Gravity-Fed Column Configuration for Acid Mine Drainage Experiment

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***Abstract*—The aim of this study was to develop a gravity feed column set-up and to set the flow parameters based on experimentally measured flow rates and pressure drops. Prior to the present study the authors used a column set-up in which acid mine drainage was pumped through pervious concrete filled columns, using electrical peristaltic fish pond pumps. The gravity feed set-up in the present study was designed to overcome the need to rely on electrical power supply. The study describes the design set-up of four gravity columns. The design requirements comprised determination of appropriate column sizes, pressure heads and hydraulic gradients required to produce a low flow rate of about 1 mL/min at outlets of the columns filled with pervious concrete media. Of special interest is the hydraulic gradient being responsible for continuous flow in each column. Following completion of the design set-up, continuous flow rates of 0.60 to 0.80 mL/min were attained with a Reynolds number of about 4.0 in the columns filled with pervious concrete. Further research is in progress involving employment of the gravity-feed system for acid mine drainage treatment investigations.**

***Index Terms*—Gravity column, acid mine drainage (AMD), pervious concrete, darcy's flow regime.**

I. Introduction

A. Pervious Concrete in Column Experiments

Various recent studies [1]-[3] have shown pervious concrete to be an effective medium for treatment of acid mine drainage (AMD). This material is made by mixing single–size coarse aggregate with Portland cement and water to produce highly porous concrete. Consequently, hardened porous concrete typically has 20 to 30% porosity and high hydraulic conductivity, which allows water to flow uninhibited through the concrete.

The ores from which precious minerals and other resources such as gold, copper, platinum, coal, nickel etc are mined, typically contain pyrites (Fe_2S) that are immobilized underground and deprived of atmospheric conditions. Following the conduct of mining operations, these pyritic materials are exposed to oxygen and moisture in the atmosphere, leading to oxidation and formation of acidic discharge, commonly referred to as AMD. The AMD formed typically has low pH and contains high concentrations of heavy metals. AMD discharge leads to contamination of surface water bodies and underground water. It is severely detrimental to the ecological system and strangulates plant, animal and aquatic life, as it impairs soil fertility, irrigation water quality and infrastructures [1], [4]-[8].

Laboratory column studies are typically conducted to investigate the treatability of AMD using reactive materials of various types including zero-valent iron, limestone, zeolites, pervious concrete etc [2], [8]-[13].

More importantly, laboratory column experiments allow simulation of field water seepage or flow, to determine realistic parameters especially the residence time which can be used for modelling of geochemical changes due to the treatment. In treatments utilizing permeable reactive barriers (PRBs), these experimental parameters are essential for calculation of the barrier thickness and for modelling the lifespan prediction of the treatment system.

Pervious concrete is an emerging technology for treatment of AMD as a reactive material in PRBs. Accordingly, there are presently no site-installed pervious concrete PRBs reported in the literatures. Concrete has high alkalinity of about pH = 12.6. As contaminated water of low pH passes at a low flow rate through the concrete, the pH of AMD increases leading to precipitation of dissolved heavy elements from solution [14], [15].

B. Study Objectives

During column tests, submersible fishpond pumps are often used to pump contaminated AMD water through the column. This set-up was designated as the "pumped column system" and was used by the authors in earlier studies [2], [11], [12]. For most developing countries in Africa, power supply can be unreliable and typically marked by power outages commonly referred to as "load shedding". In such situations, continuously running laboratory experiments that are reliant on electricity can be severely affected due to interruptions resulting from power outages. Indeed, the authors of the present study experienced such difficulties due to rampant power outages that regularly interrupted the experimental runs of the column studies.

This problem led the authors to design a gravity fed system, as this type of configuration does not require power supply and thus the experiment can run continuously uninterrupted, under gravitational water flow. However, the set-up of the gravity-fed system requires careful design and testing, which this article describes in detail.

The second objective of the study was to configure the flow parameters in order to obtain a flow rate of about 1.0 mL/min, being the nominal value typically used in field

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applications (Table I).

