

Interaction of industrial effluents and bentonite: a comparative study of their physico-chemical and geotechnical characteristics

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Abstract. One-dimensional soil-column studies were carried out to understand the interaction of three industrial effluents namely amino acid ('highly acidic'), surfactant ('highly organic') and pharmaceutical ('organic and toxic') on the physicochemical behavior, index properties and shear strength of bentonite due to artificial contamination extending to nearly 300 days. Changes in inorganic and organic pollutants present in the effluents due to the interaction of the above effluents and soil were assessed to understand the physico-chemical behaviour. Batch and continuous modes of operation, 8 hrs and 16 hrs Hydraulic Retention Time [HRT] and 25%, 50% concentrations of effluents, were the parameters considered. Amino acid, surfactant and pharmaceutical effluents have shown a high variation in pH (7 to 8) after artificial contamination on bentonite that is their original characteristics of the above effluents have been completely reversed. Further, it is found that the shear strength of bentonite has reduced by about 20%, and with respect to liquid limit and plastic limit shows an increasing trend with time within the period of contamination.

Keywords: industrial effluents; amino acid; surfactant; pharmaceutical; bentonite; physico-chemical behavior; index properties and strength strength of soils.

1. Introduction

During early 2000, isolated instances of once fertile lands becoming barren within a year were reported, due to indiscriminate discharge of effluents on land in certain parts of Pondicherry, India. Based on a survey conducted covering the various industries located within 50-75 km from the above region, a few types of effluents from process industries which are considered to be potentially polluting, were identified. Further, critical review of literature was undertaken to identify effluent types, which are rather rarely or scarcely investigated. Understanding the engineering properties of clay soils is of vital importance in geotechnical engineering practice. In comparison to the natural clay soils, the engineering properties of clay minerals exhibit a much wider range and further within a group, the range may also be significant. The types of clay mineral play a dominant role in

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controlling the physical and engineering properties of fine grained soils (Sridharan 1990). Rapid industrialization has resulted in enormous production of liquid and solid wastes. Indiscriminate disposal of such wastes, especially on land has caused serious environmental problems (Fang 1986). Failure of foundation/structures due to ground contamination/accidental spill of chemicals etc., has been reported (Sridharan and Rao 1979, Peirce *et al.* 1987, Sivapulliah *et al.* 1994, Miura *et al.* 1998, Deane *et al.* 1999). It has been established that the inorganic and organic pollutants present in industrial effluents, in general, affect various geotechnical characteristics of fine-grained soils (Kamon *et al.* 2002, Sharma and Mohamed 2003, Gallipol *et al.* 2003). Critical review of published literature has revealed that only very few studies have been reported on the effect of industrial effluents on soils, and that the focus so far has been on understanding the effect of pure chemicals on commercial soils (bentonite/kaolinite). Further, effort has not been directed to simulate the process of contamination close to the field conditions, in the laboratory studies (Murugaiyan *et al.* 2004, 2005, 2008). However, it is necessary to study and understand the effect of contaminants/ industrial effluents on various geotechnical properties of soils, for various engineering applications. The best way to understand the interaction of effluents on fine grained soil is to consider a soil which is commercially available and rich in a particular clay mineral. Hence 'bentonite' soil was chosen for studying its interactions with the three chosen industrial effluents namely, amino acid (A), surfactant (S) and pharmaceutical (P) effluents. The interactions were studied in terms of the physio-chemical behavior and geotechnical characteristics (i.e. index properties and unconfined compressive strength) of bentonite soil and the experimental results presented and discussed.

2. Materials and methods

2.1. Source and collection of effluents

Based on the above, three effluents namely, amino acid, surfactant and pharmaceutical effluents were selected for the present study. Samples of the above effluents were collected from process industries located in and around Pondicherry region, South India. The effluent parameters, namely, pH, electrical conductivity, alkalinity, total solids, total dissolved solids (TDS), total volatile solids (TVS), chloride, sulphate, nitrite, and chemical oxygen demand (COD), were estimated characterizing the various effluents before the commencement of the experimental investigations and for the outflow from the experimental set-up i.e., soil-column (described later), at specified intervals during the actual progress of experimental work. The above parameters are comprehensive and sufficient to characterize the effluent and to understand their effect on chosen soils. The procedure for the analyses of the above parameters were as per APHA Standard Methods (2005). The characteristics of above three effluents are presented in Tables 1 to 3.

2.2. Bentonite soil-selection, source and characteristics

Bentonite soil, which is easily available in the market, was chosen for the present study to determine the independent behavior when it is artificially contaminated with the three chosen industrial effluents A, P and S. Bentonite is the most abundant and widely available clay mineral, containing predominantly montmorillonite. Much less is known about the behavior of this soil in a polluted environment. Bentonite minerals are more susceptible to environmental changes as the

Table 1 Characteristics of amino acid effluent (A)

Sl.No.	Parameter*	Value
1.	PH	3-4
2.	Electrical Conductivity	12389
3.	Alkalinity	0
4.	Total Solids	18000-19000
5.	Total Dissolved Solids	17800
6.	Total Volatile Solids	16300
7.	Chloride	100-155
8.	Sulphate	200-260
9.	Nitrite	70-118
10.	Chemical Oxygen Demand (COD)	19000-20000
11.	Biological Oxygen Demand (BOD)	4972-5234

Note: (i)*All parameters except pH and electrical conductivity are in mg/L
(ii) Electrical conductivity is in $\mu\text{S}/\text{cm}$

Table 2 Characteristics of surfactant effluent (S)

Sl.No.	Parameter	Value*
1.	pH	6-12.1
2.	Electrical Conductivity ($\times 10^3$)	15-45
3.	Alkalinity	1000-5000
4.	Total Solids	8100-16400
5.	Total Dissolved Solids	5000-10000
6.	Total Volatile Solids	1200-4800
7.	Chloride	1900-2500
8.	Sulphate	200-4500
9.	Nitrite	600-1000
10.	Chemical Oxygen Demand (COD)	10200-14500
11.	Biological Oxygen Demand (BOD)	5000-10000

