Study of effects of some metals and hydraulic retention time on performance of AMD treatment by SAPS

M. D. Patel

Associate Professor, Department of Mining Engineering, National Institute of Technology, Raipur, India
Email- mdpatel.min@nitrr.ac.in

Abstract: Acid mine drainage (AMD) is presently observed as one of the major water pollution problems in mining area throughout the world. Proper scientific management of AMD is essential for achieving the national goals for environmental norms. In this study performance of AMD treatment by laboratory successive alkalinity producing system (SAPS) by observing the effects of some metals and hydraulic retention time. In this study the experiments were conducted in laboratory successive alkalinity producing system (SAPS) with different synthetic AMDs for five Hydraulic retention times (HRTs). The successive alkalinity producing system shown the promising results during the AMD treatment. The effects of iron, aluminium and manganese were jointly investigated, which showed that Net alkalinity generation (NAG) increases with increase in influent metal contents. It was also observed that NAG also showed increasing tendency with HRT during AMD treatment by SAPS. The obtained findings from this study can be applied for efficient design and operation of successive alkalinity producing system for AMD treatment process in mining industry.

1. Introduction

AMD is an environmental problem that deteriorates the water resources in mining areas. In India, the coal of Barakar series of Lower Gondwana system in Madhya Pradesh, Chhattisgarh and Maharashtra and tertiary system of Assam and Jammu and Kashmir contains sulfide, which is responsible for AMD generation. The occurrence of sulfide minerals dictates the generation of AMD besides other factors like hydrogeology of area, nature of adjoining rocks, presence of water, temperature, and oxygen supply, etc. [7, 18]. The AMD generation reaction can be expressed as

\[
4 \text{FeS}_2 + 15 \text{O}_2 + 14 \text{H}_2\text{O} \rightarrow 4 \text{Fe(OH)}_3 \downarrow + 8 \text{H}_2\text{SO}_4
\]

The surrounding aquatic environment is adversely affected by AMD discharge and as a result aquatic livings are killed. AMD also increases the probability of corrosion in mining machine and fittings and reduces the mining machinery’s life. The adverse effects of AMD can be minimized by the treatment of AMD either by active treatment or passive treatment methods. SAPS is latest modified passive treatment system. SAPS eliminate the armoring of limestone by oxidation of iron, therefore life of SAPS passive treatment system increases. The treatment of AMD by SAPS was first observed in late 1980s [9]. Many SAPS systems were installed throughout the world for treatment of AMD[17, 5, 10, 2].

SAPS is a bioreactor in which biological and chemical processes take place during treatment of AMD at certain HRT. The reduction in acidity, generation of alkalinity and removal of dissolved metals is achieved by utilizing organic matter and limestone in the SAPS units during treatment of AMD [11]. The AMD contains commonly iron, aluminium and manganese there for these metals are selected for investigation. Presently very limited information is available on the effects of composition of AMD, especially of total iron, ferric ferrous ratio, aluminium, manganese and HRT on NAG by SAPS. Further the ferric iron and ferrous iron in the AMD exhibit influence on the chemical activity inside the SAPS cell [15]. In this investigation ferric/ferrous ratio with the total iron is selected for more comprehensive understanding of performance of the SAPS. Finally, a correlation between the NAG and the ferric/ferrous...
ratio along with total iron, manganese, aluminum, iron and HRT has been established using SPSS software.

2. Methodology

Synthetic AMDs were prepared in the laboratory with variation in metal contents. The coal mine drainage is generally contaminated with dissolved iron, aluminum and manganese [4]. The research work were performed on the four identical laboratory SAPS units, wherein 28 varieties of artificial AMDs of a known composition were treated in seven phases (a-b-c-d-e-f-g). The experiments with five HRT from 1 day to 10 days were carried out. Hence, each phase of experiment involving of four varieties of AMD was conducted for the stipulated HRT periods. The next phases of experiments commenced on another four variety of AMDs on the identical SAPS units [12].