II. Fluid Flow Through Pervious Concrete

A. Flow Parameters

Gravity provides an additional driving force for vertical fluid flow and has a consequent influence on the spatial distribution of total head [16]. The governing flow equation (1) for one-dimensional, vertical (z plane) case is

$$q = -k\frac{dh_t}{dz} \quad (1)$$

where h_t is the total head, thus representing the sum of the matric suction head (h_m) and the elevation head (z), i.e. $h_t = h_m + z$. The gravitational component represents the change in elevation, z, from one point under consideration to another; while k is Darcy's permeability coefficient.

It is important to recognize that, it is the gradient of the total head, not the matric head which drives fluid flow through unsaturated concrete. For example, if two points in the subsurface have the same matric suction value, one cannot draw a definite conclusion regarding the existence or direction of fluid flow between the two points without knowledge of the elevation (z) for each [16]. Using the total head concept, as in equation (1) can be re-written in terms of matric suction head h_m and the gravity gradient ($dz/dz = 1$)

$$q = -k\left(\frac{dh_m}{dz} + 1\right) \quad (2)$$

Equation (2) provides a general basis to quantitatively assess the vertical distribution of total head under the steady state flow condition. Two characteristic functions of the experiment are required namely, pressure drop as a function of flow rate and the hydraulic head.

For a vertical flow problem, q is negative, and the hydraulic gradient under gravity varies within the following range [16]:

$$-1.0 \le \frac{dh_m}{dz} \le 0 \quad (3)$$

The range in equation (3) represents the condition when the vertical flow is zero or the hydrostatic condition which leads to the lower bound of -1.0 [16]. When the pervious concrete medium is nearly saturated by vertical capillary flow, the matric suction and the gradient in matric suction both approach zero. This leads to the following condition for vertical steady state flow (k_s):

$$k_s \ge k \ge -q \quad (4)$$

Equation (4) implies that one can discard the experimental data for unsaturated flow (k), less the constant flux (q). The negative sign at the right-side of equation (4) indicates that the AMD water flow occurs from a location of relatively high head to a location of relatively low head. Seepage velocity (Vs), which describes the average actual flow velocity through the pores of the medium, is equal to the discharge velocity divided by porosity of the pervious concrete medium. The velocity of AMD water through pervious concrete is linearly proportional to the gradient in the relevant driving head.

B. Hydrologic Properties

As mentioned earlier, pervious concrete has high porosity, large pores of sizes up to 10 mm and continuous pore connectivity. The hydraulic conductivity of pervious concrete is typically determined as the falling permeability expressed in mm/s. The typical apparatus used is the falling permeameter, as described in the various literatures [1], [17], [18].

Some researches in the literatures [19] show the hydraulic conductivity of pervious concrete to be 2 to 8 mm/s. However, Ekolu *et al* [1] found a wider variation in hydraulic conductivity ranging from 2 to 20 mm/s. The study [1] involved several mix design parameters including a widely varied water /cementitious ratio of 0.25 to 0.40, different types and sizes of coarse aggregate comprising 6.7, 9.5, 13.2 mm granite; 6.7 mm shale and 9.5 mm dolomite. In addition, supplementary cementitious materials comprising fly ash (FA) and ground granulated blast-furnace slag (GGBS) were incorporated into pervious concrete mixtures in proportions of 20, 30, 50% FA or 30%, 50% GGBS. In all mixtures, the cementitious content and aggregate /cement ratio were maintained constant at 360 kg/m^3 and 4.0, respectively. Evidently, the extensive range of the mixture design parameters employed, expectedly led to the wide ranging values of hydraulic conductivity results obtained. The study concluded that 6.7 and 9.5 mm granite aggregate of 0.27 water/cement ratio were the most suitable mix design parameters for preparing pervious concrete of appropriate hydrologic characteristics.

Porosity along with permeability, are majorly responsible for the efficacy of pervious concrete in hydrological applications such as its use in permeable pavements for storm water management and agricultural manure beddings [20-22] or for water purification and treatment purposes [2],[11]-[12], [23], [24]. There are different techniques that may be employed to determine the porosity of pervious concrete. Of interest are ASTM C1688 [25] for measuring the porosity of fresh pervious concrete and the ASTM C1754 procedure [26] for determining the porosity of hardened concrete.

