A concrete reactive barrier for acid mine drainage treatment

Stephen O. Ekolu, PhD, MSc, BSc(Eng), MCCSA, MSAICE, PrEng
Senior Lecturer at the Department of Civil Engineering Science, University of Johannesburg, Johannesburg, South Africa, sekolu@gmail.com

Firehiwot Z. Azene, MSc, BSc, Pr. Nat. Sci.,MIAH., MSAICE, Senior Scientist at Council for Geoscience, Head Office, Pretoria, South Africa, fzegeye@gmail.com

Souleymane Diop, PhD, MSc, BSc, Pr. Nat. Sci., MSAIEG, IMAEG, Chief Engineering Geologist at Council for Geoscience, Head Office, Pretoria, South Africa, sdiop@geoscience.org.za

Abstract

Pervious concrete was investigated for potential use as a permeable reactive barrier (PRB) for treatment of acid mine drainage (AMD). Pervious concrete mixtures of varied water-cement ratios = 0.50, 0.40, 0.35, 0.30, 0.27 and cement contents = 300, 360, 380, 400 kg/m^3 were prepared. Dolomite and granite aggregates types of 9.5 mm size were employed. Tests done were density, compressive strength, porosity. Water treatment was determined by analysis of the influent and effluent AMD after passage through the pervious concrete.

It was found that a filter thickness of at least 500 mm was required to increase the pH of acidic mine water from 2.8 pH to 5 - 7 pH value, and corresponding reduction in electrical conductivity. When used in the filter mix design, the granite aggregate gave better treatment performance compared to the dolomite aggregate. The concrete PRB treatment led to effective removal of major metals from the AMD. The treatment reduced the metals in the AMD by 30% SO_4, 99% Fe, 50-83% Mn, 85% Ca, 30% TDS. There was, however, a noticeable increase in magnesium concentration in the water effluent by 49-66% Mg. These results are short-term tests and further work is underway on the system's life expectancy.

Keywords: Concrete technology and manufacture; groundwater; mining and quarrying

1. Introduction

1.1 Acid mine drainage

The occurrence of acid mine drainage is synonymous with mining activity. Most mineral ore deposits including copper, coal, gold, platinum, nickel etc. contain pyrites. After several years from closure of the mine, the pyrites or iron disulphide (FeS_2) exposed to moisture and oxygen in the atmosphere as a result of the foregone mining operations, undergo oxidation resulting in formation of AMD. The term AMD refers to polluted mine water, usually characterised by acidity and/or high concentration of heavy metals, well in excess of loads acceptable in normal water quality. AMD typically occurs in long abandoned mines. The detailed chemical process is given in the literature (Blowes *et al*. 2003) but may also be simplified as (Petrik el al. 2006):

$$2\ FeS_2 + 7.5O_2 + 7H_2O \longrightarrow 2Fe(OH)_3 + 4H_2SO_4$$

AMD is a worldwide environmental concern and a wide range of remedial approaches have been attempted including mine filling, underwater storage for tailings, coating of exposed ore surfaces, neutralization using alkaline reagents, natural biological attenuation with wetlands, physical and reactive barriers (Blowes *et al*., 2003; Johnson and Hallberg, 2005; Zhuang, 2009; Gillmor, 2011). Due to the varied primary and secondary sources of AMD (Blowes et al. 2003; Akcil and Koldas, 2006), there is no single remedy that would apply to all scenarios of its discharge. Research literature exists on PRBs of various kinds (Blowes et al., 2003; Bartzas and Komnitsas, 2010; Bartzas et al., 2006; Komnitsas et al., 2004a, 2004b). However, the work presented in this paper, involving use of pervious concrete for AMD treatment is a novel research attempt to develop a new remedial system.

1.2 Pervious concrete

While the use of pervious concrete in civil engineering can be traced to a period as early as 1892 in United Kingdom, the applications were at that time mainly structural uses in buildings i.e. for constructing walls for houses (Ghafoori and Dutta, 1995; EcoCrete). However, its structural use in houses did not seem to particularly grow widely and it would appear that the technology was to an extent neglected or abandoned for some reason(s). The re-surgence of interest in pervious concrete emerged again in 1960’s and 1970’s, the difference with the new impetus, however, was not its use in structures but rather in pavements, particularly serving the purpose of stormwater management. Since then numerous studies (Collins *et al*. 2008) have been conducted approving of the environmental benefits of pervious concrete in reducing run off, reducing peak flows thus minimizing flooding, improving water quality through capturing of pollutants. Pervious concrete has also been reported to reduce absorption of solar radiation and urban heat storage potential leading towards less elevated urban temperatures (Kevern *et al*.). These benefits of using pervious concrete in attenuating stormwater problems are quite essential largely in the urban areas where most surfaces typically consist of relatively impervious concrete or asphalt pavings and roads, causing elevated levels of surface run off. The asphalt surfaces (such as used in parking lots) may also contain pollutants that in turn contaminate streams and rivers through surface runoff, and may destroy fish, insects and other forms of aquatic life. For these reasons, pervious or permeable concrete is becoming more extensively promoted in light of its environmental sustainability impacts. Pervious concrete pavements can be 75 to 100 mm thick for sidewalks, parking lots and driveways; to 150 mm thick for streets (Ecocrete). Some literature suggests that the process by which pervious concrete improves water quality during runoff is associated with its ability to channel the water flow to soil in the base and sub-base, which in turn strain and filter the water as it percolates through.