Four PVC vessels were selected for SAPS column units (80L each). Limestone of 15 cm thickness is filled up at bottom, then saw dust and cow compost are filled up with 5 cm and 22 cm thickness respectively. Lastly, 2.5 cm gravel is packed at the top and then artificial AMD is allowed to fill up above the top gravel pack [14, 16]. The estimation of quantity of limestone (27 kg) and organic substrate (29 liters) was done on the basis of chemical calculations [12]. A perforated pipe is fixed at lowermost portion of SAPS column for the discharge of processed AMD to oxidation cell and flushing (Fig. 1).

![Fig.1. Laboratory arrangements for SAPS column study (Patel et al., 2019)](image)

A polyethylene net is placed between different layers of filled materials for separation purpose. The cow compost is taken with sufficient number of microbial counts ranging from $2.96 \times 10^5$ to $2.9 \times 10^6$ cfu/ml. The studies were conducted from 13.6°C to 43.3°C for 273 days in similar conditions. Limestone and organic substrate having similar composition were processed simultaneously in each phase (24 days), hence 28 synthetic AMDs of different compositions were processed in seven phases.

2.1 Composition of AMDs

All the 28 Artificial AMDs were prepared just before the commencement of each experiment (Fig. 2). The 28 synthetic AMDs were prepared according to ranges of composition given in Table 1.
Fig. 2. Four laboratory SAPS column operation [15]

Table 1. Summary of ranges of composition of 28 artificial AMDs

| Parameter                  | Range          |
|---------------------------|----------------|
| pH                        | 2.44-4.50      |
| DO                        | 5.52-7.13 mg/L |
| ORP                       | 104.30-113.50 mV|
| Iron (Fe$^{2+}$, Fe$^{3+}$) | 85.70 – 196.80 mg/L |
| Aluminum                  | 20-80 mg/L     |
| Manganese                 | 15-60 mg/L     |
| Calcium                   | 125 mg/L       |
| Magnesium                 | 100 mg/L       |
| Sulphate                  | 1020-1498 mg/L |
| Electrical conductivity   | 1939-2217 µS/cm|

In phase a, the aluminum + manganese concentrations in AMD were uniformly 20+15 mg/L for AMD Aa, AMD Ba, AMD Ca and AMD Da. Similarly in phase b,c,d,e,f and g, the aluminum and manganese concentration in AMDs were 40+15, 60+15, 80+15, 20+30, 20+45 and 20+60 respectively for respective group’s AMDs. The FFR$\times$TI for all the phase’s AMDs is given in Table 3.

Table 2. Phase wise distribution of AMDs for experiments

| Phase a | Phase b | Phase c | Phase d | Phase e | Phase f | Phase g |
|---------|---------|---------|---------|---------|---------|---------|
| AMD Aa  | AMD Ab  | AMD Ac  | AMD Ad  | AMD Ae  | AMD Af  | AMD Ag  |
| AMD Ba  | AMD Bb  | AMD Bc  | AMD Bd  | AMD Be  | AMD Bf  | AMD Bg  |
| AMD Ca  | AMDCb   | AMDCc   | AMDCd   | AMDCe   | AMD Cf  | AMD Cg  |
| AMD Da  | AMD Db  | AMD Dc  | AMD Dd  | AMD De  | AMD Df  | AMD Dg  |

2.2 Sample Testing

WTW multi 3620 IDS digital meter was used to measure pH, DO, ORP, temperature and electrical conductivity. The American Public Health association (APHA) standards were followed during sample testing and analysis for alkalinity, acidity, total iron, aluminum, manganese, ferric ferrous ratio, sulphate
and for other elements [1]. The Lasany UV-VIS spectrophotometer was used in above mentioned tests [12].

3. Results and Discussion

The results obtained after seven phases SAPS experiments are summarized in Table 3. The observations are discussed firstly for NAG with variation in influent metal loading with fixed HRT then for NAG with variation in HRT with fixed influent metal loading.

