Journal of Scientific & Industrial Research
Vol. 63, November 2004, pp 919-926

Predicting drainage quality for sustainable exploitation of coal

S Siddharth*, A Jamal, R K Tiwary** and B B Dhar***

Central Mining Research Institute, Dhanbad 826 001

Received 11 May 2004; accepted 02 July 2004

In this paper, a technique has been suggested to know the quality of mine drainage even before the start of mining operation. The coal and associated rock samples are collected from the mine site. The mineralogical composition and geo-chemical character of each rock types occurring at the site are determined. The geo-chemical properties are measured in terms of R-pH, pollution production potential (PPP) and acid neutralization potential (ANP). The geo-chemical characteristics of various rock types indicate that they have different geo-chemical properties. There is a discrepancy in pH values obtained under laboratory conditions and field data and an explanation is given. On the basis of geo-chemical properties and weathering tests, it is found that except sandstone, all other litho-types such as, coal, shale, and shaly coal have the potential to deteriorate water quality and whatever the water pollutants present in the mine water are just because of interaction of these rock units with water. It is predicted that drainage from coal, shale, and shaly coal may be acidic, whereas drainage from sandstone is basic. The more or less same patterns are observed in the field. The technique suggested for the prediction of drainage quality may prove helpful and can identify rock types likely to produce water contaminants during their exposure to atmosphere in a mine.

Keywords: Drainage quality, Mineralogical composition, Rock-pH, Pollution production potential, Acid neutralization potential, Total sulphur

Introduction

Coal mining is a major industry in India, which is contributing inadvertently towards the pollution of environment (mainly water). However, at the same time, it also assures the energy supply that is indispensable for the development of our country. During the process of coal mining, huge volume of water of varying chemical composition is being discharged on the surface as a waste, thus polluting the surface and ground water. Therefore, in order to make coal mining eco-friendly and to minimize its impact on the surrounding hydrologic regime, some technologies should be developed to forecast the environmental consequences of the proposed mining activity in advance. Information in advance about the probable environmental consequences of the proposed mine will not only assist in formulation of water management plan but also help in planning for effective utilization of water resources produced during mining as a waste product.

* Author for correspondence
** Department of Mining Engineering, IT, Banaras Hindu University, Varanasi 221 005
***Senior Vice President, Amity Institutions, New Delhi
Email: susibhu@yahoo.co.in

Here, salient steps of prediction methodology have been discussed and its applicability has been validated at one of the opencast coal mine of South Eastern Coalfields Limited, Bilaspur. The findings are encouraging and may prove an effective tool for mining industry to take the decisions for pollution mitigation at EMP clearance stage.

Methodology

The typical steps of the methodology adopted for the prediction of drainage quality are:

(i) The geologic (lithologic) units that are encountered during the mining operation were defined. The information regarding geology and hydrology of the site were collected. The thickness, distribution, lateral and vertical relationships of various rock units alonwith the structural features such as fault planes were determined and identified.

(ii) The data regarding ground water quality, surface water quality, ground water table, and climatic conditions (amount of precipitation, temperature, etc.) were collected.

(iii) After collecting base line data, sampling plan was based on the geology of the site.