In the case of ASTM C1688, fresh pervious concrete is compacted in a density cylinder then weighed. The measured mass of concrete along with the theoretical density calculated from batched materials comprising cement, aggregate and water, are used to calculate porosity. The ASTM C1754 procedure (also [27]) involves drying the pervious concrete samples at 37.8°C followed by weighing in air and in water, from which the porosity value is calculated. This volumetric method is particularly relevant in the present study since the column set-ups employed were conducted using hardened pervious concrete cubes.

C. Field Flow Rates

The type and sizes of PRBs reported in the literatures vary widely, as the hydrogeological conditions and geochemical characteristics of polluted water are largely site dependent. Accordingly, each site and its contaminated water quality has to be independently characterized to determine the appropriate parameters suitable for PRB design. A survey of various field PRBs installed shows that their typical dimensions comprise a width of W_b = 2 to 50 m perpendicular to the direction of AMD flow, wall thickness of L_b = <1 to 5 m parallel to the direction of AMD flow, and a depth of H_b = < 1 to 10 m [28]. A critical parameter for determination of the PRB thickness is the residence time (t_r) which in turn is related to the flow rate i.e. the velocity of water flow (Vs). Hence $L_b = t_r . V_s . S_f$ where S_f is the factor of safety. With a known flow rate obtained from field measurements, column experiments can be conducted to obtain the reaction rate or retardation coefficient (k) of the reactive material, which can be used to calculate residence time based on the equation $t_r = -\ln(C_t/C_o)/k$, where C_t and C_o are the target and initial concentrations of the contaminant, respectively.

In PRBs, low flow rates are typically employed to achieve a sufficient residence time for the treatment to take effect through the chemical reaction interaction between AMD and the reactive material. Table I gives some flow rates that have been used in the various column experiments conducted to simulate typical field conditions [28]. It can be seen that the flow rate values used in the various literatures to depict field values tend to be low, being generally between 0.2 to 2 mL/min, for which an average may be taken roughly to be 1.0 mL/min.

TABLE I: TYPICAL FLOW RATES USED IN COLUMN EXPERIMENTS

Reference	**Pollutant**	**Reactive material**	**H (mm)**	**Size* (mm)**	**V (mL /min)**
[29]	TCE	ZVI+	1000	50D	0.5
[30]	Nitrate, metals	ZVI	900	150D	1.5
[31]	AMD	Zeolite	500	44D	0.35
[32]	AMD	ZVI	450	50D	0.23
[33]	Copper	ZVI	450	50D	0.23
[34]	Chromium VI	ZVI	1000	60D	2.55
[35]	Copper, nickel	ZVI	1000	50D	0.5
[36]	Copper, nickel	ZVI/pum#	1000	50D	0.5
[2]	AMD	PervC$	650	100sq	0.35

*D – diameter, *sq* – square; +ZVI – zero-valent iron, $PervC – pervious concrete, #pum – pumice

III. EXPERIMENT ON FACTORS AFFECTING FLOW RATE

In order to assess the factors affecting flow rate and to determine the appropriate parameter settings needed to obtain the required flow rate of 1.0 mL/min, a simple set-up was made. The main variables of the set-up were the elevation of drums containing AMD water and the volume or elevation of water levels in the storage 20 L drums. The resulting flow rate was monitored in terms of the intervals of water drops per second, coming out from the open tap located at the base of the drums. The time interval of water drops was then converted into the equivalent of flow rate in mL/min.

The AMD water used in the study was obtained from an abandoned coal mine in South Africa and designated as TDB. The AMD had a low pH of 2.93 and had high concentrations of heavy metals. The chemical composition of the AMD used in the present study is already given in an earlier associated paper [11] and therefore not repeated here. Although the viscosity of the AMD was not measured, it was assumed to be similar to that of ordinary water and to be non-sensitive to small temperature changes under room conditions.

Table II gives the incremental volume of water in drums 1 and 2, the corresponding elevation of water level in the drums and the timed water drops recorded. These results have also been plotted in Fig. 1 showing the relationship between elevation and flow speed at different elevations of the drum reservoirs.