Table 3. AMD's details and Incremental NAG value for all experiments for all five HRTs

| AMD Sample | Total metal loading (Fe+Al+Mn) (mg/L) | FFR × T I | Incremental NAG value (From base value 430 of AMD Aa for 1d HRT) mg/L |
|------------|--------------------------------------|----------|------------------------------------------------------------------|
|            |                                      |          | HRT=1d | HRT=2d | HRT=4d | HRT=7d | HRT=10d |
| AMD Aa     | 120.70                               | 4.627    | 00     | 90     | 260    | 415    | 415     |
| AMD Ab     | 150.63                               | 10.61    | 30     | 120    | 295    | 470    | 600     |
| AMD Ac     | 183.60                               | 14.01    | 120    | 190    | 470    | 700    | 820     |
| AMD Ad     | 205.70                               | 15.50    | 270    | 460    | 670    | 850    | 975     |
| AMD Ae     | 141.70                               | 10.45    | 05     | 110    | 270    | 475    | 600     |
| AMD Af     | 157.50                               | 12.67    | 10     | 115    | 280    | 505    | 645     |
| AMD Ag     | 173.20                               | 15.66    | 10     | 120    | 295    | 525    | 745     |
| AMD Ba     | 153.70                               | 30.62    | 20     | 150    | 355    | 565    | 710     |
| AMD Bb     | 176.50                               | 40.10    | 65     | 195    | 470    | 625    | 775     |
| AMD Bc     | 209.00                               | 43.01    | 190    | 330    | 515    | 740    | 850     |
| AMD Bd     | 236.10                               | 53.48    | 360    | 590    | 830    | 1060   | 1225    |
| AMD Be     | 179.20                               | 44.10    | 35     | 185    | 365    | 640    | 780     |
| AMD Bf     | 193.90                               | 49.50    | 45     | 250    | 380    | 690    | 880     |
| AMD Bg     | 208.50                               | 52.43    | 50     | 250    | 420    | 780    | 920     |
| AMD Ca     | 206.60                               | 147.75   | 185    | 345    | 500    | 715    | 875     |
| AMD Cb     | 227.30                               | 153.35   | 335    | 440    | 665    | 790    | 960     |
| AMD Cc     | 249.00                               | 160.08   | 420    | 645    | 855    | 1075   | 1275    |
3.1. NAG with variation in influent metal loading with fixed HRT

In Phase a, for AMD Aa, the metal loading is (85.70 mg/L iron + 20 mg/L aluminum + 15 mg/L manganese = 120.70 mg/L) and metal loading were gradually increased in AMD Ba, AMD Ca and AMD Da to 153.70, 206.60 and 230.50 (all in mg/L) respectively (Table 3). The NAG reported after SAPS treatment for AMD Aa was 430 mg/L. The AMD Aa was taken as base AMD because it was prepared first then metal loadings were increased gradually. Thereafter for Phase a, for fixed 1d HRT 20, 185 and 360 (all in mg/L) incremental value from base value of NAG (i.e. 430 mg/L) were reported for AMD Ba, AMD Ca and AMD Da respectively. Similarly for fixed 2d, 4d, 7d and 10d HRT and with above variations in metal loading, the incremental NAG range was 90-400, 260-580, 415-790 and 415-970 mg/L respectively. It was reported that NAG was showing increasing trend with increased metal loading in influent AMDs for a particular HRT. It is clear from above observation that the net alkalinity generation range were increasing gradually with higher HRTs. The reason for above increase in NAG range is availability of more time for microbial reaction in organic substrate and chemical reaction of AMD with limestone at the bottom level, which results in more metal precipitation and alkalinity generation.

In Phase b, for AMD Ab, AMD Bb, AMD Cb and AMD Db, the metal loadings were 150.63, 176.50, 227.30 and 259.20 (all in mg/L) respectively. The incremental NAG from base value of NAG, after SAPS treatment for AMD Ab, AMD Bb, AMD Cb and AMD Db for Phase b, for fixed 1d HRT, were also reported in increasing order i.e. 30, 35, 335 and 375 (all in mg/L) respectively. Similarly for fixed 2d, 4d, 7d and 10d HRT and with above variations in metal loading, the incremental NAG range were 120-490, 295-690, 470-835 and 600-1015 mg/L respectively. The pattern of the incremental NAG range was higher as compared to phase a. This can be justified that metal loading is higher as compared to phase a.