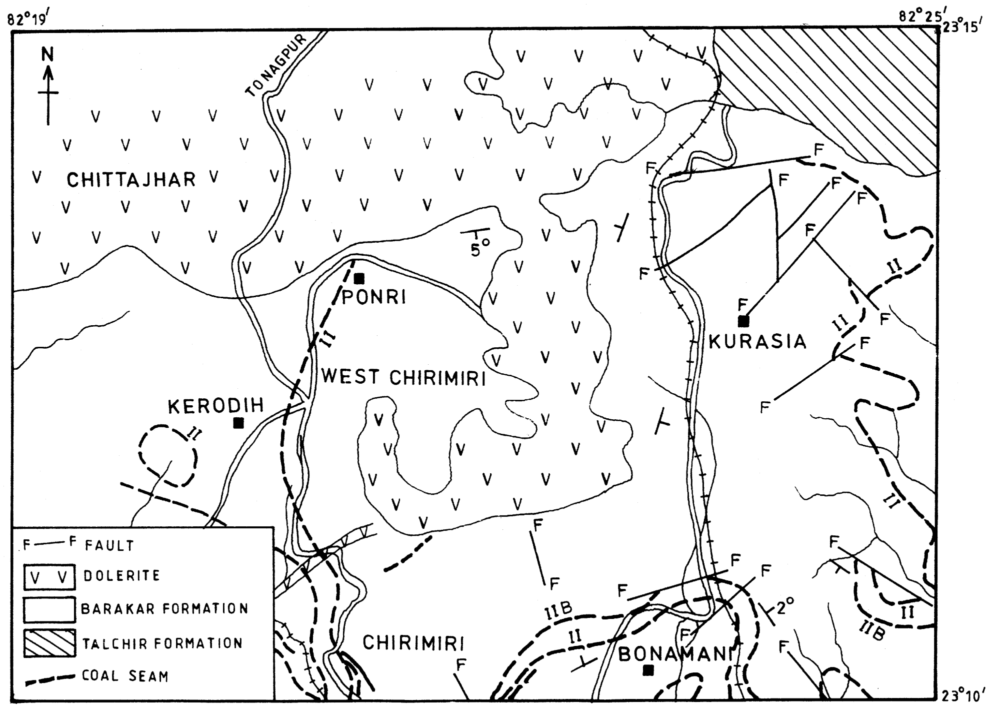

Fig. 1 — Geological map of the study area

Samples were collected in such a way that it characterized both the type and volume of rock material and also accounted for variability of rock material that was exposed during mining.

(iv) Geo-chemical property of each litho types, in terms of Rock-pH (R-pH), Total sulphur, Pollution production potential (PPP), Acid neutralization potential (ANP) were determined.

(v) The mineralogy of each litho type encountered at the site was described in detail to get information about the type of reactive and stable minerals present in rock along with the nature and type of cement/matrix.

(vi) The simulated weathering tests have been conducted on each litho type of the area individually and collectively, keeping in view the thickness of the rocks exposed during mining.

(vii) The geologic/lithologic units exposed at the mine site were classified on the basis of their geo-chemical properties, pollution production, and pollution mitigation potential.

Location of the Study Area

The study area (an opencast coal mine) belongs to Chirimiri coalfield of South Eastern Coalfields Limited (Madhya Pradesh), India and lies in the northern part of Chirimiri coalfield. The study area is located at latitudes 23°15' to 23°17' N and longitudes 82°19' to 82°25' E and has moderate climate. In winter months the temperature goes below 10°C but the summer months are not very oppressive. Rainfall in the area is quite high, the average being 150 cm/y.

Geological Set-up of the Area

The geology of the area is shown in Fig. 1. The coal bearings rocks are Upper Carboniferous to Lower Permian in age and consist primarily of sandstones with minor proportion of shale. Except the North Eastern part the maximum surface is covered by the sandstone (Fig. 1). The coal bearing formation (i.e. Barakar Formation) is represented dominantly by light gray coarse-grained sandstones the cementing material of which is normally kaolinised feldspar. The shale is typically gray and is rather insignificant in the sedimentary pile. Coal seams, however, define prominent horizons within the sandstone-dominated formation. A thick dolerite dyke demarcates the northeastern boundary of the study area. Megascopically, sandstones are medium to coarse

Table 1— Stratigraphic succession

Age	Formation	Lithology		Remarks
Upper Cretaceous to Eocene	Deccan Trap	Dolerite dykes and sills		Exposed in North-Eastern part of the area
Lower Permian to Upper Carboniferous	Barakar Formation	Medium to coarse grained sandstone with subordinate shale and coal seams	Top Seam –1.50m Parting – 50.0m Middle Seam-1.20m Parting –25.0m Main Seam –2.9-4.20m	
Middle Carboniferous	Talchir Formation	Fine grained sandstone with olive green shales		Not exposed in the area
		Unconformity		
Precambrian		Granite, Gneisses		Not exposed in the area

grained and friable in nature. The colour of sandstone varies from white to yellowish white. The overall exposure of white sandstone is rather high, as compared to other varieties of sandstone. The stratigraphic succession of the study area is enumerated in Table 1.