Table 3 Characteristics of pharmaceutical effluent (P)

Sl.No.	Parameter	Value*
1.	pH	3-4
2.	COD	2100-4200
3.	BOD	2000-2600
4.	Total Solids	24500-34500
5.	Total Suspended solids	6000-9500
6.	Total Dissolved solids	18500-25000
7.	Volatile Suspended Solids	14000-28000
8.	Kjeldahl nitrogen (as N)	8-15
9.	Phosphate (as P)	9-12

Note: (i) *All parameters except pH and electrical conductivity are in mg/L
(ii) Electrical conductivity is in $\mu\text{S}/\text{cm}$

Table 4 Characteristics of bentonite

S.No	Parameter	Bentonite
(A) Chemical Properties		
1	pH	8.2
2	Chloride (mg/L)	3980
3	Sulphate (mg/L)	2200
Index properties		
4	Liquid Limit (%)	157.0
5	Plastic Limit (%)	69.0
6	Shrinkage Limit (%)	54.0
7	Volumetric Shrinkage (%)	99.4
8	Specific gravity	2.7
(B) Sieve analysis		
Hydrometer Analysis		
9	% of clay	38
10	% of silt	62
(C) Proctor compaction test		
11	Maximum Dry Density (kN/m ³)	14.7
12	Optimum Moisture Content (%)	24.1
(D) Strength		
13	Unconfined compressive strength (q _u , N/mm ²)	0.24
(E) Classification*		Silt and clays of high compressibility

Note: *As per IS:1498-1970 (reaffirmed in 1997) liquid limit of fine grained soils having a value greater than 50, are classified as "silt and clays of high compressibility"

structural linkages between sheets are weak. Analysis of the above soil sample was carried out as per the procedure detailed in IS: 2720 (1985) and the results obtained are given in Table 4.

2.3. Choice of experimental set-up

One-dimensional column method is best suited to understand soil-pollutant interactions, as it permits investigations of such interactions under various flow rates and retention times. Hence, in the present study one-dimensional soil-column method was selected and adopted. Of the several investigators who have adopted one-dimensional soil-column, only Drewes and Fox (1999) have investigated the variation of flow rate and concentration of pollutant/(s) with respect to hydraulic travel times. As one of the objectives of the present study is to understand the physico-chemical behaviour of soil-pollutant interactions under various modes of operations, the methodology adopted by Drewes and Fox (1999) was selected. The experimental set-up adopted by Drewes and Fox (1999) was for studying the characteristics of recalcitrant compounds (DOC-Dissolved Organic Carbon) in ground water (i.e. raw water) through a soil-column. The above soil-column system simulates aquifer conditions in a series of four columns and was operated under saturated, anoxic-redox conditions. In fact the experiments conducted by Drewes and Fox (1999) were only under a batch mode of operation and the hydraulic travel times adopted were found to be too large. Hence, the above methodology cannot be considered as a true representation of field conditions relevant to

the present study. It was therefore decided to consider the methodology adopted by Drewes and Fox (1999) as a 'conceptual model' and modify it to suit the present investigations so as to represent field conditions.

2.4. Description of experimental set-up

The experimental set-up adopted for the present study consisted of a number of batteries of soil-column. Each battery consists of six soil-columns (identical in dimensions) which were fabricated according to the schematic diagram shown in Fig. 1. Each soil-column was made of perspex pipes with an anti-corrosive coated MS (mild steel) hopper portion. A wire mesh was placed between the soil-column and hopper portion. In the hopper portion, an outlet control valve was fixed to regulate the outlet flow, which in turn is connected to a drain outlet. A drain pipe was provided to collect the effluent from the drain outlet. The effluent to the soil-column was fed through a feed tank fitted with an inlet control valve at the bottom and an inlet feed which connects the soil-column to the feed tank. Fig. 2 shows the photographic view of the experimental set up.

One and half battery of soil-columns was used for the following purpose/(s):

(i) Samples were collected from separate soil columns marked ST and CT respectively, for conducting tests to determine soil and chemical characteristics, after various periods of (artificial) contamination.

(ii) Since three effluents were used to study the effect on bentonite soil, nine soil-columns were used for simultaneous investigation. Hence, two batteries of soils-columns (each battery having 6 soil columns) were exclusively used for the investigations.

2.5. Preparation of soil specimen and operating schemes

The experimental set-up was used for two modes of operation, namely: (i) batch-mode and (ii) continuous-mode, with varying hydraulic retention times (HRTs). 'HRT' is defined as the time taken by the first droplet of the effluent to flow from the inlet to the outlet of the soil-column. The batch-mode was operated to study the chemical equilibrium that gets established between the soil and the

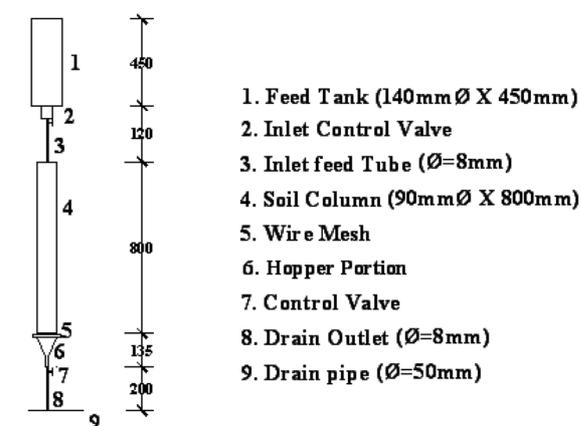


Fig. 1 Schematic diagram of the single soil column of experimental set-up

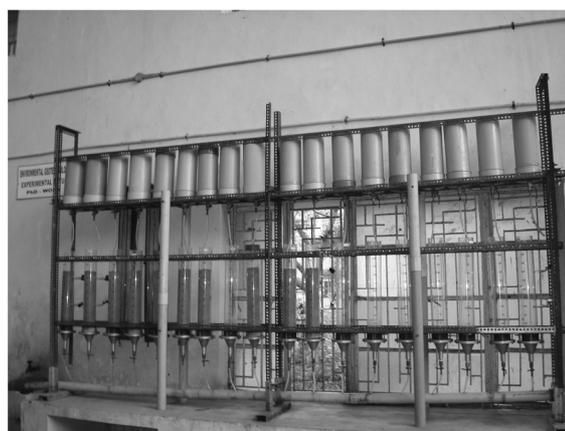


Fig. 2 Photographic view of the experimental set-up

Table 5 Flow rates

Sl. No	Effluent	HRT (hr)	Flow rates (ml/min)
1	amino acid	8	1.50
		16	0.75
2	Surfactant	8	0.70
		16	0.35
3	Pharmaceutical	8	2.40
		16	1.20