In Phase c, for AMD Ac, AMD Bc, AMD Cc and AMD Dc, the metal loadings were 183.60, 209.00, 249.00 and 269.30 (all in mg/L) respectively. The incremental NAG from base value of NAG, after SAPS treatment for AMD Ac, AMD Bc, AMD Cc and AMD Dc for Phase c, for fixed 1d HRT, were also reported in increasing order i.e. 120, 190, 420 and 550 (all in mg/L) respectively. Similarly for fixed 2d, 4d, 7d and 10d HRT and with above variations in metal loading, the incremental NAG range were 190-
790, 470-980, 700-1120 and 820-1330 mg/L respectively. The incremental NAG range in Phase c, again indicating similar trends as discussed. The higher NAG range was obtained because of increase in metal loading in phase c.

In Phase d, for AMD Ad, AMD Bd, AMD Cd and AMD Dd, the metal loadings were 205.70, 236.10, 269.00 and 291.80 (all in mg/L) respectively. The incremental NAG from base value of NAG, after SAPS treatment for AMD Ad, AMD Bd, AMD Cd and AMD Dd for Phase d, for 1d HRT, were also reported in increasing order i.e., 270, 360, 585 and 670 (all in mg/L) respectively. Similarly for fixed 2d, 4d, 7d and 10d HRT and with above variations in metal loading, the incremental NAG range were reported as 460-1000, 670-1290, 850-1630 and 975-1840 mg/L respectively. The incremental NAG range is gradually increasing due to increase in metal loading.

In Phase e, for AMD Ae, AMD Be, AMD Ce and AMD De, the metal loadings were 141.70, 179.20, 224.00 and 244.35 (all in mg/L) respectively. The incremental NAG from base value of NAG, after SAPS treatment for AMD Ae, AMD Be, AMD Ce and AMD Dd for Phase e, for 1d HRT, were also reported in increasing order i.e., 05, 35, 230 and 285 (all in mg/L) respectively. Similarly for fixed 2d, 4d, 7d and 10d HRT and with above variations in metal loading, the incremental NAG range were 110-495, 270-720, 475-970 and 600-1080 mg/L respectively.

In Phase f, for AMD Af, AMD Bf, AMD Cf and AMD Df, the metal loadings were 157.50, 193.90, 237.80 and 250.90 (all in mg/L) respectively. The incremental NAG from base value of NAG, after SAPS treatment for AMD Af, AMD Bf, AMD Cf and AMD Df for Phase f, for 1d HRT, were also reported in increasing order i.e., 10, 45, 250 and 310 (all in mg/L) respectively. Similarly for fixed 2d, 4d, 7d and 10d HRT and with above variations in metal loading, the incremental NAG range were 115-545, 280-760, 505-1020 and 645-1160 mg/L respectively.

In Phase g, for AMD Ag, AMD Bg, AMD Cg and AMD Dg, the metal loadings were 173.20, 208.50, 251.50 and 270.80 (all in mg/L) respectively. The incremental NAG from base value of NAG, after SAPS treatment for AMD Ag, AMD Bg, AMD Cg and AMD Dg for Phase g, for 1d HRT, were also reported in increasing order i.e., 10, 50, 250 and 340 (all in mg/L) respectively. Similarly for fixed 2d, 4d, 7d and 10d HRT and with above variations in metal loading, the incremental NAG range were 120-570, 295-810, 525-1065 and 745-1210 mg/L respectively.

