treatment and discussed its performance in comparison with a sand filter. Further the use of slag in dual media filter along with charcoal and the head losses developed in a slag filter in comparison to the existing mathematical model was also discussed.

Chapter 5 presents the conclusions of the research objectives based on the results of the experimental study.

CHAPTER 2

LITERATURE REVIEW

The waste material from the industries could be used as a resource for various applications to improve and protect the quality of the environment. The disposal results in the degradation of land, surface, and groundwater contamination besides the aesthetic appearance of the adjacent areas of the industries. The by-products of industries are generally used as adsorbents for removing nutrients and heavy metals from water and wastewater (Singh *et al*., 2018; Yasipourtehrani *et al*., 2019). Mercado-Borrayo *et al*. (2018) described the practice of using iron slag as sorbents or reagents for the co-precipitation of contaminants. *Gao et al.* (2017) investigated the adsorptive ability of treated water quenched blast furnace slag in three different forms for methyl orange from aqueous solutions. Ferrous slag has found wide applications in the environmental field.

2.1 BLAST FURNACE SLAG

Ferrous slag is one of the significant by-products generated from the blast furnace during the production of iron (Lim *et al*., 2016). In general, blast furnace slag production ranges from about 300-540 kg per tonne of pig or crude iron from an ore feed containing 60 to 65% iron. It has been estimated that around 10 million tonnes of blast furnace slag per year are generated in India from the iron and steel industry (IMB, 2018). Approximately 19.5 and 4.7 million tonnes of granulated and air-cooled slag are generated annually in Japan (Isawa, 2013) and about 346 kg/t hot metal in China (Li and Guo, 2014).

The blast furnace is charged with sources of iron oxide (ores, pellets, sinter, etc.), flux stone (limestone and dolomite), and fuel (coke) at a high temperature of about 3000^{o}C to produce pig iron. In this process, slag is generated as a by-product. The blast furnace slag is defined as a non-metallic product consisting primarily of silicates and alumina-silicates of calcium and other bases developed in a molten condition simultaneously with iron in a blast furnace (BIS: 12089, 1987; Lewis, 1982). It consists of the impurities from iron ore such as silica and alumina combined with calcium and magnesium oxides from the flux stone along with small amounts of sulphur and ash. Accordingly, it indicates the presence of calcium, magnesium, manganese and aluminium silicates and a combination of all these components. The blast furnace slag also contains beryllium, total chromium, manganese, molybdenum, and selenium, only a little above the general soil concentrations. The chemical composition of blast furnace slag generated from Indian steel industries and worldwide is given in Tables 2.1 and 2.2, respectively.

The important physical properties of slag are grain size, density, porosity and hydraulic conductivity and are listed for different types of slag in Table 2.3. The physical and chemical composition of ferrous slag varies depending upon the places or sources of generation, the temperature at the time of water quenching, and the process changes/ different methods of operations or the changes in methodologies involved (Korkusuz *et al*., 2007). The SiO_2 and CaO values were found to be high, followed by Al_2O_3, whereas the iron content is around 0.5% in blast furnace slag (IBM, 2018). The high pH could be attributed to the presence of free lime, iron, and calcium silicates in slag (Bowden *et al.*, 2006). The leachate from the slag is usually alkaline due to its calcium and magnesium contents (O'Kelly, 2008).

Table 2.1 Chemical Composition of Blast Furnace Slag Generated in Indian Steel Plants (IBM, 2018)

Name of plant	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	MnO (%)	FeO (%)	S (%)
Bhilai Steel Plant, Durg, Chhattisgarh	34.52	20.66	32.43	10.09	0.23	0.57	0.77
Bokaro Steel Plant, Bokaro, Jharkhand	30.06-31.85	21.12-22.71	32.48-34.17	10.12-10.39	-	0.26-0.37	-
Rourkela Steel Plant, Rourkela, Odisha	34.38-34.85	17.82-20.91	32.99-34.26	9.29-9.68	0.07-0.12	0.46-0.58	0.47-0.61
Durgapur Steel Plant, Durgapur, West Bengal	32.68	21.23	32.14	-	-	-	-
Visvesvaraya Iron and Steel Plant, Bhadravati, Karnataka	32.00	18.00	33.00	9.00	-	0.50	-
IISCO Steel Plant, Burnpur, West Bengal	32.60	23.30	33.70	7.60	-	-	-
Rashtriya Ispat Nigam Ltd., Visakhapatnam, Andhra Pradesh	35.33	16.60	36.89	8.48	0.12	0.51	-
IDCOL, Kalinga Iron Works Ltd., Barbil, Odisha	33.00-34.00	24.00-25.00	29.00-30.00	8.00-9.00	0.50-0.60	0.70-0.80	1.00
Tata Steel Ltd., Jamshedpur, Jharkhand	34.50	20.80	34.30	7.30	0.052	0.60	-
JSW Steel Ltd., Bellary, Karnataka	35.20	19.00	34.90	8.76	0.14	0.039	-
Visa Steel Ltd., Kalinganagar, Odisha	33.80	15.39	35.38	10.25	0.64	0.74	0.92
Neelachal Ispat Nigam Ltd., Kalinganagar, Odisha	32.62	32.62	33.25	9.91	0.40	0.55	0.62

Table 2.2 Chemical Composition of Different Types of Slag

Type of Slag	SiO_2 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	MnO (%)	FeO (%)	S (%)	References
Blast Furnace Slag	32.00-42.00	7.00-16.00	32.00-45.00	5.00-15.00	0.20- 1.00	0.10-1.50[a]	1.00-2.00	Lewis, 1982
Blast Furnace Slag	35.00	14.00	41.00	7.00	nm[c]	nm[c]	0.80	WRAP, 2007
Blast Furnace Slag	37.14	9.15	37.40	11.70	nm[c]	1.05[a]	0.37[b]	Das *et al.*, 2007
Granulated Slag	32.20	14.90	43.00	5.26	0.34	0.53[a]	1.98[b]	Hizon-Fradejas *et al.*, 2009
Air-cooled Slag	30.60	15.5	42.00	7.19	0.30	0.38[a]	1.97[b]	
Blast Furnace Slag	33.26	15.63	38.69	9.41	nm[c]	0.83	0.35[b]	Gong *et al.*, 2009
Crystalline Blast Furnace Slag (Oxelösund)	34.00	13.00	30.00	16.50	0.60	0.50	1.00	Johansson, 2010
Crystalline Blast Furnace Slag (Luleå)	33.00	12.50	32.50	16.50	0.30	0.20	1.10	
Blast Furnace Slag	39.56	10.82	37.68	6.79	nm[c]	0.33[a]	-[d]	Oguz, 2004
Fine Amorphous slag	35.30	9.30	35.00	13.70	0.40	0.36	nm[c]	Johansson and Gustafsson, 2000
Coarse Amorphous slag	35.50	9.60	35.00	13.70	0.41	0.34	nm[c]	
Fine Crystalline Slag	35.10	10.60	33.70	14.40	0.47	0.43	nm[c]	
Coarse Crystalline Slag	35.20	11.40	33.40	14.30	0.47	0.43	nm[c]	
Blast Furnace Slag	21.82	16.9	37.82	5.53	nm[c]	13.10[a]	nm[c]	Ge *et al.,* 2015
Blast Furnace Slag	33.2	13.2	30.10	16.40	0.50	0.30[a]	1.10	Hallberg and Renman, 2008
Granulated Blast Furnace Slag	36.00	10.00	39.00	nm[c]	nm[c]	0.50[a]	nm[c]	Agrawal *et al.*, 2011
Blast Furnace Slag	36.11	8.46	36.23	3.14	nm[c]	0.63	nm[c]	Lu *et al.*, 2008

[a] as Fe_2O_3 [b] as SO_3 [c] nm not mentioned [d] as Sulphide (S^{2-}) [e] as FeO_3 [f] as iron compounds

Table 2.3 Physical Properties of Blast Furnace Slag

Type of Slag	Grain size (mm)	Density (kg/m^3)	Porosity (%)	Hydraulic Conductivity (m/day)	References
Fine Blast Furnace Slag	0.5 - 2.0	1245	55	1990	Hedström and Rastas, 2006
Coarse Blast Furnace Slag	1.0 - 5.6	1158	54	4260	
Blast Furnace Slag	0.5 - 4.0	2200	28	255	Nilsson *et al.*, 2013
Amorphous Slag Coarse	0.25 - 4.0	nmb	46.7	40.6	Hylander *et al.*, 2006
Crystalline Slag Coarse	0.25 - 4.0	nmb	45.5	15.9	
Crystalline Slag Very Coarse	2.0 - 7.0	nmb	50.9	4950	
Fine Amorphous Slag	nmb	1380	55	3.2	Johansson and Gustafsson, 2000
Coarse Amorphous Slag	nmb	1500	44	40.6	
Fine Crystalline Slag	nmb	1610	45	0.8	
Coarse Crystalline Slag	nmb	1600	40	15.9	
Granulated Blast Furnace Slag	2.0 - 2.8	1300 - 1500	nm[b]	nm[b]	Agrawal *et al.*, 2011

[b] nm not mentioned

The ferrous slag is cooled for making different types of slag *viz.* air-cooled slag, granulated slag, and expanded slag. Air-cooled slag is produced by allowing the molten slag to cool slowly in a pit under atmospheric conditions. The escaping gases make it porous and cellular or vesicular structure resulting in low density. The unique physical properties, such as porosity and cellular structure, attracted its suitability for numerous applications. Under controlled cooling, the slag becomes hard and dense, which finds application in landfills (IBM, 2018). Granulated slag is a glassy granular product processed by rapid chilling or quenching of molten slag with high-pressure water jets or steam and air or a combination of water and air. It is suitable for drainage works and soil conditioning for the growth of plants and microbes (BIS: 12089, 1987; Lewis, 1982). Expanded slag is formed by controlled cooling of molten slag with water or water with a combination of steam and compressed air. It has high porosity and vesicular nature compared to air-cooled slag.

2.1.1 VALORISATION OF FERROUS SLAG

The best waste management practices could be attained by utilizing slag in technically feasible and commercially viable applications. Pre-treatment is occasionally necessary to eliminate impurities, and it depends on the characteristics and possible utilization areas of slag (WRAP, 2007). The vesicular nature and mineralogical properties of slag find application as a barrier material in landfill sites against heavy metal contamination.

The ferrous slag has a diverse role in water and wastewater treatment. It has a significant role in removing various pollutants (Ge *et al.*, 2015). The iron slag can be applied for neutralizing acidic wastes and mine drainage, agricultural uses such as remineralization and conditioning of soil, as a liming agent, fertilizer, etc. (Proctor *et al.*, 2000). Studies have demonstrated that it could be used as media for eliminating nutrients in wastewater (Johansson, 2010; Oguz, 2004; Johansson and Gustafsson, 2000; Hedström and Rastas, 2006; Korkusuz *et al.*, 2007; Ballantine and Tanner, 2010; Shilton *et al.*, 2013).

Hedstrom and Rastas (2006) and Westholm (2010) described the phosphorus sorption capacity of slag from wastewater. The earlier research was mainly carried out for removing phosphate from synthetic wastewater (Oguz, 2004). Johansson and

Gustafsson (2000) suggested further research on nutrient uptake by plants and its usage as fertilizers while conducting studies on different media such as blast furnace slag and opaka (50% $CaCO_3$, 40% SiO_2 and 10% Al, Fe, and other oxides). Phosphorous recycling was also found possible by growing barley seeds in mixed media consisting of blast furnace slag, limestone, polonite, opaka and sand (Hylander *et al*., 2006) and reed beds planted with *Phragmites australis* in composite media using gravel, blast furnace slag and sand (Korkusuz *et al*., 2007). Thus it is evident that phosphate removal from wastewater could be achieved with the help of either blast furnace slag alone or in combination with other materials such as hydrated lime, as pointed out by Gong *et al*. (2009). Nilsson *et al*. (2013) distinctly compared the removal of phosphorous and bacteria using polonite and blast furnace slag.

The blast furnace slag could be used for eliminating heavy metals such as copper, zinc and nickel (Dimitrova *et al*., 2000) and a combination of these metals along with cadmium and chromium from wastewater. It would be more effective if pre-treatment were given to eliminate suspended solids (Hallberg and Renman, 2008). Crystalline and amorphous blast furnace slag along with pine bark of size 2.5 to 10 mm were used for column studies for removing copper, zinc and nickel. Pine bark was more stable with respect to metal sorption than slag (Nehrenheim *et al*., 2008). The study conducted by Nehrenheim and Gustaffon (2008) showed its efficiency as a sorbent for nickel, zinc, lead, and chromium at higher concentrations, which is in contrast to the previous study. Apart from the pure form, an activated slag was used as a filter media for removing lead and chromium (Srivastava *et al*., 1997).

Wetlands are found to be useful for wastewater treatments. High BOD and suspended solids could be removed using a bed containing sand, gravel, organic matter, and minerals (Karczmarczyk, 2004). Moreover, constructed wetlands using slag makes a low cost and energy-efficient technology (Korkusuz *et al*., 2004).

The factors influencing the operation of various treatments in addition to the design of filters using slag are particle size (Nilsson *et al*., 2013), pH (Johansson and Gustafsson, 2000; Ge *et al*., 2015; Srivastava *et al*., 1997), porosity (Korkusuz *et al*., 2007), hydraulic conductivity (Calder *et al*., 2006) and calcium content (Korkusuz *et al*., 2007) of the media, pH of wastewater (Oguz, 2004; Nilsson *et al.*, 2013), agitation rate in the reactor (Oguz, 2004), temperature (Oguz, 2004; Srivastava *et al*., 1997) and hydraulic retention time (Nilsson *et al*., 2013; Shilton *et al*.,2013; Srivastava *et al*., 1997).

2.1.2 APPLICATIONS OF SLAG

Blast furnace slag finds application in the removal of nutrients from soil and wastewater, removal of heavy metals, etc. The usage potential of slag has been studied by various researchers and is described in the following literature.

2.1.2.1 Removal of Nutrients

The untreated disposal of sewage, overuse of fertilizers, detergents, storm water runoff, animal husbandry etc., contribute surplus amounts of nutrients in water bodies. The accumulated nutrients may enhance the eutrophication phenomenon. The blast furnace slag prevents eutrophication by making phosphorus insoluble in water and absorbs a part of the insoluble phosphorus (Horii *et al*., 2013). Its suitability as filter media has gained much attention recently since it has all the properties of efficient media.

The reaction of slag, which is rich in calcium and minor amounts of iron, with phosphate ions form complexes and precipitates out. The phosphorus removal is mainly contributed by precipitation phenomena. At low pH conditions, it might be due to the ion exchange process (Lu *et al*., 2008). Fine amorphous and crystalline slag and coarse crystalline slag were found to be efficient for removing small amounts of phosphorous according to the study conducted using fine and coarse amorphous and crystalline slag and siliceous sedimentary rock called opoka (Johansson and Gustafsson, 2000). However, fine amorphous slag showed its ineffectiveness at high phosphorus concentrations. Coarse amorphous slag and opoka were the least efficient retainers of phosphorus. A decline in pH with phosphorous accumulation was also recorded. It was reported that phosphorus might be removed by adsorption or precipitation in the form of calcium phosphates. It was also supported by Lu *et al*. (2008), Blanco *et al*. (2016) and Johansson (1999).

The suspended phosphorous can also be removed by filtration and precipitation along with suspended solids. The slag has a high affinity to phosphates due to its porosity and results in dissolved total-P removal. The calcium released from the slag reacts with phosphate-phosphorous to form precipitates such as tricalcium phosphate, octa-calcium phosphate and hydroxyapate as indicated by Ge *et al*. (2014) which was also highlighted earlier by Korkusuz *et al*. (2007). The high content of calcium oxide produces several calcium phosphates, which promote an increase in the phosphorus removal rate.

The experiments conducted by Oguz (2004) for removal of phosphate from synthetic wastewater using slag in a batch reactor showed more than 99% efficiency. The minimum dosage of blast furnace slag was 60 g L^{-1}, for removing 180 ppm phosphate in 50 ml wastewater. In order to remove phosphate from the aqueous solution at a temperature of 25°C and 45°C, a contact time of 20 min was adequate. In the adsorption process, the critical controlling parameters were agitation rate, temperature and pH of the aqueous solution. Hedstrom and Rastas (2006) conducted experiments using blast furnace slag for the treatment of wastewater and synthetic phosphate solutions. The sorption capacity was about 1493, 821 and 380 mg Total-P/kg fresh blast furnace slag and 638, 563 and 321 mg Total-P/kg weathered blast furnace slag both at an initial phosphorus concentration of 20 mg L^{-1}, 10 mg L^{-1} and 5 mg L^{-1} respectively. The phosphorus sorption depends on the amount of dissolved calcium, which is also proved later by Ge *et al*. (2014). It was preferred to use either fresh slag, which is in unison with the suggestions of Westholm (2010) or properly stored slag without exposure to the atmosphere for wastewater treatment. Otherwise, the properties would be altered by leaching out the dissolved calcium. According to Hedstrom and Rastas (2006), the sorption capacities of blast furnace slag were considerably low for wastewater compared to the synthetic phosphate solutions. Yasipourtehrani *et al*. (2019) showed that the optimum adsorbent dose and contact time for phosphate removal using blast furnace slag was 60 g L^{-1} and 1 hr, respectively.

The removal of phosphorus is difficult in subsurface flow wetlands with sand, gravel, and improved site soil (Karczmarczyk, 2004). The slag based wetland system was found to be efficient for removing phosphate phosphorus, Total-phosphorus, total suspended solids, coliform bacteria, and COD from domestic wastewater and also for nitrate-nitrogen production or nitrification (Korkusuz *et al*., 2004; Korkusuz *et al*., 2005). Calder *et al*. (2006) suggested the need for field trials in wetlands for phosphorus sorption in order to validate the laboratory data. The study observed that hydraulic conductivity is an important parameter in determining the removal of phosphorus.

Korkusuz *et al*. (2007) carried out field application studies on domestic wastewater with primary treatment. The wastewater was applied to a wetland of 30 m^2 consisting of gravel as the bottom layer, blast furnace granulated slag as an intermediate layer, and sand as the top layer. The wetland was planted with *Phragmites australis* and domestic wastewater was applied at a hydraulic rate of 100 mm per day. Prior to the field application, batch scale experiments for phosphorus sorption capacity were conducted on standard phosphorus solutions. The sorption capacity varied between 0 and 9150 mg phosphorus per kg for initial phosphorus concentrations of 0-320 mg L^{-1}. Even at high loading rates, it could remove both phosphate-phosphorus and total phosphorus effectively. It might be due to its high values of calcium and porosity compared to other filter materials. Similar studies were conducted by Westholm (2010) and obtained better efficiency of about 95-100% in laboratory studies while it was only 40-53% for field trials. It was in contrast to the study by Valero *et al*. (2009), wherein the performance was higher for pilot scale filter in the field than bench scale filter in the laboratory.

Besides phosphorous, removal of other parameters such as total organic carbon and bacteria, *Enterococci* were possible using blast furnace slag (Nilsson *et al*., 2013). Column experiments were performed for high and low BOD_7 values, 120 mg L^{-1} and 20 mg L^{-1} (mean) for the average hydraulic residence time of 535 hours showed 22% and 18% phosphorous removal, 21% and 19% TOC removal and 81% and 16% bacteria removal respectively. The blast furnace slag with high BOD had more sorption rate than that with low BOD. The pH of wastewater, the particle size of the filter, hydraulic retention time, and organic loading rate influence the sorption behaviour and hence could have a role in the efficiency of filter media for phosphorus and TOC removal. It was, therefore, suggested to give pre-treatment to reduce the concentration of organic material.

Feng *et al*. (2012) reported that water quenched slag particles provide proper environmental conditions for the growth of nitrifying bacteria. In a study on effluent from a waste stabilization pond using a filter column filled with slag, phosphorus removal was declined logarithmically with hydraulic retention time (Shilton *et al*., 2013). Removal efficiencies of 90% and 80% were achieved during experiments with real and synthetic phosphate solution in retention periods of 70 and 30 hours, respectively. It was evident that removal efficiency was high in the case of stabilization pond effluents. In contrast, synthetic phosphate solution marked a low value due to the high initial concentration of phosphorus. The high efficiency was contributed by the presence of oxidized iron compounds, cations, algae, and other humic complexes in effluents. This study confirmed the role of iron oxyhydroxides and calcium carbonate in adsorption, which was also stated by Pratt *et al*. (2007) and Haynes (2015). The maximum sorption ratio was 1.23 kg Total-P per tonne of slag. The weathered slag was capable of removing phosphorous better than fresh slag, which was in contradiction with Hedstrom and Rastas (2006).

Zuo *et al*. (2018) noticed a decrease in phosphorus removal efficiency from 100 to 6.6% due to the inhibition of Ca-P precipitation caused by the presence of dissolved organic carbon. The main drawback observed in the media is physical clogging due to the settlement of organic solids and other solids and may ultimately affect the hydraulic conductivity of media. Among the various parameters affecting the operation of the filter, the hydraulic retention time is to be considered as an important parameter since it gives an idea about the replacement of the filter and the degree of treatment required for effluent.

The results of the study conducted by Lu *et al*. (2008) indicated a strong bond between slag particles and adsorbed phosphate preventing further desorption of phosphorus. The pH played a significant role in the rate and mechanism of removal. It was observed in the study that phosphorus removal was by chemical precipitation at pH above 8. The removal was by adsorption when pH was below 6 and by ion exchange and precipitation when pH in the range of 3 to 8.5. The chemical precipitation could recover or regenerate the exhausted filter media by stripping phosphorus from it (Pratt *et al*., 2011). Long term monitoring of active slag filter removed 77% of the Total-P initially. During the first five years, its mean concentration in the effluent was 2.3 mg $L^{-1,}$ and removal was 19.7 tonnes and increased to 22.4 tonnes by the end of the eleventh year (Shilton *et al*., 2006). The maximum phosphorus retention ratio was 1.23 kg Total-P per tonne of slag. The results proved that media replacement was required only after half a decade. Higher efficiency was also reported for real effluent than synthetic phosphate solution due to the difference in phosphate concentrations and the presence of dissolved and particulate constituents in the real effluent.

Gong *et al*. (2009) conducted batch experiments for phosphorous adsorption, but it was remarkably less for the combination of blast furnace slag-hydrated lime than hydrated lime alone. The suitability of granulated blast furnace slag, cement kiln dust, zeolite, coconut shell, and silica sand for phosphorus sorption was studied by Agrawal *et al*. (2011a). But it was later observed while treating drainage water that a filter bed comprising of these materials was not competent for removing phosphate and pesticides like mefenoxa and propiconazole. In contrast, it could efficiently remove chlorothalonil from wastewater Agrawal *et al*. (2011b).

2.1.2.2 Removal of Heavy Metals

According to Nehrenheim and Gustafsson (2008), slag could act as a sorbent for nickel, zinc, lead, and chromium ions at higher concentrations. The column study conducted by Hallberg and Renman (2008) for removing total and dissolved metals present in road runoff performed excellently. The removal of total cadmium was more than 99%, zinc more than 93%, copper 71-88%, nickel 40-69%, and chromium 18% and dissolved cadmium and zinc more than 90%, copper 77-86%, nickel 44-72% and chromium 6% respectively. The removal of total cadmium was much affected at lower and higher salt concentrations. The ungranulated and thermally treated slag achieved more than 99% reduction for copper and the sorption was mainly due to the ion exchange mechanism and dependent on the calcium ion concentration (Dimitrova and Mehanjiev, 2000). It was concluded that crystalline slag has a more sorption rate than amorphous slag.

Srivastava *et al*. (1997) developed an activated slag filter by conducting batch experiments for the sorption of lead and chromium and studied the various factors affecting the sorption such as pH, sorbent dosage, the concentration of adsorbate, presence of other metal ions, temperature and contact time. The adsorption followed Freundlich and Langmuir models and its performance was comparable to those of activated carbon. The uptake of lead was possible using slag and was recovered by chemical regeneration. Pratt *et al*. (2009) also regenerated the used melter slag similarly. When the dosage varied from 5 to 10 g L^{-1} the sorption was more. No significant removal was noticed at a higher dosage. Besides, an increased amount of adsorbent decreased the half-life of the sorption process. The influence of other metal ions reduced the uptake of chromium and lead in the presence of surfactant and the reduction was only 1.5% and 5.3%, respectively. The process of adsorption was endothermic and the rate of removal increased with an increase in temperature. The amounts of lead and chromium adsorbed in first hour at temperatures 30, 40 and 50 (±1°C) were 1×10^{-4}, 1.23×10^{-4} and 1.30×10^{-4} mol g^{-1} and 0.77×10^{-5}, 0.88×10^{-5} and 1×10^{-5} mol g^{-1} respectively. The sorption capacity was 50 to 80% after 1 hour contact time. The adsorption capacity of blast furnace slag for heavy metals such as lead, copper, cadmium, chromium and zinc varied from 4.3- 5.2 mg g^{-1}. The highest adsorption capacities were recorded by lead, copper and cadmium, followed by chromium and nickel (Nguyen *et al*., 2018). Alkali activated slag was found effective for the immobilization of Cr (VI), which finds its application for the treatment of Cr (VI) bearing wastes (Zhang *et al*., 2017).

Separate column studies were conducted using crystalline and amorphous blast furnace slag along with sand and pine bark for copper, zinc, and nickel removal (Nehrenheim *et al*., 2008). A longer retention time of 90 min increased the sorption rate of pine bark more stable with respect to metal sorption than slag. The slag filter attained 35% accumulation of suspended solids similar to that of sand. Nehrenheim and Gustaffon (2008) found that sorption was higher for slag than pine bark at short contact time. At higher concentrations, slag was an efficient sorbent for nickel, zinc, lead, and chromium.

2.1.2.3 General Water and Wastewater Treatment

El-Taweel and Ali (2000) evaluated the performance of a roughing filter consisting of blast furnace slag and obtained 63%, 55%, 69%, 72% and 71% removal for chlorophyll-a content, green algae, blue-green algae, diatoms and total algal count respectively. Total bacterial count at 22°C and 37°C were 71% and 60% respectively and the removal of total coliform, fecal coliform, fecal streptococci, yeasts and *Candida albicans* were ranged from 55-69%. The percentage removal of turbidity was above 80% in the roughing filter. The above results depicted a substantial reduction of microorganisms and turbidity, whereas poor performance was recorded for various other physicochemical parameters. Abdolahnejad *et al*. (2014) studied the water softening behaviour of the slow sand filter using Iranian natural zeolite and blast furnace slag and showed that adsorption had a critical role in removing turbidity similar to the previous study. The cation exchange capacity of slag was 6.3, which represents a value between that of natural zeolite and sand. The slag modified filter showed 98.98% turbidity removal, 51.95% hardness removal. The mean EC reduction was 11.02%.

A laboratory filter made of granulated blast furnace slag could completely remove turbidity, total suspended solids, and colour from a synthetic influent containing 28.26 NTU, 128.85 mg L^{-1} and 177.05 PCU respectively at 0.32 m^3hr^{-1} m^2. Furthermore, the effect of increasing the flow rates and concentrations of influent were conducted for various other parameters such as hardness, sulphate, nitrate, chloride and iron. The removal of iron was always above 95% and there was no change in its removal efficiency with an increase in filtration rates and concentrations.

Nehrenheim *et al*. (2008) proposed field studies for treating landfill leachate, which depends on various metal concentrations and other environmental factors. As the residence time is increased, the ion retention rate is also increased. The removal of heavy metals from landfill leachate depends on the pH and chemical composition of the media and the characteristics of leachate (Kietlińska and Renman 2005). The removal efficiency obtained was 66% for copper and 62% for zinc. A significant reduction could not be achieved for other metals except nickel (19%) and molybdenum (16%). Koupai *et al*. (2015) demonstrated its application in urban stormwater treatment along with porous concrete in the presence of sand filter and found a 44% reduction in COD and more than 90% reduction for both total suspended solids and lead.

A hybrid wetland system used by Saeed *et al*. (2012) for treating tannery wastewater was similar to the one carried out by Korkusuz *et al*. (2007) for domestic wastewater. The horizontal flow wetland system used cupola slag and removed an average phosphate of 61% by adsorption alone. Korkusuz *et al*. (2004) previously suggested that constructed wetlands would be successfully employed for secondary and tertiary treatment of wastewater in Turkey. The average removal efficiencies for total suspended solids, chemical oxygen demand, ammonia nitrogen, total nitrogen, phosphate-phosphorus and total phosphorus were 63%, 47%, 88%, 44%, 44% and 45% respectively (Korkusuz *et al*., 2005).

A study by Ge *et al*. (2014) on remediation of highly polluted river water using horizontal subsurface flow constructed wetland systems using slag and gravel media was useful for *Phragmites australis* growth. The dissolved metals could be removed considerably by uptake of plants or by wetland treatment (Hallberg and Renman, 2008). The polluted river water was fed intermittently for the favourable condition for plant growth and development of biofilm. Higher coefficients of correlation could be achieved when fitted to the Langmuir isotherm equation for slag than gravel. Adsorption for slag was 3.15 mg g^{-1}, whereas gravel recorded only 0.81 mg g^{-1} (Ge *et al*., 2015). Surface adsorption and diffusion into the slag brought about the phosphorus adsorption. It might also be due to the higher content of calcium in slag, as supported by Johansson and Gustafsson (2000) and Korkusuz *et al*. (2007). The average removal efficiencies of COD and BOD_5 using slag were 72.4% and 84.3%, respectively, when compared with gravel. The Total-P in the wastewater consisted of 47.3% suspended and 57.3% dissolved parts, of which 70.6% removal of suspended Total-P could be achieved. Nitrogen removal was also reported during the study period of 2 years. But the findings indicated that the plants grown in slag could absorb fewer nutrients compared to gravel media. It could be further extended on a large scale.

Although particle size and texture of slag could result in better growth of plants, leaching of chemicals from slag, especially the release of phytotoxins such as zinc and the presence of less organic matter might have created stunted growth of eelgrass (Hizon-Fradejas *et al*., 2009). There was a possibility of producing leachate with high pH values and electrical conductivities when steel slag was used in constructed wetlands. In order to counteract these problems, effective pre-treatment methods are to be implemented before its utilization (Hizon-Fradejas *et al*., 2009; Blanco *et al*., 2016).