Sample Collection and Laboratory Analysis

The samples of coal and associated rocks such as, shale, shaly coal, and sandstones were collected from the study area. High wall samples were collected from freshly exposed surfaces. Wherever possible, entire length of each litho-unit was sampled to account for intrastratum differences in composition. The collected rock samples were analyzed for R-pH (Rock-pH), percentage of total sulphur, pollution production potential (PPP) and acid neutralization potential (ANP). These parameters were analyzed for various reasons: to measure native acidity or alkalinity of the different litho-types as the case may be; to establish litho-types which are rich in pyretic or other potentially toxic materials. Rock-pH (R-pH) measurements were made with glass electrode pH meter using ground rock powder of 200 mesh with the water of 7.0 pH value at 25°C in a solid: liquid ratio of 1:10 by volume[1, 2]. The percentage of total sulphur in coal samples was determined by hydrogen peroxide oxidation method[3]. Pollution production and acid neutralization potentials were determined for each sample by digestion methods[3-6]. The pollution production potential (PPP) is defined as it is the maximum amount of acid that can be produced from the oxidation of sulphur minerals in the rock material if all sulphides present in the samples react according to the following stoichiometry.

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow Fe(OH)_3 + 2/5\ SO_4 + 4H^+$$

PPP is determined in kg of $CaCO_3$ equivalent per tonne of associated rock (expressed as kg of $CaCO_3$/tonne). The acid neutralization potential (ANP) is a measure of the amount of neutralizing compounds (mostly carbonates, exchangeable alkali, and alkali earth cations) present in the coal and the overburden. The ANP was determined by treating 2 g sample with 20 to 80 mL of 0.1 *M* HCl, heating nearly to boiling and swirling periodically until no gas evolution was observed. The sample was then made up to 125 mL with distilled water, boiled for 1 min, and cooled to room temperature. The treated sample was then titrated with standard NaOH (0.1 or 0.5*M*) to pH 7. The ANP was calculated as the amount of HCl consumed by the sample and converted to the units of tons $CaCO_3$/tonne material. The thin sections of coal associated rock samples were prepared and studied under the petrological microscope for identification of mineral constituents along with the type and nature of cement/matrix and modal percentage of minerals in terms of reactive and stable mineral components.

Table 2 — Mineralogical composition of sandstone

Type of sandstone	Percentage of reactive component				Nature of cement	Percentage of stable component			Per cent
	Feldspar	Muscovite	Biotite	Cement/matrix		Quartz	Rock fragments	Heavy minerals	
Coarse grained sandstone	19.6- 25.2	1.8 - 3.0	0.4 - 0.8	22.0 - 29.4	Calcareous and argillaceous	44.5 - 50.8	0.9 - 2.0	0 - 0.5	100
Medium grained sandstone	18.9 - 23.2	1.9 - 2.7	1.1 - 1.6	21.2 - 26.1	Calcareous	46.8 - 53.0	0 - 2.4	0.2 - 1.0	100
Fine grained sandstone	21.2 - 24.8	2.1 - 2.9	0.6 - 1.4	23.2 - 27.8	Argillaceous and calcareous	45.0 - 52.4	0.6 - 2.2	0 - 0.9	100