While much attention for use of pervious concrete has been given to stormwater management, it has been shown that pervious concrete on its own contains water treatment qualities but very limited work has been done to scientifically establish the essence of this property. Experimental studies (Park and Tia, 2004; Collins *et al.,* 2008; Majersky, 2009; Luck *et al.,* 2009, Brown) have shown that properly designed pervious concrete can be effective in treating polluted or acidic water not only raising its pH but also efficiently removing most of the undesirable contaminants including sulphate, iron, zinc, sodium, magnesium, manganese and most other metals. Further quality improvements in field applications of pervious concrete in pavements include reduction in oil and grease, and petroleum products (PAH's – Polycyclic Aromatic Hydrocarbons) from the water effluent drained through pervious concrete (Brown). Use of different cementitious materials systems and mixture designs influence the quality of the treatment process. Equally important are reports that pervious concrete is capable of removing different kinds of bacteria or micro-organisms such as feacal coliforms, micrococcus leteus etc. that may easily be found in contaminated water systems of various sources. The suitable range of pH for domestic water use is 5 to 9. Pervious concrete can raise the pH to higher levels beyond this range, depending on the mixture designs. The pH surges immediately upon contact with concrete and then stabilizes within 15 to 20 minutes (Brown). Conflicting results have been reported as to whether use of fly ash and/or slag extenders raise the pH any greater than plain Portland cement (PC) mixtures. Park and Tia (2004), reported fly ash concrete showing higher pH than plain PC concretes at least initially, while Brown's results indicated quite the opposite. Brown's results also suggest incorporation of fly ash in proportions of 20 to 30% to be the most suited, with higher proportions in the range of 50% showing less effective results in raising the pH. Both reports, however, show that the pH levels decrease (from about 11 to below 9) over a time period of up to three months. Smaller aggregate sizes of 5 to 10 mm grading improve the consumption of dissolved oxygen and removal of metals, relative to larger aggregates of 10 to 20 mm grading. The effectiveness of the small aggregate can be attributed to its relatively larger surface area that would be available for kinetic reactions.

Absorption, straining and decomposition of microbiological organisms in soils have been suggested as the main removal mechanisms by pervious concrete pavements (Brown). Indeed, aggregates can absorb significant amounts of run-off water, following some dry spells or during intermittent dry-wet conditions. And while some metals may be absorbed with water, it does not reasonably represent a process capable of significantly impacting their efficient removal. Straining can occur, physically filtering out agents of sizes incapable of passing through finer pores. However, these mechanisms alone do not fully account for the efficient removal of chemical agents, which apparently deteriorates with time. It is thought that the adsorption mechanism is perhaps the dominant process in pervious concrete. It is also known that high pH exceeding 9.0 is destructive to microbiological organisms (Park and Tia, 2004; Majersky 2009). Such a high pH can be generated in the water flowing through pervious concrete.

2.0 Experimental

2.1 Materials and mix designs

A number of parameters were considered in the mix designs including the type of extender and aggregates. Porosity was the most important characteristic used to inform the design process with the aim of achieving 20 to 30% void content (Schaefer *et al*., 2006). Accordingly, mixtures of varied w/cm ratios and different materials systems were prepared. These parameters are given in Table 1, also showing the physical and chemical tests conducted.

CEM I 52.5 N ordinary Portland cement was used throughout the different sets of pervious concrete mixtures. In all the mixtures, 9.5 mm aggregate sizes consisting of dolomite and granites types were maintained. For all mixtures, a superplasticizer Chryso Fluid Premia 310 was used to achieve a minimum level of workability. It was found that adding the superplasticizer separately in the mixer, at the last stage of the mixing cycle, was more efficient compared to adding it to mixing water. Therefore, the former method was employed in all the mixtures. Commercially available fly ash, typically used in concrete was incorporated in selected mixtures in order to assess the influence of using the extender. The mixtures were prepared in the laboratory using a flat pan mixer of 50 litre capacity. The slumps achieved varied quite widely with the mix designs and the amount of superplasticizer added.

Mixture :	Plain concretes; concretes containing extenders
Curing temperature :	23ºC room temperature
Water /cementitious ratio :	0.50, 0.40, 0.35, 0.30, 0.27
Cement content :	300, 360, 380, 400 kg/m^3
Extenders :	30% Fly ash
Sand and stone aggregates :	9.5 mm dolomite, granite
Admixtures :	Superplasticizer
Physical tests :	Density, compressive strength, porosity
Chemical tests :	Treated water analysis: pH, Electrical conductivity (EC), iron, sulphate, zinc, calcium, sodium, magnesium
Test media :	Three types of AMD water from the gold mines (AMD-Wz, AMD-Lc), and from the coal mines (AMD-MpK)

Table 1. Mix design parameters for pervious concretes

Different sample types and sizes were made from various mixtures. The samples consisted of 100 mm cubes, 300 x 300 x 50 mm thick slabs, 325 x 500 x 100 mm thick slabs, large 150 mm cubes, large 400 mm cubes, 100 x 150 x 1500 mm long beams. These specimens were cured for at least 7 days prior to conduction of the filtration tests. After several trials, pervious concrete of 0.27 w/c of cement content = 360 kg/m^3, with or without 30% fly ash made using dolomite or granite aggregates of 9.5 mm size was preliminarily found to be most suited and was therefore selected for conducting treatment tests.

2.2 Density, compressive strength, and porosity

Wet-density measurements were done on the pervious concrete mixtures. Wet density measurements and void contents were determined on freshly cast pervious concrete mixtures, in accordance with ASTM C 1688 using a cylindrical steel container of 250 mm diameter and 200 mm height. The test method also allows determination of the void content (porosity) of the pervious concrete basing on fresh mixtures.

2.3 AMD treatment tests

2.3.1 AMD quality

The underground AMD used in this investigation originated from a South African gold mine. Samples were collected from the source of AMD decant and stored in air-tight drums. All water analyses were conducted in accordance with the standard methods described in APHA, 1995. Chemical analysis showed the predominant ions in the water to be calcium (Ca^+), magnesium (Mg^+), sodium (Na^+), manganese (Mn^+), Iron (Fe^{2+}) and sulphate (SO_4^{2-}) (see Table 2). The SO_4^{2-} anion was the most dominant of all the ion species present, falling in the range of 3100 ppm. The presence of high sulphate concentration appears to be characteristic of the chemical nature of the water source, and was of interest in this study.

2.3.2 Concrete filter

The experiment was set up to firstly, assess the potential of the pervious concrete mixtures in improving the quality of AMD water. The process occurs by filtration as water flows through the pore network of the pervious concrete while ion exchange and other mechanisms effect removal of the contaminants in the polluted water. The investigation was carried out using cubes of 100, 200, 400 mm sizes, and slabs of sizes 300 x 300 x 50 mm thick, and 325 x 500 x 100 mm thick. The main variables of interest in the experiment were the flow rate, thickness of the concrete filter, and material system of the concrete filter, set up as shown in Figure 1. A flow rate of 100 mls /min was used throughout the investigation. The effluent water at the discharge end of the filter was collected and then analysed for pH, electrical conductivity (EC), iron, sulphate, zinc, calcium, sodium, magnesium. In the investigation, the thickness of the filter was varied in order to evaluate its influence on AMD treatment quality. In the analyses used to examine the effect of filter thickness on water quality, 100 mm cubes were used and their number added or reduced to achieve the prescribed thickness for the test.