pollutants of the effluent, whereas, continuous-mode of operation was aimed at analyzing and reporting soil-pollutant interactions (with respect to HRT) as applicable to field conditions (i.e. discharge of effluent on soil is continuous with varying flow rate and concentration of pollutants). Any process industry is operated in shifts of 8 hours duration. Hence, 8 hours HRT can represent one shift and it also represents a 'shock-load' imparted to the soil (sample) at maximum flow rate and concentration of pollutants. On the other hand, 16 hours HRT represents a situation where in the flow and the concentration of pollutants are likely to be minimum. Hence, the effect of 8 hr and 16 hr HRT with 25% and 50% concentrations on soil-pollutant interactions were investigated.

Soil samples (weighing about 2.7 kg) were mixed with the effluent, (the quantity added corresponds to the respective optimum moisture content (OMC) for each type of soil) and filled to a height of 650 mm in the respective soil-column. Chemical analysis was carried out on the effluent collected from the outlet of the soil-columns marked as CT and soil analysis was performed on the soil samples collected from soil-columns marked as ST for the respective soils. Soil samples (weighing about 300 gm) were collected at intervals of 15 days during both the modes of operation. Effluent samples were collected from the outlet of soil-columns at intervals of 24 hrs during the batch-mode and at intervals of 8 hr, 12 hr and 16 hr during the continuous mode of operation.

An effluent volume of 1.2 liters was used to fill the feed tanks for batch-mode of operation. However, for continuous-mode of operation, flow rates for the various soils and for the various HRTs considered were calculated based on the porosity of the soil samples at the end of the batch-mode. The flow rates thus arrived at for various types of soils are summarized in Table 5.

3. Results and discussion

3.1. Physico-chemical behaviour

Soil-pollutant interactions with respect to changes in concentrations of pH, alkalinity, Chlorides and Sulphates in the case of inorganic pollutants and for COD in the case of organic pollutants are shown in Figs. 3 to 8 were only critically assessed to understand their physico-chemical behaviour.

3.2. Bentonite-inorganic pollutant interactions: batch mode

(1) *pH and alkalinity*: The pH values of amino acid, surfactant and pharmaceutical effluents were respectively in the range of 3 to 4, 6 to 12.1 and 3 to 4 before passing through the soil column (i.e. before contamination). The pH values were found to vary after contamination from 4.5 to 8.9, 6.9 to

8.5, and 6.5 to 9 for amino acid, surfactant, and pharmaceutical effluents, respectively. Amino acid and surfactant effluents showed peak pH values of 8.9 and 8.5 at the end of 36th day and 85th day respectively, whereas, a peak pH value of 9.0 was observed at the end of 64th day for the pharmaceutical effluent. Steady state condition was found to have been reached at the end of 61st day, 75th day and 78th day for amino acid, surfactant and pharmaceutical effluents, respectively. pH variation in this experimental study was found to follow a similar trend with that of Ruhl and Daniel (1997) for the experiments conducted by them on geosynthetic clay liners (tested for fly ash and bentonite) for the permeation of acidic and alkaline chemical solutions. The pH of the permeated solutions (with 0.1 M NaOH and 0.1 M HCL as influent in the above study) was respectively found to vary from 9.5 to 13 and 3 to 8.6. These pH variations are comparable to the pH variations observed in the present study, for amino acid and pharmaceutical effluents.

Alkalinity of amino acid and pharmaceutical effluents were zero, whereas, it was 1000 to 5000 mg/L for surfactant effluent, before passing through the soil column. However, the alkalinity was found to vary (after contamination) from 37 to 552, 172 to 491 and 92 to 564 mg/L for amino acid, surfactant and pharmaceutical effluents, respectively. Amino acid, surfactant and pharmaceutical effluents (after contamination), showed peak alkalinity values of 552, 491 and 564 mg/L at the end of 50th, 2nd day and 19th day respectively. Steady state condition was found to have been reached at the end of 61st day, 75th day and 78th day for amino acid, surfactant and pharmaceutical effluents, respectively. Variation in pH and alkalinity as observed above were found to be minimum due to high clay content. The variations in hydrogen-ion concentration were found to be appreciable from 2nd to 84th day and then it gets stabilized to a consistent value towards the end of batch mode. The above phenomenon is in agreement with the reported physico-chemical changes of soil properties investigated by Wosten and Genuchten (1988) and for the study reported by Chu (2003) carried out for surfactant contaminated soil under a two phase system (i.e. gaseous & liquid phase).

(2) *Chloride and Sulphate*: Chloride concentration of amino acid and pharmaceutical effluents were zero, whereas, it was 1900 to 2500 mg/L for surfactant effluent before passing through the soil column. The chloride concentrations were found to vary after contamination from 204 to 2925; 106 to 1728 and 62 to 2180 mg/L for amino acid, surfactant and pharmaceutical effluents, respectively. Amino acid, surfactant and pharmaceutical effluents, showed peak chloride concentrations of 2925, 1728 and 2180 mg/L at the end of 2nd, 40th and 12th day, respectively. Steady state condition was found to have been reached at the end of 61st day, 64th and 50th day, respectively, for amino acid, surfactant and pharmaceutical effluents.