The main operational problem of any filter is clogging due to excessive organic loading, which reduces filter efficiency. The risk of clogging in wastewater treatment due to organic solids was reported by Hedstrom and Rastas (2006) and Westholm (2010). The mechanical adsorption also increased the head loss resulting in clogging of the media, as pointed out by El-Taweel and Ali (2000). A remedial measure, such as pre-treatment to remove total suspended solids from wastewater, has been suggested by Hallberg and Renman (2008).

2.2 FILTRATION

The main objective of filtration is to produce a high quality drinking water. Filtration is a solid-liquid separation where the liquid passes through a porous medium to remove fine suspended solids. It is used to remove suspended particles or flocs, causing turbidity and pathogenic organisms. Filtration operations are of two types, namely gravity filtration and pressure filtration. Gravity filtration is the standard mode of filter operation in which the driving force that enables filtration of water is the head of water available above the filter that overcomes the head loss through the filter. The filtration rates decline due to the clogging of media. Low rate slow sand filters are mainly suitable in small communities as a single step treatment where a little turbidity surface water is required. High rate rapid sand filters are usually operated on a large scale in the declining rate mode of operation. It is the most widely used filtration process in water treatment. Pressure filtration is mainly employed when the quantity of water to be treated is small.

A minimum water level must be maintained at the inlet level to ensure sufficient head over the filter. It also prevents air binding, which is detrimental to the proper operation of the filter. The filtration rates may be regulated either at the inlet (inlet control) or at the outlet (outlet control). Accordingly, there are two filter rate control systems, such as constant rate and declining rate filtration systems. In constant rate filtration, the filtration rate is maintained constant throughout the filter run. It is further classified into constant rate filtration with rate controllers and constant rate filtration with the increasing water level. Inlet control may be used in the case of small, gravity flow systems in remote locations where daily flow regulation will be difficult. Outlet control may be adopted where it will not be difficult to provide daily flow regulation (BIS: 11401 Part 2, 1990).

2.2.1 Particle Removal Mechanisms

The particle removal mechanisms during treatment process are straining, interception, settling, adhesion, biological adsorption, inertial impaction, electrolytic action, charge neutralization and ion exchange.

2.2.2 Filter Clogging and Development of Headloss

Due to the deposition of solids on the filter media, the porosity decreases and specific deposit increases. As a result, the driving force of water is prevented and the filter run is decreased. It causes the filter velocity to drop below a predetermined level resulting in the exhaustion of storage capacity of the filter bed.

Clogging is defined as the formation of a semi-permeable layer throughout a range of depths due to which there is a build-up of head loss (pressure drop) across the filter media. It is mainly responsible for the blockage of media pores by suspension and sedimentation of insoluble matter, leading to a breakthrough, a condition in which already overloaded filters can no longer remove solids. Head loss is an indicator to start filter washing (Akinmolayan, 2017). Hence the filter is generally operated until just before clogging or breakthrough occurs (EPA, 1995). Sometimes the solids begin to appear in the effluent. The filter must be back washed at this point.

2.2.3 Backwashing

Backwashing is the process of reversing the flow of water through the filter media to remove the entrapped solids. It results in poor performance of the filter. It may comprise the application of water alone, air, and water separately and sequentially or air and water simultaneously (EPA, 1995).

As the particles accumulate, the porosity changes with time. Generally, the backwash flow rate equal to 10% of the settling velocity of the media is used for backwashing. The solids concentration in the filter backwash ranges from 0.01 to 0.1 percent depending on the efficiency of the filter and the degree of pre-treatment provided (CPHEEO, 1999). According to EPA (1995), the maximum backwash water flow rate should not exceed 20 m/hr, as higher flow rates will result in excessive media loss. The filter bed should be expanded by a minimum of 10% and a maximum of 20% to ensure adequate cleaning. In order to ensure effective backwashing, the upper media layer must have a settling velocity compatible with that of the bottom media layer.

2.2.3.1 Hydraulics of Backwashing Process

The filters are given a backwash to remove impurities present in the medium. As the water moves upward through the media, frictional resistance is offered by the filter grains due to skin friction and form drag. Low backwash velocity may result in the orientation of the particles to minimize frictional resistance. The filter media does not expand, and its porosity does not change. Thus at low velocities, the head loss is a linear function of upward flow velocity. The frictional resistance increases with an increase in velocity until it reaches a value equal to the gravitational force acting upon the filter grains. Any further increase in the velocity fluidizes the media resulting in bed expansion and an increase in porosity. Backwashing is done in such a way that 40-50% bed expansion occurs during the process. It is observed that optimal cleaning occurs at bed expansion of 16-18% only (CPHEEO, 1999).

2.3 SUMMARY OF LITERATURE

The applications of slag are manifold in water and wastewater treatment.

- The adsorption and chemical precipitation may sometimes encounter physical clogging.

- The recovery or regeneration technologies are found to be useful only for a small duration.

- Innovative researches are being done in constructed wetlands using slag as media, but its longevity is to be determined.

- Since the slag is disposed of in large quantities around the premises of ferrous industries, its effective utilization in pollution remediation technology should be strongly appreciated.

- The literature strongly manifests the need for further studies for reusing ferrous slag in water/wastewater treatment, which would be effectively, efficiently, and environmentally managed for a long duration.

2.4 LITERATURE GAP

- Most of the wastewater treatment studies are on adsorption using slag combined with other naturally available/ processed materials.

- Only a few literature is available on water treatment using slag in which it is combined with other filters such as a roughing filter.

- So far, no technology has been developed based on slag alone as filter media for drinking water treatment.

In this regard, an initiative has been made to develop a filter using ferrous slag as media.

CHAPTER 3

MATERIALS AND METHODS

The granulated blast furnace slag was collected from Kirloskar Ferrous Industries Limited, Bevinahalli, Koppal District, Karnataka, India. The slag samples were collected from different locations within the slag dump yard and was transported to the laboratory at National Institute of Technology, Karnataka. It was then stored carefully in the laboratory at room temperature. Figure 3.1 shows the granulated blast furnace slag.

Figure 3.1 Granulated Blast Furnace Slag

The natural river sand and charcoal needed for the present study were sampled and stored in the laboratory at National Institute of Technology, Karnataka.

3.1 EXPERIMENTAL METHODOLOGY

Laboratory tests were performed to find the characteristics of slag and natural river sand such as, specific gravity (BIS: 2720 Part 4 1985), bulk density (BIS: 2386 Part III 1963), grain size analysis (BIS: 2720 Part 3 1980) and permeability (BIS: 2720 Part 7 1986).

The slag and sand samples were oven dried for a period of 24 hours at a temperature of about 100±10°C prior to tests.

The pH was determined by mixing a 3 g slag sample with 75 ml distilled water. The suspension was stirred and allowed to stand for 1 hour and the average pH of the samples was found (BIS: 2720 Part 26, 1987). The chemical composition of slags such as silica (SiO_2), alumina (Al_2O_3), ferric oxide Fe_2O_3), calcium oxide (CaO) and magnesium oxide (MgO) were also analysed as per BIS: 1727, 1967. The impurities such as clay, loam, silt etc. (BIS: 8419 Part I, 1977), acid solubility and loss on ignition (BIS: 8419 Part I, 1977) respectively were also carried out.

The granulated slag was ground, powdered and sieved through a 105-micron sieve and the sample less than 105-micron sieve was then subjected to various studies. The samples were characterised for surface morphology and elemental composition using FESEM (Field Emission Scanning Electron Microscopy consisting of Carl Zeiss Gemini column) and EDX (Oxford Instruments, Energy Dispersive X-Ray Spectrometer with Gold sputtering unit). Diffraction pattern with mineralogical composition was determined using XRD (X-Ray Diffraction, Rigaku Miniflex 600 XRD, Cu K_α radiation ($\lambda = 1.54$Å), 40kV voltage, 15mA current, with a scanning rate of 1^o per min and 2θ range from $5\text{-}90^o$). Functional groups were found out by FTIR (Fourier Transform Infrared Spectroscopy, Bruker Alpha II, wavenumber range from 350-4000 cm^{-1}).

The presence of heavy metals in blast furnace slag such as lead, cadmium, chromium, copper, manganese and zinc were analysed through Atomic Absorption Spectroscopy (GBC 932 Plus) by acid digestion. The batch leaching with distilled water and toxicity characteristic leaching procedure was also performed to determine the release of these metals into the leachate. For distilled water leaching test, 5 g sample was mixed with 25 ml distilled water and was shaken in a rotary shaker for 24 hr. For TCLP test, 4 g sample was mixed with 20 times extraction fluid, 1M sodium acetate buffer and shaken in a rotary shaker for 18 hr with 30±2 rpm (USEPA Method 1311, 1972; Sarode *et al*., 2010; Tiwari *et al*., 2015). The leachate was then filtered using 42 No filter paper, diluted to 100 ml and analysed for various heavy metals. The treated water from the slag filter samples in triplicate were also tested to analyse the presence of heavy metals.

3.2 EXPERIMENTAL SET-UP OF FILTERS

The experimental set-up of filters for the present study were done at the Environmental Engineering Laboratory of National Institute of Technology Surathkal, Karnataka, India. Figure. 3.2 depicts the schematic of the slag, sand and dual media filter set-up.

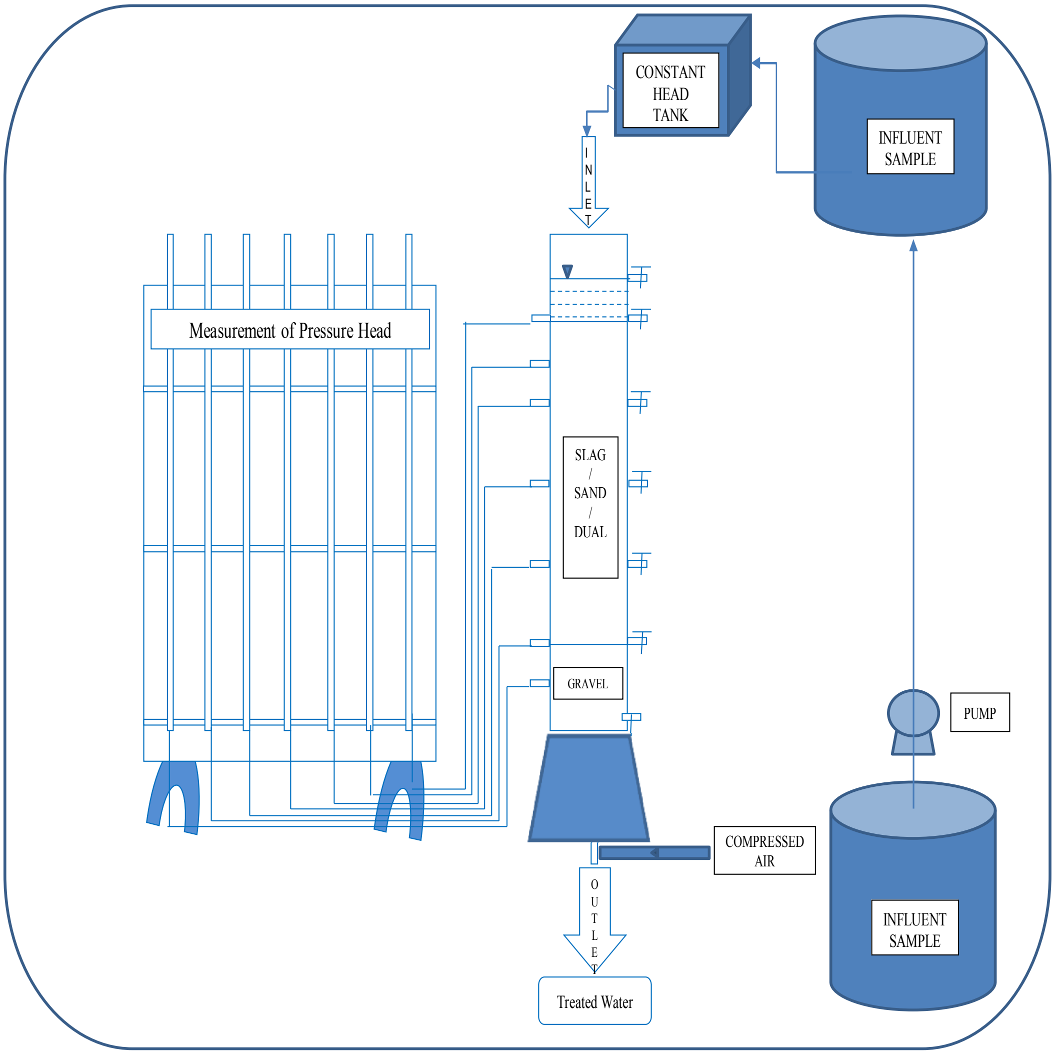


Figure 3.2 Schematic Diagram of Slag, Sand and Dual Media Filter Set-up

The synthetic influent was taken to an overhead tank from where it was taken to a constant head tank. The influent was allowed to flow downwards through the filter and a constant influent level was maintained at the top and the effluent was collected though the bottom. Openings are provided in the filter to measure the head loss.

3.2.1 Ferrous Slag Filter

The laboratory-scale filter assembly comprised of slag filter media supported on gravel bed confined in an acrylic column of 100 mm external diameter, 10 mm thickness and 650 mm length clamped vertically using a filter holder. Various brass openings of 5 mm inner diameter were provided at different lengths 50 mm, 100 mm, 200 mm, 300 mm, 400 mm, 450 mm and 500 mm from the top to the bottom of the filter column as shown in Figure 3.3.

Figure 3.3 Laboratory Scale Acrylic Column Filters

One end of the transparent tube is connected to the brass opening and the other end is connected to a manometer fitted with a measuring scale as shown in Figure 3.4.

Figure 3.4 Experimental Set-up of Filters with Manometer

The filter bed was 400 mm deep. The sizes of slag retained on IS sieves 1.18 mm (layer 1 at top), 600 µm (layer II), 450 µm, 300 µm (layer III) and 150 µm (layer IV at bottom) respectively were used up to a height of 400 mm.

3.2.2 Sand Filter

The sand filter assembly was similar to the slag filter with sand as filter media, supported on a gravel bed. The filter bed of sand was 400 mm height with sand retained on IS sieves of the same dimensions as that of the slag filter.

3.2.3 Slag and Charcoal as Dual Media

The dual media filter was made up of charcoal over granulated blast furnace slag, each of 20 cm depth. Charcoal of size passing through 10 mm and retained on 4 mm and slag retained on IS sieves 1.18 mm, 600 µm, 450 µm, 300 µm and 150 µm respectively were filled up in the column.

Gravel layer of 100 mm was used as supportive media to enable uniform and better distribution of water during filtration and backwashing. All the media were thoroughly washed with tap water and were filled in the column filters. Figure 3.5 (a), (b) and (c) shows slag, sand and dual media filters respectively.

(a) **(b)** **(c)**

Figure 3.5 (a) Slag (b) Sand and (c) Dual Media Filters

As shown in Figure 3.6, the sample was initially taken from a 50 L vessel at a flowrate of 2 Lhr^{-1} but a constant head could not be maintained at the inlet all the time.

Figure 3.6 Experimental Set-up of Slag and Sand Filters for Small Flowrate

In order to reduce the flow variations, the influent was pumped using 0.25 HP centrifugal pump and stored in a 300 L capacity tank. It was allowed to flow downwards to a constant head rectangular tank (400 mm x 300 mm x 300 mm) made of glass fitted with a float valve arrangement to ensure a continuous rate of flow. The outlet of the constant head tank was provided 50 mm above the tank bottom and was connected to the inlet valve at the top of the slag, sand and dual media filters as shown in Figure 3.7

Figure 3.7 Experimental Set-up with Constant Head Tank

The laboratory set up was used to provide basic performance and hydraulic data. A constant head of 500 mm water was always maintained above the top surface of media of each filter by providing a control valve at the bottom of the feed tank and excess water coming at the top of the filter was taken out through an overflow valve and collected in a vessel. It was then recirculated to the feed tank/ constant head tank using a peristaltic pump. Adequate depth of water above the media surface is essential to ensure that the inflow does not disturb (scour) the media. The filter was also provided with a constant rate outlet control system. The head losses at various ports of the filters were determined by using a manometer fitted with a measuring scale. The filter pressure drop was the difference in head measured between the influent constant water level at the top of the filter and the head available at various ports and the treated water level.

As the filtration progressed, deposition of particles on the top surface and within the depth of the filter increased the head loss. Even though the filter media was clogged, the quality of filtered water was acceptable since the accumulated particles within the media also assisted in further straining out of suspended impurities. Backwashing process generally arises when there is an increase in head loss or a decrease in the quality of water. Hence it is evident from preliminary studies of filtration without backwash that the filter to be washed for every change in loading and filtration rate for further experimentation.

The filters are generally backwashed to remove the deposited sediments on the surface of the media. In the present study, filters were washed when there were changes in loading and filtration rates. An acrylic tube of 90 mm internal diameter and 650 mm long was connected to the top of the filter column during backwashing to take care of the bed expansion as shown in Figure 3.8. The filter backwash rate was 20-25 cm min^{-1} and continued for 15-30 minutes. It was ensured that 40-50% expansion of media took place throughout backwashing period.

Figure 3.8 Filter Backwash Arrangement

The manometer stand was fixed at a higher level to take care of increased head while backwashing. The final set-up is shown in Figure 3.9.

Figure 3.9 Experimental Set-up with Backwash Arrangement

3.3 WORKING OF FILTERS

The influent water was prepared daily by mixing tap water with varying amounts of Kaolin ($Al_2Si_2O_5(OH)_4$), Calcium Chloride ($CaCl_2$), Sodium Sulphate (Na_2SO_4), Potassium Nitrate (KNO_3) and Ferric Chloride ($FeCl_3$) (Merck, India). The influent was then pumped using 0.25 HP centrifugal pump and stored in a 300 L capacity tank. It was allowed to flow downwards to a constant head rectangular tank (400 mm x 300 mm x 300 mm) made of glass fitted with a float valve arrangement to ensure a continuous rate of flow. The outlet of the constant head tank was provided 50 mm above the tank bottom and was connected to the inlet valve at the top of the slag, sand and dual media filters. The characteristics of influent water at different combinations are shown in Table 3.1 and Table 3.2. The influent water was allowed to flow downwards through the filter columns containing media. One cycle of operation was fixed as 8 hours per day throughout the study period. The filters were run under different operating conditions such as varying loadings and filtration rates of influent and the quality of treated water from the filter outlet were studied. The filters were provided with a continuous rate outlet control system.

Table 3.1 Details of Parameters for Various Concentration Levels

Parameters	Concentration1 (mean)	Concentration2 (mean)	Concentration3 (mean)	Limit as per BIS:10500, 2012
Turbidity (NTU)	9.81 (<15)	27.49 (15-30)	32.94 (>30)	Acceptable Limit - 1 NTU Permissible Limit - 5 NTU
Hardness (mg L^{-1})	535.78 (500-550)	575.96 (550-600)	626.30 (600-650)	Acceptable Limit - 200 mg L^{-1} Permissible Limit - 600 mg L^{-1}
Sulphate (mg L^{-1})	289.13 (260-300)	325.75 (300-340)	360.36 (340-380)	Acceptable Limit - 200 mg L^{-1} Permissible Limit - 400 mg L^{-1}
Nitrate (mg L^{-1})	89 (70-100)	113.52 (100-130)	144.74 (130-160)	Acceptable Limit - 45 mg L^{-1} Permissible Limit - No relaxation
Chloride (mg L^{-1})	303.20 (275-325)	335.07 (325-375)	383.31 (375-425)	Acceptable Limit - 250 mg L^{-1} Permissible Limit - 1000 mg L^{-1}
Iron (mg L^{-1})	2.04 (<2.5)	3.17±0.56 (2.5-4.0)	4..32±1.19 (>4)	Acceptable Limit - 0.3 mg L^{-1} Permissible Limit - No relaxation

Table 3.2 Observed values of Parameters at Different Concentration Levels

Parameters	Concentration1 (mean)	Concentration2 (mean)	Concentration3 (mean)	Limit as per BIS:10500, 2012
pH	7.22	6.94	6.11	6.5-8.5
EC (µS cm^{-1})	1109	1176	1333	-----
TDS (mg L^{-1})	687.33	739.13	826.43	Acceptable Limit - 500 mg L^{-1} Permissible Limit - 2000 mg L^{-1}
TSS (mg L^{-1})	44.711	125.332	150.206	-----
Colour (PCU)	103.50	201.25	287.75	Acceptable Limit - 5 PCU Permissible Limit - 15 PCU

The water quality analysis was done for pH, EC, turbidity, total suspended solids (TSS), total dissolved solids (TDS), colour, hardness, sulphate, nitrate, chloride and iron based on APHA (2005). The enumeration of all *Coliform* along with a differential count of *E. coli* was done using HiTouch *E.coli*/*Coliform* Count Flexi Plate FL002. The cultural characteristics were observed after incubation at 44°C for 18-24 hours. Growth of bluish-purple colonies indicate the presence of Escherichia Coli and red to maroon colonies indicate the presence of non-E coli.

3.4 COMPARISON OF HEADLOSS OF SLAG FILTER WITH EXISTING MATHEMATICAL MODEL

3.4.1 Head Loss through Clean Filter Media using Carmen-Kozeny Equation

The following expression can be used to calculate the head loss through a clean filter media

$$H_L = \left(\frac{f}{\phi}\right)\left(\frac{L}{D_p}\right)\left(\frac{1-\varepsilon}{\varepsilon^3}\right)\left(\frac{V^2}{g}\right) \text{ .... } (3.1)$$

Friction factor, $f = 150\frac{(1-\varepsilon)}{N_R} + 1.75$ and Reynold's Number, $N_R = \frac{\rho\, V\, D_p}{\mu}$

ϕ shape factor

L	filter bed depth (m)
D_p	effective size of the particle (m)
ε	porosity
V	fluid velocity (m s^{-1})
g	acceleration due to gravity (m s^{-2})
μ	viscosity of water (N s m^{-2})

3.4.2 Equation for Head Loss through Clogged Filter Media

According to Mays and Hunt (2005) and Han *et al*. (2008), the expression for hydraulic gradient within a clogged filter is given by

$$J = J_o \left(1 + \frac{\gamma}{\rho_p} \sigma\right)^2 \quad \text{……………………………………………………….(3.2)}$$

γ is an empirical parameter which is related to the flow rate, particle surface area to volume ratio, filter grain size and clean filter bed porosity and can be expressed as

$$\gamma = \gamma_o \, u^{-0.55}$$

γ_o is a constant for a specific filtration system varying from 25-30.

Therefore, head loss through the filter w, $J = J_o \int_0^L \left(1 + \frac{\gamma}{\rho_p} \sigma\right)^2 dz$ …………(3.3)

J_o	hydraulic gradient in the clean filter bed (calculated by Carman-Kozeny equation or experimentally obtained)
L	filter bed depth (m)
σ	specific deposit (mg L^{-1})
ρ_p	particle density (kg m^{-3})
z	position in the filter bed (m)

Due to the accumulation of impurities, porosity of the filter bed decreases and specific deposit increases. The porosity and specific deposit vary with time and depth. The specific deposit is calculated as the volume of the deposit of the turbidity causing material per unit volume of the influent which can be found out from the influent turbidity of the turbidity causing material in units or mg L^{-1} and the specific gravity of the turbidity causing material. (Bhargava and Ojha, 1999).

3.5 Statistical Analysis

All the statistical analyses were performed using IBM SPSS Statistics 23. Statistically significant differences were determined at $p=0.05$ using the factorial test. LSD (Least Significant Difference) and Tukey HSD (Honestly Significant Difference) tests were conducted to determine multiple pairwise comparisons based on the nature and magnitude of these differences.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter deals with the results of characteristic studies of slag and its performance in a column filter for water treatment. It discusses the performance of a slag filter with that of a sand filter and a dual media filter made of slag and charcoal. The chapter also compares the head loss in the slag filter with existing mathematical model.

4.1 STUDIES ON SLAG AS FILTER MEDIA FOR WATER TREATMENT

4.1.1 Physical Properties of Slag

Various physical properties were determined to assess the suitability of slag as a filter media. The specific gravity of slag was found to be low, around 1.65 as compared to sand and was light in weight. The results of dry sieve analysis of raw slag showed that coarse and fine fractions were 2.2% and 5%, respectively. Almost 92.08% was sand-size particles. The percentage values reported in the literature were high for medium sand (0.425–0.85 mm) and 2.10% for silt-clay particles (Hizon-Fradejas *et al*., 2009). It was non-plastic in nature and found to be highly permeable. The physical properties of slag are listed in Table 4.1.

Table 4.1 Physical Properties of Raw Slag

Properties	Value
Specific gravity	1.65
Porosity	0.58
Effective size, D_{10}	0.29
Uniformity coefficient, C_u	5.17
Permeability, k	2.63×10^{-4} cm s^{-1}

4.1.2 Chemical Properties of Raw Slag

The chemical properties of slag are given in Table 4.2. The average pH of the samples were found to be 9.0. This would imply that it is good for slightly acidic ground water treatment also. The pH of the slag reported by Kietlińska and Renman (2005) was 9.13, but high values ranging from 9.7–12.2 were also observed due to the dissolution of Ca content of the slag into the solution (Isawa, 2013; Hizon-Fradejas *et al*., 2009; Lu *et al*., 2008). The acid soluble matter was above 5% and loss on ignition around 2.18 %, which indicated the presence of organic matter. The impurities such as clay, loam silt etc. were less than 5%.

Table 4.2 Chemical Properties of Raw Slag

Properties	Value
pH	9.0
Acid-soluble matter	6.49 %
Loss on ignition	2.18 %
Impurities such as clay, loam, silt, etc	4 %

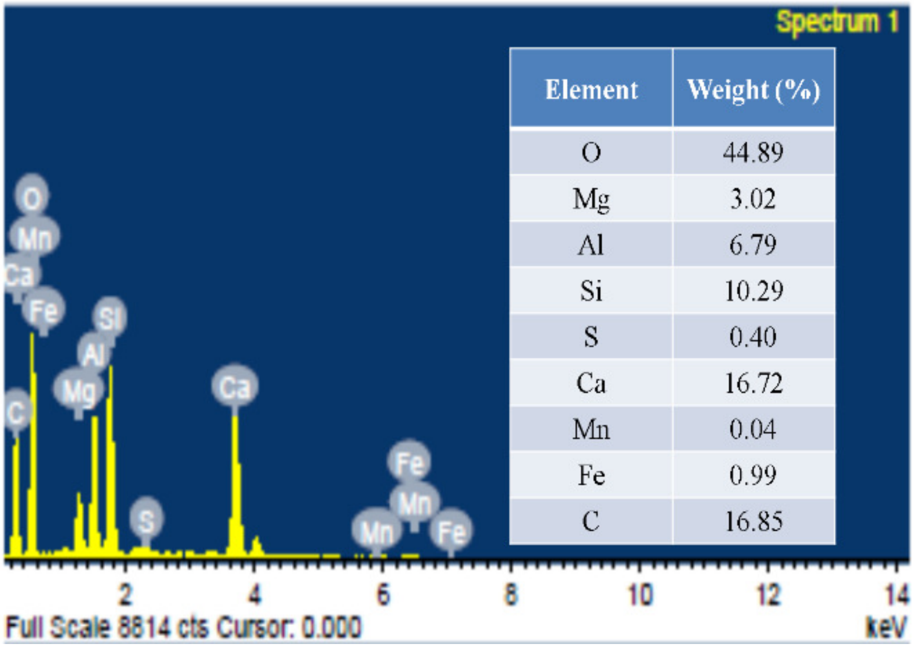
4.1.3 Composition of Slag

The chemical composition of slag used in the study is given in Table 4.3. The average values of CaO and SiO_2 amounts of the slag in the present study were found to be in the range similar to that reported by Lewis (1982); Hedström and Rastas (2006); and Hallberg and Renman (2008). The Al_2O_3 values were found to be higher than that reported by Dimitrova and Mehenjeiv (2000); Kietlińska and Renman (2005); Lu *et al*. (2008); Johansson (1999). The Fe_2O_3 concentration was almost similar to the observations of Hizon-Fradejas *et al*. (2009) and Hallberg and Renman (2008).

The elemental composition as analysed by EDX and the images using FESEM at different magnifications are depicted in Figure 4.1 and Figure 4.2 respectively. The images of the raw slag showed the highly porous texture of slag, which indicates its suitability for use as an adsorbent.