Based on above findings it was indicated that metal loading affects the NAG in SAPS. The AMD with high metal loading has higher mineral acidity and their rate of reaction become faster and higher NAG was observed. In phase a, continuous increase in alkalinity generation reported because there was a continuous increase in metal loading along with iron component, FFR × T I (i.e., 4.627, 30.62, 147.75, 223.46). Similar trends were reported for all the phases. The reason for more NAG after metal removal is reduction in mineral acidity. Asper the mechanism SAPS AMD is passes through a layer of an organic material in environment favorable for reduction, where chemical and biological reactions take place. The SAPS processes generate alkalinity, increase the pH, reduce sulfates content, and encourage the metals removal. These findings are showing an agreement with research work of Johnson and Hallberg [8]. The above phenomena can be better explained by following equations:

\[ 2\text{CH}_2\text{O} + \text{SO}_4^{2-} \rightarrow \text{S}^2 + 2\text{CO}_2 + 2\text{H}_2\text{O} \]

\[ \text{S}^2 + 2\text{CO}_2 + 2\text{H}_2\text{O} \rightarrow 2\text{HCO}_3^- + \text{H}_2\text{S} \]

where CH\text{O} represents a simple organic carbon source. The influent AMD high metal loading contains high concentration of sulphate. The high sulphate removal produces high bicarbonate alkalinity in the form HCO\text{3}^- and high amount of H\text{2}S. The H\text{2}S react with metals to form metal sulphide precipitates. Therefore, the increase in metal loading in influent AMD increases the alkalinity generation.
during treatment by SAPS, is in line with principle chemistry. Similar findings were also reported by Zipper and Skousen [20].

In all the experiments initially, alkalinity was generated with faster rate, then it became slower after passes of time due to reaching towards saturation level. This confirmed the slower dissolution rate of limestone at higher pH level which agrees with Jageet works [6]. In other words, more acidic AMD showed higher alkalinity generation trends in SAPS as compared to less acidic AMD. From trends of NAG, it was evident that NAG increases with increase in metal loading in AMD, the reason for more NAG after metal removal is reduction in mineral acidity.

3.2. NAG with variation in HRT with fixed influent metal loading

In phase a, the NAG observations with variation in HRT with constant metal loading i.e., 120.70 mg/L, for AMD Aa, was carried out to understand the behavior of NAG during AMD treatment by SAPS. The incremental NAG from base value of NAG (=430), for 2d HRT was reported as 90 mg/L (Table 3). Further the incremental NAG for AMD Aa, for 4d, 7d and 10d HRTs were reported as 260, 415 and 415 (all in mg/L) respectively (Figure 3). Similarly the incremental NAG from base value, for AMD Ba with constant metal loading of 153.70 mg/L for 1d, 2d, 4d, 7d and 10d HRTs were reported as 20, 150, 355, 565 and 710 (all in mg/L) respectively. The incremental NAG from base value, for AMD Ca with constant metal loading of 147.75 mg/L, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 185, 345, 500, 715 and 875 (all in mg/L) respectively. The incremental NAG from base value, for AMD Da with constant metal loading of 230.50 mg/L, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 360, 400, 580, 790 and 970 (all in mg/L) respectively. Further it is clear that substantial increase in NAG were observed in all the four AMDs of phase a experiment with increasing HRT with constant metal loading.

In phase b, the metal loading for AMD Ab was kept constant at 150.63 mg/L whereas the incremental NAG from base value, for AMD Ab, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 30, 120, 295, 470 and 600 (all in mg/L) respectively (Figure 4). Similarly the incremental NAG from base value, for AMD Bb with constant metal loading of 176.50 mg/L, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 65, 195, 470, 625 and 775 (all in mg/L) respectively. The incremental NAG from base value, for AMD Cb with constant metal loading of 227.30 mg/L, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 335, 440, 665, 790 and 960 (all in mg/L) respectively. The incremental NAG from base value, for AMD Db with constant metal loading of 249.20 mg/L, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 375, 490, 690, 835 and 1015 (all in mg/L) respectively. It is again indicating that increase in NAG in all the four AMDs of phase b experiment with increasing HRT with constant metal loadings.