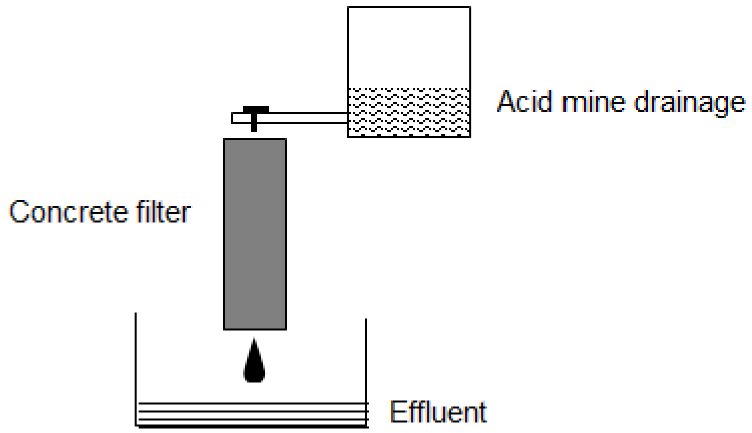

Figure 1. Simplified schematic of experimental set up for the treatment system

3.0 Results and discussions

3.1 Hydrologic and engineering properties

In order to determine pervious concrete mixtures with hydrological properties and material characteristics suitable to produce quality water filtrate while maintaining adequate structural integrity, a number of mixes were cast and tested. The main variables were the water-cement ratio, cement content and compressive strength while porosity was considered as the governing hydrologic parameter of interest. Figure 2 gives the relationship between water-cement ratio and porosity of the mixes prepared. Clearly, there is a strong correlation between the two parameters, with porosity increasing as the w/c decreases. The scatter in data is enhanced by variation in cement content used in the mixtures. From field experience and practice, 20 to 30% porosity of pervious concrete is typically recommended for stormwater management. It can be deduced from the data that w/c = 0.25 to 0.35 was required to achieve a porosity of at least 20% (Schaefer *et al*., 2006). Accordingly, a water-cement ratio of 0.27 was selected for casting of the concrete filter used in treatment of AMD water, as earlier mentioned.

Comparisons were also done between the properties of density and porosity, as shown in Figure 3. Again a strong inverse relationship exists between the two parameters, with density decreasing as porosity increased. It can be seen that the density of the pervious mixes varied from 1860 kg/m^3 to 2060 kg/m^3. Since the same granite aggregate type was used in all the mixtures, the density variation is primarily a function of the water /cement ratio and cement contents used in the mix designs. The uniqueness of pervious concrete properties can also be observed with its compressive strength behaviour. In normal concrete mixtures, a decrease in w/c ratios is directly related to strength increase, with low w/c's below 0.35 MPa typically leading to high strengths in excess 50 MPa. Figure 4 gives the 7-day compressive strengths for pervious concrete mixes of varied water /cement ratio's. The compressive strength results gave a relationship trend that is opposite to that of normal concrete, with strength decreasing as the w/c reduced. For the w/c's used in this investigation, the compressive strengths ranged from 14 to 20 MPa. It may however be noted, that while strength rises with increase in w/c, it does so at a slow rate as indicated by a generally flat slope. For a change of w/c from 0.25 to 0.50 (doubling the w/c), strength increased by only about 6 MPa. It follows that similar relations (as the strength-w/c ratio) exists for the strength-porosity properties given in Figure 5, and strength-density properties of the pervious concrete.

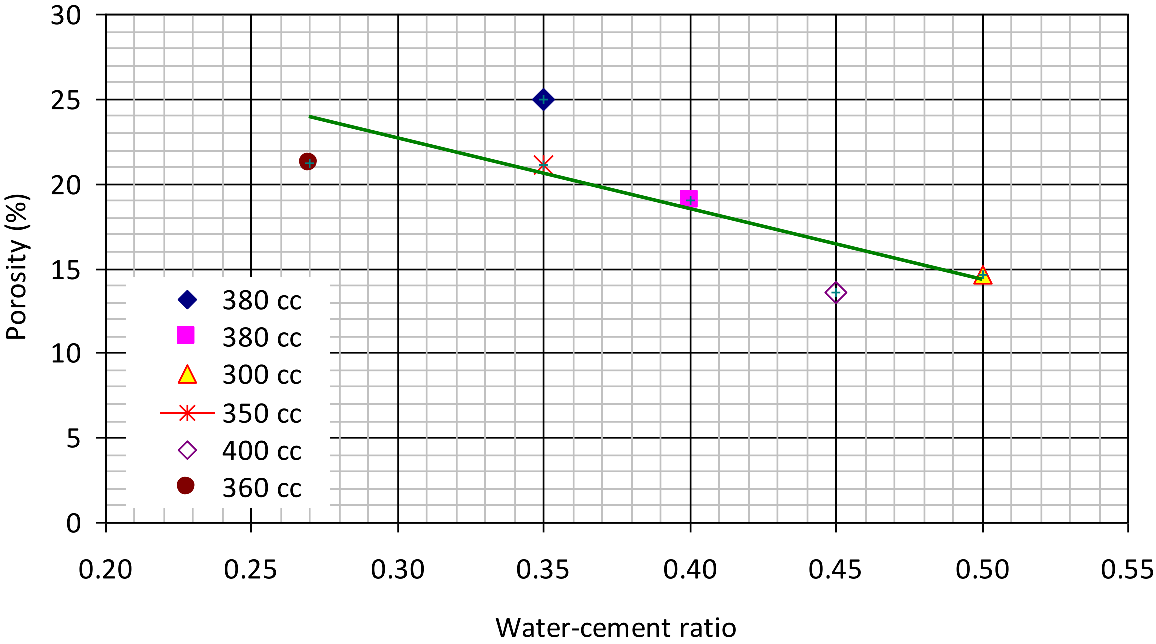

Figure 2. A plot of water-cement ratio versus porosity (cc = cement content)