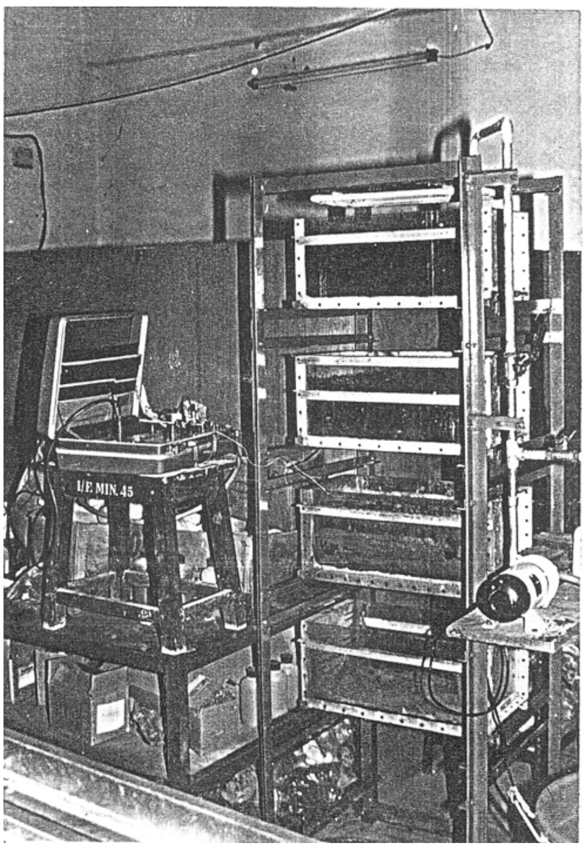

Fig. 2 — Laboratory weathering model

Experimental Set-up

The impact of different litho-types on mine water quality was assessed in the laboratory. A simple box model was designed and fabricated in the laboratory (Fig. 2). The base of each box was perforated in order to allow percolation of water through rocks filled in succeeding lower boxes. The samples of different litho-types exposed at the site were prepared in desirable sizes (0.5 mm-0.42 mm and -0.5 mm) by conventional sieve technique. The actual thickness of each litho-types and its relative proportion to each other had been taken into consideration while filling the boxes with corresponding rock units in the loose form. Water was added to the boxes at a pre-determined rate to simulate rainfall in the area. Experiments were conducted on each litho-types both individually and collectively. Water samples from sump, coalface, and other locations within the mine were collected and analyzed in order to validate the laboratory findings.

Results and Discussion

Mineralogical Character

The sandstone is the dominant rock type exposed at the site. The mineral constituents of sandstones are summarized in Table 2. The modal mineralogical composition of the sandstones as determined under the microscope, consisted primarily of quartz (44.5 to 52.8 per cent), feldspar (18.9 to 25.2 per cent) and mica. Other minerals present in trace include magnetite, ilmenite and rock fragments. The sandstones are characterized by high binding material ranging form 21.2 to 26.1 per cent which is mostly argillaceous and calcareous in nature. It can be seen from Table 2 that the model percentage of reactive component in each sandstone sample is relatively high and are responsible for the basic nature of sandstones.

Table 3 — Geo-chemical characteristics of coal and associated rocks

Lithological unit	Rock-pH	Total Sulphur (per cent)	PPP (kg of $CaCO_3$/t)	ANP (kg of $CaCO_3$/t)
Barakar sandstone				
coarse-grained	9.32-9.43	Nil	Nil	65-69
medium-grained	9.01-9.19	Nil	Nil	54-61
fine-grained	8.79-8.93	Nil	Nil	47-56
Shaly coal	4.08-4.42	1.30 – 1.42	41-45	3-7
Shale	2.88-3.07	1.62 – 1.73	51-54	5-11
Coal seam				
top	3.89-3.99	1.48 – 1.55	46-49	Nil
middle	3.98-4.27	1.34 – 1.42	42-45	Nil
bottom	3.79-3.91	1.46 – 1.58	47-50	Nil