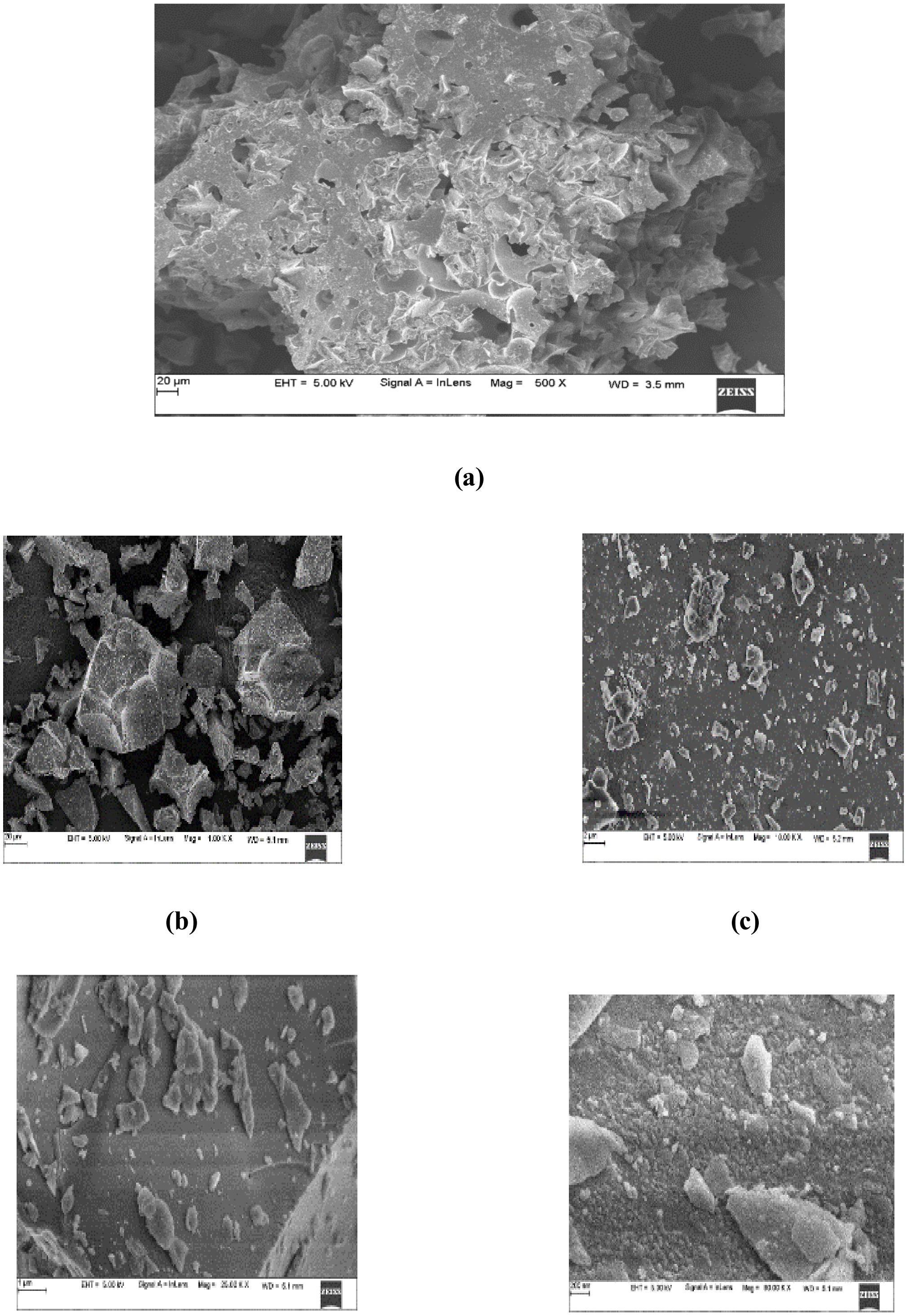
Table 4.3 Composition of Raw Slag

Chemical composition	Value (%)
SiO_2	34.6
Al_2O_3	20.0
CaO	32.0
MgO	12.0
Fe_2O_3	0.6



Element	Weight (%)
O	44.89
Mg	3.02
Al	6.79
Si	10.29
S	0.40
Ca	16.72
Mn	0.04
Fe	0.99
C	16.85

Figure 4.1 Elemental Composition of Slag



(a)

(b) (c)

(d) (e)

Figure 4.2 SEM Images of Slag at (a) 500 X (b) 1KX (c) 10 KX (d) 25KX and (e) 90KX

4.1.4 Results of XRD and FTIR Analysis of Slag

The irregular X-ray diffraction spectra of granulated slag represented its amorphous nature since no significant peaks were found, as shown in Figure 4.3.

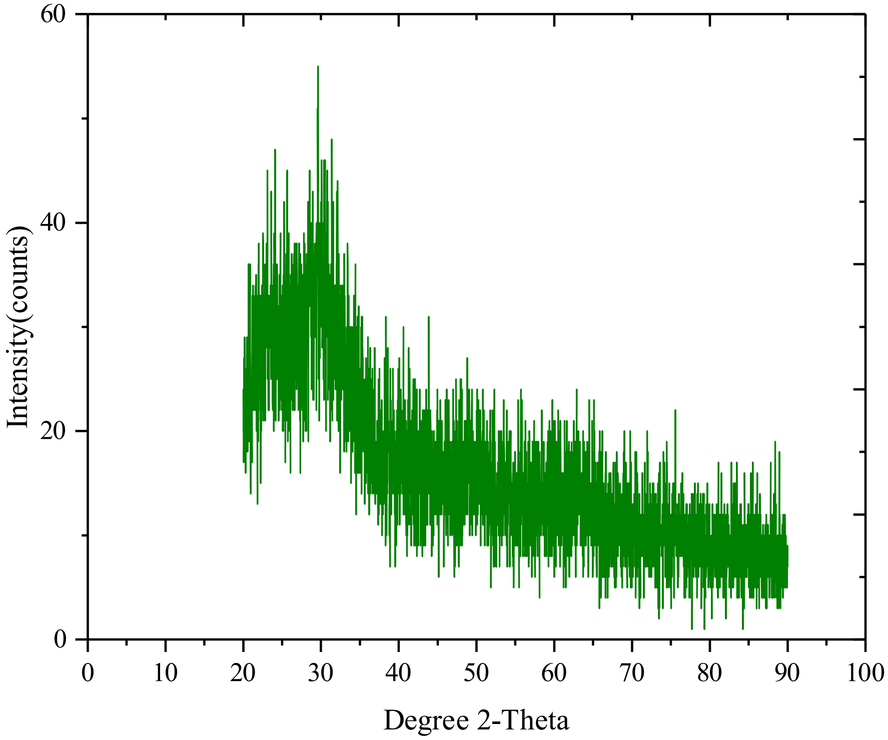


Figure 4.3 XRD Spectrum of Blast Furnace Slag

Figure 4.4 shows the functional groups identified in the raw slag using FTIR. The adsorption band of 3613 cm^{-1} corresponded to OH whereas bands such as 1698 cm^{-1}, 1649 cm^{-1} and 1520 cm^{-1} indicated H-O-H bending mode of vibrations of molecularly bound water of crystallization. The wavenumber 978 cm^{-1}(1250-950 cm^{-1}) showed Si-Al-Si asymmetric stretching vibrations (Sivasankar and Ramachandramoorthy, 2011; Kumar *et al*., 2013), 689 cm^{-1} (720-650 cm^{-1}) assigned to Si-Al-O symmetric stretching and 495 cm^{-1} and 451 (420-500 cm^{-1}) corresponded to Si-Al-O bending mode and 411 cm^{-1}for Fe-O group.

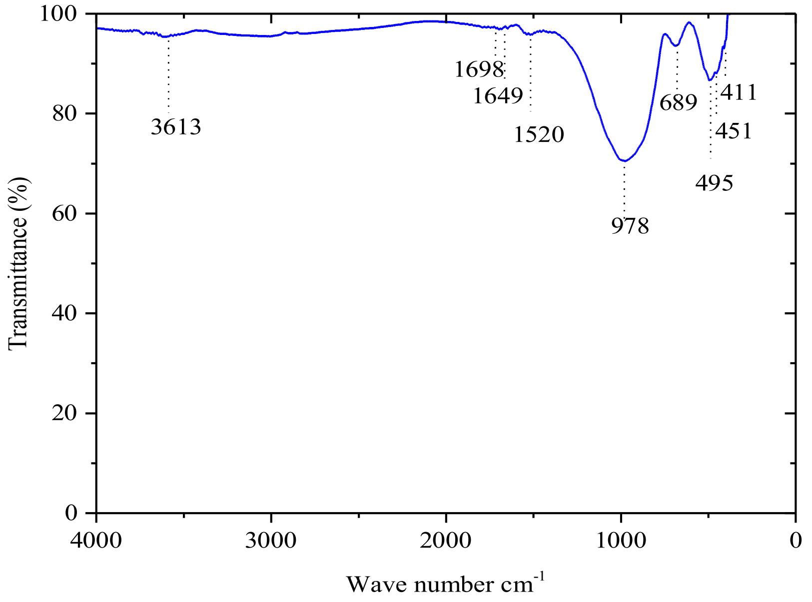


Figure 4.4 FTIR Spectrum of Raw Slag

Table 4.4 shows the mean values of heavy metals present in raw slag as analysed using acid digestion test (ADT), distilled water leaching test (DWLT), and toxicity characteristic leaching procedure (TCLP). Even though the slag samples contain heavy metals, the leaching of metals from the sample was less particularly in DWLT compared to TCLP. In the present study, the TCLP conducted at acidic pH indicated a higher concentration of elements in the leachate compared to the DWLT operated at the neutral condition.

Table 4.4 Mean Values of Heavy Metals in Raw Slag

Test	**Pb (mg g^{-1})**	**Cr (mg g^{-1})**	**Cd (mg g^{-1})**	**Cu (mg g^{-1})**	**Mn (mg g^{-1})**	**Zn (mg g^{-1})**
ADT	0.3381	0.0088	0.0518	0.0769	0.2110	0.0993
TCLP	0.0222	0.0058	0.0016	0.0057	0.0018	0.0027
DWLT	0.0087	0.0048	0.0000	0.0008	0.0015	0.0057

The test results of blast furnace slag reported by Kietlińska and Renman (2005) for Cr, Cu, and Zn were 46.4 ppm, 10.5 ppm, and 87.1 ppm, respectively. Hizon- Fradejas *et al*. (2009) obtained low values for Zn, Cu, Cr, and Cd in leaching test as 0.103 mg L^{-1}, 0.013 mg L^{-1}, 0.006 mg L^{-1}, and 0.003 mg L^{-1}, respectively. The ASTM water leachate test result reported by Proctor *et al*. (2000) showed 0.0038 mg $L^{-1}$for Cr, 0.0014 mgL^{-1} for Mn, and nil for Cd. The variation might be due to the pH difference between the extraction liquids and the leachate as pointed out by Tiwari *et al*. (2015). It is reported that iron slag might be used safely in aquatic systems without deteriorating water quality (IBM, 2014). It is also stated that slags are harmless and not showing any leaching behaviour (Kumar *et al*., 2016). According to Taylor (2006), even though slag had high total concentrations of trace metals compared to non-contaminated soil, only a little is likely to leach out into the environment, and there is minimal environmental or health hazard.

The treated water from the slag filter samples in triplicate were tested to analyse the presence of heavy metals such as Pb, Cr, Cd, Cu, Mn and Zn. Since the suspended solids were absent, water coming out from the slag filter was directly analysed using atomic absorption spectrometer. The heavy metals could not be detected in the treated water coming out from the slag filter and hence it is considered safe.

4.2 PERFORMANCE EVALUATION OF FERROUS SLAG FILTER WITH RESPECT TO THE WATER QUALITY PARAMETERS

The slag filter was operated for four different filtration rates designated as Run 1 (0.32 $m^3hr^{-1}m^{-2}$), Run 2 (0.64 $m^3hr^{-1}m^{-2}$), Run 3 (0.96 $m^3hr^{-1}m^{-2}$) and Run 4 (1.28 $m^3hr^{-1}m^{-2}$) with three concentrations namely Concentration1 (Low), Concentration2 (Medium) and Concentration3 (High) respectively as shown in Chapter 3 Table 3.1 and Table 3.2. Backwashing need generally arises when there is an increase in head loss or a decrease in the quality of water. In the present study, the slag filter is backwashed to remove the accumulated particles on the surface and within the medium of the filter and thereby increasing its performance. It was continued till the waste wash water was relatively free from impurities, and it was confirmed that all the piezometric heads were at the same level as that of the influent head after backwashing. The filter was subjected to intermittent backwashing with tap water after every five cycles of operation.

4.2.1 Removal of Physico-Chemical Impurities

The mean values of influent and treated water turbidity, TSS and colour with filtration rates for different runs are given in Table 4.5. The slag filter always showed more than 99% removal of turbidity, TSS and colour at all concentrations and filtration runs. The increased concentrations and filtration rates did not affect the removal of physical impurities.

Table 4.5 Mean Values of Turbidity, TSS and Colour for

Influent and Treated Water

Parameters	Influent Concentration	Treated Water Concentration			
		F1	F2	F3	F4
Turbidity (NTU)	9.81	0.00	0.00	0.00	0.00
	27.49	0.00	0.06	0.00	0.14
	32.94	0.00	0.00	0.04	0.24
TSS mg L^{-1}	44.711	0.00	0.00	0.00	0.00
	125.332	0.00	0.30	0.00	0.60
	150.206	0.00	0.00	0.20	1.10
Colour (PCU)	103.50	0.00	0.00	0.00	0.00
	201.25	0.00	0.00	0.00	0.00
	287.75	0.00	0.00	0.00	0.00

The concentrations of hardness for the influent and treated water are shown in Figure 4.5. The removal of hardness varied from 33-43% for all the loading rates. The presence of calcium and magnesium ions present in slag also might have contributed to hardness in filtered water.

The concentrations of sulphate for the influent and treated water are shown in Figure 4.6. The average removal of sulphate was 20.5% at 0.32 $m^3hr^{-1}m^{-2}$, and it declined rapidly. It might be attributed to the formation of end products in the form of aluminium, calcium and magnesium sulphates. Most often, the treated water contained more sulphate than influent. It showed that sulphate breakthrough occurred at higher filtration rates and media washing could not regain its efficiency even after backwashing.

Even though the nitrate loading was 144 mg L^{-1} at 0.32 $m^3hr^{-1}m^{-2}$, the treated water levels were always below 45 mg L^{-1}, which is the acceptable limit prescribed by BIS 10500, 2012. Initial nitrate efficiency varied from 68-86%, but a gradual decrease could be observed subsequently. Initially, chloride removal was more than 60%, and as the filtration velocity increased, the removal efficiency decreased considerably. In the case of chloride, backwashing was found to be effective to maintain a constant removal rate. The concentrations of nitrate and chloride for the influent and treated water are shown in Figure 4.7 and Figure 4.8, respectively.

The concentrations of iron for the influent and treated water are shown in Figure 4.9. The removal efficiency of iron was always above 90%.

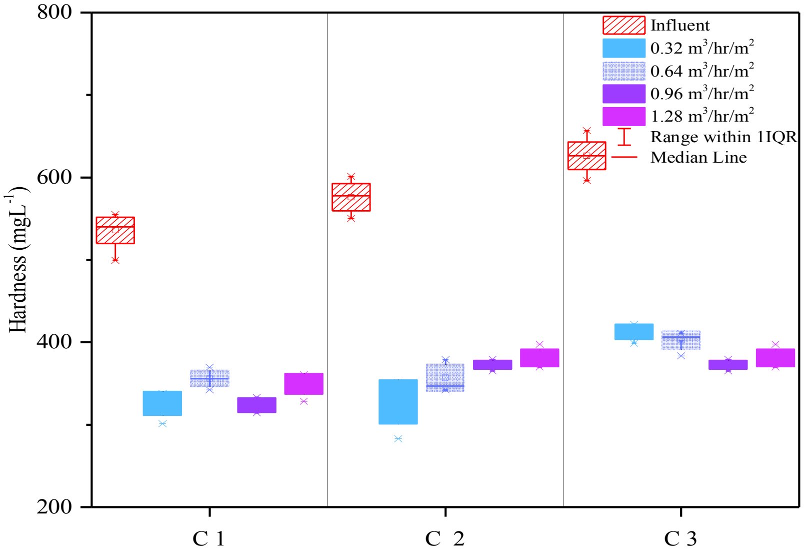


Figure 4.5 Concentrations of Hardness for the Influent and Treated Water

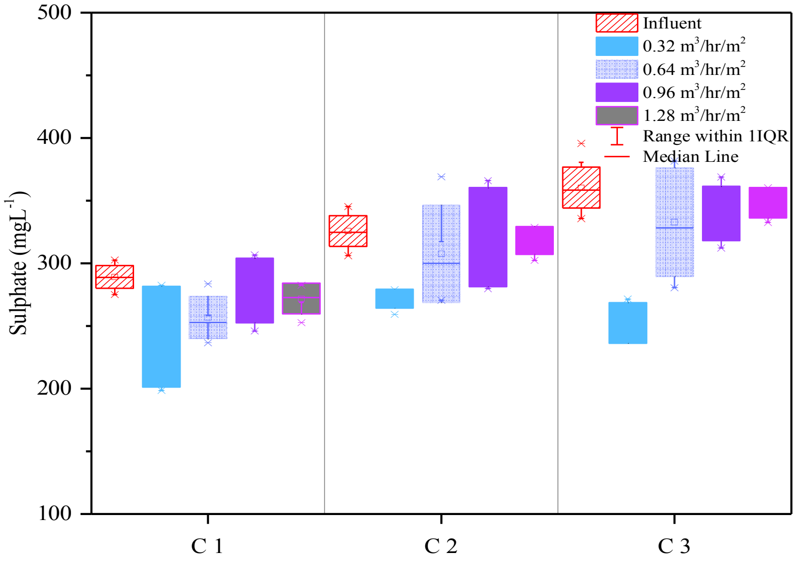


Figure 4.6 Concentrations of Sulphate for the Influent and Treated Water

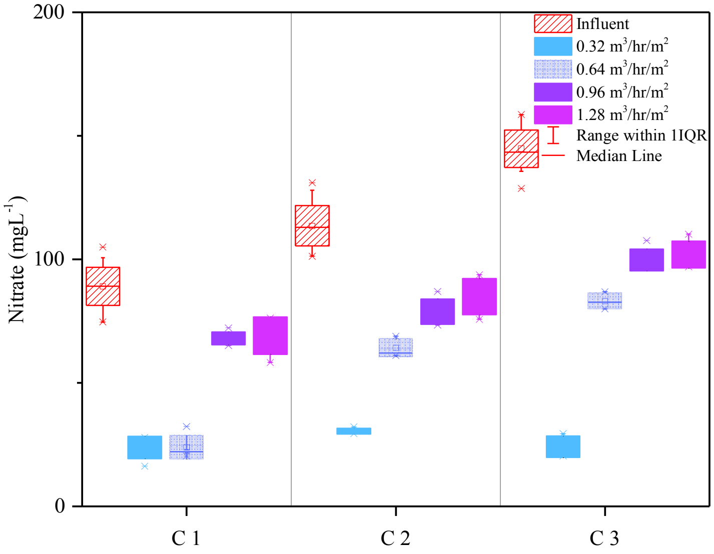


Figure 4.7 Concentrations of Nitrate for the Influent and Treated Water

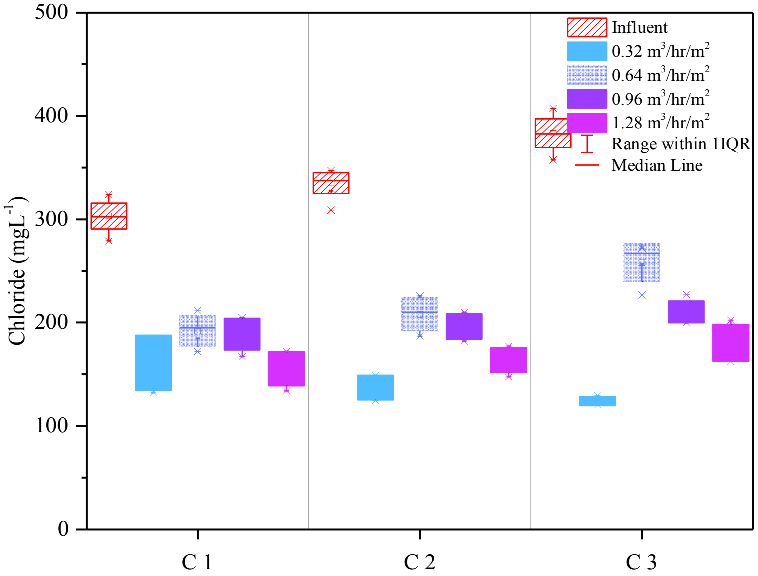


Figure 4.8 Concentrations of Chloride for the Influent and Treated Water

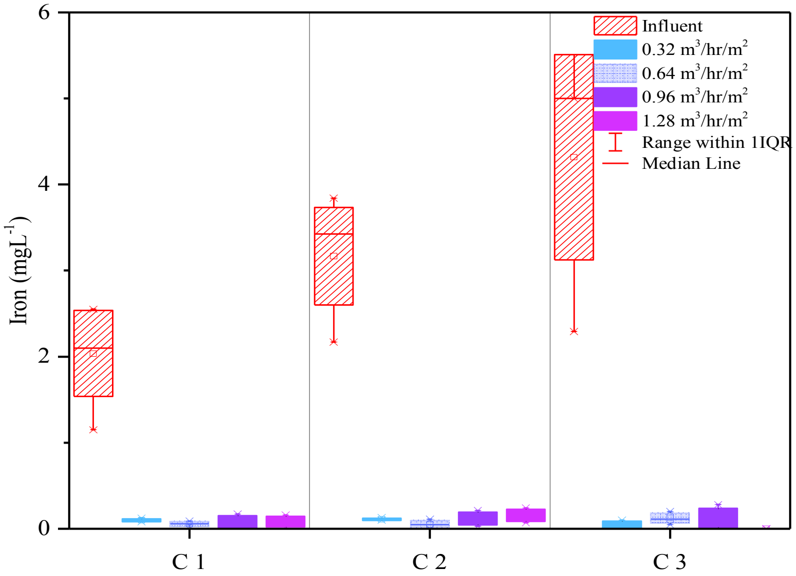


Figure 4.9 Concentrations of Iron for the Influent and Treated Water

4.2.1.1 Variation of pH and EC in a Slag Filter

Figure 4.10 shows the variation of pH and EC for various filtration rates (Run 1 to 4) and concentrations (C1 to C3). The electrical conductivity of treated water was less than that of the influent initially, for 0.32 $m^3hr^{-1}m^{-2}$, whereas it surpassed the influent conductivity levels at higher filtration rates several times. Total dissolved solids indicate the amount of cations and anions dissolved in water (Kumar *et al*., 2020). The mean values of pH of the treated water varied from 6.5 to 7.

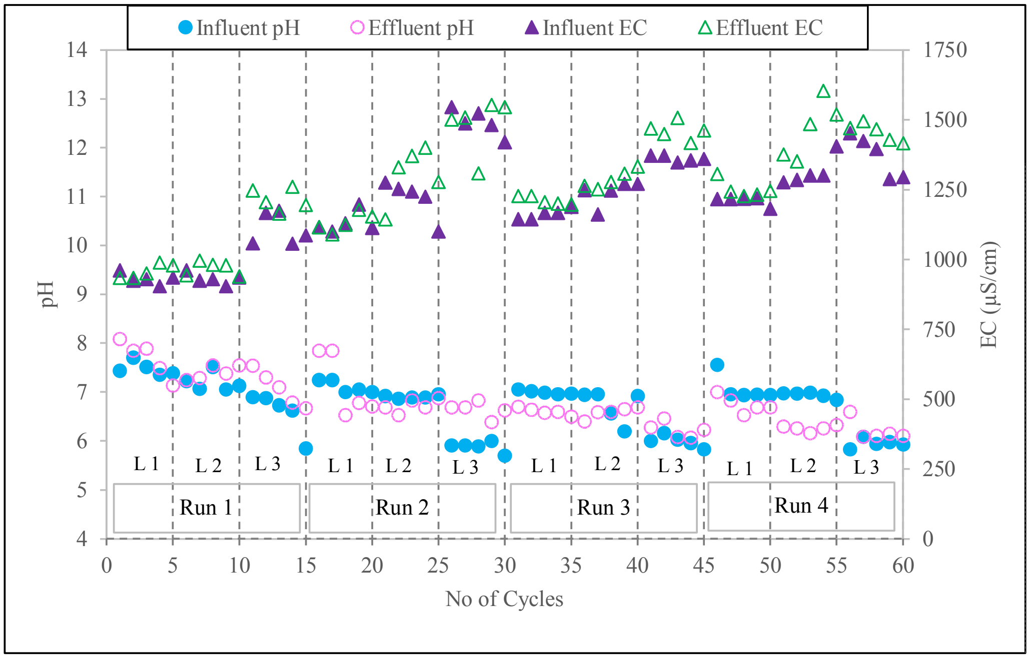


Figure 4.10 Variation of pH and EC in a Slag Filter

4.2.2 Statistical Analysis

Factorial experiments are employed when there are two or more factors and each factor at certain levels. It is generally used to evaluate the combined or interaction effect of different factors with more precision. In the present study, an asymmetrical factorial experiment with two factors viz., filtration rates and concentration each at four and three levels respectively. The four different filtration rates are designated as Run1 (0.32 $m^3hr^{-1}m^{-2}$), Run2 (0.64 $m^3hr^{-1}m^{-2}$), Run3 (0.96 $m^3hr^{-1}m^{-2}$) and Run4 (1.28 $m^3hr^{-1}m^{-2}$)

and concentrations as Concentration-1 (Low), Concentration-2 (Medium) and Concentration-3 (High) respectively.

The Analysis of Variance (ANOVA) results of the filtrate from the slag filter are shown in Table 4.6. The factorial ANOVA describes the individual effects of the two different factors, filtration rate and concentration as well as their interaction effects. There is no significant difference in the values of iron for different levels of concentrations ($p=0.474$) and filtration rates ($p=0.13$). There are significant variations in all other parameters concerning filtration rates and concentrations ($p\leq0.01$).

Interaction effects between filtration rates and concentrations show that the effects of pH ($p= 0.511$) and sulphate ($p= 0.126$) are insignificant, specifying that there is not much difference in values of pH and sulphate concerning treatments. But there are interaction effects between filtration rates and concentrations for parameters such as electrical conductivity, total dissolved solids, hardness, nitrate, chloride and iron at 1% level of significance.

Table 4.7 shows the Least Significant Difference test indicating the pairwise multiple comparison between concentrations. The three different concentrations are designated as Concentration-1 (Low), Concentration-2 (Medium) and Concentration-3 (High) respectively. The test results show that there were significant differences between 1 & 2, 1 & 3 and 2 & 3 for parameters such as pH, electrical conductivity, total dissolved solids, hardness and nitrate. Significant differences were also noticed between 1 & 2 and 1 & 3 for sulphate and 1 & 3 and 2 & 3 for chloride. There were no significant difference between 2 & 3 concentrations for sulphate ($p=0.116>0.05$) and 2 &1 concentrations for chloride ($p=0.668>0.05$). Similarly, for iron, all the pairwise comparisons between concentrations were found to be insignificant.

Table 4.8 represents the pairwise multiple comparison between different filter runs. The four different filtration rates are designated as Run1 (0.32 $m^3hr^{-1}m^{-2}$), Run2 (0.64 $m^3hr^{-1}m^{-2}$), Run3 (0.96 $m^3hr^{-1}m^{-2}$) and Run4 (1.28 $m^3hr^{-1}m^{-2}$) respectively. There are significant difference among all the filtration rates except runs 3 and 4 ($p= 0.522$) for pH, runs 3 and 2 ($p= 0.536$) for EC, runs 3 and 2 ($p= 0.536$) for TDS, runs 2 and 3 (p=

0.538) for hardness, runs 3 and 2 (p= 0.165), runs 3 and 4 (p= 0.987), runs 4 and 2 (p= 0.169) for sulphate and runs 4 and 3 (p= 0.084) for nitrate. But there are no significant difference for iron between runs 1 and 2 (p=0.785), runs 1 and 4 (p=0.927), runs 3 and 1 (p=0.251), runs 3 and 4 (p=0.216) and runs 4 and 2 (p=0.855).

Table 4.6 ANOVA Results for Filtrate

Tests of Between-Subjects Effects						
Source	**Dependent Variable**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	pH	12.172[a]	11	1.107	15.002	0
	EC	1857483.250[b]	11	168862.11	51.262	0
	TDS	714016.561[c]	11	64910.596	51.262	0
	Hardness	66400.040[d]	11	6036.367	32.375	0
	Sulphate	75605.997[e]	11	6873.272	9.446	0
	NItrate	48465.582[f]	11	4405.962	188.166	0
	Chloride	72194.117[g]	11	6563.102	27.164	0
	Iron	0.110[h]	11	0.01	2.807	0.007
Intercept	pH	2755.799	1	2755.799	37362.97	0
	EC	96172956.15	1	96172956	29195.37	0
	TDS	36968884.34	1	36968884	29195.37	0
	Hardness	8193862.158	1	8193862.2	43946.851	0
	Sulphate	5221464.6	1	5221464.6	7175.967	0
	NItrate	235597.841	1	235597.84	10061.697	0
	Chloride	1972359.078	1	1972359.1	8163.372	0
	Iron	0.44	1	0.44	123.312	0
Run* Concentration	pH	0.393	6	0.065	0.888	0.511
	EC	123654.967	6	20609.161	6.256	0
	TDS	47532.969	6	7922.162	6.256	0
	Hardness	7345.015	6	1224.169	6.566	0
	Sulphate	7712.123	6	1285.354	1.766	0.126
	NItrate	4850.379	6	808.397	34.524	0
	Chloride	13953.184	6	2325.531	9.625	0
	Iron	0.086	6	0.014	4.012	0.002
Run	pH	9.18	3	3.06	41.489	0
	EC	1024974.983	3	341658.33	103.718	0
	TDS	394000.384	3	131333.46	103.718	0

	Hardness	5405.869	3	1801.956	9.665	0
	Sulphate	33476.513	3	11158.838	15.336	0
	NItrate	33885.99	3	11295.33	482.391	0
	Chloride	53915.344	3	17971.781	74.383	0
	Iron	0.009	3	0.003	0.849	0.474
Concentration	pH	2.598	2	1.299	17.615	0
	EC	708853.3	2	354426.65	107.594	0
	TDS	272483.209	2	136241.6	107.594	0
	Hardness	53649.156	2	26824.578	143.871	0
	Sulphate	34417.361	2	17208.681	23.65	0
	NItrate	9729.213	2	4864.606	207.753	0
	Chloride	4325.589	2	2162.794	8.952	0
	Iron	0.015	2	0.008	2.13	0.13
Error	pH	3.54	48	0.074		
	EC	158117.6	48	3294.117		
	TDS	60780.405	48	1266.258		
	Hardness	8949.569	48	186.449		
	Sulphate	34926.347	48	727.632		
	NItrate	1123.935	48	23.415		
	Chloride	11597.32	48	241.611		
	Iron	0.171	48	0.004		
Corrected Total	pH	15.712	59			
	EC	2015600.85	59			
	TDS	774796.967	59			
	Hardness	75349.609	59			
	Sulphate	110532.345	59			
	NItrate	49589.518	59			
	Chloride	83791.437	59			
	Iron	0.282	59			

a. R Squared = .775 (Adjusted R Squared = .723)	e. R Squared = .684 (Adjusted R Squared = .612)
b. R Squared = .922 (Adjusted R Squared = .904)	f. R Squared = .977 (Adjusted R Squared = .972)
c. R Squared = .922 (Adjusted R Squared = .904)	g. R Squared = .862 (Adjusted R Squared = .830)
d. R Squared = .881 (Adjusted R Squared = .854)	h. R Squared = .391 (Adjusted R Squared = .252)

Table 4.7 LSD Test for Multiple Comparisons between Concentrations

Dependent Variable	(I) Loading	(J) Loading	Mean Difference (I-J)	Std. Error	Sig.
pH	1	2	0.3030*	0.0859	0.001
	1	3	0.5065*	0.0859	0
	2	3	0.2035*	0.0859	0.022
EC	2	1	118.8500*	18.1497	0
	3	1	265.7500*	18.1497	0
	3	2	146.9000*	18.1497	0
TDS	2	1	73.6870*	11.2528	0
	3	1	164.7650*	11.2528	0
	3	2	91.0780*	11.2528	0
Hardness	2	1	20.7770*	4.3180	0
	3	1	71.2155*	4.3180	0
	3	2	50.4385*	4.3180	0
Sulphate	2	1	42.5875*	8.5301	0
	3	1	56.2370*	8.5301	0
	3	2	13.6495	8.5301	0.116
Nitrate	2	1	18.3710*	1.5302	0
	3	1	31.0160*	1.5302	0
	3	2	12.6450*	1.5302	0
Chloride	2	1	2.118	4.9154	0.668
	3	1	18.9770*	4.9154	0
	3	2	16.8590*	4.9154	0.001
Iron	1	3	0.005	0.0189	0.792
	2	1	0.031	0.0189	0.107
	2	3	0.036	0.0189	0.063

Based on the observed means.