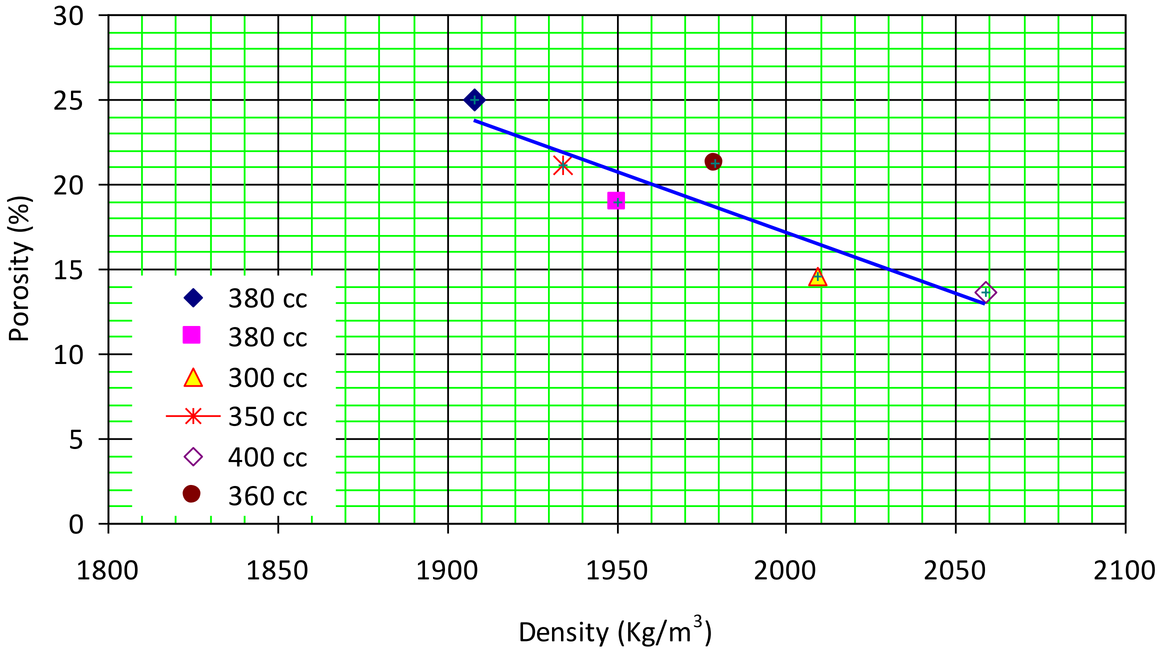

Figure 3. A plot of density versus porosity (cc = cement content)

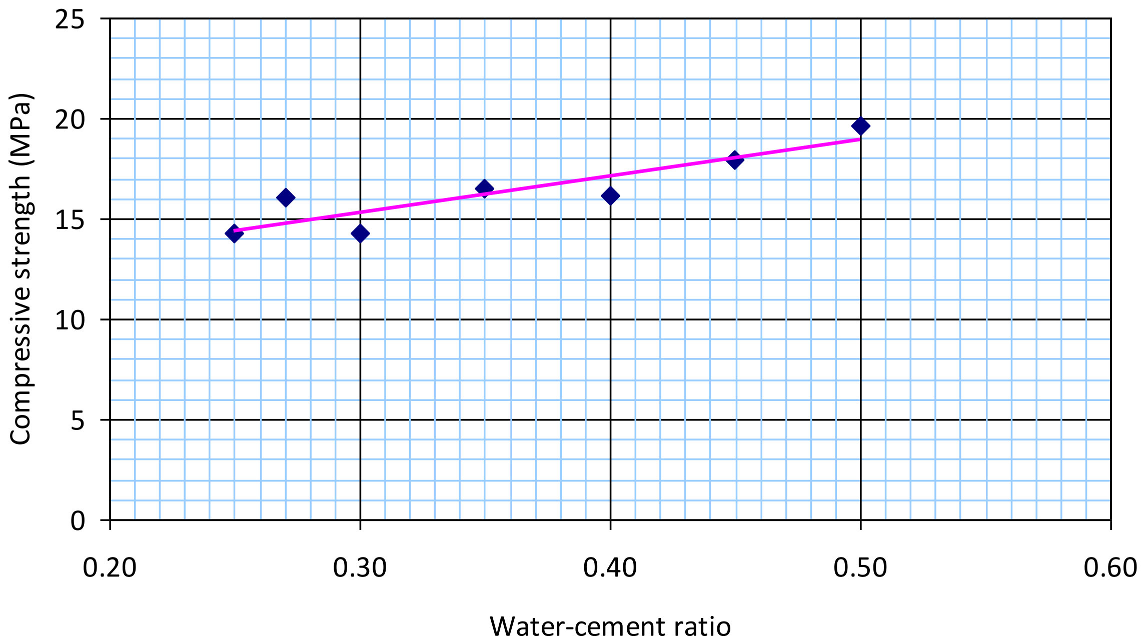

Figure 4. A plot of water/cement ratio versus 7-day compressive strength

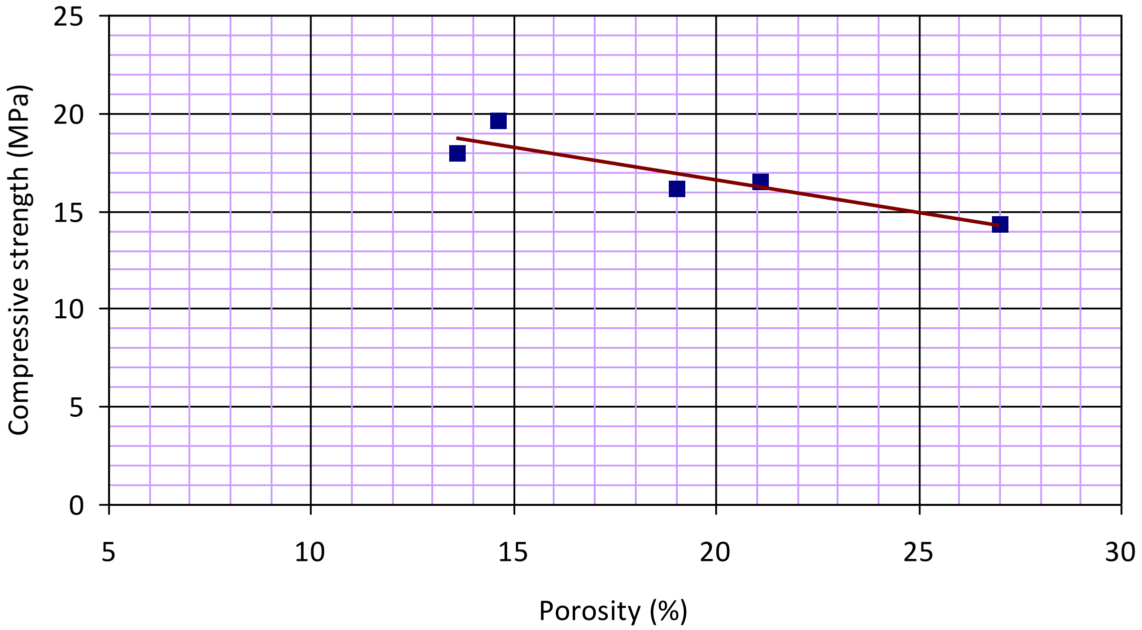

Figure 5. A plot of 7-day compressive strength versus porosity

3.2 Water treatment properties

The pervious concrete application is intended for use as a permeable reactive barrier, through which AMD water can be made to flow, resulting in its treatment based on mechanisms that at this point are not fully understood. The main factors of influence to the quality of water effluent therefore are the flow rate and reaction flow time (flow path distance).