Geo-chemical Character

Percentage of Total Sulphur

The analytical results of coal and associated rock samples collected from the study area indicated a range of total sulphur (Table 3). The percentage of total sulphur in working coal seam varies from top to bottom. The top and bottom section of coal seam contains higher percentage of total sulphur than middle section. The results indicate that there is enrichment of sulphur at the top and bottom section of the coal seam. In shaly coal, stratigraphically underlying and overlying the coal seam, the percentage of sulphur varies from 1.30 to 1.42. In general, percentage of total sulphur in shale is high in comparison to coal and shaly coal. The absence of sulphur noted in sandstone is due to the absence of secondary enrichment of sulphur and the depositional environment of the sandstone. The size of pyrite crystals and clusters identified in coal, shaly coal, and shale is variable. The diameter of some individual crystals or clusters in coal is as great as 50 µ or even larger, but 5 to 25 µ is a common range.

Rock-pH (R-pH)

To get the general information about the geo-chemical nature of coal and associated rocks, R-pH values were determined and are shown in Table 3. The R-pH of coal sample ranges from 3.97 to 4.33, whereas R-pH of shaly coal ranges from 4.04 to 4.38. The R-pH of shale lying over the shaly coal ranges from 2.86 to 3.01. The R-pH of sandstone ranges from 8.94 to 9.36. Low R-pH of coal, shaly coal and shale may have been resulted due to the presence of sulfide minerals. High R-pH values of sandstone indicate that they are basic in nature. The basic nature of sandstone is due to the presence of reactive mineral components such as, feldspar, mica and calcareous/ argillaceous cement/matrix. These reactive mineral components of sandstones are most important and may affect the drainage quality to a great extent.

Pollution Production Potential (PPP)

The pollution production potential data (Table 3) obtained from analyses of coal and associated rock sample (shale and shaly coal) shows that these rocks are acidic in nature and are producing acidic water due to high sulphur content. It can be seen from Table 3 that pollution production potential of coal samples varies with variation in sulphur content within the coal seam. The top and bottom sections of coal seam have high pollution production potential in comparison to middle section. It is evident from the analytical results that shale associated with coal has high potential to produce acid water due to higher per centage of total sulphur in comparison to coal and shaly coal.

Acid Neutralization Potential (ANP)

The acid neutralization potential of rock samples (Table 3) shows that all sandstone samples have high neutralization potential irrespective of grain size, nature and colour, however the coarse grained sandstone samples have high neutralization potential in comparison to medium and fine grained sandstone samples. The high neutralization potential of sandstone samples is probably due to the presence of reactive basic silicate minerals (feldspar, mica, etc.) and calcareous and argillaceous matrix/cementing material. The results indicate that sandstone samples possess significant capacity for consuming acidity.

On the basis of geo-chemical data, one could easily visualize that in the study area, different litho-types have different geo-chemical properties. Coal, shaly coal and shale have potential to produce acid water due to high sulphur content, whereas sandstones have basic properties and may be capable of supplying adequate amount of base cations to buffer acidity produced from other litho-types.

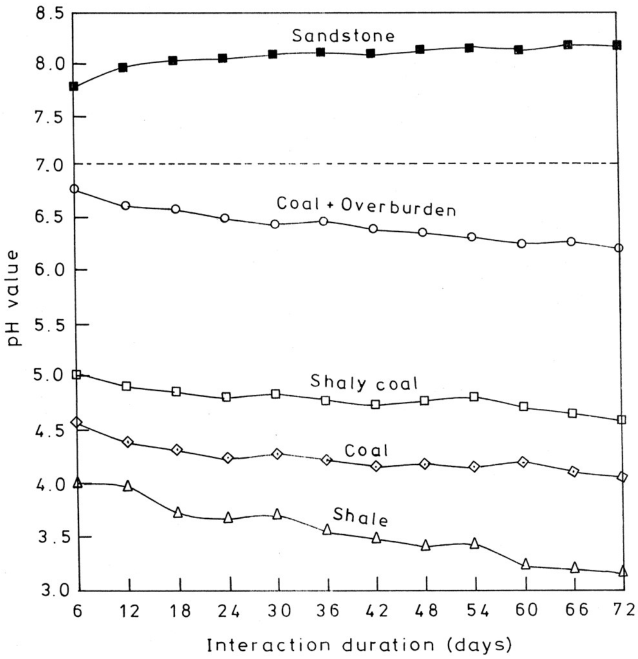

Fig. 3 — Drainage pH value vs Interaction Duration in rocks of particle size 35 to 40 ASTM (0.5 mm- 0.42 mm)