It can be seen that increments in volume of water for the drum 1 led to corresponding increases in flow speed of drops, reducing from 7 seconds per drop at 5.4 L to 2 seconds per drop at 15.5 L volume of water (Fig. 1a). Drum 2 which was at a higher elevation than drum 1, showed the opposite trend with the timed drops increasing from 18 seconds per drop at 5.4 L to 23 seconds per drop at 15.5 L (Fig. 1b). This contradictory observation is directly related to the elevation difference from ground level. The lower the elevation of the drum, the greater the gravitational force thereby causing faster flow speed in terms of seconds per water drop.

TABLE II: WATER FLOW SPEEDS AT DIFFERENT WATER VOLUMES AND RESERVOIR ELEVATIONS

	Volume of water in the drum (L)	Water elevation from ground (cm)	Timed water drops from tap (secs. per drop)
Drum 1	-	129	-
	5.4	136	7
	9	140	4
	13.5	148	2
	15.5	151	2
Drum 2	-	167	-
	5.4	174	18
	9	178	16
	13.5	186	13
	15.5	189	23

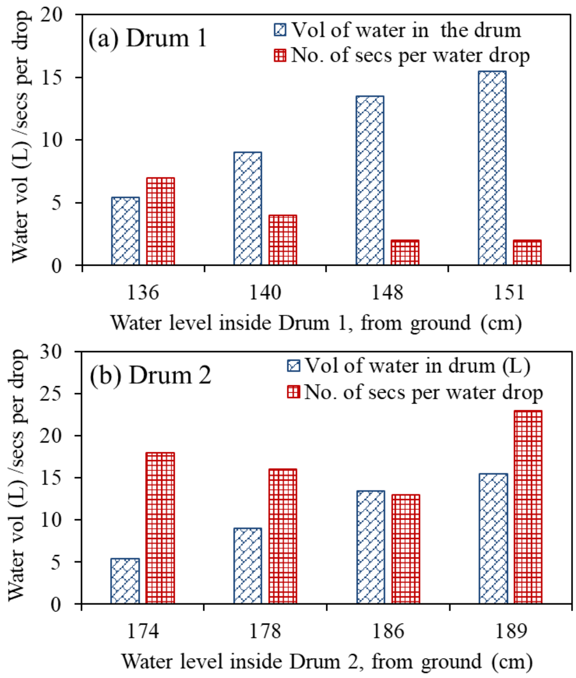

Fig. 1. Relationship between elevation, water volume and water flow speed.

To evaluate the repeatability of the flow rate results, test runs were conducted for both drums 1 and 2 placed at their elevations of 129 and 167 cm, respectively. All measurements were done at a fixed water volume of 15.5 L. It can be seen in Fig. 2 that highly repeatable results were obtained for measurements of both drums 1 and 2. The measurements for drum 1 at elevation of 129 cm, gave flow rates of 0.8 to 1.0 mL/min, while the measurements done for drum 2 were relatively more widely varied, giving flow rates of 0.7 to 1.2 mL/min. Hence the elevation settings used for drum 1 were considered to be more appropriate and were used in the main configuration discussed in Section IV.

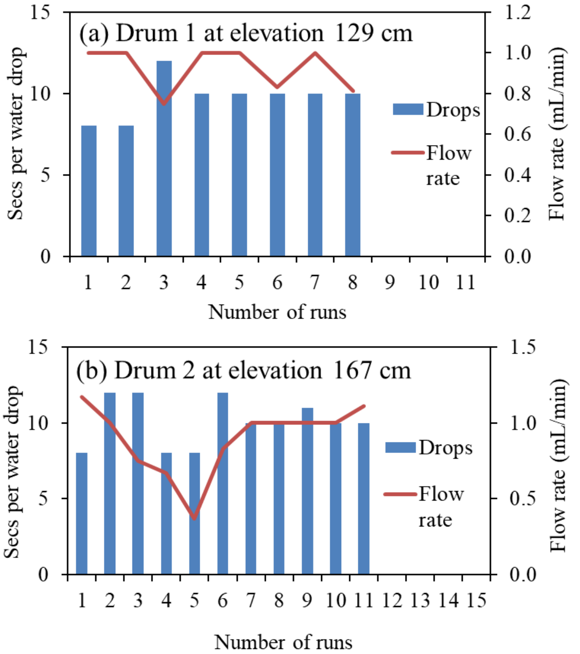

Fig. 2. Flow rate measurements at a fixed water volume of 15.5 L.