3.2.1 Influence of flow reaction time

In order to evaluate the effect of reaction flow time through the filter, experiments were conducted at a constant flow rate of 100 mls/min while the filter length was varied. The pH and EC of the AMD water treatment quality were determined at end of the treatment. Three AMD water types of AMD-Wz, AMD-Lc, and AMD-MpK were treated by the concrete PRB. Figure 6 gives results of change in pH as the reaction flow distance was varied to 300, 500 and 600 mm. It can be seen that the pH of filtered acidic mine water steadily increased as the filter height was increased. The pH of AMD-Wz changed from 2.8 pH for the untreated water to 4.6 pH and 6.8 pH for filter heights of 300 mm and 600 mm respectively. However, the response of the different AMD water types varies. The differences in response of the various AMD types emerge more significantly with the filter height > 300 mm. The improvement in AMD water quality was greater in the order AMD-Wz > AMD-MpK > AMD-Lc. The AMD-Lc was least responsive to the PRB treatment. In this investigation, the pH achieved with 600 mm filter was only 4.8 pH for AMD-Lc, compared to 6.2 pH and 6.9 pH for AMD-MpK and AMD-Wz respectively.

EC is driven by the presence of solid particles in the water. In the concrete filter study, Figure 7 shows that the EC of the filtered AMD water decreased as the filter height was increased. The decrease in EC signifies removal of metal concentrations and their precipitates from the AMD water. The ability of the concrete PRB to neutralise and remove contaminants, disassociating them from filtered effluent water is incredibly an important benefit not possible with other forms of treatments which may improve water quality while leaving metal precipitates inseparable from water effluent. The EC values of water from the goldfields (initial EC= 490 mS/cm for AMD-Wz; initial EC = 435 mS/cm for AMD-Lc) are greater than those for AMD-MpK (initial EC = 263 mS/cm for AMD-MpK) from the coalfields, indicating the greater presence of pollutants in the former. It is also seen that a filter height of 300 mm was sufficient to reduce the EC to its ultimate stable measurement. There appear to be indications of EC tending to rise for the 600 mm filter thickness. It is possible that this effect may be attributed to prolonged use of the filter, reaching a point at which its adsorption capacity may be exceeded. Eventually, a breakthrough at the adsorption surface occurs, then the metals and their precipitates begin to be slowly and incrementally released into the water effluent. The presence of these precipitates in the water effluent could lead to an increase in the conductivity measurements, as may have began to occur in the observed results.