Sulphate concentration of amino acid and surfactant effluents were in the range of 200 to 260 and 200 to 4500 mg/L, whereas, it was zero for pharmaceutical effluent, before passing through the soil column. However, the concentrations were found to vary after contamination on bentonite from 200 to 1880; 400 to 1680 and 200 to 1840 mg/L for amino acid, surfactant and pharmaceutical effluents, respectively. Amino acid, surfactant and pharmaceutical effluents (after contamination) showed peak sulphate concentrations of 1880 mg/L, 1680 mg/L and 1840 mg/L at the end of 68th, 15th day and 57th day, respectively. Steady state condition was found to have been reached at the end of 50th, 47th and 40th day, for amino acid, surfactant and pharmaceutical effluents, respectively. The variation of concentrations were caused due to the adsorption and leaching of sulphate in bentonite.

It is evident from the above, that the retention of sulphate concentration undergoes a larger variation when compared to that of chloride, before attaining the steady state condition. This is due to the reason that sulphate is reacting at higher rate and assists in breakup of soil interstices leading to permeation of more sulphate ions than that of chloride ions. Moreover, the variation in sulphate

concentration is comparably less for pharmaceutical effluent, when compared to the other two effluents considered.

Variation in chloride concentration observed in the present study is found to be very close to the value reported by Badv and Rowe (1996) for the experimental study on silt and clayey silt for chloride transport under unsaturated condition (batch mode). The reported variation i.e., chloride concentration 800 to 1200 mg/L for the above study is comparable to the steady state chloride concentration 2250 mg/L for surfactant under batch mode. They are different in magnitude but possess characteristically comparable behavior.

It is also seen that the variation in chloride concentration observed in the present study is found to be similar to the reported results by Rowe and Badv (1996) for this experimental study on chloride migration through clayey silt underlain by fine silt under near saturated condition.

3.3. Bentonite-inorganic pollutants interaction: continuous mode

The characteristics of the three effluents due to artificial contamination on bentonite are presented in Figs. 3 to 5 for 8 hr and 16 hr HRT at 25 and 50% concentration. Amino acid, surfactant and pharmaceutical effluents attained the steady state condition within a period of 56 days for 8 hr HRT and 15 days for 16 hr HRT at 25% concentration, whereas, the above effluents attained the steady state condition within a period of 17 days for 8 hr HRT and 14 days for 16 hr HRT at 50% concentration.

(1) *pH and Alkalinity*: pH values were found to vary from 8.0 to 8.9; 7.0 to 7.9 and 6.5 to 8.1 for 8hr HRT, and 6.0 to 7.5; 7.0 to 7.2 and 6.3 to 8.1 for 16hr HRT, respectively, for amino acid, surfactant and pharmaceutical effluents.

Alkalinity values were found to vary from 153 to 183; 122 to 214 and 153 to 183 mg/L for 8 hr HRT, and 123 to 168, 153 to 195 and 153 to 290 mg/L for 16 hr HRT, respectively, for amino acid, surfactant and pharmaceutical effluents.

(2) *Chloride and Sulphate*: Chloride concentrations were found to vary from 48 to 525; 310 to 990 and 157 to 750 mg/L for 8 hr HRT and 80 to 285; 310 to 889 and 168 to 467 mg/L for 16 hr HRT, respectively, for amino acid, surfactant and pharmaceutical effluents.

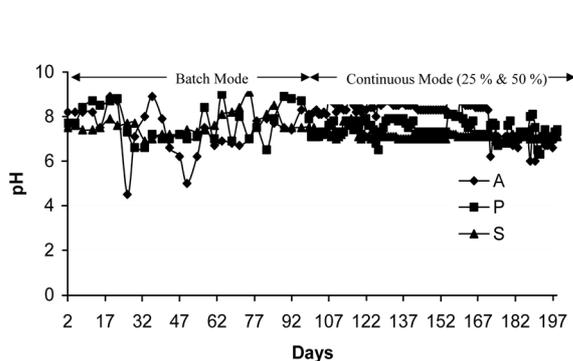


Fig. 3 Variation of pH due to artificial contamination of amino acid, surfactant, pharmaceutical effluents on bentonite soil (CS2)-batch mode and continuous mode (8, 16 hr HRT at 25% & 50%)

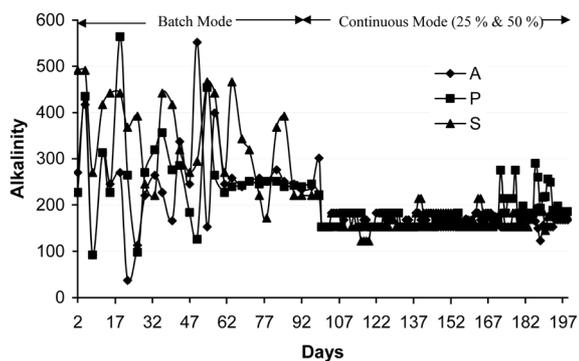


Fig. 4 Variation of alkalinity due to artificial contamination of amino acid, surfactant, pharmaceutical effluents on bentonite soil (CS2)-batch mode and continuous mode (8, 16 hr HRT at 25% & 50%)