The error term is Mean Square (Error) = .004.

*. The mean difference is significant at the .05 level.

Table 4.8 LSD Test for Multiple Comparisons between Filter Runs

Dependent Variable	(I) Run	(J) Run	Mean Difference (I-J)	Std. Error	Sig.
pH	1	2	0.5540*	0.09917	0
	1	3	0.9207*	0.09917	0
	1	4	0.9847*	0.09917	0
	2	3	0.3667*	0.09917	0.001
	2	4	0.4307*	0.09917	0
	3	4	0.064	0.09917	0.522
EC	2	1	260.1333*	20.95747	0
	3	1	273.2000*	20.95747	0
	3	2	13.0667	20.95747	0.536
	4	1	344.4667*	20.95747	0
	4	2	84.3333*	20.95747	0
	4	3	71.2667*	20.95747	0.001
TDS	2	1	161.2827*	12.99363	0
	3	1	169.3840*	12.99363	0
	3	2	8.1013	12.99363	0.536
	4	1	213.5693*	12.99363	0
	4	2	52.2867*	12.99363	0
	4	3	44.1853*	12.99363	0.001
Hardness	2	1	16.4420*	4.98597	0.002
	2	3	3.092	4.98597	0.538
	3	1	13.3500*	4.98597	0.01
	4	1	26.5713*	4.98597	0
	4	2	10.1293*	4.98597	0.048
	4	3	13.2213*	4.98597	0.011
Sulphate	2	1	43.7553*	9.84975	0
	3	1	57.6580*	9.84975	0
	3	2	13.9027	9.84975	0.165
	3	4	0.1607	9.84975	0.987
	4	1	57.4973*	9.84975	0
	4	2	13.742	9.84975	0.169
Nitrate	2	1	30.9360*	1.76693	0
	3	1	56.0493*	1.76693	0
	3	2	25.1133*	1.76693	0
	4	1	59.1647*	1.76693	0

	4	2	28.2287*	1.76693	0
	4	3	3.1153	1.76693	0.084
Chloride	2	1	78.4247*	5.67581	0
	2	3	20.6913*	5.67581	0.001
	2	4	52.7180*	5.67581	0
	3	1	57.7333*	5.67581	0
	3	4	32.0267*	5.67581	0
	4	1	25.7067*	5.67581	0
Iron	1	2	0.006	0.02182	0.785
	1	4	0.002	0.02182	0.927
	3	1	0.0253	0.02182	0.251
	3	2	0.0313	0.02182	0.157
	3	4	0.0273	0.02182	0.216
	4	2	0.004	0.02182	0.855
Based on observed means.					
The error term is Mean Square (Error) = .004.					
*. The mean difference is significant at the .05 level.					

4.2.3 Discussion on FTIR and XRD Results of Slag Before and After Treatment

Figure 4.11(a) shows the functional groups identified in the raw slag using FTIR. The changes in the peak value of the spectrum of slag after experimentation in Figure 4.11(b) indicates the participation of OH groups in the sorption process resulting in many hydration products of inorganic minerals and compounds. There was a shift in the OH group from 3613 cm^{-1} to 3694 - 3622 cm^{-1}representing the possibility of OH groups of Fe, Al and Si minerals (Maiti *et al*., 2010). Stretching vibrations at 1033cm^{-1} and 1010 cm^{-1} due to Si-O bonding, Al-OH bonding at 916 cm^{-1} and Si-Al-O stretch reaching at 690 cm^{-1}, Fe_2O_3 at 539 cm^{-1}, and Si-Al-O bonding at 471 cm^{-1} and 428 cm^{-1} could be visible for slag media after filtration. Hence it could be inferred that hydroxyl group present in slag can remove anionic pollutants such as NO_3^-, SO_4^{2-} and Cl^- by the ion-exchange mechanism.

As shown in Figure 4.12(a), the raw slag was amorphous in nature due to the lack of distinct peaks in the X-ray diffraction spectra as mentioned by Dimitrova and Mehanjiev (2000), Gong *et al*. (2009) and Chiang *et al*. (2014). The porous structure of slag could promote the sorption phenomenon to a considerable extent. Figure 4.12(b) displays the XRD spectra of samples of slag from the top of the filter where the peaks were obtained at 2 theta= 12.70°, 20.5°, 25.22°, 35.29°, 39.13°, 55.52° and 62.61°. These phases indicated the chemical reactions involved in slag forming various products of inorganic minerals and compounds (based on ICDD database) during chemical precipitation, adsorption and ion exchange. Hydroxyl forms were precipitated in the media as hydrates of a mixture of complex compounds of Ca, Al, Si, Mg, Mn etc. It is also inferred that the calcium and magnesium present in slag was getting replaced by sodium ions in solution. Thus it is acting as an adsorbent and can also discharge ions into the solution or interchange ions.

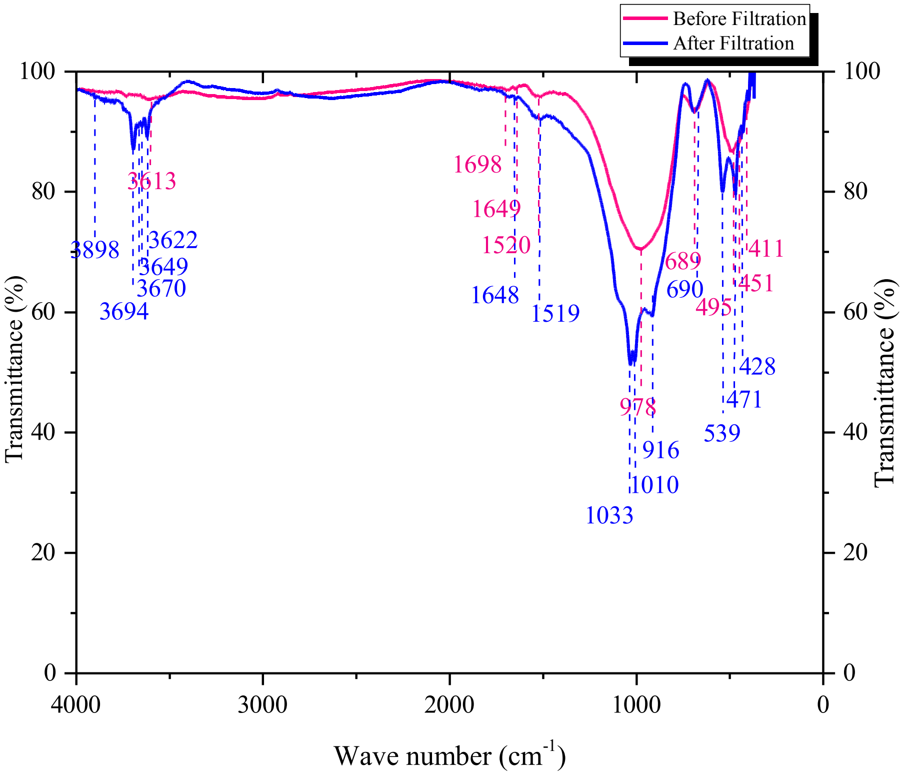


Figure 4.11 FTIR Spectra of Slag Before and After Filtration

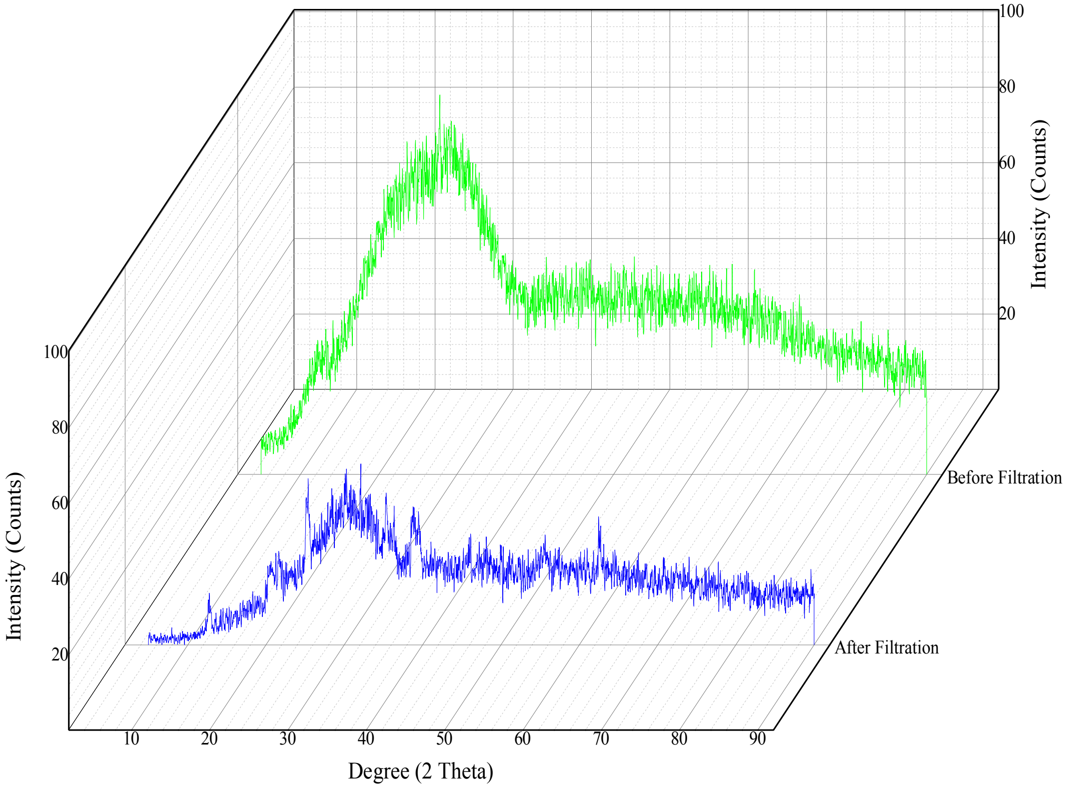


Figure 4.12 XRD Pattern of Slag Before and After Filtration

4.2.4 Effects due to Variation of Headloss

Figure 4.13 illustrates the influence of flow velocities on the head loss. The maximum head loss observed in the slag filter was 190 mm at 1.28 $m^3hr^{-1}m^{-2}$. Segismundo *et al*. (2017) reported that entrapment and entrainment of suspended solids deeper into the filter column along with the rearrangement of particles significantly reduced the effective pore volume of the filter media and thus affected its hydraulic conductivity. In the present study, even though the filter media was partially clogged, the quality of filtered water was satisfactory since the accumulated particles within the media also assisted in further straining out of impurities.

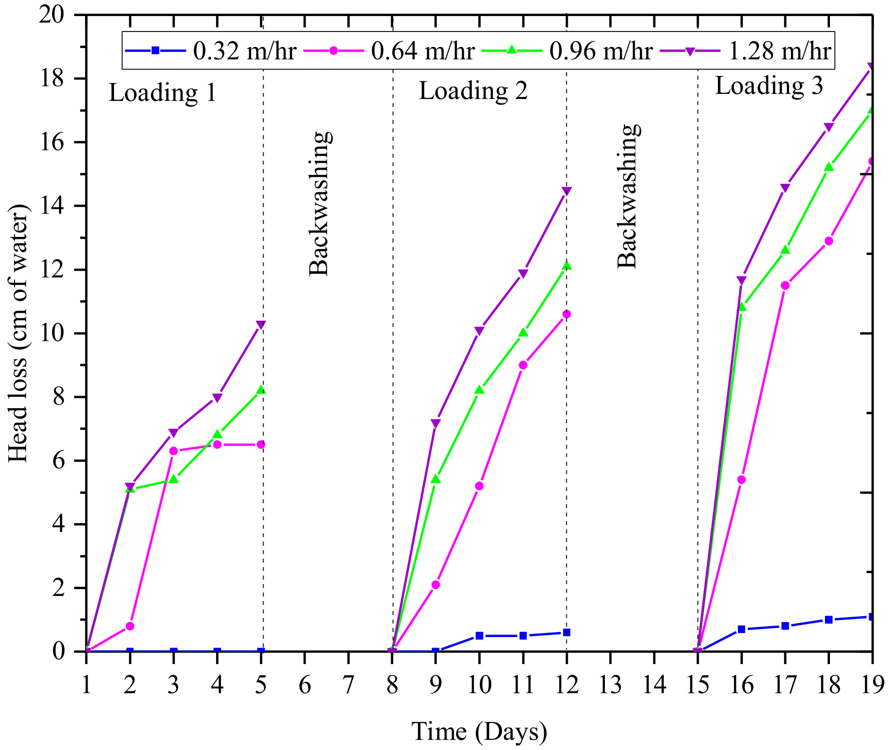


Figure 4.13 Headloss Variation at Constant Velocity Filtration

4.3 COMPARATIVE STUDIES OF SLAG AND SAND MEDIA FILTERS FOR OPERATING AND MAINTENANCE CONDITIONS

According to Anbalagan *et al*. (2010), the chemical constituents of the Indian standard sand (mass percentage) are SiO_2-99.30, Fe_2O_3-0.1, Al_2O_3-0.27, CaO-0.22 and loss on ignition- 0.13. In this perspective, a comparative study of both slag and sand filters were carried out. The typical characteristics of slag and sand are listed in Table 4.9.

Table 4.9 Typical Characteristics of Slag and Sand

Characteristics	Slag	Sand
Effective Size (mm), D_{10}	0.29	0.29
Uniformity Coefficient, C_u	5.17	2.07
Specific Gravity	1.65	2.63
Porosity	0.58	0.52
Permeability (mm s^{-1}), k	0.263×10^{-2}	1.96×10^{-2}

The prepared influent is a complex solution containing impurities causing turbidity and iron along with different anions such as sulphate, chloride, nitrates etc in more or less invariant proportions. The overall performance of slag filter was as good as a sand filter. Even though the total removal efficiency was not so large in slag filter, but has undergone some sort of removal process individually.

The anionic pollutants can be best removed by ion exchange and adsorption. The porous nature of slag improves the adsorption process. The slag and sand have hydroxyl functional group as found by FTIR and XRD studies. It might be exchanged or replaced with the anions in the synthetic solution in ion exchange process as mentioned by Bhatnagar *et al*. (2011).

Several minor peaks of inorganics compounds containing hydroxide groups could be visible in the sand output spectrum. These compounds might have been formed at low filtration rate and concentration.

4.3.1 Removal of Turbidity, TSS and Colour

The concentration details of turbidity and TSS in the treated water from the slag and sand filters are listed in Table 4.10 and Table 4.11, respectively. Most of the observations for turbidity and suspended solids were zero for the treated water from the slag and sand filters.

This study shows that the performance of slag filter is comparable to that of sand filter in removing turbidity, TSS and colour for all the loading and filtration rates. The removal might be due precipitation and adsorption. The physicochemical and molecular forces that cause bridging between particles influenced the charge of dissolved elements, thereby causing the attachment between sand grains and impurities.

Table 4.10 Turbidity Levels of the Treated Water from Slag and Sand Filter

Concentration	Type	F1	F2	F3	F4	Total
		Mean	Mean	Mean	Mean	Mean
C1	Slag	0.00	0.00	0.00	0.00	0.00
	Sand	0.00	0.00	0.00	0.00	0.00
C2	Slag	0.00	0.06	0.00	0.14	0.05
	Sand	0.04	0.10	0.00	0.08	0.06
C3	Slag	0.00	000	0.04	0.24	0.07
	Sand	0.00	0.00	0.00	0.14	0.04
Total	Slag	0.00	0.02	0.01	0.13	0.04
	Sand	0.01	0.03	0.00	0.07	0.03

Table 4.11 TSS Levels of the Treated Water from Slag and Sand Filter

Concentration	Type	F1	F2	F3	F4	Total
		Mean	Mean	Mean	Mean	Mean
C1	Slag	0.00	0.00	0.00	0.00	0.00
	Sand	0.00	0.00	0.00	0.00	0.00
C2	Slag	0.00	0.30	0.00	0.60	0.20
	Sand	0.20	0.50	0.00	0.40	0.30
C3	Slag	0.00	0.00	0.20	1.10	0.30
	Sand	0.00	0.00	0.00	0.60	0.20
Total	Slag	0.00	0.10	0.10	0.60	0.20
	Sand	0.10	0.20	0.00	0.30	0.10

The turbidity and TSS removal of slag and sand filters were always above 99%, and colour removal was 100% for all the loading and filtration rates as in Figure 4.14 and Figure 4.15 respectively. In the figures, flow rates are designated as F1, F2, F3 and F4 representing 0.32, 0.64, 0.96 and 1.28 $m^3hr^{-1}m^{-2}$ respectively and concentrations as C1, C2 and C3 representing Concentration-1, Concentration-2 and Concentration-3 as mentioned in Table 3.2 (Chapter 3).

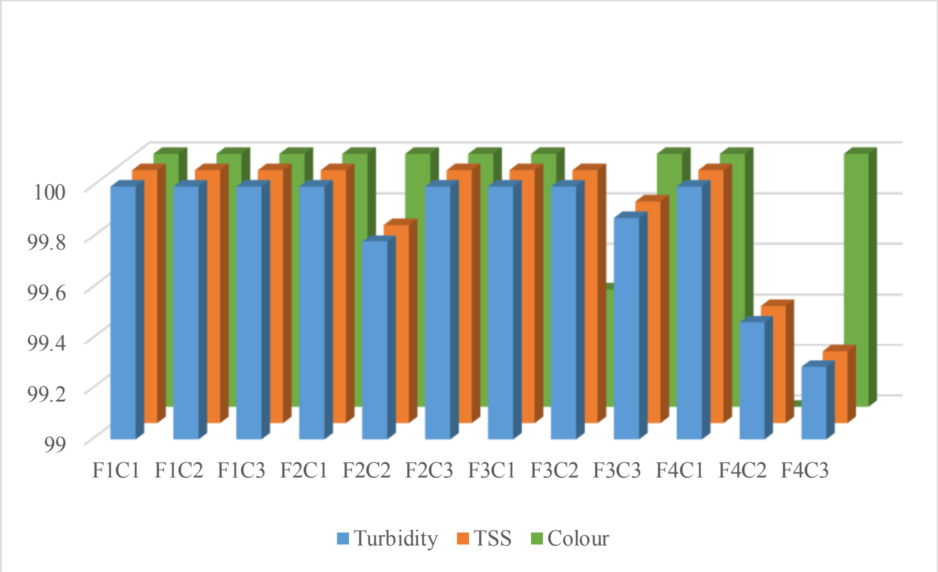


Figure 4.14 Performance of Slag Filter for Turbidity, TSS and Colour

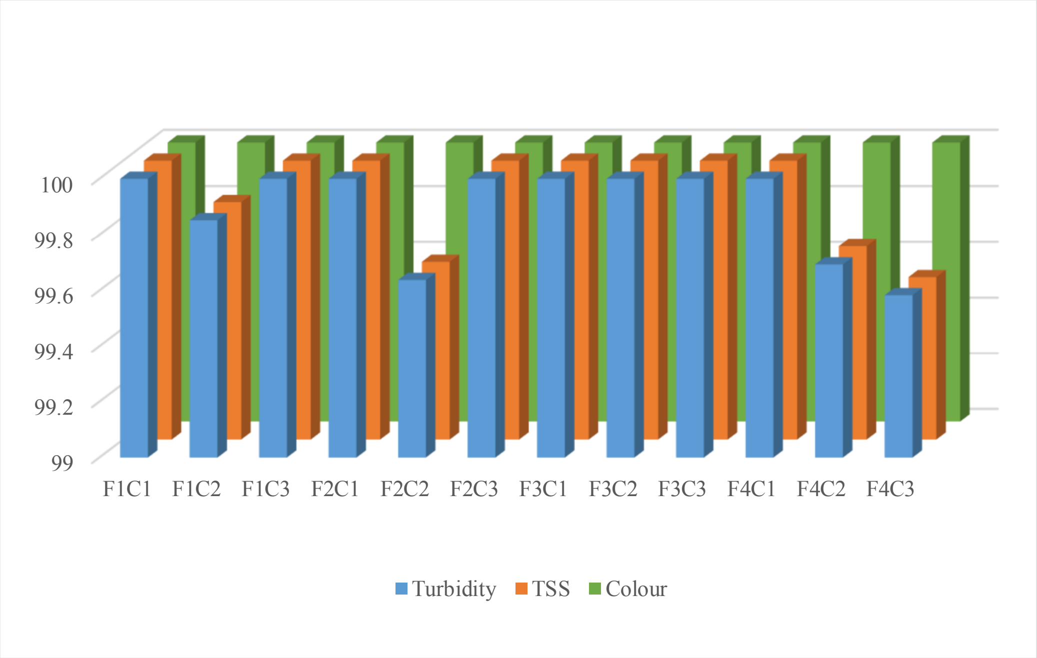


Figure 4.15 Performance of Sand Filter for Turbidity, TSS and Colour

A filter media height, each of 40 cm slag and sand filters was found to be sufficient for removing turbidity, colour and suspended solids.

Statistical tests fail for turbidity, TSS and colour since most of the observations were zero for the treated water from the slag and sand filters.

4.3.2 Removal of Hardness

The slag and sand media filters were subjected to run for four different flow rates such as F1 (2L hr^{-1}- $0.32m^3hr^{-1}m^{-2}$), F2 (4L hr^{-1}- $0.64m^3hr^{-1}m^{-2}$), F3 (6L hr^{-1}- $0.96m^3hr^{-1}m^{-2}$) and F4 (8L hr^{-1}- $1.28m^3hr^{-1}m^{-2}$) under three different concentrations namely C1 (Low), C2 (Medium) and C3 (High) respectively.

In the influent water used in this study, hardness was added by calcium chloride. The hardness concentrations of the filtered water from slag and sand filters along with the performance are shown in Table 4.12 and Figure 4.16 respectively. It is observed that the removal of hardness in slag filter is lesser than that of sand even at low flowrate and concentration. The existence of calcium, magnesium and iron also might have contributed hardness to the water. The increase in flow rate could not have any effect on the removal of hardness by slag filter and was comparable to the performance of the sand filter. This might be attributed to the low value of hydraulic retention time of influent on the media, which prevents the divalent ions from getting enough contact time to contribute the harness. The Analysis of Variance (ANOVA) result for hardness of the treated water is shown in Table 4.13.

Table 4.12 Hardness Levels of the Treated Water from Slag and Sand filter

Concentration	**Type**	**F1**		**F2**		**F3**		**F4**		**Total**	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
C1	Slag	325.9	14.3	356.1	9.7	323.9	8.8	349.7	12.5	338.9	18.0
	Sand	321.4	15.0	359.7	12.7	336.8	5.1	349.7	9.6	341.9	18.0
C2	Slag	327.8	26.5	357.0	16.3	372.8	5.3	381.1	10.6	359.7	25.9
	Sand	317.7	37.7	364.3	11.8	380.2	14.0	386.6	7.7	362.2	33.9
C3	Slag	412.7	9.2	402.6	11.4	409.8	18.4	415.3	6.9	410.1	12.2
	Sand	396.1	7.7	389.9	14.3	412.6	23.4	420.9	7.3	404.9	18.6
Total	Slag	355.5	45.1	371.9	25.4	368.8	38.1	382.0	29.3	369.5	35.7
	Sand	345.1	43.4	371.3	18.2	376.5	35.4	385.7	31.1	369.6	35.8

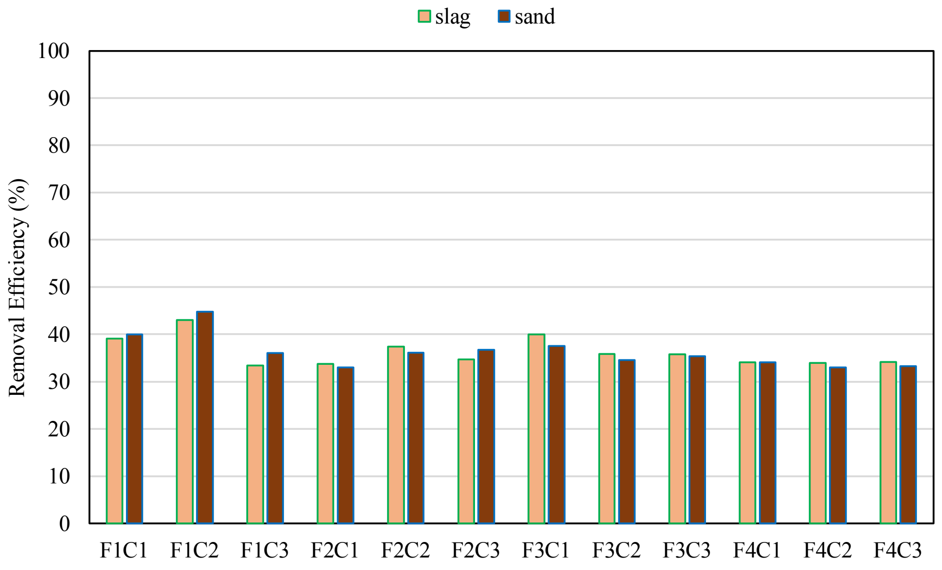


Figure 4.16 Performance of Slag and Sand Filters for Hardness Removal

Table 4.13 ANOVA Results for Hardness

Tests of Between-Subjects Effects						
Dependent Variable: Hardness (mg L^{-1})						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	129448.7[a]	23	5628.2	24.9	.000	.856
Intercept	16392321.8	1	16392321.8	72493.8	.000	.999
Flow	17722.8	3	5907.6	26.1	.000	.449
Concentration	94540.7	2	47270.4	209.0	.000	.813
Type	0.3	1	0.3	0.0	.970	.000
Flow * Concentration	14898.1	6	2483.0	11.0	.000	.407
Flow * Type	1355.7	3	451.9	2.0	.119	.059
Concentration * Type	429.3	2	214.7	0.9	.391	.019
Flow * Concentration * Type	501.7	6	83.6	0.4	.896	.023
Error	21707.5	96	226.1			
Total	16543478.0	120				
Corrected Total	151156.2	119				
a. R Squared = .856 (Adjusted R Squared = .822)						

The results of the Tukey test given in Tables 4.14 (a) and (b) indicates the pairwise multiple comparison tests for hardness of the treated water for different flowrates and concentrations. It is seen that hardness of the treated water is maximum at 8L hr^{-1} and minimum at 2L hr^{-1}. There is no significant difference in filtrate hardness between 4L hr^{-1} and 6L hr^{-1} flow types, indicating that there is not much variation in their removal efficiencies. It is also observed that hardness of treated water is maximum at high influent concentration and minimum at low influent concentration level, and there is a significant difference in hardness of the treated water. It could mean that the influent concentration affected the treated water quality.

Table 4.14 Pairwise Multiple Comparison Tests for Hardness between (a) Flowrates and (b) Concentrations

(a) Flowrates

Tukey HSD

Flow	N	Subset		
		1	2	3
F1	30	350.3		
F2	30		371.6	
F3	30		372.7	
F4	30			383.9
Sig.		1.000	.993	1.000

(b) Concentrations

Tukey HSD

Concentration	N	Subset		
		1	2	3
C1	40	340.38		
C2	40		360.94	
C3	40			407.48
Sig.		1.000	1.000	1.000

4.3.3 Removal of Sulphate

The sulphate concentration in the treated water from slag and sand filters and the performance are shown in Table 4.15 and Figure 4.17 respectively. The sulphate removal was less than 30% during the start-up of the filter run and declined to even less than 10%. It indicates the formation of end products in sulphate form along with the leaching out of sulphur present in the slag.

The Analysis of Variance (ANOVA) result for sulphate concentration in treated water is shown in Table 4.16. The full factorial model for sulphate removal shows that only the flow type and concentration are significant at 1% level of significance (p-value <.01) and type of material is not significant (p-value >.05). Also, it can be observed that there are no interaction effects among flow, concentration and filter type. The adjusted R square is 0.670, and it indicates 67.0% of the variation of the dependent variables explained by the independent factors.