In phase c, the metal loading for AMD Ac was kept constant at 183.60 mg/L whereas the incremental NAG from base value, for AMD Ac, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 120, 190, 470 and 820 (all in mg/L) respectively (Figure 5). Similarly the incremental NAG from base value, for AMD Bc with constant metal loading of 209.00 mg/L, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 190, 330, 515, 740 and 850 (all in mg/L) respectively. The incremental NAG from base value, for AMD Cc with constant metal loading of 249.90 mg/L, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 420, 645, 855, 1075 and 1275 (all in mg/L) respectively. The incremental NAG from base value, for AMD Dc with constant metal loading of 269.30 mg/L, for 1d, 2d, 4d, 7d and 10d HRTs were reported as 550, 790, 980, 1120 and 1330 (all in mg/L) respectively.

It was again confirmed that the increase in NAG in all the four AMDs of phase c experiment with increasing HRT with constant metal loadings.

NAG vs HRT plots for phase d, phase e, phase f and phase g are not shown for avoiding similarity and repetition. Similar trends for NAG for remaining 16 AMDs were also observed from phase d, phase e,
phase f and phase g experiments for different HRTs (i.e., 1d, 2d, 4d, 7d and 10d) with constant metal loading. (Table 3). Thus, based on the above experimental observations, it was found that NAG increases with increase in HRT with constant metal loadings. The NAG by the SAPS unit ranged between 430 mg/L to 2270 mg/L.

It was found that the pH level was increased with increase in HRT for all the seven phases’ experiments. (Fig. 3, Fig. 4 and Fig. 5). Vasquez has also found similar findings during treatment of AMD for three different HRT by biochemical passive reactor [19]. The justification for above is availability of more time for microbial activities and limestone dissolution. This can be explained due to following reasons (i) When low pH acidic AMD solution passes through organic layer, the microbe responds quickly, and bicarbonate alkalinity generated with faster rate (ii) After some time saturation level of alkalinity generation by microbe and limestone reached and the rate of pH increase became slower. The pH values in the 28 influent synthetic AMDs ranged from 2.44 to 4.50 and they were found to rise to a range from 8.30 to 8.85 at the discharge for 10d HRT. The pH levels increased in all the seven phases of experiments which confirmed the alkalinity generation by SAPS units. The strong reducing environment is observed to inside the SAPS in organic substrate thereby resulting in the precipitation of metal sulfide and at the same time generation of bicarbonate alkalinity. This is an agreement with Choudhary [3].

![Graph](image)

**Fig. 3. NAG in different HRT: Phase a**
Fig. 4. NAG in different HRT Phase b

Alkalinity Generation in Different HRT's

Fig. 5. NAG in different HRT Phase c

Alkalinity Generation in Different HRT's
Based on plots between HRT and NAG for AMD Aa, AMD Ba, AMD Ca and AMD Da (Figure 3) at Port P3, the following best fit logarithmic curve equations were obtained (Table 4):

| AMD  | Logarithmic curve equations | $R^2$ Value |
|------|----------------------------|-------------|
| Aa   | $380.9 \ln(x) + 75.62$     | 0.974       |
| Ba   | $456.3 \ln(x) + 59.06$     | 0.988       |
| Ca   | $504.5 \ln(x) + 132.5$     | 0.956       |
| Da   | $535.9 \ln(x) + 154.6$     | 0.948       |

Similar trends in logarithmic curve equations were also found for all the remaining 24 AMDs used in experiments. Therefore, it is clear that hydraulic retention time (HRT) has logarithmic relationship with NAG, hence natural log of HRT in hours is taken as input parameter for SPSS software analysis. The significant increase in the pH level in all the experiments was reported, which confirmed the NAG by SAPS units with maximum pH level of 8.85 (for AMD Dd). The similar trends in pH increase were found for remaining 27 AMDs. The strong reducing environment was prevailing inside the SAPS unit thereby resulting in the precipitation of metal sulfide and at the same time generation of bicarbonate alkalinity. This is an agreement with Choudhary [3].