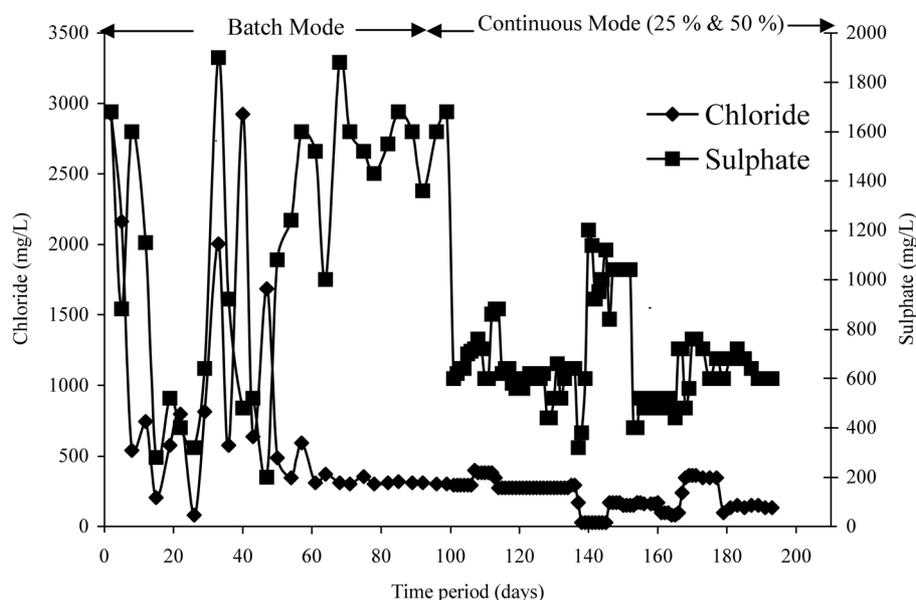


Fig. 5 Variation of chloride and sulphate due to artificial contamination of amino acid effluent on bentonite soil (CS2)-batch mode and continuous mode (8, 16 hr HRT at 25% & 50%)

Sulphate concentrations were found to vary from 440 to 2040, 280 to 1472 and 760 to 3024 mg/L for 8 hr HRT and 400 to 884, 240 to 680 and 640 to 1292 mg/L for 16 hr HRT, respectively, for amino acid, surfactant and pharmaceutical effluents.

The variation in sulphate concentration was found to be comparably less for pharmaceutical effluent when compared to that of amino acid and surfactant effluents. The permeation of chloride through the bentonite is in line with the result reported by Stern and Shakelford (1998) for the formulation of a hypothesis relating to the change in the hydraulic conductivity of sand-bentonite mixtures due to the permeation of CaCl_2 solution.

3.4. Bentonite organic pollutants interaction: batch mode

The variation of COD with time (in days) is shown in Fig. 8. The interactions between bentonite and the various organic pollutants are explained based on the critical analysis of the above results.

(1) *COD Concentration:* COD concentrations of amino acid, surfactant and pharmaceutical effluents were in the range of 3.75 to 22.50×10^3 , 7.00 to 20.00×10^3 and 3.75 to 23.00×10^3 mg/L respectively, before passing through the soil column. However the COD concentrations were found to vary in the range of 19.00 to 20.00×10^3 , 9.00 to 13.40×10^3 and 10.00 to 14.51×10^3 mg/L for amino acid, surfactant and pharmaceutical effluents, respectively, after the artificial contamination on bentonite. Amino acid, surfactant and pharmaceutical effluents showed peak COD concentrations of 22.50×10^3 , 20.00×10^3 and 23.00×10^3 mg/L at the end of and 50th, 2nd and 19th day, respectively. Steady state conditions were found to have been reached at the end of 71st day, 75th and 71st day, respectively, for amino acid, surfactant and pharmaceutical effluents.

The above results are close to the reported results of Khan *et al.* (1999) for the study of mechanism involved in the mobilization process of certain amino acids through pesticide amended

soils. Further, it is evident from the experimental investigation of Soule and Burns (2001) on organo-bentonites, (for the study of the effect of organic-cation structure on organo-bentonite behaviour) that the exchange of organo-cationic structure viz., alkyl chains and benzyltriethylammonium (BTEA) chloride drastically reduced further accumulation of organic-cations and hence, results in hydrophobic nature of bentonite. Similar behaviour was observed in the present study, as shown by the more or less uniform concentration of COD after 61st day till the end of the batch mode (99th day).

3.5. Bentonite-organic pollutants interaction: continuous mode

The characteristics of the three effluents due to artificial contamination on bentonite, in continuous mode, are presented in Figs. 6 to 8 for 8 hr HRT and 16 hr HRT at 25 and 50% concentrations. It is seen that amino acid, surfactant and pharmaceutical effluents attained steady state condition within a period on 56 days for 8 hr HRT and 15 days for 16 hr HRT at 25% concentrations, whereas, the above effluents attained the steady state condition within a period of 17 days for 8 hr HRT and 14 days for 16 hr HRT at 50% concentration. COD concentrations were found to vary from 800 to 36000, 900 to 26000 and 1000 to 32000 mg/L for 8 hr HRT, and 5000 to 20000, 8000 to 22000 and 7000 to 15000 mg/L for 16 hr HRT, respectively, for amino acid, surfactant and pharmaceutical effluents. The longer duration observed for the time dependent bio-transformation of COD concentration in the present study, at 25 and 50% concentrations under 8 hr and 16 hr HRT, is comparable to the trend reported by Soule and Burns (2001) for the experimental investigations on organo-bentonites.

3.6. Soil-pollutant interaction: effect of retention time and concentration

The effect of retention time and concentration of inorganic and organic pollutants present in amino acid, surfactant and pharmaceutical effluents, on bentonite under the continuous mode operation are shown in Figs. 3 to 8 and the salient observations/inferences drawn, are summarized below.