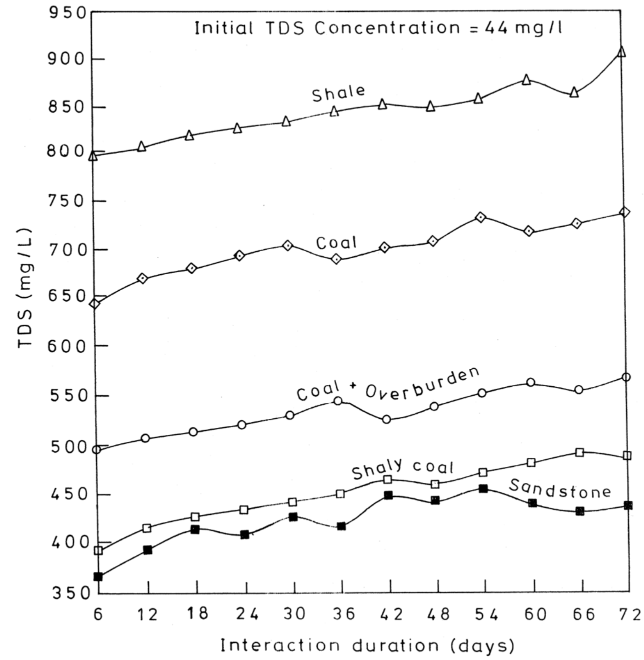

Fig. 5 — TDS Concentration vs Interaction Duration in rocks of particle size 35 to 40 ASTM (0.5 mm-0.42 mm)

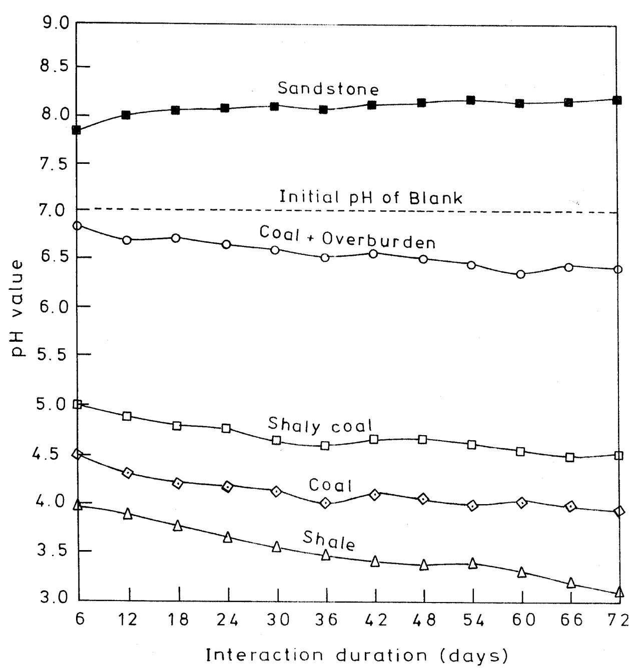

Fig. 4 — Drainage pH value vs Interaction duration in rocks of particle size -35 ASTM (-0.5 mm)