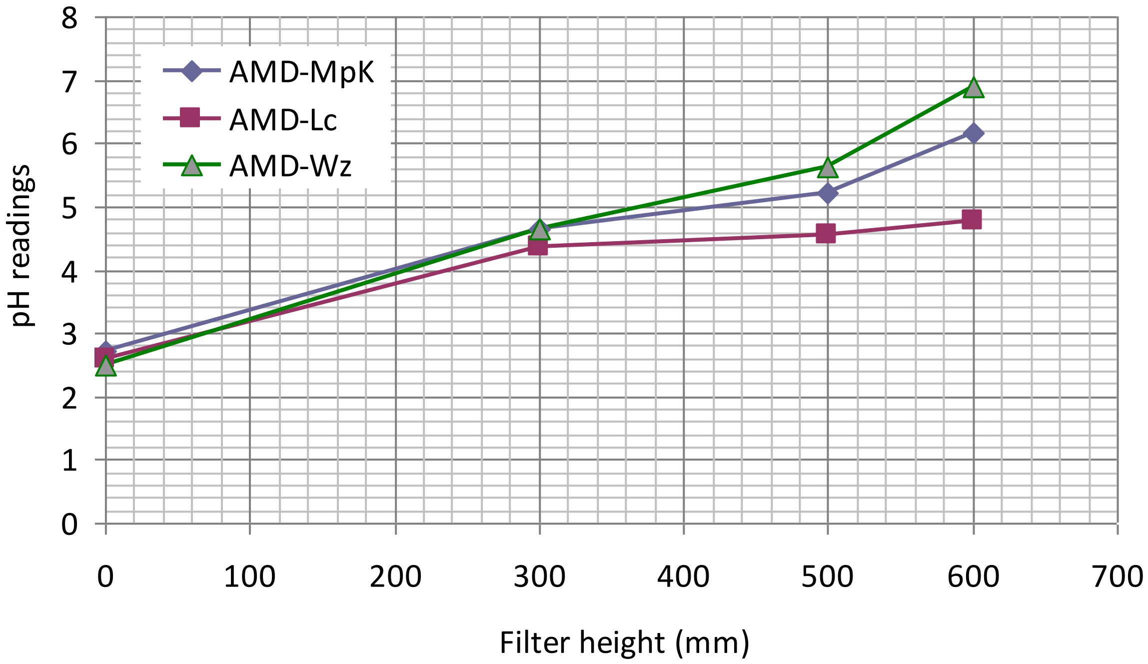

Figure 6. pH increase with change in filter height

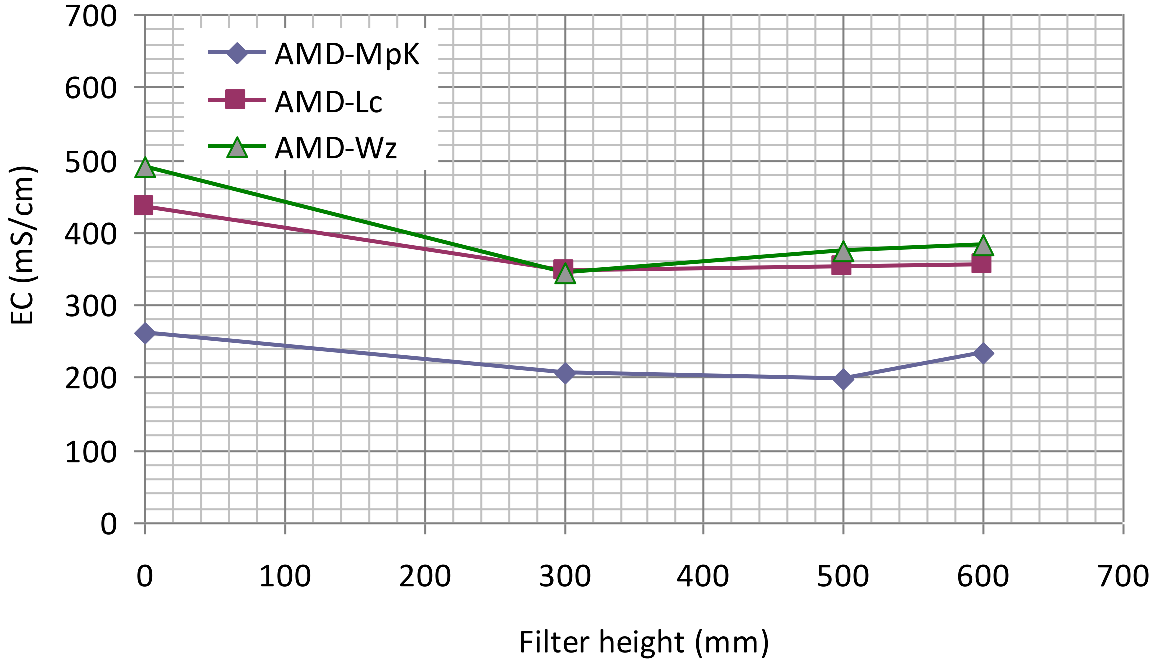

Figure 7. EC change with increase in filter height

3.2.2 Influence of fly ash and aggregate types on filtrate quality

Concrete filters of 0.27 w/c were prepared with the dolomite and granite aggregate types to assess the influence of aggregates on filter performance. In both mixtures, fly ash extender was incorporated at 30% proportion typically used in normal concrete. The filters were then used for the AMD water treatment experiment at filter heights of 300 and 500 mm. The results given in Figure 8 show that the use of granite aggregate gives better water quality improvement over the dolomite aggregate by about 1 pH unit, with or without fly ash. The use of fly ash in the concrete filter evidently gave lower pH values than the corresponding control mixtures containing no fly ash. It is known that fly ash is quite an effective alkalinising reagent for treatment of acidic mine water. It is therefore interesting to find that its use in the pervious concrete filter appears to rather reduce its efficiency, based on pH readings. It is possible that fly ash, being a pozzolanic material, consumes some calcium hydroxide of the cementitious matrix, reducing the amount available for reactive treatment in the concrete PRB. Figure 9 gives the EC measurements for the concrete PRB filter containing fly ash. It can be seen that both filters containing fly ash give lower EC values than their counterpart controls, especially at a filter height of 500 mm. These results appear to suggest that incorporation of fly ash, provides a more effective removal of metals present in the AMD water. However, further work is needed to establish the full filtrate quality as influenced by the use of fly ash.

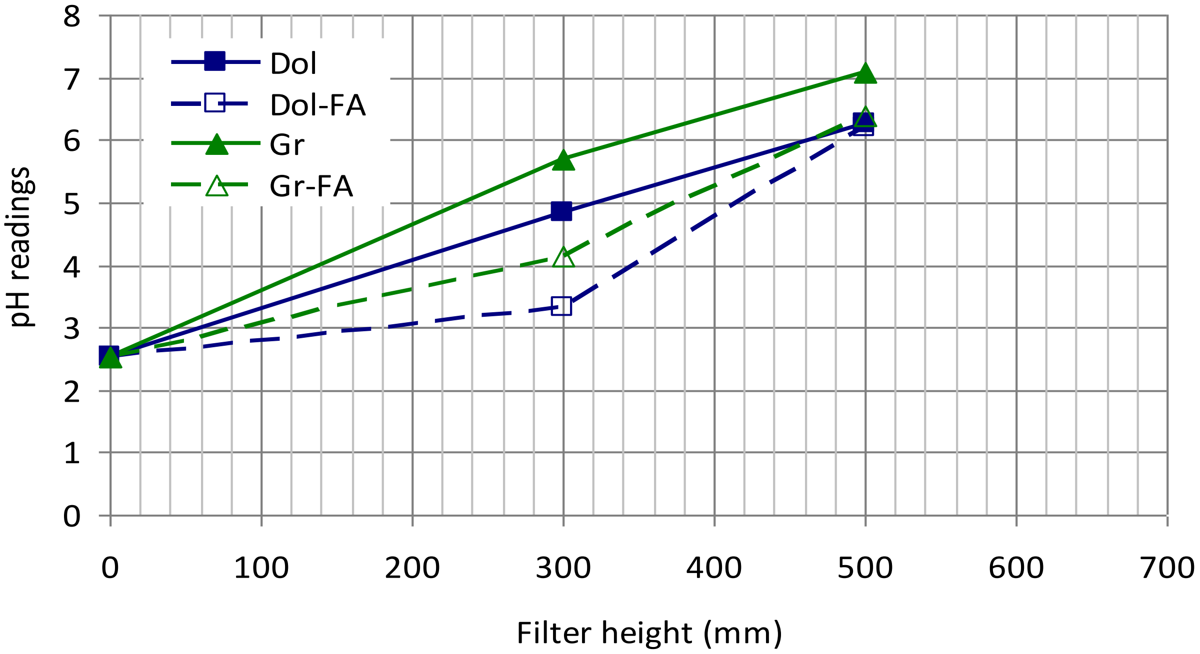

Figure 8. pH of AMD-Wz filtrate as influenced by aggregate types and fly ash (Dol = dolomite, Gr = granite, FA = fly ash)