Amino acid and surfactant effluents show a high variation in pH due to their artificial contamination on bentonite. The pH values of the above effluents after artificial contamination on bentonite is found to lie between 7 to 8, i.e., their original characteristics of the above effluents have

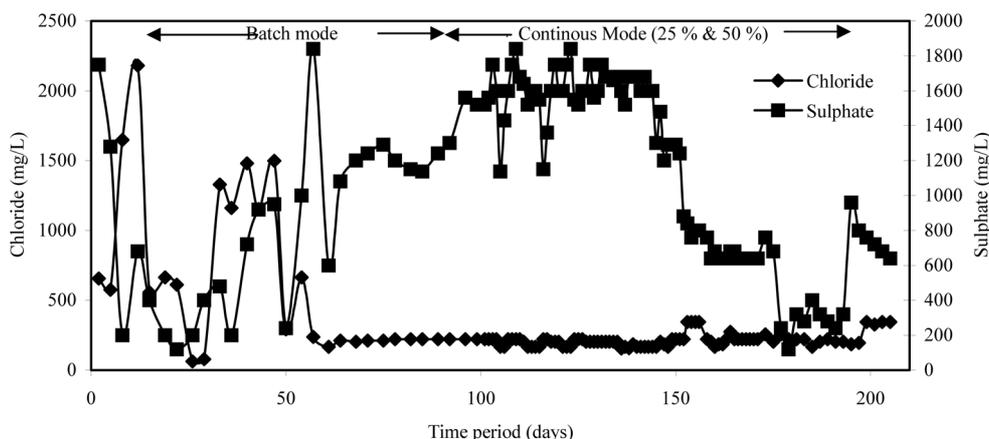


Fig. 6 Variation of chloride and sulphate due to artificial contamination of pharmaceutical effluent on bentonite soil (CS2)-batch mode and continuous mode (8, 16 hr HRT at 25% & 50%)

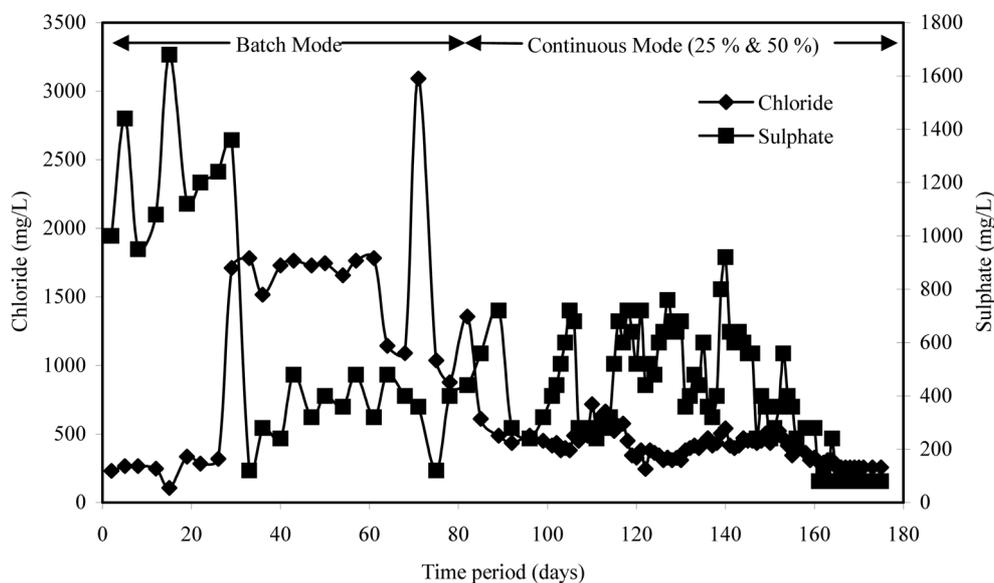


Fig. 7 Variation of chloride and sulphate due to artificial contamination of surfactant effluent on bentonite soil (CS₂)-batch mode and continuous mode (8, 16 hr HRT at 25% & 50%)

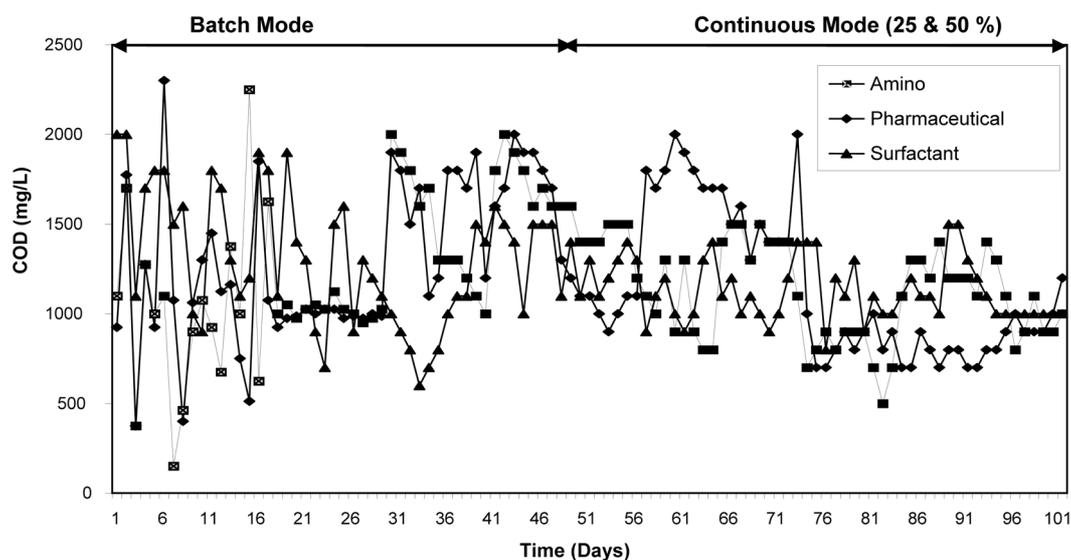


Fig. 8 Variation of COD due to artificial contamination of amino acid, pharmaceutical, and surfactant effluents on bentonite soil (CS₂)-batch mode and continuous mode (8, 16 hr HRT at 25% & 50%)

been completely reversed (acidic to alkaline in case of amino acid and medium alkaline to near neutral in case of surfactant effluent). Variation in pH of pharmaceutical effluent after artificial contamination on bentonite is also found to lie in the above range.

A high retention of chloride was observed due to artificial contamination of amino acid and pharmaceutical effluents on bentonite. Amino acid effluent showed peak chloride retention of 2681 mg/L at 16 hr HRT, at 50% concentration when compared to that of pharmaceutical effluent. The

variation in concentration (25% and 50%) at 8 hr HRT did not show high retention of chloride on bentonite.