Table 4.15 Sulphate Levels of the Treated Water from Slag and Sand Filter

Concentration	Type	F1		F2		F3		F4		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C1	Slag	241.4	40.2	256.7	17.1	278.3	25.7	271.8	12.2	262.1	28.0
	Sand	217.6	59.9	264.3	26.5	280.0	25.8	278.1	17.3	260.0	42.1
C2	Slag	271.9	7.5	307.6	38.8	320.9	39.4	318.2	11.1	304.6	32.9
	Sand	282.0	5.7	302.3	30.8	316.1	33.5	321.3	17.3	305.4	27.4
C3	Slag	252.5	16.2	332.8	43.5	339.6	21.7	348.3	12.1	318.3	46.2
	Sand	266.2	14.6	344.1	53.5	342.4	14.7	349.1	13.9	325.5	44.4
Total	Slag	255.3	26.9	299.0	46.1	312.9	38.4	312.8	34.4	295.0	43.3
	Sand	255.3	43.6	303.6	49.3	312.9	35.7	316.2	33.8	297.0	47.0

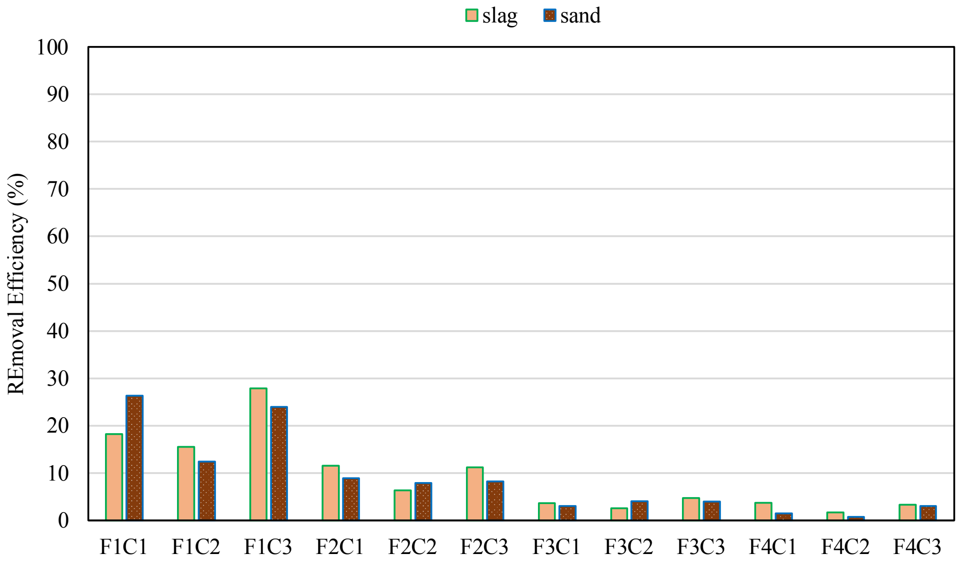


Figure 4.17 Performance of Slag and Sand filters for Sulphate Removal

Table 4.16 ANOVA Results for Sulphate

Tests of Between-Subjects Effects

Dependent Variable: Sulphate (mg L^{-1})

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	161598.6[a]	23	7026.0	8.5	.000	.670
Intercept	10512801.1	1	10512801.1	12692.1	.000	.992
Flow	69399.6	3	23133.2	27.9	.000	.466
Concentration	78971.9	2	39485.9	47.7	.000	.498
Type	116.5	1	116.5	0.1	.708	.001
Flow * Concentration	10336.0	6	1722.7	2.1	.063	.115
Flow * Type	125.9	3	42.0	0.1	.985	.002
Concentration * Type	446.0	2	223.0	0.3	.765	.006
Flow * Concentration * Type	2202.6	6	367.1	0.4	.848	.027
Error	79516.6	96	828.3			
Total	10753916.3	120				
Corrected Total	241115.1	119				

a. R Squared = .670 (Adjusted R Squared = .591)

Table 4.17 (a) and (b) shows the Tukey test indicating the pairwise multiple comparisons for sulphate between flowrates and concentrations. It is seen that sulphate of the treated water is minimum at 2 L hr^{-1} and the sulphate concentrations did not vary much at other flowrates. It is also observed that sulphate of treated water is maximum at high influent concentration and minimum at low influent concentration, and there is a significant difference among all the sulphate values of the treated water. The influent concentration could affect the treated water quality.

Table 4.17 Pairwise Multiple Comparison Tests for Sulphate between (a) Flowrates and (b) Concentrations

(a) Flowrates

Tukey HSD

Flow	N	Subset	
		1	2
F1	30	255.27	
F2	30		301.30
F3	30		312.89
F4	30		314.47
Sig.		1.000	.293

(b) Concentrations

Tukey HSD

Concentration	N	Subset		
		1	2	3
C1	40	261.03		
C2	40		305.04	
C3	40			321.88
Sig.		1.000	1.000	1.000

4.3.4 Removal of Nitrate

The treated water nitrate from slag and sand filters and the performance are shown in Table 4.18 and Figure 4.18 respectively. In this study, nitrate removal using slag filter remained similar to that of the sand filter. The removal efficiencies were high (71-82%) with fresh and clean slag and sand. As the flow rate and concentrations were increased, the efficiency was found to decrease by 25-32%. The nitrate removal might be due to the exchange of OH^- ions present in slag and sand with that of nitrate ions in solution by ion exchange process besides adsorption. Bhatnagar and Sillanpää (2011) pointed out that the presence of other anions could interfere with the nitrate adsorption in the increasing order of carbonate, phosphate, chloride and sulphate.

Table 4.18 Nitrate Levels of the Treated Water from Slag and Sand Filter

Concentration	Type	F1		F2		F3		F4		Total	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
C1	Slag	23.8	4.5	23.9	4.8	68.0	2.6	69.1	7.6	46.2	23.4
	Sand	21.8	4.8	24.2	3.8	64.6	4.3	66.2	7.9	44.2	22.4
C2	Slag	30.4	1.2	64.2	3.6	78.8	5.1	84.9	7.3	64.6	22.1
	Sand	31.4	2.5	68.6	0.8	77.6	7.3	85.6	6.6	65.8	21.8
C3	Slag	24.1	4.4	83.1	3.3	99.8	4.4	101.9	5.4	77.2	32.6
	Sand	24.2	5.3	82.3	10.5	97.9	4.1	103.8	5.3	77.0	32.9
Total	Slag	26.1	4.7	57.1	25.8	82.2	14.2	85.3	15.2	62.7	28.9
	Sand	25.8	5.8	58.4	26.4	80.0	15.0	85.2	17.1	62.3	29.2

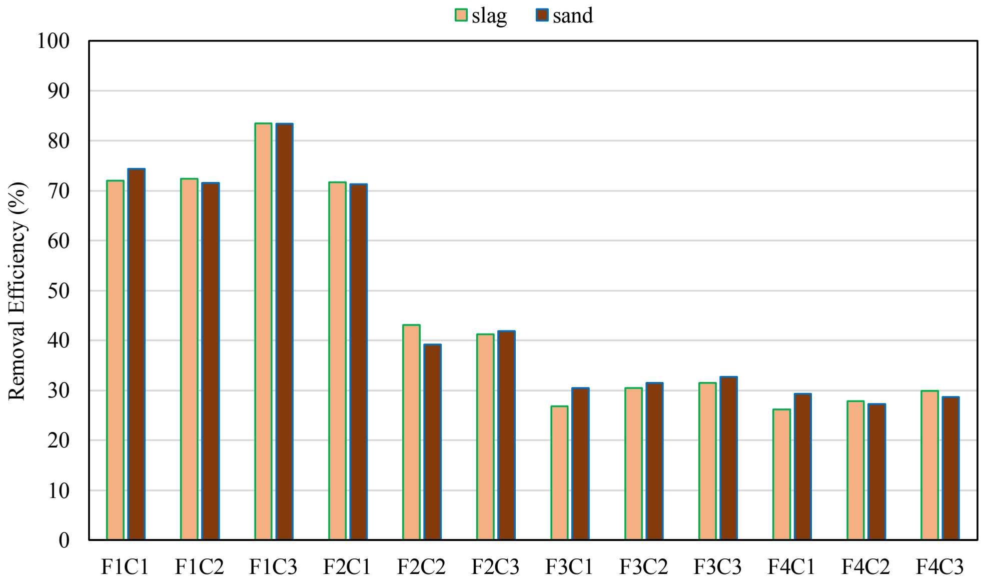


Figure 4.18 Performance of Slag and Sand Filters for Nitrate Removal

The Analysis of Variance (ANOVA) result for nitrate of the treated water is shown in Table 4.19. The full factorial model shows that only the flow type and concentration are significant at 1% level of significance (p-value <.01) and type of material is not significant (p-value >.05). It can be observed that there are interaction effects between flow and concentration. The adjusted R square is 0.966, and it indicates 96.6% of the variation of the dependent variables explained by the independent factors.

Table 4.19 ANOVA Results for Nitrate

Tests of Between-Subjects Effects

Dependent Variable: Nitrate (mg L^{-1})

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	97088.2[a]	23	4221.228	147.570	.000	.972
Intercept	468788.4	1	468788.376	1.639E4	.000	.994
Flow	66637.4	3	22212.469	776.527	.000	.960
Concentration	20823.2	2	10411.615	363.980	.000	.883
Type	3.1	1	3.084	.108	.743	.001
Flow * Concentration	9492.3	6	1582.055	55.307	.000	.776
Flow * Type	44.6	3	14.874	.520	.670	.016
Concentration * Type	52.3	2	26.126	.913	.405	.019
Flow * Concentration * Type	35.3	6	5.886	.206	.974	.013
Error	2746.1	96	28.605			
Total	568622.7	120				
Corrected Total	99834.3	119				

a. R Squared = .972 (Adjusted R Squared = .966)

Table 4.20 (a) and (b) shows the Tukey test indicating the pairwise multiple comparisons for nitrate between flowrates and concentrations.

Table 4.20 Pairwise Multiple Comparison Tests for Nitrate between (a) Flowrates and (b) Concentrations

(a) Flowrates

Tukey HSD

Flow	N	Subset			
		1	2	3	4
F1	30	26.0			
F2	30		57.7		
F3	30			81.1	
F4	30				85.2
Sig.		1.000	1.000	1.000	1.000

(b) Concentrations

Tukey HSD

Concentration	N	Subset		
		1	2	3
C1	40	45.2		
C2	40		65.2	
C3	40			77.1
Sig.		1.000	1.000	1.000

It is seen that the treated water nitrate is minimum at 2L hr^{-1} and maximum at 8L hr^{-1}. There is a significant difference in nitrate concentration of treated water for all the flow rates indicating that there are variations depending on the inflow. It is also observed that nitrate of treated water is maximum at high influent concentration and minimum at low influent concentration, and there is a significant difference among all the nitrate concentrations of the treated water.

4.3.5 Removal of Chloride

The chloride of the treated water from slag and sand filters and the performance are shown in Table 4.21 and Figure 4.19, respectively. The Analysis of Variance (ANOVA) result for treated water chloride is shown in Table 4.22. The full factorial model shows that the flow type and concentration are significant at 1% level of significance (p-value <.01) and type of material is not significant. Also, it can be observed that there are interaction effects between flow and concentration. The adjusted R square is 0.819, and it indicates 81.9% of the variation of the dependent variables explained by the independent factors.

Table 4.21 Chloride Levels of the Treated Water from Slag and Sand Filter

Concentration	Type	F1		F2		F3		F4		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C1	Slag	161.2	26.7	191.8	14.7	188.9	15.4	155.3	16.4	174.3	24.1
	Sand	152.2	40.0	196.6	14.9	181.9	14.4	150.5	15.3	170.3	29.7
C2	Slag	137.2	11.8	208.0	16.1	196.4	12.2	163.9	11.9	176.4	31.0
	Sand	138.8	10.6	210.4	14.7	188.4	10.4	158.5	12.3	174.0	30.3
C3	Slag	124.1	4.4	258.0	18.2	210.4	10.5	180.4	17.8	193.3	51.4
	Sand	124.2	5.3	255.6	4.2	209.9	12.2	174.4	17.9	191.0	50.5
Total	Slag	140.8	22.4	219.3	32.9	198.6	15.1	166.5	18.0	181.3	37.7
	Sand	138.4	25.2	220.9	28.5	193.4	16.9	161.1	17.6	178.5	38.5

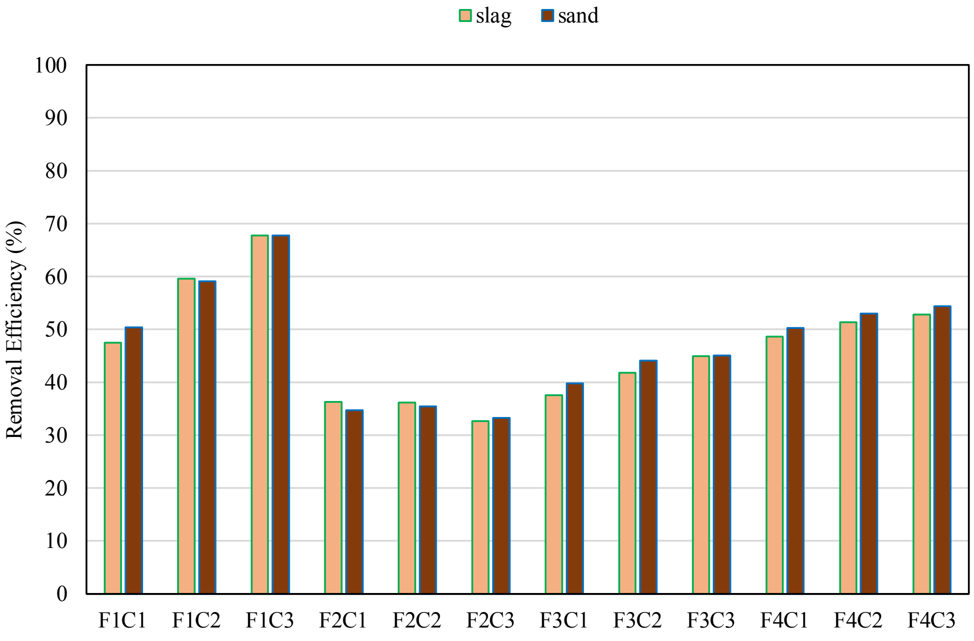


Figure 4.19 Performance of Slag and Sand Filters for Chloride Removal

Table 4.22 ANOVA results for Chloride

Tests of Between-Subjects Effects						
Dependent Variable: Chloride (mg L^{-1})						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	146497.0[a]	23	6369.4	24.4	.000	.854
Intercept	3882855.5	1	3882855.5	14861.5	.000	.994
Flow	112613.7	3	37537.9	143.7	.000	.818
Concentration	9204.4	2	4602.2	17.6	.000	.268
Type	244.4	1	244.4	0.9	.336	.010
Flow * Concentration	23881.0	6	3980.2	15.2	.000	.488
Flow * Type	238.8	3	79.6	0.3	.822	.009
Concentration * Type	19.1	2	9.5	0.0	.964	.001
Flow * Concentration * Type	295.5	6	49.3	0.2	.979	.012
Error	25081.8	96	261.3			
Total	4054434.3	120				
Corrected Total	171578.8	119				
a. R Squared = .854 (Adjusted R Squared = .819)						

Table 4.23 (a) and (b) shows the Tukey test indicating the pairwise multiple comparisons for treated water chloride between flowrates and concentrations. It is seen that the chloride value is maximum at 4L hr^{-1} and minimum at 2L hr^{-1}. Also, the interaction of chloride is significant at all flowrates. It seems that chlorides in treated water are significant only at high concentration.

Table 4.23 Pairwise Multiple Comparison Tests for Chloride between (a) Flowrates and (b) Concentrations

(a) Flowrates

Tukey HSD

Flow	N	Subset			
		1	2	3	4
F1	30	139.62			
F2	30		163.83		
F3	30			196.01	
F4	30				220.07
Sig.		1.000	1.000	1.000	1.000

(b) Concentrations

Tukey HSD

Concentration	N	Subset	
		1	2
C1	40	172.29	
C2	40	175.20	
C3	40		192.15
Sig.		.700	1.000

4.3.6 Removal of Iron

The iron of the treated water from slag and sand filters and the performance are shown in Table 4.24 and Figure 4.20, respectively.

Table 4.24 Iron Levels of the Treated Water from Slag and Sand Filter

Concentration	Type	F1		F2		F3		F4		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C1	Slag	0.10	0.02	0.05	0.03	0.07	0.08	0.08	0.06	0.08	0.05
	Sand	0.01	0.01	0.02	0.04	0.07	0.08	0.04	0.06	0.04	0.06
C2	Slag	0.11	0.01	0.05	0.05	0.12	0.07	0.16	0.07	0.11	0.07
	Sand	0.09	0.01	0.03	0.04	0.08	0.09	0.12	0.10	0.08	0.07
C3	Slag	0.04	0.05	0.12	0.06	0.13	0.11	0.00	0.00	0.07	0.08
	Sand	0.01	0.02	0.10	0.08	0.10	0.09	0.00	0.00	0.05	0.07
Total	Slag	0.08	0.04	0.08	0.06	0.11	0.09	0.08	0.08	0.09	0.07
	Sand	0.04	0.04	0.05	0.06	0.09	0.08	0.06	0.08	0.06	0.07

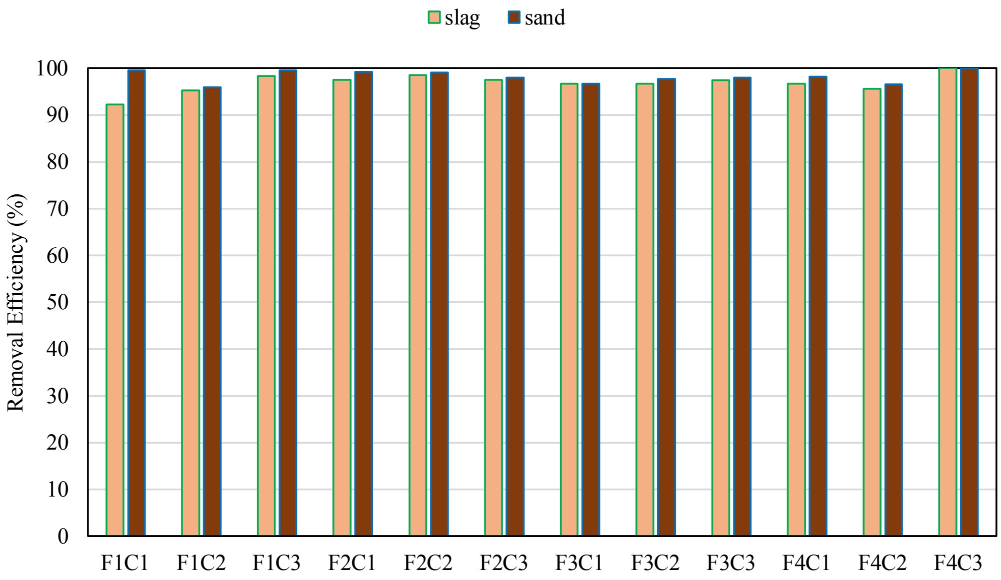


Figure 4.20 Performance of Slag and Sand Filters for Iron Removal

The iron removal was always above 90% for both the slag and sand filters. The performance of the slag filter was slightly lower compared to the sand filter. It might be due to the presence of trace amounts of iron present in slag. It is stated by Clifford and Weber (1978) that the iron deposits are only partially removed with simple backwashing. The Analysis of Variance (ANOVA) result for treated water iron is shown in Table 4.25.

Table 4.25 ANOVA Results for Iron

Tests of Between-Subjects Effects						
Dependent Variable: Iron (mg L^{-1})						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	0.24[a]	23	.010	2.81	.000	.403
Intercept	0.60	1	.602	162.63	.000	.629
Flow	0.03	3	.009	2.39	.074	.069
Concentration	0.03	2	.017	4.72	.011	.090
Type	0.03	1	.026	7.13	.009	.069
Flow * Concentration	0.14	6	.023	6.13	.000	.277
Flow * Type	0.00	3	.001	0.24	.871	.007
Concentration * Type	0.00	2	.001	0.33	.718	.007
Flow * Concentration * Type	0.01	6	.002	0.46	.835	.028
Error	0.36	96	.004			
Total	1.20	120				
Corrected Total	0.59	119				
a. R Squared = .403 (Adjusted R Squared = .259)						

The full factorial model for treated water iron shows that concentration is significant at 5% level of significance (p-value <.05) and type of material is significant at 1% level of significance (p-value <.01). It can be observed that there are interaction effects between flow and concentration. Iron is the only parameter whose removal efficiency is dependent on the type of media. There are interaction effects between flowrates and concentrations at 1% level of significance. The adjusted R square is 0.259, and it indicates 25.9% of the variation of the dependent variables explained by the independent factors.

Table 4.26 shows the Tukey test indicating the pairwise multiple comparisons for treated water iron between concentrations. It is seen that treated water iron is maximum at medium concentration, and there is a significant difference in iron concerning treatments.

Table 4.26 Pairwise Multiple Comparison Tests for Iron between Concentrations

Concentrations			
Tukey HSD			
		Subset	
Concentration	N	1	2
C1	40	0.06	
C2	40	0.06	
C3	40		0.09
Sig.		.906	1.000

The insoluble suspended solids, including ferric oxide precipitate, might have prevented the exchangeable counter ions from gaining access to the interior of the media (Clifford and Weber, 1978).

4.3.7 Variation of pH, Electrical Conductivity and Total Dissolved Solids

Figure 4.21 shows the variation of pH and EC for various filtration rates (Run 1 to 4) and concntrations (C1 to C3) for slag and sand filters. The mean values of influent pH were 7.17, 6.94 and 6.11 respectively, and the treated water mean pH for both the filters showed fairly consistent pH in the normal range of drinking water. The electrical conductivity of treated water in both the filters exceeded the influent conductivity levels quite a lot of times and consequently affected the concentration of total dissolved solids in the treated water.

The values of pH, EC and TDS are not maintained constant for various concentrations but are dependent upon the concentration of various chemicals added for the preparation of influent characteristics. The mean and standard deviation for pH of the treated water from slag and sand filters are presented in Table 4.27.

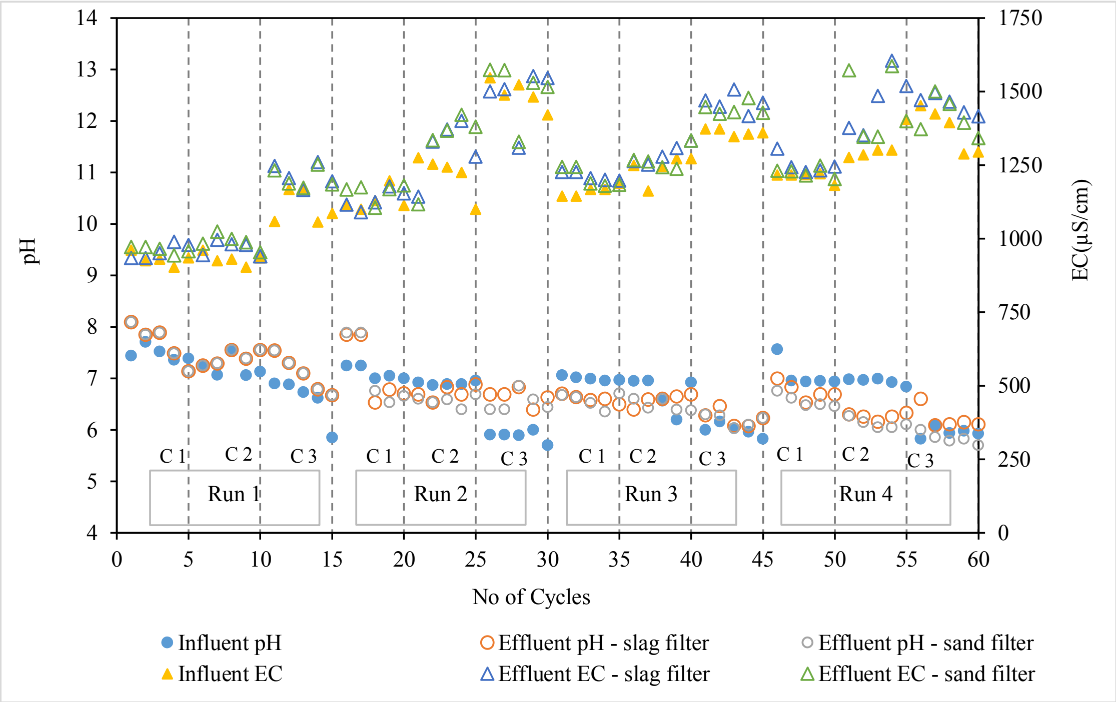


Figure 4.21 Variation of pH and EC for Various Filtration Rates (Run1 to Run4) and Concentrations (C1 to C3) for Slag and Sand Filters

Table 4.27 pH Levels of the Treated Water from Slag and Sand Filter

Concentration	Type	F1		F2		F3		F4		Total	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C1	Slag	7.7	0.4	7.1	0.7	6.6	0.1	6.7	0.2	7.0	0.6
	Sand	7.6	0.3	7.1	0.7	6.6	0.1	6.6	0.1	7.0	0.6
C2	Slag	7.4	0.1	6.7	0.1	6.6	0.1	6.3	0.1	6.7	0.4
	Sand	7.3	0.2	6.6	0.1	6.5	0.1	6.1	0.1	6.6	0.5
C3	Slag	7.1	0.4	6.6	0.2	6.2	0.2	6.2	0.2	6.5	0.4
	Sand	7.1	0.3	6.5	0.2	6.2	0.1	5.8	0.1	6.4	0.5
Total	Slag	7.4	0.4	6.8	0.4	6.5	0.2	6.4	0.3	6.8	0.5
	Sand	7.3	0.3	6.7	0.5	6.4	0.2	6.2	0.3	6.7	0.6

The full factorial model for pH presented in Table 4.28 shows that the flow type and concentration are significant at 1% level of significance (p-value <.01) and type of material is significant at 5% level of significance-(p-value <.05). Also, it can be observed that there are no interaction effects. The adjusted R square is 0.754, and it indicates 75.4% of the variation of the dependent variables explained by the independent factors.

Table 4.28 ANOVA Results for pH

Tests of Between-Subjects Effects						
Dependent Variable: pH						
Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	27.44[a]	23	1.19	16.83	.000	.801
Intercept	5422.64	1	5422.64	76468.52	.000	.999
Flow	20.30	3	6.77	95.40	.000	.749
Concentration	5.82	2	2.91	41.04	.000	.461
Type	0.36	1	0.36	5.10	.026	.050
Flow * Concentration	0.67	6	0.11	1.58	.161	.090
Flow * Type	0.15	3	0.05	0.72	.540	.022
Concentration * Type	0.02	2	0.01	0.13	.874	.003
Flow * Concentration * Type	0.12	6	0.02	0.28	.947	.017
Error	6.81	96	0.07			
Total	5456.89	120				
Corrected Total	34.25	119				
R Squared = .801 (Adjusted R Squared = .754)						

The Tukey test results are given in Tables 4.29 (a) and (b) which show the pairwise multiple comparison tests for pH between flowrates and concentrations. It is seen that pH is maximum at 2L hr^{-1} and minimum at 8L hr^{-1}. There is no significant difference in pH between 8L hr^{-1} and 6L hr^{-1} flow types. It is also observed that pH value of the treated water is maximum at low concentration of influent and minimum value at high concentration of influent, and there is a significant difference among all the pH values of the treated water.

Table 4.29 Pairwise Multiple Comparison Tests for Treated Water pH between (a) Flowrates (b) Concentrations

(a) Flowrates				
Tukey HSD				
		Subset		
Flow	N	1	2	3
F1	30	6.29		
F2	30	6.44		
F3	30		6.79	
F4	30			7.36
Sig.		.128	1.000	1.000

(b) Concentrations (mg L^{-1})				
Tukey HSD				
		Subset		
Concentration	N	1	2	3
C1	40	6.47		
C2	40		6.68	
C3	40			7.01
Sig.		1.000	1.000	1.000

The mean and standard deviation and Analysis of Variance (ANOVA) result for EC of the treated water from slag and sand filters are presented in Table 4.30 and Table 4.31 respectively. It is seen that the flowrates and concentrations are significant at 1% level of significance, and there is no variation in EC concerning the type of the filter media since $p=0.764$ ($p>0.05$). But the interaction effects between flow rates and concentrations are significant at 1% level of significance.

Table 4.30 EC Levels of the Treated Water from Slag and Sand Filter

Concentration	Type	F1		F2		F3		F4		Total	
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
C1	Slag	957.2	25.6	1132.2	34.3	1211.4	14.6	1250.6	31.9	1137.9	118.4
	Sand	962.2	12.2	1159.2	30.8	1207.8	33.2	1225.0	17.2	1138.6	109.8
C2	Slag	968.0	24.7	1304.6	101.5	1287.0	33.1	1467.2	104.0	1256.7	198.1
	Sand	989.6	25.4	1324.0	119.8	1268.6	38.0	1450.4	119.5	1258.1	190.6
C3	Slag	1214.6	38.8	1483.4	100.1	1461.0	32.7	1455.4	32.3	1403.6	124.6
	Sand	1206.0	34.1	1504.4	101.4	1441.6	22.3	1413.6	64.8	1391.4	128.8
Total	Slag	1046.6	126.2	1306.7	167.8	1319.8	111.3	1391.1	119.5	1266.1	184.8
	Sand	1052.6	115.3	1329.2	169.1	1306.0	106.7	1363.0	125.7	1262.7	178.3

Table 4.31 ANOVA Results for EC

Tests of Between-Subjects Effects

Dependent Variable: Electrical Conductivity (µS cm^{-1})

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	3535144.9[a]	23	153701.95	41.51	.000	.909
Intercept	191837296.9	1	191837297	51805.74	.000	.998
Flow	1921408.3	3	640469.43	172.96	.000	.844
Concentration	1347627.9	2	673813.97	181.96	.000	.791
Type	336.7	1	336.67	0.09	.764	.001
Flow * Concentration	252297.2	6	42049.53	11.36	.000	.415
Flow * Type	11055.3	3	3685.10	1.00	.399	.030
Concentration * Type	1177.6	2	588.82	0.16	.853	.003
Flow * Concentration * Type	1241.9	6	206.98	0.06	.999	.003
Error	355489.2	96	3703.01			
Total	195727931.0	120				
Corrected Total	3890634.1	119				

a. R Squared = .909 (Adjusted R Squared = .887)

Table 4.32 (a) and (b) shows the Tukey test indicating the pairwise multiple comparisons for EC between flowrates and concentrations. It is seen that EC is maximum at 8L hr^{-1} and minimum at 2L hr^{-1}, and there are no significant differences in treated water EC between 4L hr^{-1} and 6L hr^{-1} flowrates. However, all the pairwise comparisons between concentrations were found to be statistically significant.