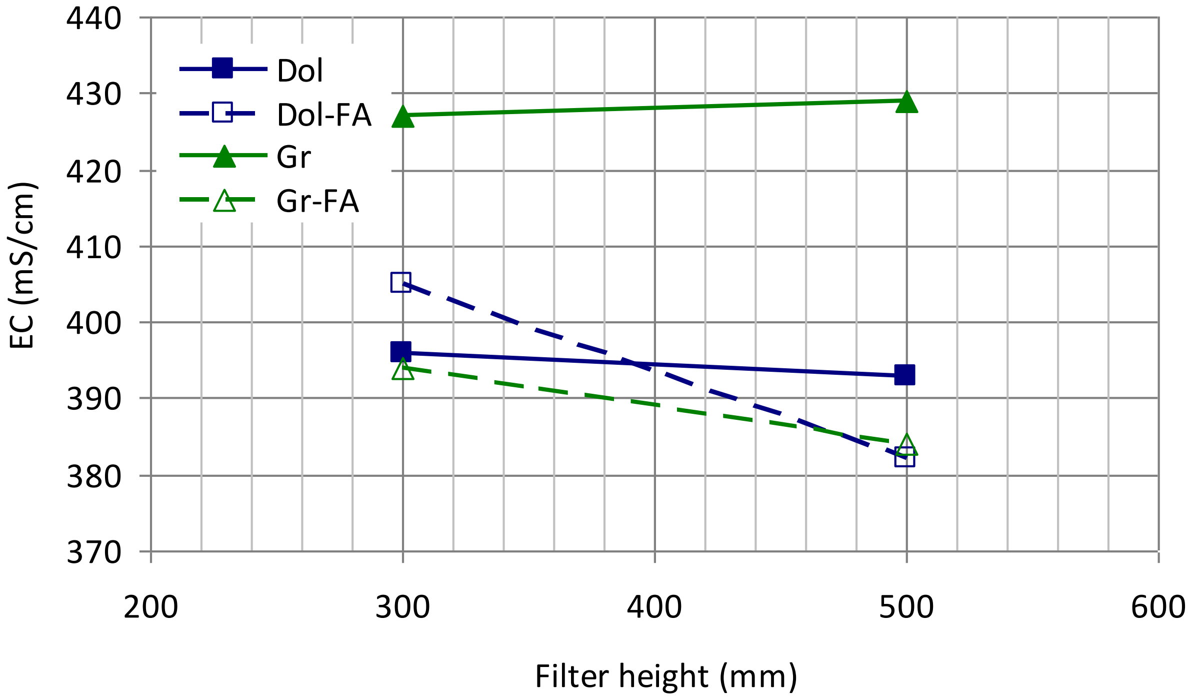

Figure 9. EC of AMD-Wz filtrate as influenced by use of fly ash

3.2.3 Metal removal from AMD

Following the treatment of AMD-Wz using the PRB filter, chemical analyses were conducted to determine the removal efficiency of various metals present. Table 2 gives results of metal concentrations before and after the treatment. There is general significant improvement in AMD water quality. The increased pH is likely to have resulted in precipitation of the metals which in turn were adsorbed and held within the concrete pore network. The PRB treatment achieved removal of 30% SO_4, 99% Fe, 59-83% Mn, 85% Ca, 30% TDS, which by any standards can be collectively considered a significant efficiency. These reductions in metal concentrations have also been plotted in Figure 10 displaying the removal effectiveness of the concrete filter. While the indicative removal capacity of metals is impressive, the experiment was done on a once-off use of the filter. Also, the magnesium concentration showed an increase of 49-66% Mg rather than a reduction. Challenges exist if the filter is to be subjected to prolonged use, as is the case in field application. An investigation into this aspect is presently underway and will be reported in the near future.

Parameter	AMD-Wz	AMD-Wz after PRB treatment			
	Non-treated	Treated		% Reduction	
		Dolomite	Granite	Dol C1	Gr 1
pH	3.1	9.8	11.0		
Conductivity (mS/m)	240	265	213		
Sulphate as SO_4 (mg/l)	3100	2190	2170	-29.3	-30.0
Calcium as Ca (mg/l)	1630	240	250	-85.0	-84.7
Iron as Fe (mg/l)	218	0.88	1.04	-99.6	-99.5
Magnesium as Mg (mg/l)	67	100	111	+49.3	+65.7
Manganese as Mn (mg/l)	17	8.4	2.96	-50.6	-82.6
TDS (mg/l)	4828	3360	3450	-30.4	-28.5

Table 2. Removal of metals by the concrete PRB filter

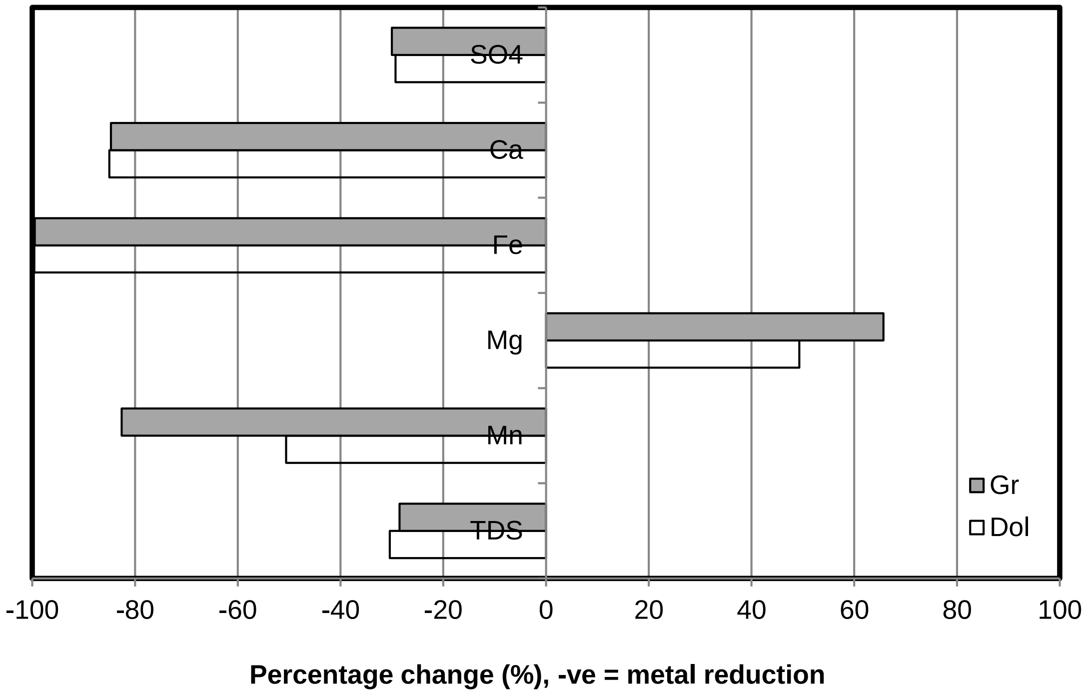

Figure 10. Removal of metals from AMD water by the concrete PRB filter

4.0 Conclusions

The novel potential of using pervious concrete as a permeable reactive barrier for treatment of AMD water was investigated in the foregone. The influence of a range of concrete mix parameters was examined including varied aggregate types, cementitious materials and water-cementitious ratios. Water treatment tests were done on three types of AMD taken from the gold mines and coal mines of South Africa.