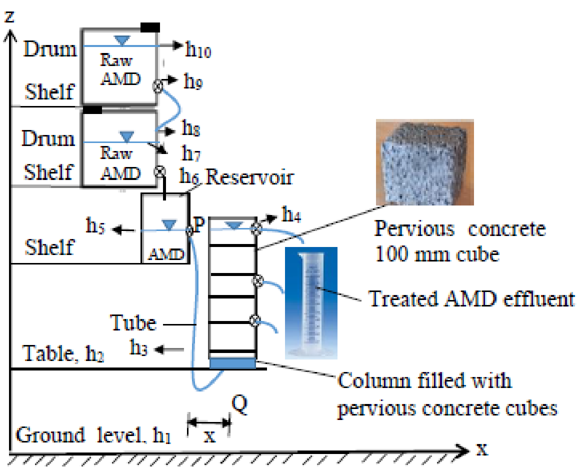

Fig. 3. Schematic diagram of the gravity column set-up; parameter definitions are given in Tables II to V, AMD - acid mine drainage

IV. Configuration

A. Gravity Column Set-up

A sketch of the gravity column set-up developed for the experimental investigations, is given in Fig. 3. In the study, four columns were set-up, each of them being made of transparent perspex plastic. Each column was of size 650 mm height and 100 mm square internal dimension. Each column had an inlet port at its base to provide the inflow of AMD sample. Three side ports were located at 155 mm (bottom port), 310 mm (middle port), 465 mm (top port at height level h_4 from the ground) along the column height. A connecting tube was used to convey AMD water coming from the reservoir to the base port of the column.

Four pervious concrete cubes of 100 mm size were placed inside each column. The concrete used was prepared at 0.27 water /cement ratio using 6.7 mm granite aggregate, Portland cement of CEM I 52.5 N supplied by Pretoria Portland Cement (pty) Ltd, and tap water. The material quantities, mixing, casting and curing procedures employed are already described in an earlier associated publication [2] and accordingly not repeated here.

It can be seen in Fig. 3 that there were ten (10) different key height levels with h_1 and h_2 being the ground level and table levels respectively. The heights h_3 and h_4 marked the lowest and the highest water levels within each column. Reservoirs were placed at elevated levels besides each column at which height level h_5 was located. The reservoirs received the raw AMD from two 20 L storage drums, that were placed at the uppermost levels, within which were located the height levels h_6 to h_{10}. The four column set-ups were assigned the numbers 1 to 4.

After the AMD water passes through the pervious concrete medium, water reaches the upper port (h_4), and then, the treated water is collected in the graduated cylinder. For each column, AMD sample was gravity fed at a time drop of 8 to 12 seconds from the reservoir which is connected in series with the upper and lower drums in order to obtain the flow rate of about 1 mL/min at the collection outlet.

The flow intensity time pressure (p) is measured by the gradient in the relevant driving total head (h_t):

$$h_t = \frac{p}{\rho . g} + z \tag{4}$$

where g is the gravity acceleration (m/s^2), ρ is density of water (kg/m^3) and z is the elevation of the position above the chosen datum (elevation head) which is a fixed reference ground level in (m). The main parameters of the set-up are summarized in Table I.