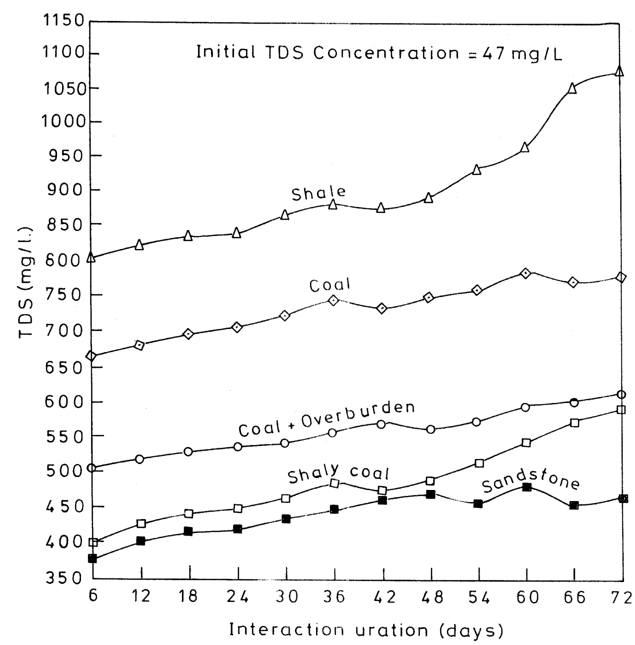

Fig. 6 — TDS Concentration vs Interaction Duration in rocks particle size -35 ASTM (-0.5mm)

Experimental Results

The experimental data show that there is appreciable impact of rock types on drainage quality. The water passing through the different litho-types undergo reciprocal changes in terms of pH, TDS and other dissolved toxic constituents. Figs 3-6 contain experimental results for different litho-types, both individually and collectively.

Rock Type vs pH

The variation in pH value of water leached from various litho-units with respect to time is shown in Fig. 3 and 4. It can be seen from these figures that sandstones associated with coal as overburden produce alkaline water and an increase in alkalinity was noted with reduction in size and with increase in interaction duration, whereas the impact of coal, shaly coal and shale on water quality in terms of *p*H is just reverse. They all produced acid water and the acidity increased with increase in interaction duration and decrease in particle size. The lowering in pH value of leached water with decrease in particle size confirms that the rate of pyrite oxidation is greatly affected by the particle size of pyrite present in the sample. Particle size of sulfide minerals is important because rate of iron sulfide oxidation is proportional to the available surface area. The rates of sulfide oxidation per unit mass of these samples are magnified due to smaller particle size resulting in decrease in *p*H value of leachates. Most researchers agree that, in general, the smaller the grain of sulfide minerals, the more reactive the sulfides and greater will be the acidity[7-9]. In general, during the experiment, drainage *p*H decreased as the sulphur content of the samples and the duration of rock-water interaction increased. The *p*H value of leached water from sandstone was initially in alkaline range and with increase in interaction duration and decrease in particle sizes the *p*H value reached up to 8.44. The increase in pH value of water leached from sandstone is due to the dissolution of reactive silicate minerals such as feldspar, mica, and calcareous/argillaceous matrix/ cementing material and easy liberation of base cations such as, K^+, Na^+, Ca^{2+}, Mg^{2+} due to friable and porous nature of sandstone. The water leached from the vertical litho-profile comprising coal and overburden was initially more or less neutral. With increase in interaction duration the pH value of leached water gradually decreased, but it remained over 6 after 72 d of interaction indicating that the rate of dissolution of reactive basic components of sandstone decreases with time but at the same time it indicates that the sandstone has ample capacity to buffer the acidity produced by other litho-units. Hence, it may be concluded that geo-chemical and mineralogical properties of different litho-units occurring within a basin play a role in determining the mine water quality.

Rock Type vs TDS

Fig. 5 and 6 show the impact of various litho-units on water quality with respect to release of total dissolved solids (TDS). It may be observed from these figures that different lithotypes release different amount of TDS concentration. The concentration of TDS is maximum in the case of shale, probably due to high content of active mineral pyrite. The high concentration of TDS in acidic water leached from coal, shaly coal, and shale suggest that the acidic water has high dissolving capacity. The concentration of TDS in leached water increased with decrease in particle size and with increase in interaction duration. In general the concentration of TDS in leached water increased as pH decreased. The high concentration of TDS in leached water further magnifies the problem of acid mine drainage.