1. It was found that mix designs of w/c's of 0.20 to 0.35 were required to obtain porosities in the range of 20 to 30%. Over the same range, the 7-day compressive strengths ranged from 14 to 17 MPa.
2. The treated water quality of AMD improves steadily with the flow distance, which represents the reaction time. A filter thickness of at least 500 mm was required to increase the pH of acidic mine water from 2.8 pH to 5 - 7 pH value.
3. AMD from the gold tailings dam was found to be least responsive to the PRB filter treatment, much less than the underground acidic mine water from the goldfields and the open pit mine water from the coalfields.

4. The concrete PRB treatment on acidic mine water led to reduction in the electrical conductivity of the filtrate. The effect is indicative of the dual impact of the pervious concrete treatment, causing not only metal precipitation in the pore network as the pH increases but it also adsorbs metals, separating them out from water effluent.
5. Different aggregate types influence the treatment efficiency of the PRB filter. When used in the filter mix design, the granite aggregate gave better treatment performance than the dolomite aggregate.
6. Use of fly ash in the pervious concrete mixtures reduced the final pH of the filtrate but it appeared to improve the electrical conductivity, suggesting that its presence may enhance the removal of metals from mine water filtrate.
7. The concrete PRB treatment led to effective removal of major metals from the AMD. The treatment reduced the metals in the AMD by 30% SO_4, 99% Fe, 50-83% Mn, 85% Ca, 30% TDS. There was, however, a noticeable increase in magnesium concentration in the water effluent by 49-66% Mg. However, the results presented in this paper are based on short-term observations and further work is being undertaken to study the performance and life expectancy of the treatment system under prolonged exposure to AMD.

References

Akcil A and Koldas S (2006) Acid Mine Drainage (AMD): causes, treatment and case studies. *Journal of Cleaner Production*, 14, 1139-1145

APHA (1995) Standard methods for the examination of water and wastewater, *American Public Health Association*. Washington DC, ISBN 0-87553-223-3

Bartzas G and Komnitsas K (2010) Solid phase studies and geochemical modelling of low-cost permeable reactive barriers, *Journal of Hazardous Materials*, **183(1-3):** 301-308

Bartzas G, Komnitsas K, Paspaliaris I (2006) Laboratory evaluation of Fe0 barriers to treat acidic leachates, *Minerals Engineering*, 19, 505-514

Blowes DW, Ptacek CJ, Jambor JL, Weisener CG (2003) The geochemistry of acid mine drainage, *Treatise on Geochemistry*, Vol.9, 149–204, Elsevier Ltd, ISBN: 0-08-044344-3

Brown HJ, Monitoring pervious concrete for water quality in a laboratory and field environment, *Concrete Industry Management*, presentation, 62 slides, http://www.rmc-foundation.org/, accessed 28 May 2013

Collins KA, Hunt WF, Hathaway JM (2008) Hydrological and water quality evaluation of four permeable pavements in North Carolina, USA, *11th International Conference on Urban Drainage*, Edinburgh, Scotland, UK, 10p

Ecocrete, Pervious concrete, *Ecocrete International Inc*., presentation /brochure, 22 slides. http://www.ecocreto.com/Techdata/BASICSPR.PDF. Accessed 18 June 2012

Ghafoori N and Dutta S (1995) Building and non-pavement applications of no-fins concrete, *Journal of Materials in Civil Engineering*, **7(4):** November 1995, 286-289

Gillmor, AM (2011) Attenuation of acid mine drainage enhanced by organic carbon and limestone addition: a process characterization, MSc Thesis, *Geosciences Dept*, University of Massachusetts, 116p.

Johnson DB and Hallberg KB (2005) Acid mine drainage remediation options: a review, *Science of the Total Environment*: 338, 3-14

Kevern JT, Haselbach L, Schaefer VR, Hot weather comparative heat balances in pervious concrete and impervious concrete pavement systems, *University of Missouri*, Kansas City, USA, 9p. http://heatisland2009.lbl.gov/docs/211340-haselbach-doc.pdf, accessed 28 May 2013

Komnitsas K, Bartzas G, Paspaliaris I (2004a) Efficiency of limestone and red mud barriers: laboratory column studies, *Minerals Engineering*:17, 183-194

Komnitsas K, Kolitsa D, Paspaliaris I (2004b) Clean up of acidic leachates using fly ash barriers: laboratory column studies, *Global Nest: the Int. J.*, **6(1):** 81-89

Luck JD, Workman SR, Coyne MS, Stephen F (2009) Consequences of manure filtration through pervious concrete during simulated rainfall events, *Biosystems Engineering*, Vol. 102, Issue 4, April 2009, 417-423

Majersky G (2009) Metals recovery from acid mine drainage using pervious concrete, *VDM Publishing House,* ISBN 978-3-639-02618-4, paperback, 69 Pages

Park S-B and Tia M (2004), An experimental study on water purification properties of porous concrete, *Cement and Concrete Research*, 34, 177-184

Petrik L, Burgers C, Gitari W, Surrender D, Reynolds K, Ellendt A, Etcvhebers O, Vadaphalli VRK, Key D, Iwuoha E (2006) Stability and neutralisation capacity of potential mine backfilling material formed by neutralisation of fly ash and acid mine drainage, *Water Research Commission*, WRC Report No. 1458/1/06, December 2006, 254p

Schaefer VR, Wang K, Suleiman MT, Kevern JT (2006) Mix Design Development for Pervious Concrete in Cold Weather Climates, Final Report, February 2006, *National Concrete Pavement Technology Center*, 67p

Zhuang J-M (2009) Acidic Rock Drainage Treatment: A Review, *Recent Patents on Chemical Engineering*, 2, 238-252