TABLE III: Parameters of the Experiment

Parameter	Symbol	Value
Laboratory temperature	T	23℃
Density of water	ρ	1000 (kg/m^3)
Volumetric flow	q	mL/min
Gravity acceleration	g	9.81 (m/s^2)
Volumetric flow	Q	mm^3/s
Velocity at out let	V	mm/s
Diameter of outlet tube	d	7 (mm)
Area of outlet tube	A	19.24 (mm^2)
Kinematic viscosity [37]	η	1.005 (mm^2/s)
Reynolds number	Re	(-)
Elevation head	h_z	mm
Pressure head	h_w	mm
Total head	h_p	mm
Pore-water pressure	u_p	kPa
Driving head	Δh	m
Pressure drop	Δp	kPa

TABLE IV: Parameters of Driving Head (ΔH) and Pressure Drop (ΔP) Calculation Results

Head (m)	Column 1	Column 2	Column 3	Column 4
h_{10}	2.56	2.56	2.58	2.58
h_9	2.2	2.2	2.20	2.20
h_8	1.99	1.99	1.95	1.95
h_7	1.88	1.88	1.87	1.87
h_6	1.67	1.67	1.64	1.64
h_5	1.49	1.48	1.48	1.48
h_4	1.47	1.47	1.44	1.44
h_3	1.03	1.03	1.03	1.03
h_2	1.01	1.01	1.01	1.01
h_1	0	0	0	0
$\Delta h_{10\text{-}9}$ (m)	0.36	0.36	0.38	0.38
$\Delta h_{7\text{-}6}$ (m)	0.21	0.21	0.22	0.22
$\Delta h_{6\text{-}5}$ (m)	0.17	0.19	0.16	0.16
$\Delta p_{10\text{-}9}$ (Pa)	3580.65	3580.65	3727.80	3727.80
$\Delta p_{7\text{-}6}$ (Pa)	2060.10	2060.10	2207.25	2207.25
$\Delta p_{6\text{-}5}$ (Pa)	1716.75	1863.90	1618.65	1618.65

TABLE V: PARAMETERS TO CALCULATE HYDRAULIC GRADIENT

	Column 1	Column 2	Column 3	Column 4
Elevation head at P, h_z (mm)	-95	-75	-121	-102
Pressure head at P, h_w (mm)	110	95	125	107
Total head at P, h_P (mm)	15	20	4	5
Elevation head at Q, h_z (mm)	-470	-475	-466	-473
Pressure head at Q, h_w (mm)	470	475	466	473
Total head at Q, h_Q (mm)	0	0	0	0
Pore-water pressure, U_P (Pa)	1079.10	735.75	1226.25	1096.70
Pore-water pressure, U_Q (Pa)	4610.70	4659.75	4571.46	4640.13
Distance from P to Q, x (mm)	195	175	255	315
Hydraulic gradient, i_{PQ^*}	-0.8	-0.11	-0.02	-0.02

$i_{PQ(1-4)}* = \frac{h_Q - h_p}{x_{1-4}}$

TABLE VI. RESULTS OF MEASUREMENTS

Time of record interval	Calculated parameters	Column 1	Column 2	Column 3	Column 4
30 mins	Q (mL/min)	0.79	0.82	0.71	0.72
	Q (mm^3/s)	13.10	13.70	11.80	11.90
	V* (mm/s)	0.68	0.71	0.61	0.62
	Re* (-)	4.74	4.94	4.24	4.32
One-day collection calculated at 24 hrs	Q (mL/min)	0.64	0.79	0.68	0.69
	Q (mm^3/s)	10.70	13.10	11.30	11.50
	V* (mm/s)	0.56	0.68	0.59	0.60
	Re* (-)	3.90	4.74	4.11	4.18
Higher flow rate readings	Q (mL/min)	1.79	2.04	2.64	1.84
	Q (mm^3/s)	29.8	34.0	44.0	30.6
	V* (mm/s)	1.55	1.77	2.27	1.59
	Re* (-)	10.80	12.33	15.81	11.07

$v^* = Q/A,\ Re^* = \frac{V.d}{\eta}$

A. Physical Measurements

Physical measurements were conducted for the experimental set-up shown in Fig. 3 based on the parameters given in Table III. Table IV gives the physical measurements done for each of the four columns 1 to 4. As the pressure difference increases, the flow rate of the water also increases (h_4). Thus, as the velocity of the same system increases, the total head pressure also increases for both the reservoir and the column outlet flow.