3.3 Selection of iron component ($FFR \times TI$)

The effects of iron on NAG by SAPS can be only understand better if its composition in the form of ferric iron and ferrous iron is considered along with total iron (TI). The ferric iron/ferrous iron ratio ($FFR$) gives an idea about redox status of the AMD solution. Therefore, total iron must be considered along with ferric iron/ferrous iron ratio. Generally, in very acidic AMD the ferric iron concentration is higher than ferrous iron and during treatment by SAPS, the most of ferric iron is converted to ferrous iron form. The representation of ferric/ferrous ratio is always associated with corresponding total iron. The expression of ferric/ferrous ratio alone does not give any meaning unless it is represented together with corresponding total iron [13]. Therefore, in this study we have selected an iron component factor as $FFR \times TI$, a product of $FFR$ and TI, so that the effects of ferric/ferrous ratio along with total iron on NAG can be evaluated in a more appropriate manner. Patel [15] has also selected ($FFR \times TI$) as important evaluating parameter for NAG by SAPS. Therefore, iron component ($FFR \times TI$), aluminum and manganese contents are used in software analysis, for obtaining the more accurate relationship for NAG.

4. Analysis of SAPS Results by SPSS Software

The analysis of results obtained from laboratory SAPS experiments processed by SPSS statistical software. The analysis of SPSS software provides a relationship between NAG by the SAPS unit and the influencing parameters such as HRT, Iron component i.e., total iron along with ferric iron/ferrous iron ratio ($FFR \times TI$), aluminum and manganese contents in influent AMD solution. A total of 140 samples were collected from SAPS unit effluent at Port P3 for all 28 synthetic AMDs for 1d, 2d, 4d, 7d and 10d HRTs. Total 140 AMD samples data are considered as qualified for SPSS software analysis by ANOVA multivariate analysis. The input data of SAPS treatment for NAG were processed by SPSS software and the following output data were obtained as given below.
### Descriptive Statistics

|                | Mean   | Std. Deviation | N  |
|----------------|--------|----------------|----|
| NAG P3         | 1032.68| 381.370        | 140|
| FFR*TI         | 120.012857 | 96.7195501    | 140|
| Al (mg/L)      | 37.14  | 22.578         | 140|
| Mn (mg/L)      | 27.86  | 16.933         | 140|
| HRT in natural log | 4.443641 | 0.8375231     | 140|

### Correlations

|                | NAG P3   | FFR*TI  | Al (mg/L) | Mn (mg/L) | HRT in natural log |
|----------------|----------|---------|-----------|-----------|-------------------|
| Pearson Correlation |          |         |           |           |                   |
| NAG P3          | 1.000    |         | -0.126    | 0.719     |                   |
| FFR*TI          | 0.478    | 1.000   | 0.101     | 0.000     |                   |
| Al (mg/L)       | 0.422    | -0.008  | 1.000     | 0.000     |                   |
| Mn (mg/L)       | -0.126   | 0.101   | -0.581    | 0.000     |                   |
| HRT in natural log | 0.719    | 0.000   | 0.000     | 1.000     |                   |
| Sig. (1-tailed) |          |         |           |           |                   |
| NAG P3          | 0.000    |         | 0.000     | 0.068     | 0.000             |
| FFR*TI          | 0.000    | 0.461   | 0.418     | 0.500     |                   |
| Al (mg/L)       | 0.068    | 0.118   | 0.000     | 0.500     |                   |
| Mn (mg/L)       | 0.000    | 0.500   | 0.500     |           |                   |
| HRT in natural log | 140      | 140     | 140       | 140       | 140               |

### Model Summary

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate | Change Statistics | F | df1 | df2 | Sig. F Change |
|-------|---|----------|-------------------|-----------------------------|-------------------|---|-----|-----|---------------|
| 1     | 0.967<sup>a</sup> | 0.935    | 0.933             | 98.923                      | 482.729           | 4 | 135 | 0.000 |               |

- a. Predictors: (Constant), HRT in natural log, Mn (mg/L), FFR*TI, Al (mg/L)

### ANOVA<sup>a</sup>

| Model | Sum of Squares | df | Mean Square | F | Sig. |
|-------|----------------|----|-------------|---|------|
| 1     | Regression     | 18895537.95 | 4 | 4723884.487 | 482.729 | 0.000<sup>b</sup> |
|       | Residual       | 1321082.587 | 135 | 9785.797 |
|       | Total          | 20216620.54 | 139 |              |