The retention of sulphate was observed to be high (1110 mg/L) due to artificial contamination of pharmaceutical effluent at 16 hr HRT at 50% concentration on bentonite. Amino Acid relatively showed a lower retention of sulphate on bentonite at 16 hr. HRT, at 50% concentration as that of pharmaceutical effluent. This behaviour is attributed to the 'high reactivity' of sulphate on bentonite with respect to pharmaceutical effluent. Surfactant effluent showed a very low variation (with respect to sulphate retention) due to artificial contamination on bentonite, at all HRTs and concentrations considered. However, no significant variation of chloride was observed at 8 hr HRT for 25 and 50% concentrations for the amino acid and pharmaceutical effluents. On the other hand, surfactant effluent shows identical behavior as that of chloride due to artificial contamination on CS2.

Pharmaceutical effluent showed a high retention of organic content (COD) on bentonite (200 mg/L), when compared to that of amino acid effluent (50 mg/L) at 50% concentration at 16 hr HRT. This is attributed to the unique characteristics of the above effluent. Surfactant effluent was observed to show an insignificant variation in retention of organic content (COD) on bentonite, at all HRTs and concentrations, considered.

3.7. Effect of effluents on the index properties of bentonite

3.7.1. Effect on liquid limit (LL)

Variation of LL of bentonite with time, due to artificial contamination of the chosen, three effluents are shown in Fig. 9. Bentonite which has montmorillonite as the major mineral, exhibit significant changes in the LL with respect to time, due to (artificial) contamination of amino acid effluent (Fig. 9). The LL of bentonite has increased to a maximum value of 173% (at the end of 200th day of contamination) from the initial value of 157% (i.e. at zeroth day). However, beyond 150 days, the LL of bentonite remained almost constant. The decrease in the LL for surfactant effluent was caused due to particle aggregation. Significant increase in the LL with time may be attributed to the presence of sulphate and chloride in the amino acid effluent, which generally

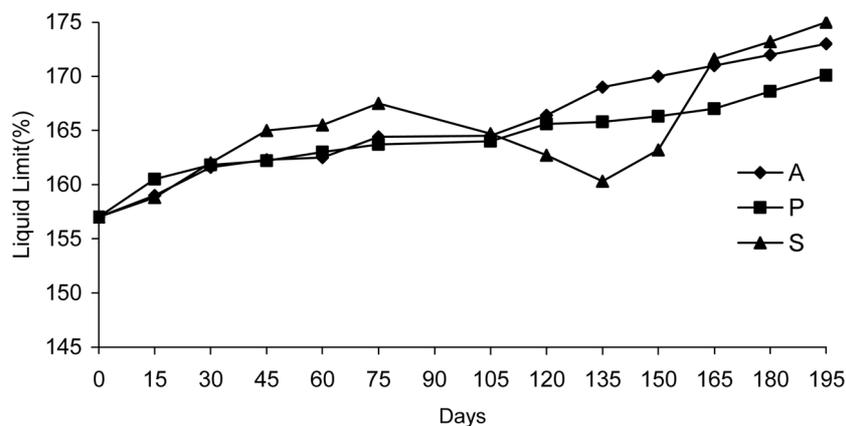


Fig. 9 Variation of liquid limit with time due to the artificial contamination of amino acid, surfactant, pharmaceutical effluents on bentonite soil

causes particle disassociation and hence, increases the LL (Sivapullaiah *et al.* 1995).

Variation of LL of bentonite due to (artificial) contamination of surfactant and pharmaceutical effluent (Fig. 9) are found to be almost identical with that of amino acid effluent, considering the total period of contamination. This again could be attributed to the presence of sulphate and chloride in the surfactant and pharmaceutical effluents and their interaction with the bentonite.

3.7.2. Effect on plastic limit (PL)

Variations of PL of bentonite (with time) due to artificial contamination of three chosen effluents are shown in Fig. 10. It can be seen that the PL varies generally between 67-75, during the period of contamination and considering the effect due to all the three effluents. Further, the trend in the variation of LL and PL of bentonite is similar, considering the range of values over the period of contamination.

3.7.3. Effect on shrinkage limit (SL)

Variation of SL of bentonite due to artificial contamination of three chosen effluents are shown in Fig. 11. SL of bentonite has shown considerable variation (i.e. about 8-25) due to amino acid during the period of contamination, which is significant. Highest SL values was found at the end of the period contamination, whereas, the lowest value at the beginning of contamination. Presence of chloride and sulphate in the effluent has increased the particle flocculation, resulting in higher values of SL. This shows that the behaviour of bentonite has changed from 'worse' to 'good' with respect to shrinkage limit. In other words, there is a 'positive influence' in bentonite, due to contamination of amino acid effluent.

Comparing the variation of 'SL' values due to the contamination of surfactant effluent with that of amino acid effluent it is found that actual values of SL in the former are found to be less than the latter. The above behaviour of bentonite soil is attributed to the highest chloride content present in surfactant effluent. In the case of bentonite, a 'negative influence' due to the contamination of surfactant effluent i.e., from 'better' to 'worse' is observed.

Bentonite has shown considerable variation in SL values (i.e. about 6-26), during the period of

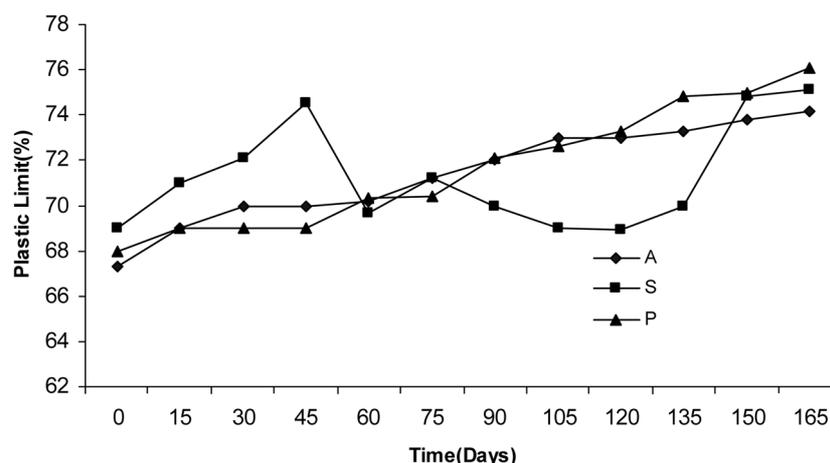


Fig. 10 Variation of plastic limit with time due to the artificial contamination of amino acid, surfactant, pharmaceutical effluents on bentonite soil