Comparison of Laboratory and Field Data

Laboratory data on the test samples suggest that the rock geo-chemistry and particle size have a marked influence on the mine water quality. The pH range, generated in the laboratory from individual litho-types was quite close to that observed in the study area. Leaching tests run with smaller particle sizes have yielded lower pH value in the case of coal samples. The concentration of TDS in leached water increased as the pH value decreased in both laboratory and field condition. However the concentration of TDS was higher in water collected from the study area. The combined impact of litho-units, on leached water quality, as observed in the laboratory, differs from the sump water quality because the drainage water in the field gets little chance of interaction with the overlying basic sandstone. Under field conditions the pH value of mine sump water varies from 4.27 to 4.68, whereas in laboratory the pH value of water leached from the vertical column of different litho-units ranging between 6.22 to 6.44.

Conclusions

The study shows that the methodology adopted for the prediction of drainage quality can be helpful in forecasting the potential water pollution problem. The study shows that the rock mineralogy along with the geo-chemical properties is the important factor that influences the drainage quality to a great extent. The sulphur content in the samples of different litho-units examined indicated a range of value. The concentration of sulphur was highest in case of shale (1.62-1.73 per cent). The potential of different litho-units to produce acid mine water increased with increase in sulphur content. Rocks such as, sandstone, rich in reactive basic silicate minerals such as, feldspar, mica, basic matrix/cementing material produced alkaline water, whereas all other rock types produced acid water. The leaching results were consistent with the field observations as far as the individual impact of rock were concerned. The laboratory and field observations along with experimental result showed that that the proper mineralogical and geo-chemical investigation could be helpful in forecasting the types of pollutants and formulation of management plans.

Acknowledgement

The authors acknowledge the financial assistance (Grant No. EMR/II/P-81102) from the Council of Scientific and Industrial Research (CSIR), New Delhi in support of this research.

References

1 Dhar B B, Ratan S & Jamal A, Rocks as a neutralizer in acid mine drainage, *Proc Nat Sem Environ Pollut Contr Min, Coal Miner Based Ind*, 13-15 February, Indian Institute of Technology, Kharagpur, (1987) 276-280.

2 Siddharth S, *Assessment and management of acid mine drainage in coal mines,* Ph D Thesis, Department of Mining Engineering, BHU, India, 2001.

3 Sobek A A, Schuler W A, Freeman J R & Smith R M, *Field and laboratory methods applicable to overburden and mine spoils,* US Environmental Protection Agency (EPA-600/2-78-054), Cincinnati, OH, 1978, pp 203.

4 Skousen J, Burnett M M, Bassage D, Balck C, Ziemkewicz P & Zucker D, *The watershed approach to acid mine drainage abatement- Sovern run. green lands*, West Virginia Mining Reclamation Assosciation, Charleston, 1997, pp 43-49.

5 O'Shay T, Hossner L R & Dixon J B, A modified hydrogen peroxide oxidation method for determination of potential acidity in pyretic overburden, *J Environ Qual*, 19 (1990) 778-782.

6 Jamal A, Siddharth S & Tiwary R K, Impact of overburden geo-chemistry on the quality of mine effluent – a case study, *Int Symp Geo-environ Reclamat,* 20-22 November, RKNEC, Nagpur, India, (2000).

7 Caruccio F T, The quantification of reactive pyrite by grain size distribution, *Third Symp Coal Mine Drainage Res*, Pittsburg, PA, (1970) 123-131.

8 Erickson P M, Hammack R W & Kleinmann R L P, *Prediction of acid drainage potential in advance of mining,* U S Bureau of Mines Information Circular 9023, 1985, pp 3-11.

9 Lapakko K A, *Kinetics and mechanisms of the oxidative dissolution of metal sulfide and silicate minerals present in the Duluth Gabbro*, M S Thesis, University of .Minneapolis, MN, 1980.