- a. Dependent Variable: NAG P3
- b. Predictors: (Constant), HRT in natural log, Mn (mg/L), FFR*TI, Al (mg/L)
Coefficients

| Model       | Unstandardized Coefficients | Standardized Coefficients | t    | Sig. |
|-------------|----------------------------|---------------------------|------|------|
|             | B                          | Std. Error                | Beta |      |
| 1 (Constant)| -1021.530                  | 54.914                    | -18.602 | 0.000 |
| FFR*TI      | 1.858                      | 0.087                     | 0.471 | 21.264 | 0.000 |
| Al (mg/L)   | 8.280                      | 0.457                     | 0.490 | 18.106 | 0.000 |
| Mn (mg/L)   | 2.495                      | 0.613                     | 0.111 | 4.072  | 0.000 |
| HRT in natural log | 327.253                  | 10.018                    | 0.719 | 32.666 | 0.000 |

a. **Dependent Variable: NAG P3**
b. **Predictors: (Constant), HRT in natural log, mn (mg/L), FFR*TI, Al (mg/L)**

### 4.1. Interpretations of SPSS Software output

The following relationship is obtained for NAG and iron component i.e. ferric/ferrous iron ratio x total iron (FFR× TI), aluminum, manganese and HRT,

$$NAG = 1.86 \times (FFR\times TI) + 8.28 \times Al + 2.49 \times Mn + 327.25 \ln(HRT) - 1021.53$$

Where, NAG in mg/L (in terms of CaCO$_3$ equivalence), HRT in hours, TI (total iron), aluminum and manganese in mg/L. In the SPSS analysis 140 dataset were processed with ANOVA model for 95% confidence level and for ln(HRT) , FFR×TI , aluminum and manganese. Therefore, all these four parameters had significant impact on net alkalinity generation. The coefficient of multiple determinations was found as $R^2=0.935$, which means that above relationship for given dataset is better fit and highly acceptable. It is evident that from above obtained relationship that net alkalinity generation increases with metal loading and HRT. It is also very clear that the FFR×TI gives more clarity on behavior of iron. Jage [6] reported SAPS performance by incorporating HRT, total iron and non-manganese acidity and given following relationship

$$\text{Net alkalinity generation} = 59.33 \ln(tr) +1.03 \times Fe+0.32 \times \text{non-Mn acidity} -80.43$$

Where tr = residence time in hours, Fe = total iron in mg/L, Non-manganese acidity in mg/L.

Therefore, the relationship obtained by this research work (equation 5.2) is more comprehensive and acceptable because it had incorporated aluminum and manganese along with iron component (ferric/ferrous ratio×total iron).

### 5. Conclusions

- The experimental investigations, observations and analysis conducted in the research work led to the following important conclusions. The relationship between iron component, aluminum, manganese, HRT and NAG by SAPS is obtained as

$$NAG = 1.86 \times (FFR\times TI) + 8.28 \times Al + 2.49 \times Mn + 327.25 \ln(HRT) - 1021.53$$

- On the basis of above relationship, it can be concluded that the NAG increase with increase in total iron, ferric/ferrous iron ratio, aluminum, manganese contents and hydraulic retention time in influent AMD.

- Based on the experiments in all cases of AMDs, the performance of SAPS as indicated by the NAG has been found to improve with the increase in HRT. The NAG by the SAPS unit ranged between 430 mg/L to 2270 mg/L.
The above obtained relationship after SPSS software analysis shows the importance of composition of the influent AMD on the treatment process by SAPS. Large scale SAPS unit in the mine can be designed for better performance, cost effective and for longer life by taking into consideration the quality of the influent AMD and HRT.

It is recommended that SAPS should be operated with appropriate influent metal load for longer life of SAPS. If influent AMD contains high metal concentration, then it will exhaust the carbon source and limestone rapidly. Therefore, a number of SAPS shall have to be used in series where treatment of AMD with higher metal content and acidic load is proposed.

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