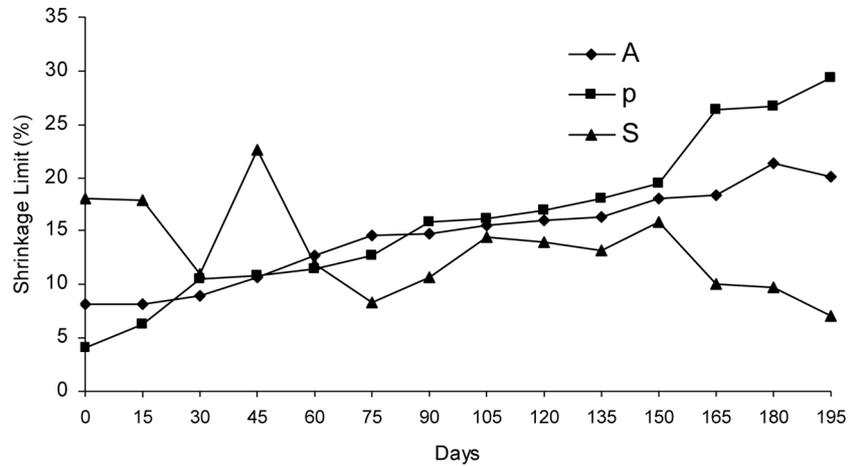


Fig. 11 Variation of shrinkage limit with time due to the artificial contamination of amino acid, surfactant, pharmaceutical effluents on bentonite soil

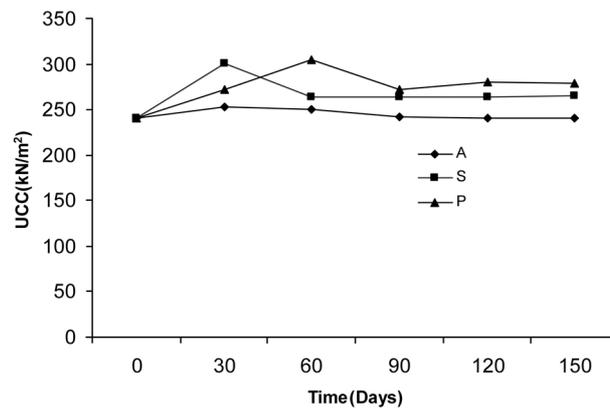


Fig. 12 Variation of UCC with time due to the artificial contamination of amino acid, surfactant, pharmaceutical effluents on bentonite soil

artificial contamination by the pharmaceutical effluents, which is significant. Highest SL value was found at the end of the period of contamination, which shows that the behavior of bentonite has changed from 'worse' to 'good' with respect to SL. The above behavior is similar to that of the behavior exhibited by bentonite due to contamination of amino acid effluent.

3.8. Effect of effluents on the shear strength of bentonite

Variations of unconfined compressive strength (UCC) of bentonite due to (artificial) contamination of three chosen effluents are shown in Fig. 12.

UCC values generally show a moderate increase up to 60 days of contamination due to amino acid effluent and thereafter, decrease gently. The above behavior may be attributed to the combined predominate role of sulphate and chloride in flocculating the particles and hence leading to increase in the strength. However, beyond the above initial period, exchange of ions may have ceased and

hence would have resulted in dispersion of particles leading to reduction in strength. However, UCC values generally show a moderate increase up to 30 days and thereafter decrease, gently due to the effect of surfactant and pharmaceutical effluents on bentonite. It can be seen that the trend in the variation of UCC due to the effect of three chosen effluents is similar.

4. Conclusions

Following are the salient conclusions based on the interaction of three industrial effluents on bentonite:

1. The original characteristics of all the three effluents (amino acid, surfactant and pharmaceutical) in terms of pH have been completely reversed (i.e. 'acidic' to alkaline in the case of amino acid and pharmaceutical effluents and 'medium alkaline' to near neutral in the case of surfactant effluent) after contamination.

2. Amino acid and pharmaceutical effluents exhibit 'high retentivity' of chloride and sulphate in the soil mass due to their artificial contamination on bentonite. The above behaviour is primarily due to the presence of high clay content in bentonite. However, surfactant effluent does not seem to influence the accumulation of both chloride and sulphate in bentonite, which is attributed to the 'unique characteristic' of the surfactant effluent, i.e. its highly alkaline nature which imparts imperviousness on bentonite.

3. There is higher retention of organic content (COD) in bentonite, due to artificial contamination of amino acid and pharmaceutical effluents. This is attributed to the unique characteristic of surfactant effluent, which prevents permeation of the effluent and hence there is no interaction between the organic pollutant present in the effluent and bentonite.

4. The effect of all three chosen effluents are found to be similar (i.e. show an increase trend with time), with respect to liquid limit and plastic limit of the bentonite, after contamination.

5. Amino acid and pharmaceutical effluents, which are acidic in nature interact in a similar way i.e., the behavior of bentonite has changed from 'worse' to 'good' with respect to the shrinkage limit of bentonite due to artificial contamination. However, there is a 'negative influence' (i.e. from 'better' to 'worse') due to artificial contamination of surfactant effluent on bentonite.

6. The possible effects of organic and inorganic pollutants in the three chosen effluents was found to be highly reactive and reduce the shear strength of bentonite by about 20%, (within the period of contamination). Thus the study of these effects form a fundamental findings to compare such behaviour in natural soil system.

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