Table 4.32 Pairwise Multiple Comparison Tests for Treated Water EC between (a) Flowrates (b) Concentrations

(a) Electrical Conductivity (µS cm^{-1})

Tukey HSD

Flow	N	Subset		
		1	2	3
2L/hr	30	1049.6		
6L/hr	30		1312.9	
4L/hr	30		1318.0	
8L/hr	30			1377.0
Sig.		1.000	.988	1.000

(b) Concentrations (µS cm^{-1})

Tukey HSD

Concentration	N	Subset		
		1	2	3
Low	40	1138.2		
Medium	40		1257.4	
High	40			1397.5
Sig.		1.000	1.000	1.000

The mean and standard deviation for TDS of the treated water from slag and sand filters are presented in Table 4.33.

Table 4.33 TDS Levels of the Treated Water from Slag and Sand Filter

Concentration	**Type**	**F1**		**F2**		**F3**		**F4**		**Total**	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
C1	Slag	593.5	15.9	702.0	21.3	751.1	9.1	775.4	19.8	705.5	73.4
	Sand	596.6	7.5	718.7	19.1	748.8	20.6	759.5	10.7	705.9	68.1
C2	Slag	600.2	15.3	808.9	62.9	797.9	20.5	909.7	64.5	779.2	122.8
	Sand	613.6	15.8	820.9	74.2	786.5	23.6	899.2	74.1	780.1	118.2
C3	Slag	753.1	24.1	919.7	62.1	905.8	20.3	902.3	20.0	870.2	77.2
	Sand	747.7	21.1	932.7	62.9	893.8	13.8	876.4	40.2	862.7	79.9
Total	Slag	648.9	78.3	810.2	104.1	818.3	69.0	862.5	74.1	785.0	114.6
	Sand	652.6	71.5	824.1	104.8	809.7	66.1	845.1	78.0	782.9	110.5

The full factorial model for TDS listed in Table 4.34 shows that the flow type and concentration are significant at 1% level of significance (p-value <.01) and type of material is not significant. Also, it can be observed that there are interaction effects between flow and concentration. The adjusted R square is 0.887, and it indicates 88.7% of the variation of the dependent variables explained by the independent factors.

Table 4.34 ANOVA Results for TDS

Tests of Between-Subjects Effects

Dependent Variable: Total Dissolved Solids (mg L^{-1})

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	1358909.7[a]	23	59083.0	41.5	.000	.909
Intercept	73742256.9	1	73742256.9	51805.7	.000	.998
Flow	738589.3	3	246196.4	173.0	.000	.844
Concentration	518028.2	2	259014.1	182.0	.000	.791
Type	129.4	1	129.4	0.1	.764	.001
Flow * Concentration	96983.0	6	16163.8	11.4	.000	.415
Flow * Type	4249.7	3	1416.6	1.0	.399	.030
Concentration * Type	452.7	2	226.3	0.2	.853	.003
Flow * Concentration * Type	477.4	6	79.6	0.1	.999	.003
Error	136650.0	96	1423.4			
Total	75237816.7	120				
Corrected Total	1495559.8	119				

a. R Squared = .909 (Adjusted R Squared = .887)

Table 4.35 Pairwise Multiple Comparison Tests for TDS between (a) Flowrates (b) Concentrations

(a) Flowrates

Tukey HSD

low	N	Subset		
		1	2	3
2L/hr	30	650.75		
6L/hr	30		814.00	
4L/hr	30		817.14	
8L/hr	30			853.76
Sig.		1.000	.988	1.000

(b) Concentrations (mg L^{-1})

Tukey HSD

Concentration	N	Subset		
		1	2	3
Low	40	705.68		
Medium	40		779.60	
High	40			866.45
Sig.		1.000	1.000	1.000

4.3.8 Discussion on FTIR and XRD Results of Sand Before and After Treatment

The Figure 4.22 (a) shows FTIR spectrum of sand before filtration. The FTIR peak observed at 468 cm^{-1} and 692 cm^{-1}show Si-O asymmetric and symmetric bending vibration. The peak at 1082 cm^{-1} indicates Si-O-Si stretching whereas the peak at 3620 $cm^{-1}$and 3693 cm^{-1} indicates symmetric and asymmetric stretching of calcium hydrate group and 1453.1 cm^{-1} exhibits CO_3 stretching of calcite at. The OH group stretching was observed at 1618 cm^{-1} (Muttashar *et al.*, 2018, Sharma *et al.*, 2019). There were not many changes visible in the peak values of sand before and after treatment as in Figure 4.22 (b). Hence there is a possibility of weak ion-exchange mechanism existing in the sand.

The XRD spectra of sand before and after filtration is shown in Figure 4.23 (a) and (b). The XRD pattern of raw sand before filtration shows crystalline structure in which the maximum peak at 2θ= 26.78 ° indicated the presence of SiO_2 (quartz) as stated by Srivastava and Vaishya (2015), Muttashar *et al*. (2018) and Sharma *et al*. (2019). It also reveals the existence of several minor peaks of SiO_2 and $CaCO_3$. When the used sand sample after filtration was subjected to the analysis major peaks were obtained at 2θ= 21.03°, 26.67° and 50.23° indicating the presence of silica and 2θ= 21.03°, 26.86°, 50.23°, 68.67° as CaCO3. Several inorganic minerals were also present as indicated by the peaks at 2θ= 21.03°, 26.86°, 50.23° for calcium silicate hydrate, 2θ= 21.03° for magnesium sulphate hydrate and sodium aluminum sulphate hydrate, 2θ= 26.67° for magnesium hydroxide sulphate hydrate, 2θ=39.68° for magnesium silicate hydroxide and calcium nitrate, 2θ= at 67.91° for Fe_2O_3 and 2θ= 61.11°, 81.66° for FeO. Thus it shows some of the retention of inorganic compounds formed during the filtration process. It is apparent that sand is capable of discharging calcium ions into the water in exchange for sodium in the influent solution.

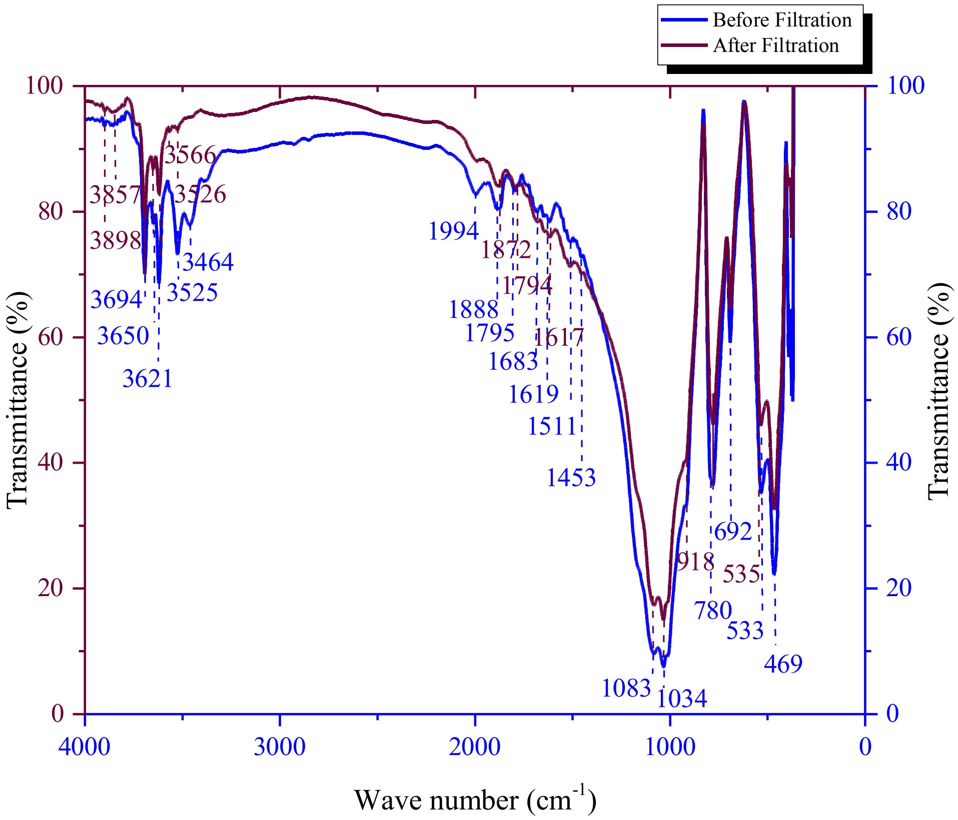


Figure 4.22 FTIR Spectra of Sand Before and After Filtration

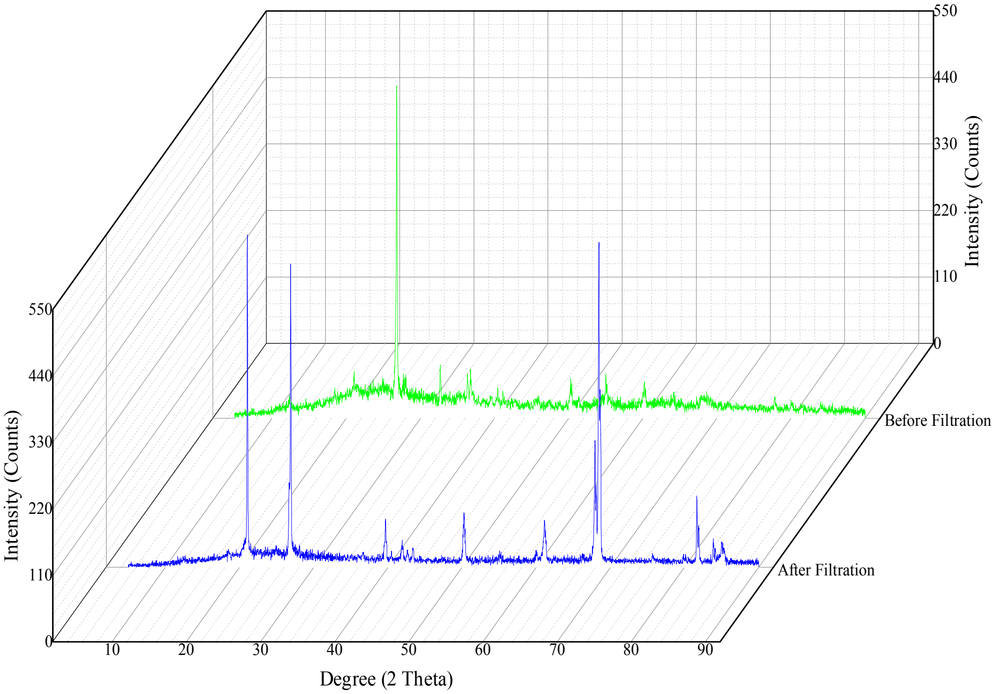


Figure 4.23 XRD Spectra of Sand Before and After Filtration

4.3.9 Performance of Filters for Total Coliforms and E Coli Removals

The sample of water was collected from a polluted open well and the influent was made by diluting the sample with tap water. The experiments for biological characteristics started after the completion of physico-chemical treatment. The influent sample was fed to the filter for seeding for five days, and experiments were conducted later for ten days. The prepared water was allowed to flow through the filter at a lower flow rate of 0.32 $m^3hr^{-1}m^{-2}$. Daily samples were taken for the study. The mean values of total coliform and *E. coli* of influent samples were 280cfu/100 ml and 120cfu/100 ml, respectively. *E. coli* and non-*E. coli* were absent in the treated water from the sand filter. Slag filter performed similarly to the sand filter in removing *E. coli*, but a non *E. coli* count of 10 cfu/ml could be observed in the treated water. It implied that filtration should be followed by disinfection.

4.3.10 Headlosses in Slag and Sand Filters

According to EPA (1995), filter unit design, filter media type and depth play a role in determining solids removal efficiency. The head loss variations at different flow rates and concentration loadings are shown in Figure 4.24, Figure 4.25, Figure 4.26 and Figure 4.27, respectively. The clean bed head loss, i.e., the head loss at the start of the filtration cycle, was always zero.

The results show that slag had better hydraulic characteristics compared to sand media. Sand filters have fine light grains on the top, which retain all the floc and particulates at or near the surface of the filter (EPA, 1995). Generally, filters remove larger particles by straining at the top surface of the filter media and smaller particles by the mechanisms of transport such as interception, sedimentation, diffusion and attachment to the more in-depth filter media. The straining causes an exponential head loss increase with time as in previous literature. However, it was mentioned that the time rate of head loss increase is linear with depth filtration.

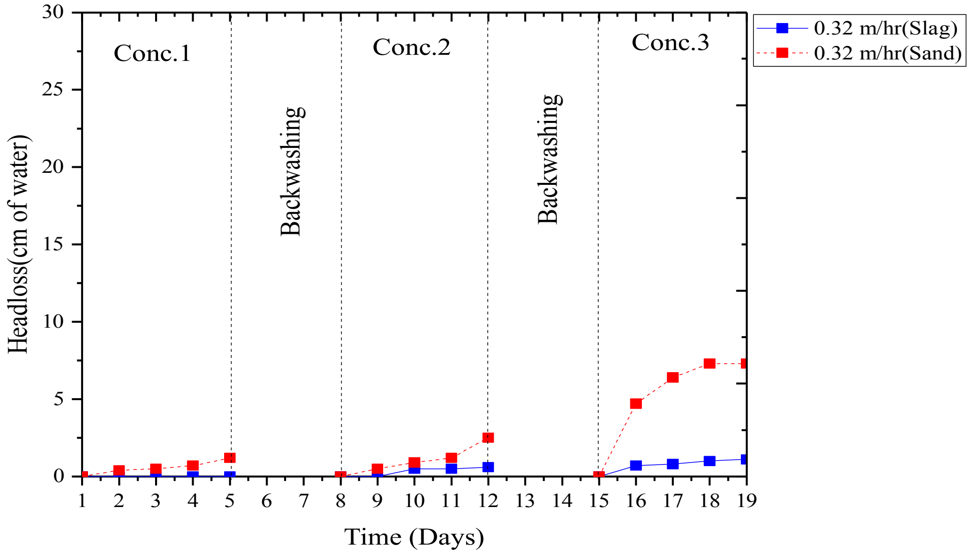


Figure 4.24 Headloss Variation at 0.32 m hr^{-1}

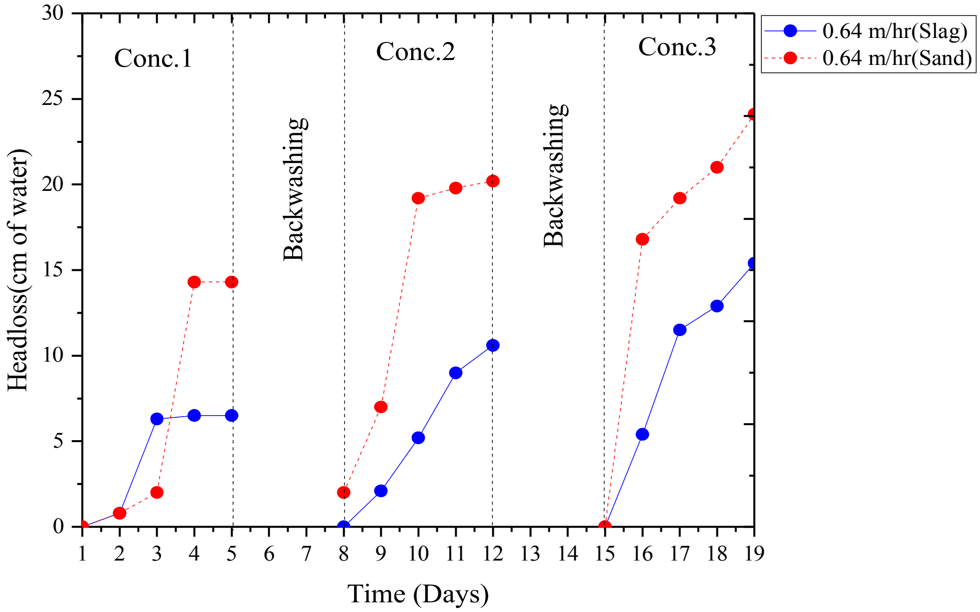


Figure 4.25 Headloss Variation at 0.64 m hr^{-1}

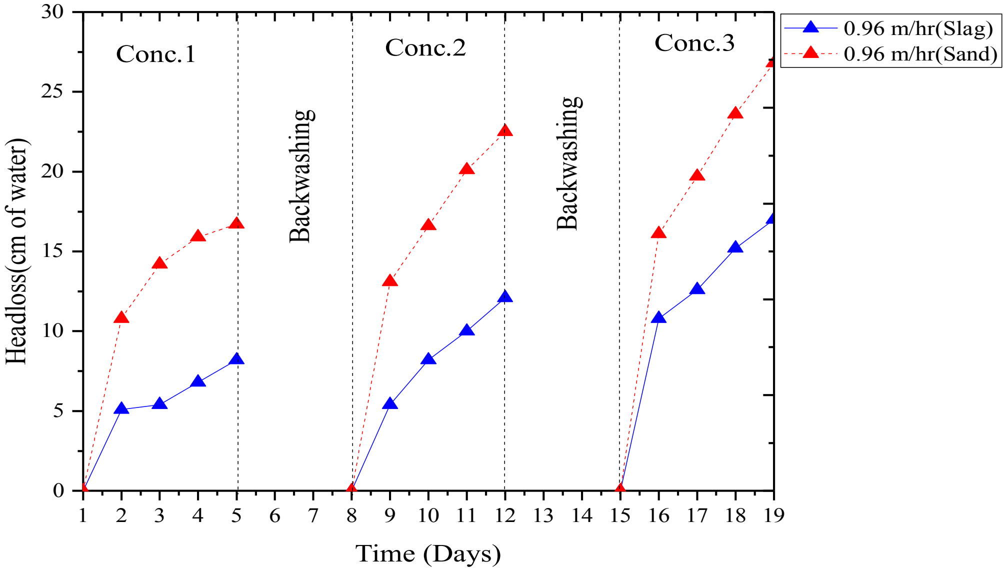


Figure 4.26 Headloss Variation at 0.96 m hr^{-1}

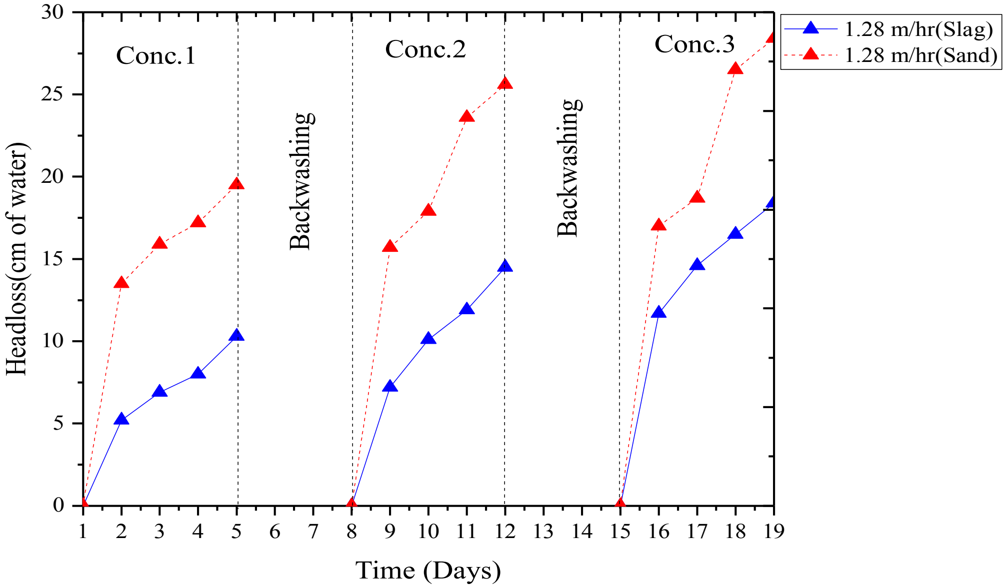


Figure 4.27 Headloss Variation at 1.28 m hr^{-1}

The maximum head loss in slag and sand filters were 18.4 cm and 28.4 cm, respectively. It implies that even though the removal efficiency of various parameters was good, more frequent backwashing is required to keep the sand filter operating efficiently with a minimum head loss.

4.4 EVALUATION OF THE PERFORMANCE OF DUAL MEDIA FILTER USING SLAG AND CHARCOAL

The study describes the effectiveness of ferrous slag in dual media filter in combination with charcoal for the removal of pollutants from water. A laboratory bench scale dual media filter of total depth 40 cm, comprising of 20 cm granular activated charcoal over 20 cm slag having a total bed area of 0.00636 m^2 supported on 10 cm thick gravel bed was used for the experiment.

The filter could remove most commonly occurring drinking water pollutants to a considerable extent, as in Figure 4.28. The filter was operated for four different flowrates of 0.32 $m^3hr^{-1}m^{-2}$, 0.64 $m^3hr^{-1}m^{-2}$, 0.96 $m^3hr^{-1}m^{-2}$ and 1.28 $m^3hr^{-1}m^{-2}$ represented as F1, F2, F3 and F4 for three different concentrations namely C1, C2 and C3 as detailed in Table 3, similar to the slag and sand filters. The removal efficiency of total suspended solids, turbidity and colour were 99-100% and that of iron >95%. It might be due to the precipitation of solids, forming a mat on the surface of media grains besides adsorption.

The results presented in Figure 4.29, Figure 4.30 and Figure 4.31 show that the increased flow rates and concentrations could not have any effect on chloride removal even though it was less around 30-40%. The sulphate removal was very less, showing that it was greatly affected by all the flowrates and concentrations of influent synthetic water. The iron removal was always above 95% for 0.32 $m^3hr^{-1}m^{-2}$ and 0.64 $m^3hr^{-1}m^{-2}$ of filter area. The removal mechanism of charcoal was mainly by precipitation and adsorption phenomena. But in the case of slag, the removal of various impurities was by chemical precipitation, adsorption and by the ion-exchange mechanism. The lower removal of sulphate might be due to the interaction of several anions at the same time. There was only a marginal variation in chloride removal except at a high flow rate of

1.28 $m^3hr^{-1}m^{-2}$. It is observed that the adsorption rate of charcoal is in the order of nitrate>chlorides>hardness>sulphate.

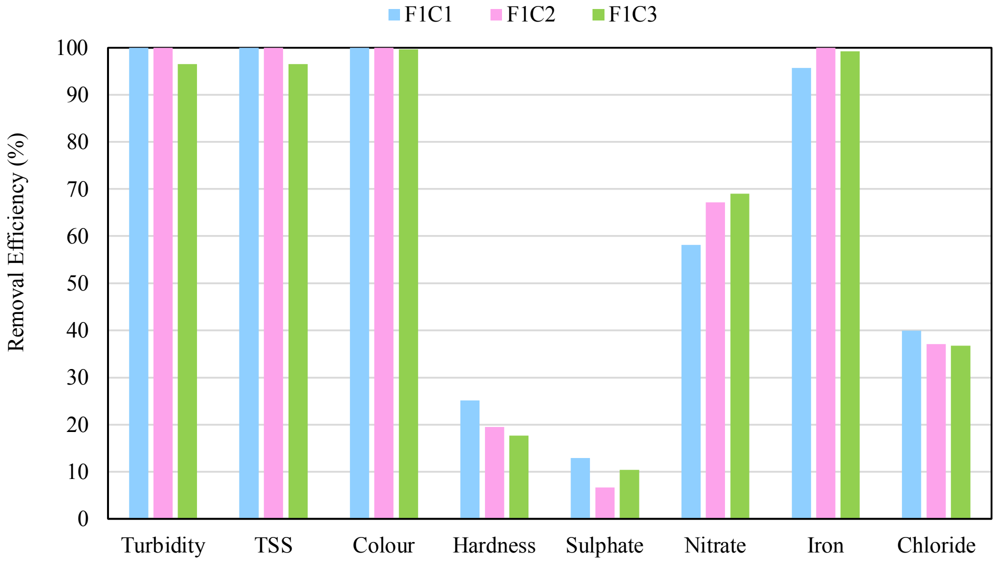


Figure 4.28 Performance of Dual Media Filter at 0.32 $m^3hr^{-1}m^{-2}$

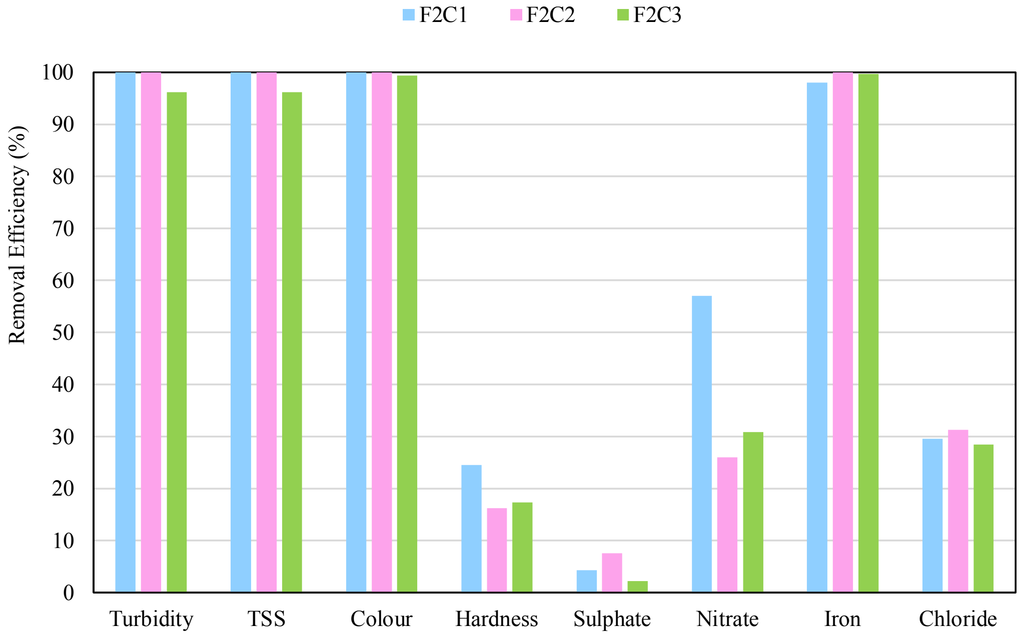


Figure 4.29 Performance of Dual Media Filter at 0.64 $m^3hr^{-1}m^{-2}$

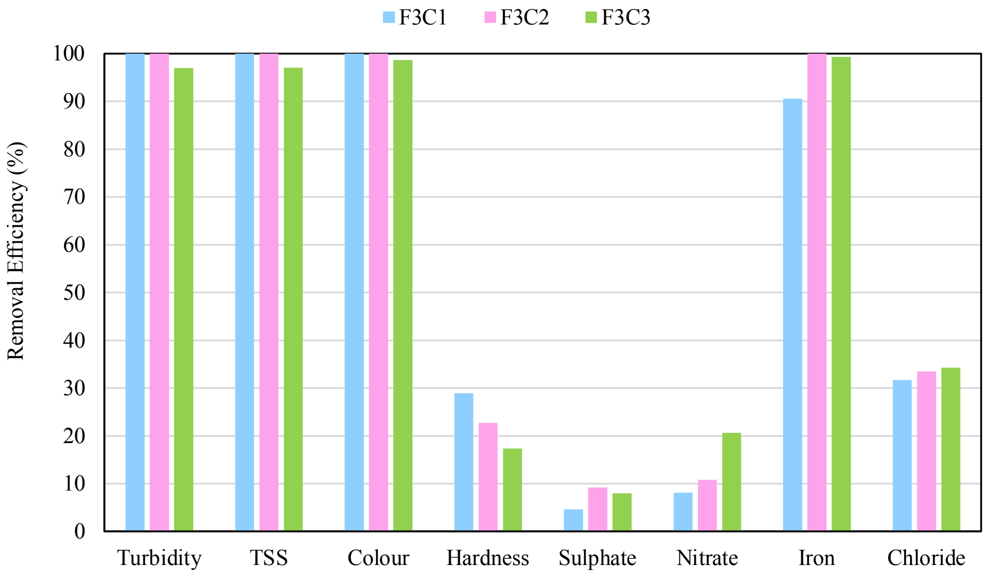


Figure 4.30 Performance of Dual Media Filter at 0.96 $m^3hr^{-1}m^{-2}$

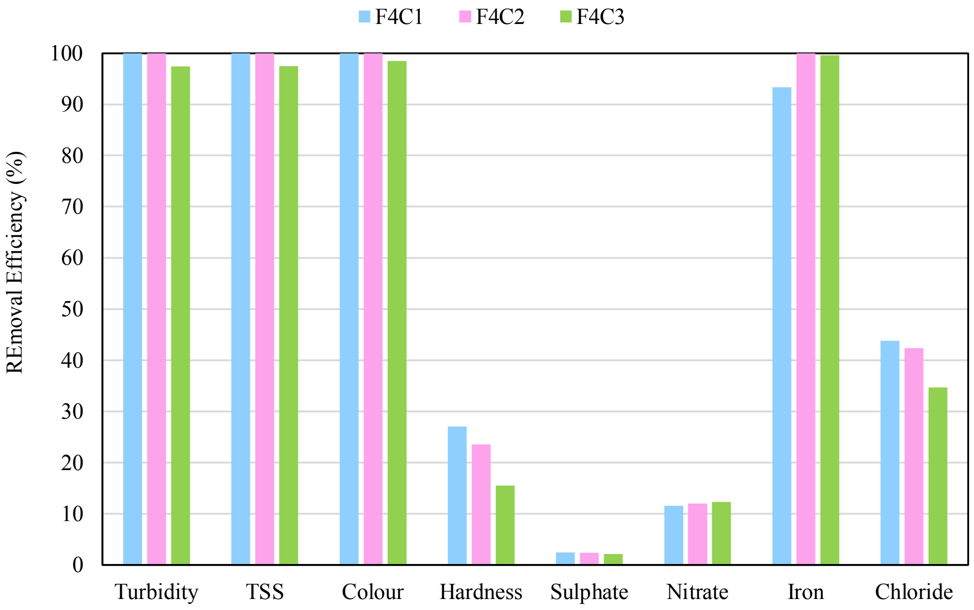


Figure 4.31 Performance of Dual Media Filter at 1.28 $m^3hr^{-1}m^{-2}$

Figure 4.32 shows the variation of pH and EC for different filtration rates and concentrations. The influent pH ranged from 5.8-7.5, and the pH of the treated water varied from 6.3-7.8. The electrical conductivity of treated water most often exceeded or remained the same due to the presence of end products in the form of dissolved solids.