From the pressure head data collected in the experiment, the total head, hydraulic gradient, volumetric flow rates and pressure drops for each column were calculated. Table V and Table VI show the calculated values for all the columns. The fundamental thermodynamic quantity governing the flow of liquid water in unsaturated media is the total potential of the pore water, most commonly described in terms of total suction or total head. For example, media described by a total suction of 200 kPa has a pore-water potential of 200 J/kg or a driving head for fluid flow of about 20.4 m [16].

During the experiment, three measurements were made for each of the four column values to obtain the volumetric flow (Q) shown in Table V. For a given volumetric flow, the resulting water levels, from h_1 to h_{10} (measured relative to ground level z = h_1, as a reference) along the measurement elevation head, were recorded. The measurement points were distributed along each column at heights of h_{10} = 2.58 m, h_9 = 2.20 m, h_8 = 1.95 m, h_7 = 1.87 m, h_6 = 1.67 m, h_5 = 1.47 m, h_4 = 1.46 m, h_3 = 1.03 m, h_2 = 1.01 m and h_1 = 0 m with horizontal length at x_1 = 195 mm, x_2 = 175 mm, x_3 = 255 mm and x_4 = 315 mm respectively, for the columns 1 to 4 from reservoir outlet (P) to column inlet (Q). Based on these values and the column outlet tube area cross-section (A), flow velocity as well as the Reynolds number, were computed for every flow rate. In order to unify data and facilitate comparison of results, flow rates were related to the highest measurement point (higher flow rate in Table VI). Results of the measurements are summarized in Table VI.

V. DISCUSSION OF RESULTS

Distribution of pressure along the column as a function of flow velocity was obtained by numerical simulation of the linear model as confirmed by Reynolds number and by measurements. There is also distribution of static pressure along the column axis as a function of flow velocity obtained by continuous volumetric flow, shown in Tables II to IV. There is a relationship between pressure drop as a function of flow velocity in the experiment. As the velocity in all cases increases, the dynamic head values also seem to increase. Flow velocity depends on the diameter of the tube while the pressure depends on velocity of the flow. Increasing the flow rate leads to increasing the velocity at any point, thus causing the pressure drop.

The Reynolds number value for this gravity feed column set-up measurement was halfway below the transition limit of Re = 10, most often suggested in the literature, although there are questions regarding the borderline between linear and nonlinear velocity ranges [38-40]. The critical values of Re numbers are between ~ 0(1) up to 15 [38,41-43]. In this experiment, all velocity measurements fell within the regime of Darcy's model.

The choice between the linear Darcy's flow regime and the nonlinear Forchheimer flow, has an important numerical implication. The numerical solution codes applied to simulate flows in porous media are usually based on the linear Darcy's law. For moderately fast flows, a linear model may still prove satisfactory to provide a good solution.

For flows with low Reynolds numbers of typically 3 to 15, it is still appropriate to apply the linear model, as demonstrated in the gravity feed system used in the present study.

VI. CONCLUSIONS

A configuration of a gravity feed column set-up was developed and tested for water flow parameters. The experimental data and results calculated, confirm the validity of the Darcy's linear flow regime.

In the experiment, measurements were done on four independent columns and then Reynolds number was calculated for each test to verify the steady-state condition of Darcy's law. For practical acid mine drainage treatment using the column experiment, the most important parameters are flow rates and pressure drops. The configuration was set-up to regulate these parameters based on hydraulic gradients to achieve timed drop intervals of 8 to 12 seconds from the reservoir, giving flow rates of 0.64 to 0.80 mL/min at Reynolds number of 4.0, which indicates consistency with linear Darcy's flow regime. However, seasonal or day/night temperature fluctuations were found to significantly affect the flow rates.

The next stage of the study is to utilize the column configuration to conduct treatment of acid mine drainage. This aspect of the study is presently ongoing. This gravity feed system has resolved the challenge of electricity outages in addition to the significant costs of setting-up and maintaining the pumped column system.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The roles of the authors were as follows: **F. Solomon** conducted the research to set-up the configuration and conduct test runs. He also prepared the initial draft of the paper. **S. Ekolu** provided postgraduate supervision and edited the paper to its final version. **I. Musonda** contributed to editing of the paper and provided the CARINBE bursary for the study**.**

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