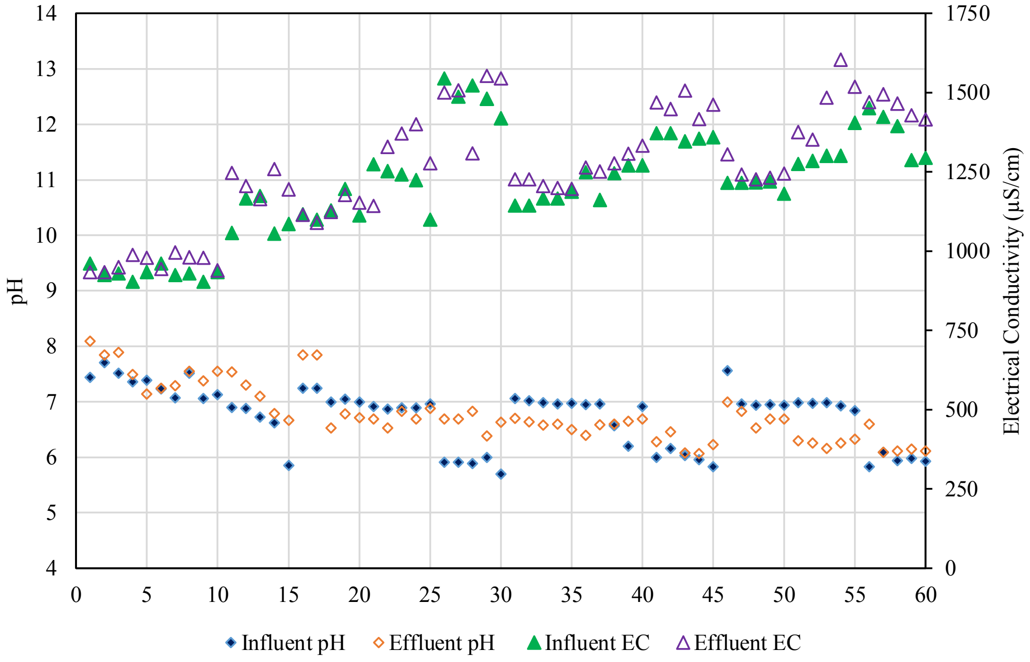


Figure 4.32 Variation of pH and EC in Dual Media Filter

The high hydraulic conductivity of charcoal and slag allowed filtration without much head loss. The maximum pressure drop observed was only 90 mm. The upper media layer must have a settling velocity compatible with that of the bottom media layer to ensure effective backwashing.

4.5 COMPARISON OF HEADLOSS OF SLAG FILTER WITH MATHEMATICAL MODEL

The Carman-Kozeny Equation (Equation 3.1 in Chapter 3) was taken as a model for all flow rates at low concentrations. At a flowrate of 0.32 $m^3hr^{-1}m^{-2}$ for low concentration, the observed head losses through a clean filter bed were zero and also, the calculated values were minimal. The head loss in the laboratory filter was maintained almost constant. At medium and high concentrations, the equation for head loss for a clogged filter (Equation 3.3 in Chapter 3) was taken as a model for all flowrates.

The scatter plots of measured and calculated head losses were drawn with X and Y values having the same intervals with 1:1 trend line (45°) fitted diagonally at point (0,0) across the plot area and were compared as shown in Figure 4.33 (at 0.64 $m^3hr^{-1}m^{-2}$ for C1), Figure 4.34 (at 0.96 $m^3hr^{-1}m^{-2}$ for C1), Figure 4.35 (at 1.28 $m^3hr^{-1}m^{-2}$ for C1), Figure 4.36 (at 0.32 $m^3hr^{-1}m^{-2}$ for C2), Figure 4.37 (at 0.64 $m^3hr^{-1}m^{-2}$ for C2), Figure 4.38 (at 0.96 $m^3hr^{-1}m^{-2}$ for C2), Figure 4.39 (at 1.28 $m^3hr^{-1}m^{-2}$ for C2), Figure 4.40 (at 0.32 $m^3hr^{-1}m^{-2}$ for C3), Figure 4.41 (at 0.64 $m^3hr^{-1}m^{-2}$ for C3), Figure 4.42 (at 0.96 $m^3hr^{-1}m^{-2}$ for C3) and Figure 4.43 (at 1.28 $m^3hr^{-1}m^{-2}$ for C3) respectively. The model values were seen to be in confirmation with the observed values. The deviations in some of the observed values might be due to the additional head losses incurred due to the outlet control apart from clogging head loss.

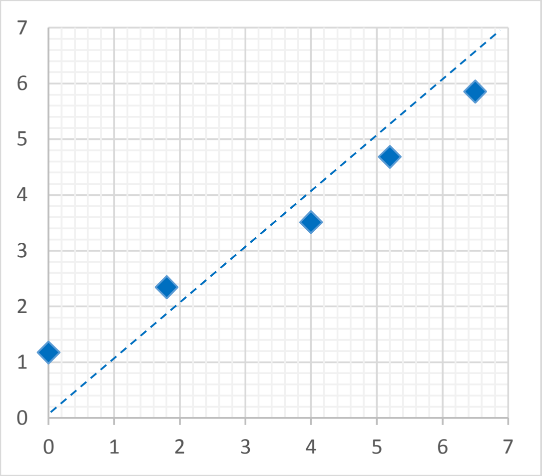


Figure 4.33 Observed and Calculated Headloss at 0.64 $m^3hr^{-1}m^{-2}$ for C1

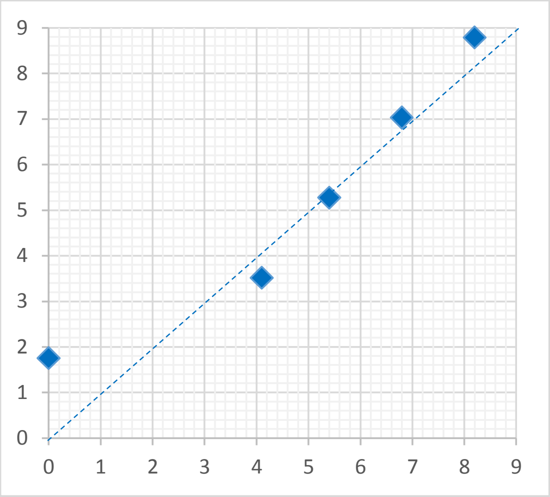


Figure 4.34 Observed and Calculated Headloss at 0.96 m^{3}hr^{-1}m^{-2} for C1

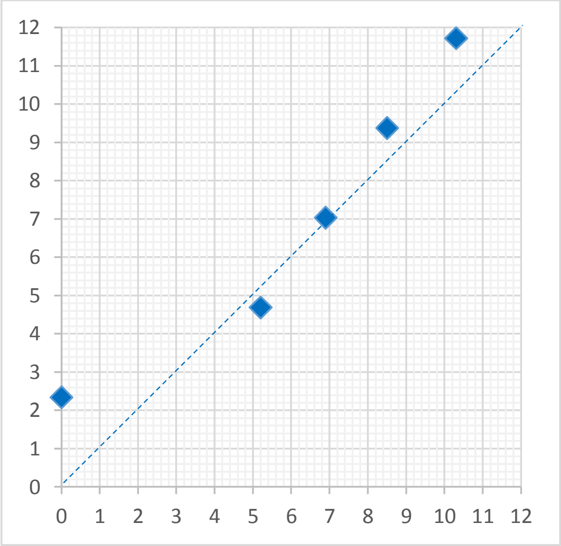


Figure 4.35 Observed and Calculated Headloss at 1.28 m^{3}hr^{-1}m^{-2} for C1

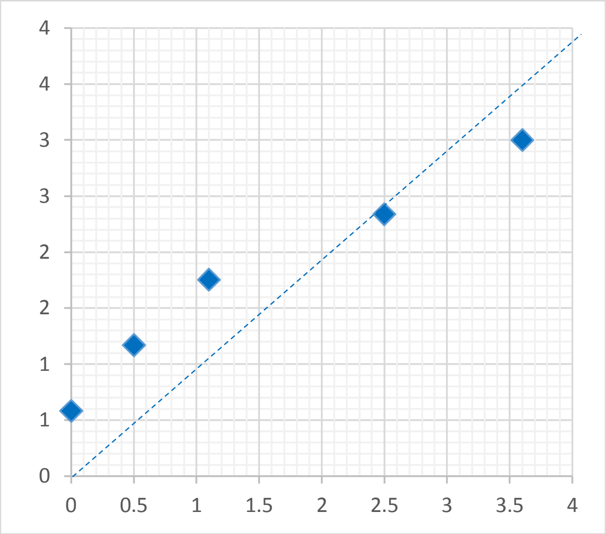


Figure 4.36 Observed and Calculated Headloss at 0.32 $m^3hr^{-1}m^{-2}$ for C2

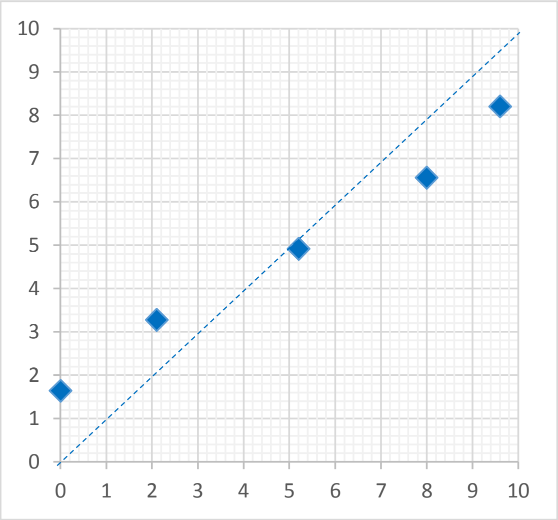


Figure 4.37 Observed and Calculated Headloss at 0.64 $m^3hr^{-1}m^{-2}$ for C2

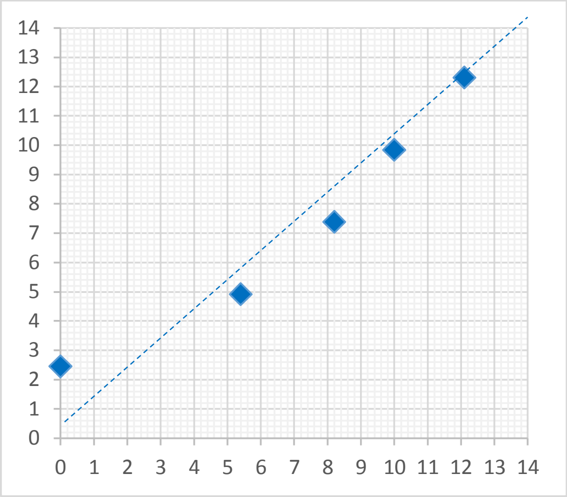


Figure 4.38 Observed and Calculated Headloss at 0.96 $m^3hr^{-1}m^{-2}$ for C2

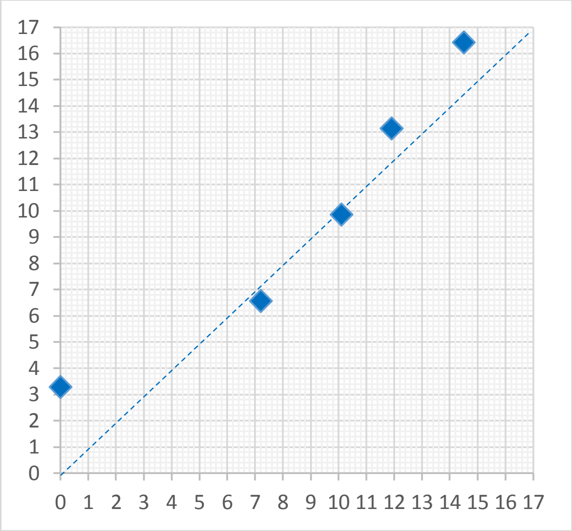


Figure 4.39 Observed and Calculated Headloss at 1.28 $m^3hr^{-1}m^{-2}$ for C2

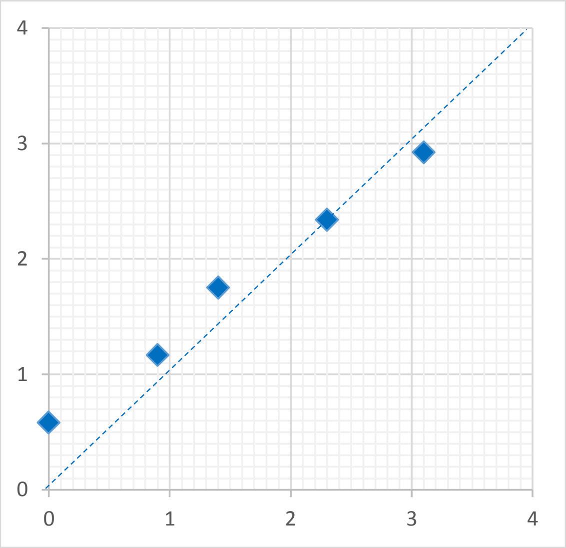


Figure 4.40 Observed and Calculated Headloss at 0.32 $m^3hr^{-1}m^{-2}$ for C3

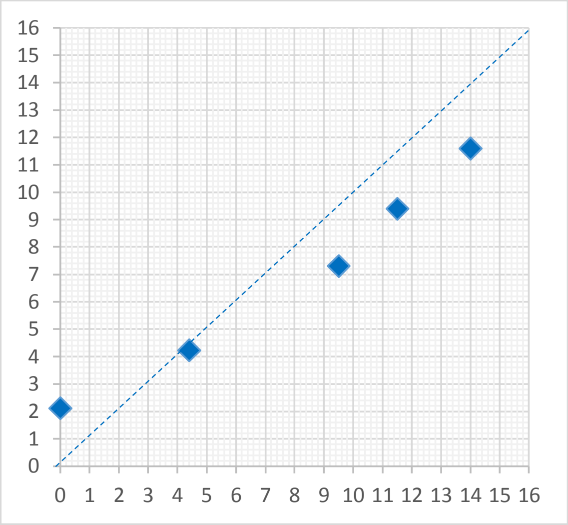


Figure 4.41 Observed and Calculated Headloss at 0.64 $m^3hr^{-1}m^{-2}$ for C3

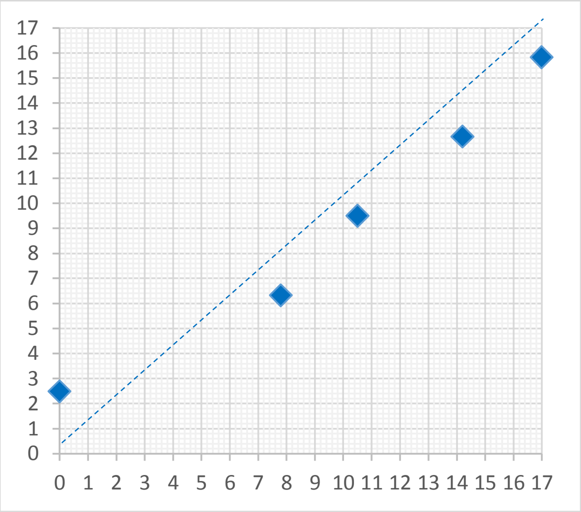


Figure 4.42 Observed and Calculated Headloss at 0.96 $m^3hr^{-1}m^{-2}$ for C3

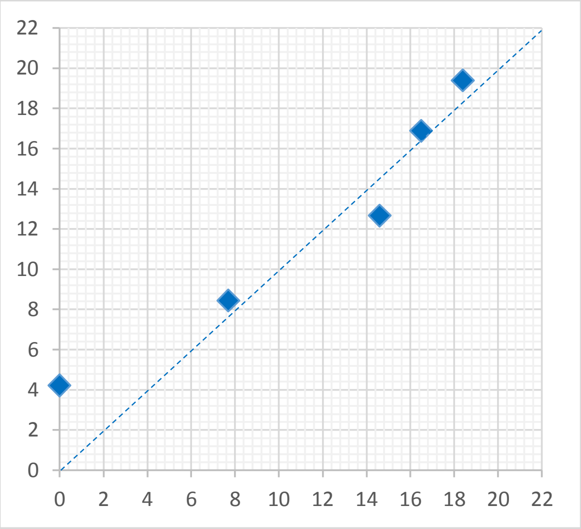


Figure 4.43 Observed and Calculated Headloss at 1.28 $m^3hr^{-1}m^{-2}$ for C3

The scatter plots of measured and calculated head losses were drawn with X and Y values having the same intervals with R^2 value are shown in Figure 4.44 to Figure 4.54. The coefficient of determination R^2 value indicates the degree of co-linearity between the measured and calculated data and the proportion of the variance in the observed data. The R^2 varies from 0.7 to 0.9 in all the cases and are acceptable.

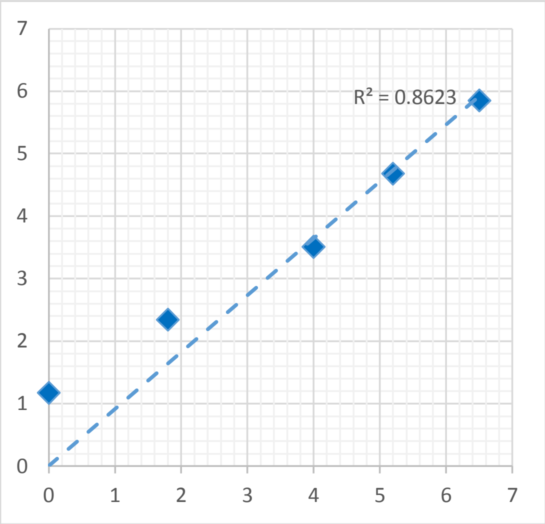


Figure 4.44 Observed and Calculated Headloss (with R^2) at 0.64 $m^3hr^{-1}m^{-2}$ for C1

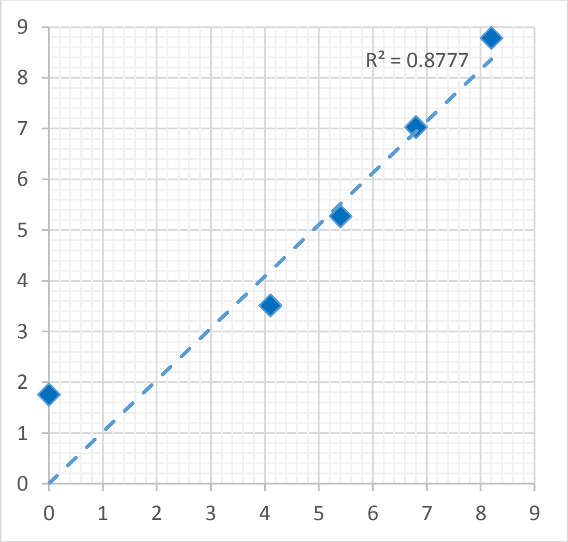


Figure 4.45 Observed and Calculated Headloss (with R^2) at 0.96 $m^3hr^{-1}m^{-2}$ for C1

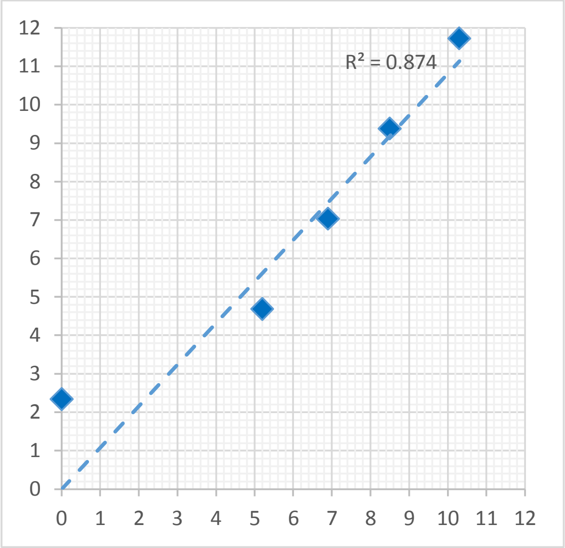


Figure 4.46 Observed and Calculated Headloss (with R^2) at 1.28 $m^3hr^{-1}m^{-2}$ for C1

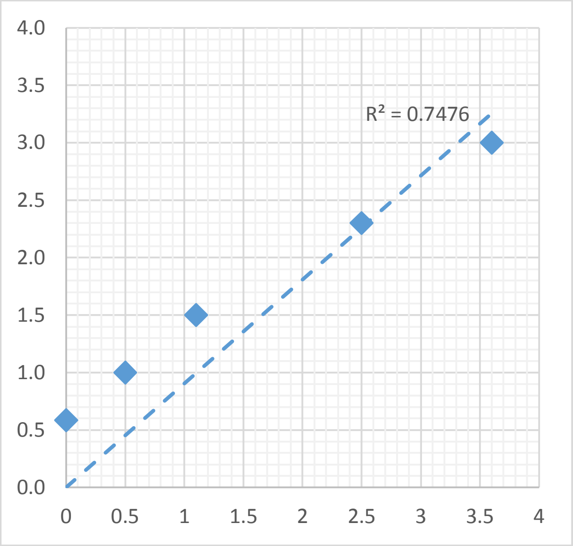


Figure 4.47 Observed and Calculated Headloss (with R^2) at 0.32 $m^3hr^{-1}m^{-2}$ for C2

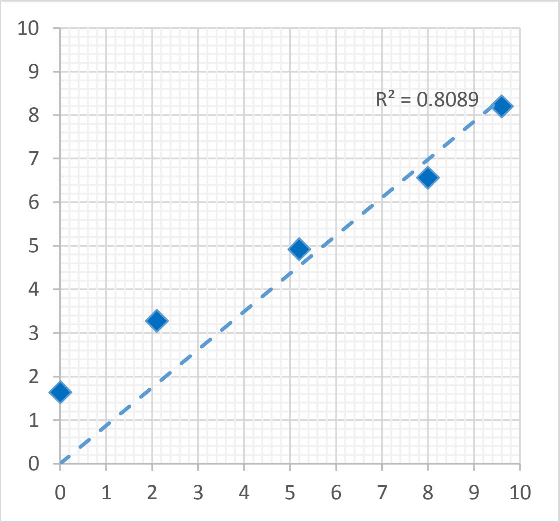


Figure 4.48 Observed and Calculated Headloss (with R^2) at 0.64 $m^3hr^{-1}m^{-2}$ for C2

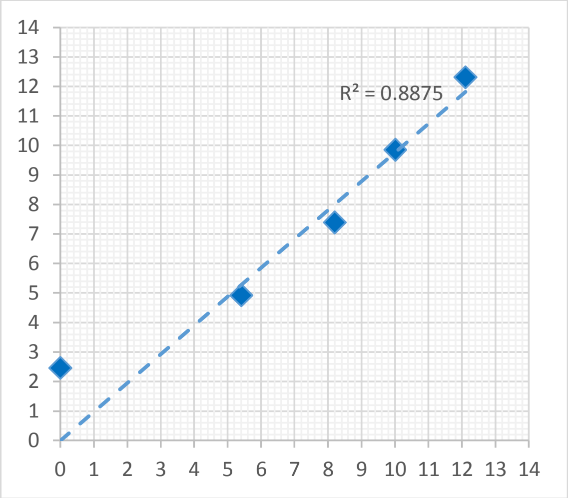


Figure 4.49 Observed and Calculated Headloss (with R^2) at 0.96 $m^3hr^{-1}m^{-2}$ for C2

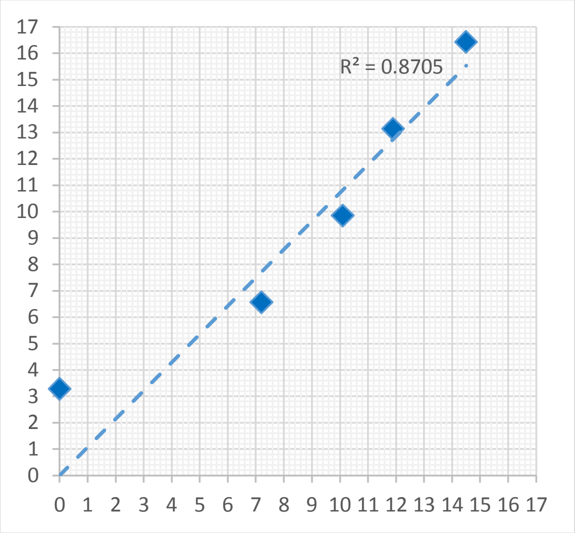


Figure 4.50 Observed and Calculated Headloss (with R^2) at 1.28 $m^3hr^{-1}m^{-2}$ for C2

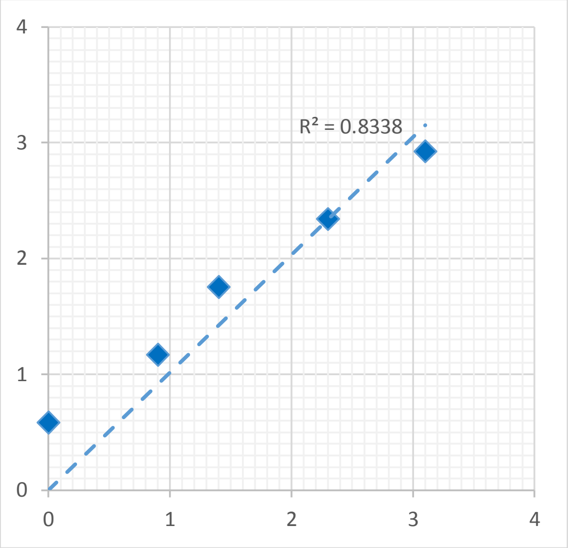


Figure 4.51 Observed and Calculated Headloss (with R^2) at 0.32 $m^3hr^{-1}m^{-2}$ for C3

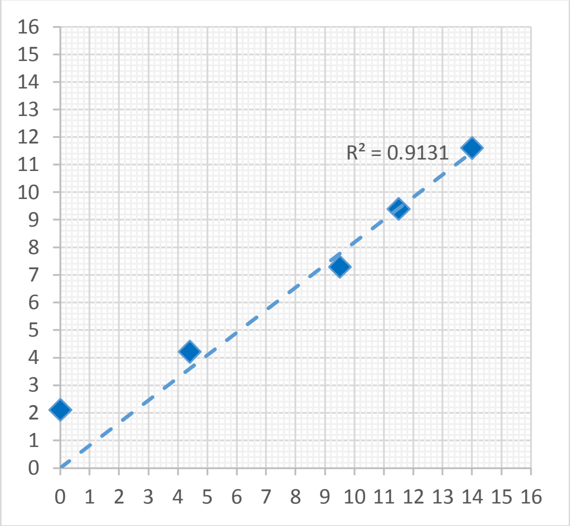


Figure 4.52 Observed and Calculated Headloss (with R^2) at 0.64 $m^3hr^{-1}m^{-2}$ for C3

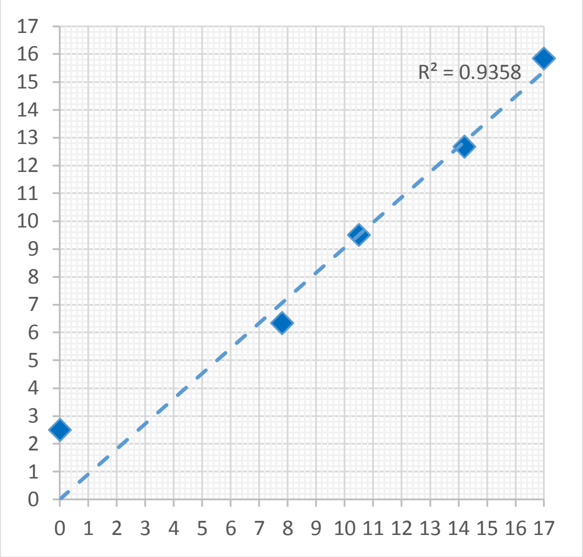


Figure 4.53 Observed and Calculated Headloss (with R^2) at 0.96 $m^3hr^{-1}m^{-2}$ for C3

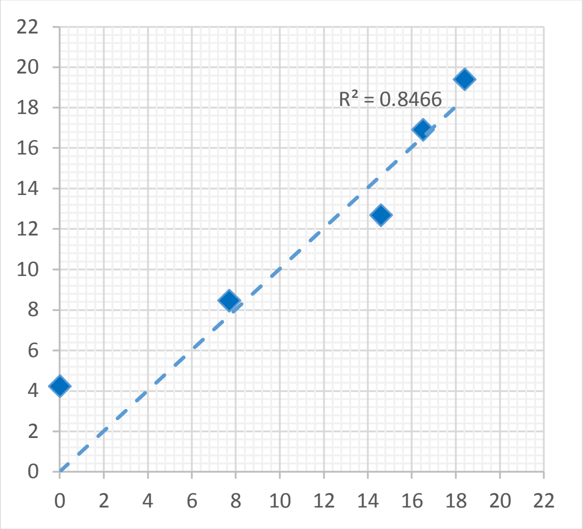


Figure 4.54 Observed and Calculated Headloss (with R^2) at 1.28 $m^3hr^{-1}m^{-2}$ for C3

CHAPTER 5

SUMMARY AND CONCLUSIONS

There are widespread applications of slag in water and wastewater treatment. The applications are limited to removal of nitrate, phosphate, heavy metals, acid mine waste, surrogate and fertilizer, landfill containment, leachate treatment. Since the slag is disposed of in large quantities around the premises of ferrous industries, its effective utilization in pollution remediation technology should be strongly appreciated. The literature strongly recommends the need for developing an appropriate technique for using ferrous slag in water/wastewater treatment which would be effectively, efficiently and environmentally managed for a long duration. The present research provides an innovative solution for drinking water treatment where there is a lack of availability of river sand.

The present research aims at the application of ferrous slag in drinking water treatment. Bench-scale filter proved the ability of slag as a potential alternative material to sand. In the present work, the performance evaluation of slag filter with sand as a control, a filter with partial replacement of slag with charcoal and the variation of head loss in the slag filter and its comparison with existing models were studied.

From the present investigation the following conclusions were drawn:

- The results of physicochemical properties of slag support its application as a suitable filter medium. Of the several parameters, the highly porous texture which makes the increased adsorption rate is quite mentionable.
- Slag filter, with intermittent backwashing, performed well during the experimentation for various filtration rates *viz*. 0.32, 0.64, 0.96 and 1.28 $m^3hr^{-1}m^{-2}$ for different concentration ranges of water quality parameters except sulphate removal.
- Slag filter media height of 40 cm was found to be sufficient for removing turbidity, colour and suspended solids at all concentrations and filtration rates.

- The analysis performed by FTIR and XRD clearly indicated the presence of hydroxyl groups in slag. This further substantiated the removal efficiency of soluble impurities such as chlorides, nitrates and sulphates by ion exchange mechanism.
- Comparing the performance of slag filter with sand filter, the removal of hardness, nitrate and chloride were almost the same as that of a sand filter. However, the performance of the slag filter for iron removal was slightly lower as compared to the sand filter due to the presence of 0.5-0.6% iron content in slag.
- When the full factorial model was analysed for different parameters, the flow type and concentration were significant for hardness, sulphate, chloride and nitrate whereas the concentration and type of filter medium were found to be significant for iron. As far as the removal efficiency was concerned, iron was the only parameter dependent on the type of media.
- The performance of slag filter in removing *E. coli* was similar to that of sand filter.
- On comparison, it was found that the dual media filter of slag with charcoal was not as good as slag filter in removing suspended impurities from the water. Also, the dissolved impurities such as nitrate and hardness removal declined with time, but chloride removal remained the same with increasing concentrations and flow rates of influent.
- Sorption rates of anions during filtration were in the decreasing order of NO_3^- > Cl^-> hardness > SO_4^-. But at higher filtration rates, it showed a pattern with Cl^- > hardness > NO_3^- > SO_4^-. This might be due to the interference of different anions in the influent.
- The scatter plots of measured and calculated head losses showed that the model fits the observed heads

Hence ferrous slag could be suggested as a suitable filter medium for water purification. The present investigation warrants further experimentation on other parameters also, so as to adopt the medium as a profitable and cost effective one.

5.1 ECONOMICAL AND SOCIAL BENEFITS OF THE WORK

Sand mining has been prohibited in most parts of India, due to its environmental impacts on water bodies. At the same time, slag is available in plenty, and the industries are finding it difficult to dispose of on land. In this respect, utilization of slag as a replacement for sand is both sustainable as well as economical.

5.2 SUGGESTION FOR FUTURE WORK

- The laboratory-scale study of slag filter shows positive results for water treatment and its implementation on a large scale needs to be studied.

- Detailed investigation on the removal of biological organisms could be performed since the preliminary result suggests disinfection after filtration.

- The present study should be extended to the treatment of actual surface and groundwater sources.

- Assessment of performance on compact filtration equipment could be done.

- The present investigation warrants further experimentation on other parameters also, so as to adopt the medium as a profitable and cost effective one. Together, this might be executed as an innovative solution for sustainable waste management also, in future.

APPENDIX

COST ANALYSIS

Sl No	DESCRIPTION	PRICE (Rs.)	
		SLAG	SAND
1	Cost of procurement of slag per kg including labour, material and transportation cost	10	100
2	UTILITY CHARGES		
a	Water requirement for washing media and utensils, backwashing etc. Max charge- Rs. 20/ month	240	240
b	Power consumption for pumping influent for 30 minutes =Rs.50/day*0.5/24 =Rs.1/ day	365	365
c	Power consumption for backwashing after every 5 days of operation for 30 minutes =Rs.1/day for 73 days	73	73
3	Total Utility Charges = (a + b + c)	678	678
Cost for treating 23360 litres/year (based on 64 litres / day) = 1+3		**688 per year**	**778 per year**

REFERENCES

Abdolahnejad, A., Ebrahimi, A. and Jafari, N. (2014). “Application of Iranian natural zeolite and blast furnace slag as slow sand filters media for water softening.” *International Journal of Environmental Health Engineering*, *3*(1), 26.

Agrawal, S. G., King, K. W., Fischer, E. N. and Woner, D. N. (2011 a). “PO_4^{3-} Removal by and Permeability of Industrial Byproducts and Minerals: Granulated Blast Furnace Slag, Cement Kiln Dust, Coconut Shell Activated Carbon, Silica Sand, and Zeolite.” *Water, Air, & Soil Pollution*, *219*(1-4), 91-101.

Agrawal, S.G., King, K.W., Moore, J.F., Levison, P. and McDonald, J. (2011b), “Use of industrial byproducts to filter phosphorus and pesticides in golf green drainage water”, *Journal of Environmental Quality*, 40(4), 1273-1280.

Ahammed, M. M. and Davra, K. (2011). “Performance evaluation of biosand filter modified with iron oxide-coated sand for household treatment of drinking water.” *Desalination,* Vol 276, 287–293.

Ahammed, M. M. and Meera, V. (2010). “Metal oxide/hydroxide-coated dual-media filter for simultaneous removal of bacteria and heavy metals from natural waters.” *Journal of Hazardous Materials*, Vol 181, 788–793.

Akinmolayan F. (2017). “Mathematical modelling of clean water treatment works.” Doctoal Thesis, University College London.

Anbalagan, G., Prabakaran, A. R. and Gunasekaran, S. (2010). “Spctroscopic characterization of Indian standard sand.” *Journal of Applied Spectroscopy*, Vol. 77, No. 1, 95-103.

APHA, AWWA, WPCF (Eds.). (2005). Standard methods for the examination of water and wastewater. Washington DC.

Asish, D.K., Singh, B. and Verma, S.K. (2016), “The effect of attack of chloride & sulphate on ground granulated blast furnace slag concrete”, *Adv. Concrete Construct.*, 4(2), 107-121.

Ballantine, D. J. and Tanner, C. C. (2010). “Substrate and filter materials to enhance phosphorus removal in constructed wetlands treating diffuse farm runoff: a review.” *New Zealand Journal of Agricultural Research*, *53*(1), 71-95.

Bhargava, D. S. and Ojha, C. S. P. (1999). “Genesis of porosity and predicting specific deposit of rapid sand filters”, *Indian Journal of Engineering and Materials Sciences*, 6, 144-152.

Bhatnagar, A., Kumar, E. and Sillanpääa, M. (2010). Nitrate removal from water by nano – alumina: Characterization and sorption studies. *Chemical Engineering Journal*, 163 (3), 317–323.

Bhatnagar, A., Sillanpää, M. (2011). A review of emerging adsorbents for nitrate removal from water. *Chemical Engineering Journal*, 168 (2), 493–504.

BIS: 1727 1967 (Reaffirmed 2004) silica, alumina, ferric oxide, calcium oxide and magneisum oxide.

BIS: 2720 (Part 17) 1986 (Reaffirmed 2002) Method of test for soils - Laboratory determination of permeability.

BIS: 2720 (Part 26) 1987 (Reaffirmed 2002) Method of test for soils - Determination of pH value.

BIS: 2720 (Part 3) 1980 (Reaffirmed 2002) Method of test for soils - Determination of Specific gravity.

BIS: 2720 (Part 4) - 1985 (Reaffirmed 2006) Indian standard methods of test for soils - grain size analysis.

BIS: 8419 (Part 1) 1977 Indian Standard Requirements for Filtration Equipment Part 1 Filtration Media- Sand and Gravel.

BIS: 10500 2012 Drinking water – Specification.

BIS: 11401 (Part 2): 1990 General requirements for slow sand filters.

BIS: 12089 (1987), Indian standard specification for granulated slag for the manufacture of Portland slag cement.

Blanco, I., Molle, P., de Miera, L. E. S. and Ansola, G. (2016). “Basic oxygen furnace steel slag aggregates for phosphorus treatment. Evaluation of its potential use as a substrate in constructed wetlands.” *Water research*, *89*, 355-365.

Bowden, L. I., Johnson, K. L., Jarvis, A.P., Robinson, H., Ghazireh, N. and Younger, P.L. (2006, March). “The use of basic oxygen steel furnace slag (BOS) as a high surface area media for the removal of iron from circum neutral mine waters.” In: *Proceedings of the 7th International Conference on Acid Rock Drainage (ICARD),* St. Louis, MO, USA (pp. 26-30).

Calder, N., Anderson, B. C. and Martin, D. G. (2006). “Field investigation of advanced filtration for phosphorus removal from constructed treatment wetland effluents.” *Environmental technology*, *27*(10), 1063-1071.

Clifford and Weber, (1978). “Nitrate removal from water by ion exchange.” EPA-600/2-78-052.

Chiang, Y.W., Santos, R.M., Elsen, J., Meesschaert, B., Martens, J.A., Van Gerven, T.: Towards zero-waste mineral carbon sequestration via two-way valorization of ironmaking slag. Chemical Engineering Journal, 249, 260-269 (2014)

Das, B., Prakash, S., Reddy, P. S. R. and Misra, V. N. (2007). "An overview of utilization of slag and sludge from steel industries." *Resources, conservation and recycling*, *50*(1), 40-57.

Dimitrova, S. V. (2002). Use of granular slag columns for lead removal. Water Res. 36(16), 4001–4008.

Dimitrova, S. V. and Mehanjiev, D. R. (2000). "Interaction of blast-furnace slag with heavy metal ions in water solutions." *Water research*, *34*(6), 1957-1961.

El-Taweel, G. E. and Ali, G. H. (2000). "Evaluation of roughing and slow sand filters for water treatment". *Water, Air, & Soil Pollution*, *120*(1), 21-28.

EPA (1995). Water Treatment Manuals Filtration.

Feng, Y., Yu, Y., Qiu, L. and Wan, X. (2012), "Performance of water quenched slag particles (WQSP) for municipal wastewater treatment in a biological aerated filter (BAF)", *Biomass and Bioenergy*, 45**,** 280-287.

Gao, H., Song, Z., Zhang, W., Yang, X., Wang, X. and Wang, D. (2017), " Synthesis of highly effective absorbnets with aste quenching blast furnace slag to remove Methyl Orange from aqueous solution", *Journal of Environmental Sciences (China)*, 53, 68-77.

Garg A, Kripalani C, Brighu U, 2004 "Heavy Metals in the Waters of a Wastewater Drain (Amanishah Nallah) Near Mansarover Region in Jaipur and Ground Water in the Vicinity" Nature, Environment and Pollution Technology, 3(1), 73.

Ge, Y., Wang, X., Zheng, Y., Dzakpasu, M., Xiong, J. and Zhao, Y. (2014), "Comparison of slags and gravels as substrates in horizontal subsurface flow constructed wetlands for polluted river water treatment", *Journal of Water Sustainability*, 4(4), 247-258.

Ge, Y., Wang, X., Zheng, Y., Dzakpasu, M., Zhao, Y. and Xiong, J. (2015). "Functions of slags and gravels as substrates in large-scale demonstration constructed wetland systems for polluted river water treatment." *Environmental Science and Pollution Research*, *22*(17), 12982-12991.

Goel, G., Kalamdhad, A. S. (2017) "Degraded municipal solid waste as partial substitute for manufacturing fired bricks" Construction and Building Materials, 155, 259–266.

Gong, G., Ye, S., Tian, Y., Wang, Q., Ni, J. and Chen, Y. (2009). "Preparation of a new sorbent with hydrated lime and blast furnace slag for phosphorus removal from aqueous solution." *Journal of hazardous materials*, *166*(2), 714-719.

Hallberg, M. and Renman, G. (2008). “Removal of heavy metals from road runoff by filtration in granular slag columns.” In *Proceedings of the 11th International Conference on Urban Drainage*. Edinburgh, Scotland, UK.

Han, S., Fitzpatrick C. S. B. and Wetherill A. (2008). “Mathematical Modelling of Particle Removal and Head Loss in Rapid Gravity Filtration”, *Separation Science and Technology*, 43:7, 1798-1812, DOI: 10.1080/01496390801973631.

Haynes, R.J. (2015), “Use of industrial wastes as media in constructed wetlands and filter beds—prospects for removal of phosphate and metals from wastewater streams”, *Critical Reviews in Environmental Science and Technology*, **45**(10), 1041-1103.

Hedström, A. and Rastas, L. (2006). “Methodological aspects of using blast furnace slag for wastewater phosphorus removal.” *Journal of environmental engineering*, *132*(11), 1431-1438.

Hizon-Fradejas, A. B., Nakano, Y., Nakai, S., Nishijima, W. and Okada, M. (2009). “Evaluation of blast furnace slag as basal media for eelgrass bed.” *Journal of hazardous materials*, *166*(2), 1560-1566.

Horii, K., Tsutsumi, N., Kitano, Y. and Kato, T. (2013). “Processing and reusing technologies for steelmaking slag.” *Nippon Steel Technical Report 104:*123-129.

Hylander, L. D., Kietlińska, A., Renman, G. and Simán, G. (2006). “Phosphorus retention in filter materials for wastewater treatment and its subsequent suitability for plant production.” *Bioresource technology*, *97*(7), 914-921.

IBM Indian Minerals Yearbook 2012 (Part- II: Metals & Alloys). Slag- Iron and Steel (Final Release). Government of India, Ministry of Mines, Indian Bureau of Mines. 51st Ed., January 2014.

IBM Indian Minerals Yearbook 2018 (Part- II: Metals & Alloys). Slag- Iron and Steel (Final Release). Government of India, Ministry of Mines, Indian Bureau of Mines, 57th Edition.

Isawa, T. (2013, March) “Update of iron and steel slag in Japan and current developments for valorisation.” In: Malfliet A *et al*. (ed.), *3rd International slag valorisation symposium*, Leuven, Belgium (pp. 87-98).

Johansson Westholm L. (2010). “The use of blast furnace slag for removal of phosphorus from wastewater in Sweden—A review”. *Water* 2(4), 826-837.

Johansson, L. (1999). “Industrial by-products and natural substrata as phosphorus sorbents.” *Environmental Technology 20*(3):309-316.

Johansson, L. and Gustafsson, J. P. (2000). “Phosphate removal using blast furnace slags and opoka-mechanisms.” *Water research*, *34*(1), 259-265.

Kalyoncu, R.S. (2001). Slag–iron and steel. US geological survey minerals yearbook

Karczmarczyk, A. (2004). “Phosphorus removal from domestic wastewater in horizontal subsurface flow constructed wetland after 8 years of operation–a case study.” *Journal of Environmental Engineering and Landscape Management 12*(4):126-131.

Kietlińska, A. and Renman, G. (2005). “An evaluation of reactive filter media for treating landfill leachate.” *Chemosphere*, *61*(7), 933-940.

Korkusuz, E. A., Beklioğlu, M. and Demirer, G. N. (2004). “Treatment efficiencies of the vertical flow pilot-scale constructed wetlands for domestic wastewater treatment.” *Turkish Journal of Engineering and Environmental Sciences*, *28*(5), 333-344.

Korkusuz, E. A., Beklioğlu, M. and Demirer, G. N. (2005). Comparison of the treatment performances of blast furnace slag-based and gravel-based vertical flow wetlands operated identically for domestic wastewater treatment in Turkey. *Ecological Engineering*, *24*(3), 185-198.

Korkusuz, E. A., Beklioğlu, M. and Demirer, G. N. (2007). “Use of blast furnace granulated slag as a substrate in vertical flow reed beds: field application.” *Bioresource Technology*, *98*(11), 2089-2101.

Koupai, J. A., Nejad, S. S., Mostafazadeh-Fard, S. and Behfarnia, K. (2015). “Reduction of Urban Storm-Runoff Pollution Using Porous Concrete Containing Iron Slag Adsorbent.” *Journal of Environmental Engineering*, *142*(2), 04015072.

Kumar, K.M., Mandal, B.K., Kumar, K.S., Reddy, P.S. and Sreedhar, B. (2013). Biobased green method to synthesize palladium and iron nanoparticles using *Terminalia chebula* aqueous extract. Spectrochim. Acta Part A Mol. Biomol. Spectrosc. 102, 128-133.

Kumar, D.S, Manjunath, L. R., Nataraja, M. C., Kaza, M. and Prasad S. M. R. (2016). “Urgent need for a new aggregate standard.” *The Indian Concrete Journal*, pp. 65-72.

Kumar P.G.D, Viswanath N. C., Cyrus S and Abraham B. M. (2020), “Mixing data for multivariate statistical study of groundwater quality.” Environ. Monit. Assess. 192:506.

Lewis, D. W. (1982, February). “Properties and uses of iron and steel slags.” In *National Slag Association Presented at Symposium on Slag National Institute for Transport and Road Research South Africa* (p. 1).

Li, G. and Guo, M. (2014). “Current development of slag valorisation in China.” *Waste and Biomass Valorization*, *5*(3), 317-325.

Lim, J. W., Chew, L. H., Choong, T. S., Tezara, C. and Yazdi, M. H. (2016). “Overview of Steel Slag Application and Utilization.” In: *MATEC Web of Conferences* (Vol. 74, p. 00026). EDP Sciences.

Lu, S. G., Bai, S. Q. and Shan, H. D. (2008). “Mechanisms of phosphate removal from aqueous solution by blast furnace slag and steel furnace slag.” *Journal of Zhejiang University-Science A*, *9*(1), 125-132.

Maiti, A., Basu, J.K., De, S., 2010. Development of a treated laterite for arsenic adsorption: effects of treatment parameters, Ind. Eng. Chem. Res. 49, 4873–4886.

CPHEEO Manual on water supply and treatment (1999). Third Edition, Ministry of Urban Development, New Delhi.

Mays, D. C and Hunt, J. R. (2005). “Hydrodynamic Aspects of Particle Clogging in Porous Media”, *Environ. Sci. Technol.*, 2005, 39, 577-584.

Mercado-Borrayo, B.M., González-Chávez, J. L., Ramírez-Zamora, R. M. and Schouwenaars, R. (2018), “Valorization of Metallurgical Slag for the Treatment of Water Pollution: An Emerging Technology for Resource Conservation and Re-utilization”, *Journal of Sustainable Metallurgy*, 4(1), 50-67.

Muttashar, H. L., Ali, N. B., Ariffinb, M. A. M. and Hussin, M. W. (2018), “Microstructures and physical properties of waste garnets as a promising construction materials”, *Case Studies in Construction Materials*, 8, 87–96.

Nehrenheim, E. and Gustafsson, J. P. (2008). “Kinetic sorption modelling of Cu, Ni, Zn, Pb and Cr ions to pine bark and blast furnace slag by using batch experiments.” *Bioresource technology*, *99*(6), 1571-1577.

Nehrenheim, E., Waara, S. and Westholm, L. J. (2008). “Metal retention on pine bark and blast furnace slag–On-site experiment for treatment of low strength landfill leachate.” *Bioresource technology*, *99*(5), 998-1005.

Nguyen, T.C., Loganathan, P., Nguyen, T.V., Kandasamy, J., Naidu, R. and Vigneswaran, S. (2018). “Adsorptive removal of five heavy metals from water using blast furnace slag and fly ash”, *Environ. Sci. Pollut. Res.*, 25(21), 20430-20438.

Nilsson, C., Renman, G., Westholm, L. J., Renman, A. and Drizo, A. (2013). “Effect of organic load on phosphorus and bacteria removal from wastewater using alkaline filter materials.” *Water research*, *47*(16), 6289-6297.

O’Kelly, B. C. (2008, March). “Geo-engineering properties of granulated blast furnace slag.” In: *Proceedings, Innovative Geotechnical Engineering, International Conference on Geotechnical Engineering*, Tunis, Tuniia (pp. 249-257).

Oguz, E. (2004). “Removal of phosphate from aqueous solution with blast furnace slag.” *Journal of Hazardous Materials*, *114*(1), 131-137.

Park, S-J, Lee C-G, Kim J-H and Kim S-B (2015). “Bimetallic oxide-coated sand filter for simultaneous removal of bacteria, Fe(II), and Mn(II) in small- and pilot-scale column experiments.” *Desalination and Water Treatment*, 54, 3380–3391.

Patra, R.K. and Mukharjee, B.B. (2017), “Properties of concrete incorporating granulated blast furnace slag as fine aggregate”, *Adv. Concrete Construct.*, **5**(5), 437-450. https://doi.org/10.12989/acc.2017.5.5.437.

Patra, R.K. and Mukharjee, B.B. (2018), “Influence of granulated blast furnace slag as fine aggregate on properties of cement mortar”, *Adv. Concrete Construct.*, **6**(6), 611-629. https://doi.org/10.12989/acc.2018.6.6.611.

Reddy, K.R., Gopakumar, A. & Chetri, J.K. (2019). “Critical review of applications of iron and steel slags for carbon sequestration and environmental remediation”, *Rev Environ Sci Biotechnol* 18, 127–152.

Pratt, C., Shilton, A., Haverkamp, R.G, and Pratt, S. (2009). “Assessment of physical techniques to regenerate active slag filters removing phosphorus from wastewater.” *Water Research 43*(2):277-282.

Pratt, C., Shilton, A., Haverkamp, R.G. and Pratt, S. (2011), “Chemical techniques for pretreating and regenerating active slag filters for improved phosphorus removal”, *Environmental Technology*, 32(10), 1053-1062.

Pratt, C., Shilton, A., Pratt, S., Haverkamp, R. G. and Bolan, N.S. (2007), “Phosphorus removal mechanisms in active slag filters treating waste stabilization pond effluent”, *Environmental Science & Technology*, 41(9), 3296-3301.

Proctor, D.M., Fehling, K.A., Shay, E.C., Wittenborn, J.L., Green, J.J., Avent, C., Bigham, R.D., Connolly, M., Lee, B., Shepker, T.O. and Zak, M.A., 2000. “Physical and chemical characteristics of blast furnace, basic oxygen furnace, and electric arc furnace steel industry slags.” *Environmental Science & Technology*, *34*(8), pp.1576-1582.

Saeed, T., Afrin, R., Al Muyeed, A. and Sun, G. (2012). “Treatment of tannery wastewater in a pilot-scale hybrid constructed wetland system in Bangladesh.” *Chemosphere 88*(9):1065-1073.

Sarode, D. B., Jadhav, R. N., Khatik, V. A., Ingle, S. T., Attarde, S. B.(2010). “Extraction and leaching of heavy metals from thermal power plant fly ash and its admixtures.” *Polish J. of Environ. Stud. 19* (6): 1325-1330.

Segismundo, E. Q., Kim, L. Jeong, S. and Lee, B. (2017). “A laboratory study on the filtration and clogging of the sand-bottom ash mixture for storm water infiltration media.” *Water 9*(32).

Sharma, A., Syed, Z., Brighu, U., Gupta, A. B., Ram, C. (2019). “Adsorption of textile wastewater on alkali-activated sand.” *Journal of Cleaner Production*, 220.

Shilton, A., Chen, L., Elemetri, I., Pratt, C. and Pratt, S. (2013). “Active slag filters: rapid assessment of phosphorus removal efficiency from effluent as a function of retention time.” *Environmental technology*, *34*(2), 195-200.

Shilton, A.N., Elmetri, I., Drizo, A., Pratt, S., Haverkamp, R.G. and Bilby, S.C. (2006), "Phosphorus removal by an 'active'slag filter–a decade of full scale experience", Water *Research*, 40(1), 113-118.

Singh, N.B., Nagpal G., Agrawal S. and Rachna (2018), "Water purification by using Adsorbents: A Review", *Environmental Technology & Innovation*, 11, 187–240.

Sivasankar, V. and Ramachandramoorthy, T. (2011). Water softening behaviour of sand materials – Mimicking natural zeolites in some locations of Rameswaram Island, India. Chemical Engineering Journal 171, 24-32.

Srivastava, S. K., Gupta, V. K., & Mohan, D. (1997). "Removal of lead and chromium by activated slag—a blast-furnace waste." *Journal of Environmental Engineering*, *123*(5), 461-468.

Srivastava, D. and Vaishya, R. C. (2015). "Treatment of arsenic (III) contaminated water by dynamically modified iron-coated sand (DMICS)." *Desalination and Water Treatment*, 53:9, 2565-2577.

Taylor (2006). "An assessment of iron and steel slag for treatment of stormwater pollution." The Australian (iron and steel) slag association Inc.

Tiwari, M.K., Bajpai, S., Dewangan, U.K., Tamrakar, R. K.(2015). "Suitability of leaching test methods for fly ash and slag: A review." *Journal of Radiation Research and Applied Sciences*, *8*(4), 523-537.

USEPA, U.: EPA Method 1311-Toxicity Characteristic Leaching Procedure. United States Environmental Protection Agency, Washington DC (1992).

Valero, M.C., Johnson, M., Mather, T. and Mara, D.D. (2009), "Enhanced phosphorus removal in a waste stabilization pond system with blast furnace slag filters", *Desalination and Water Treatment*, 4(1-3), 122-127.

WRAP, Waste & Resources Action Programme, Environment Agency UK (2007, August). A Technical Report on the Manufacturing of Blast Furnace Slag and Material Status in UK,

Yasipourtehrani, S., Strezov, V. and Evans, T. (2019), "Investigation of Phosphate Removal Capability of Blast Furnace Slag in Wastewater Treatment", *Scientific Reports*, 9:7498.

Zhang, M., Yang, C., Zhao, M., Yang, K., Shen, R. and Zheng, Y. (2017), "Immobilization potential of Cr (VI) in sodium hydroxide activated slag pastes", *Journal of Hazardous Materials*, 321, 281–289.

Zuo M., Renman G., Gustafsson J. P. and Klysubun W. (2018), "Dual slag filters for enhanced phosphorus removal from domestic wastewater: performance and mechanisms", *Environmental Science and Pollution Research*, **25,** 7391–7400.

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List of Publications

International Journals:

Anjali, M. S., Shrihari, S. and Sunil, B. M. (2019). “Potential valorisation of ferrous slag in the treatment of water and wastewater: A review.” *Advances in Environmental Research*, Techno-Press, *Vol. 8, No. 1 (2019) 55-69*, DOI: https://doi.org/10.12989/aer.2019.8.1.055.

Anjali, M. S., Shrihari, S. and Sunil, B. M. (2019). “Experimental studies of slag filter for drinking water treatment.” *Environmental Technology & Innovation*, Elsevier, 15, 100418, 1-13, DOI: https://doi.org/10.1016/j.eti.2019.100418.

Book Chapter:

Anjali M.S., Poorani M., Shrihari S., Sunil B.M. (2020). “Assessment of Ferrous Slag with Relevance to Physico-chemical Properties.” In: Kalamdhad A. (eds) *Recent Developments in Waste Management. Lecture Notes in Civil Engineering*, Vol 57, 377-384. Springer, Singapore. https://doi.org/10.1007/978-981-15-0990-2_30.

International Conferences:

Anjali, M. S., Shrihari, S. and Sunil, B. M. (2016). “Application of Ferrous Slag in the Treatment of Water and Wastewater: A Review.” In: *Proceedings of the International Conference on Systems, Energy and Environment (ICSEE 2016)* at Government College of Engineering Kannur, Kannur, Kerala, India ISBN: 978-93-85777-85-1, 101-110.

Anjali M. S., Shrihari, S. and Sunil, B. M. (2019). “Use of Ferrous Slag as a media for the Removal of Water Pollutants.” In: *Abstract Proceedings of International Conference (TMSF-2019)* at Don Bosco College of Engineering, Fatorda, Goa, India, Page 30.

Hemalatha K., Anjali M. S. and Shrihari, S. (2019). “The Use of Blast Furnace Slag for the Removal of Iron from Water.” In: *Abstract Proceedings of International Conference (TMSF-2019)* at Don Bosco College of Engineering, Fatorda, Goa, India, Page 29.

National Conferences:

Anjali M.S., Swachchha Majumdar and Ajit Haridas. (2003). “Acidic biofilter for the removal of hydrogen sulphide from air.” *Proceedings of National Conference on Biological Treatment of Wastewater and Waste Air (BTWWA-2003)* Organized by CSIR-National Institute for Interdisciplinary Science and Technology (NIIST), Thiruvananthapuram, 34-48.

Anjali M. S., Sruthy B. Suku, Pradeep P., Vaisak S. M., Anandhu, V., Princy Purushothaman, Shahabaz Abdulla and Fathwin Muhammed. (2016). “Bioremediation of Wastewater Using the Algae, *Spirogyra Sp*.” *Proceedings of 2nd National Conference on Technological Advancements in Engineering* Organized By Sree Narayana Guru College of Engineering and Technology, Payyannur, Kerala.

Anjali, M. S., Amrutha T. K., Goutham M. N., Maneesh B. M., Midhun M., Priyamvada Prabhan, Renjima A., Vyshakh Vijay. (2017). “Performance of a Moving Bed Aerobic Reactor for the Treatment of Dairy Wastewater.” *Proceedings of National Conference on Water Conservation and Management in the Coastal Regions* Organized by Vivekananda College of Engineering & Technology, Puttur, Karnataka, ISBN: 978-81-934333-0-0, 49-53.

Anjali M.S., Akhil, S., Haritha, E., Jithesh, K., Mariyam Rahina, Muhammed Rafi, A.M., Sinda, N. (2017). “Experimental Study on Water Quality of Various Rivers in Kasaragod District, Kerala.” *Proceedings of National Conference on Water Conservation and Management in the Coastal Regions* Organized by Vivekananda College of Engineering & Technology, Puttur, Karnataka ISBN: 978-81-934333-0-0, 105-110.

Seminar:

Anjali M.S., Thahira Beevi M.S. and Swachchha Majumdar (2001). “Removal of hydrogen sulphide using biofilter under low pH condition.” *Proceedings of the Regional Seminar on Technological Developments for the Third Millennium* Organized by College of Engineering, Trivandrum, Kerala, Vol (3), 544-551.

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