Desiccation Induced Cracking Characteristics of Locally Available Soils in Warangal

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Abstract. In this study, locally available soils in Warangal (Telangana) are chosen to assess the feasibility of using as clay liner. The focus of the work is to carry out a laboratory study on locally available prominent clayey soils for the effect of desiccation induced cracks and hydraulic conductivity on the compacted clay soils under the influence of varying pH as well as organic and inorganic chemicals. Three types of locally available soils were selected (red earth, black cotton soil and the soil that is available near Rampur dumping yard location in Warangal) and the tests were conducted by compacting these soils at optimum moisture content with varying pH, organic (Humic Acid, EDTA, Dichloromethane) and inorganic (NaOH, HCl) chemicals. These compacted soil samples were tested for the desiccation cracks and hydraulic conductivity with the same solutions which were used in the preparation of soil sample. Variation of pH and organic-inorganic chemicals has shown a significant effect on crack intensity factor (CIF) and hydraulic conductivity. From the test results, it is observed that in acidic condition, CIF values of soil are decreasing with a decrease in pH while in basic condition, CIF values are increasing with the increase in pH. With the decrease of pH, the hydraulic conductivity of soil is increasing for an uncracked sample and decreasing for cracked sample in acidic condition. While in basic condition both cracked and uncracked permeability is increasing with the increase in pH. In all the cases of tests done with different pH and organic-inorganic chemicals, red earth soil showed minimum values of CIF, hydraulic conductivities and also permeability ratios hence red earth soil should be chosen as a liner material among selected locally available soils.

Keywords: Crack Intensity Factor, Humic acid, EDTA, pH, Desiccation Cracks.

1 Introduction

Among the various waste disposal methods, landfilling is considered to be safe and cost-effective compared to others. Without appropriate treatment, landfill leachate could be a potential source of surface and groundwater contamination, as it could seep into soils and subsoil causing severe pollution to receiving water body (Nurshazwani Binti Azmi et al., 2014) [1]. The main concern about these landfills is that the bottom clay liner should prevent the migration of toxic leachate into the ground. Compacted clay liners and geo-synthetic clay liners are commonly used in modern sanitary landfill designs. If the clay liner undergoes desiccation cracking there is a possibility of leachate to escape into ground/groundwater.

The presence of high amounts of clay particles in a soil, particularly highly active clay minerals such as smectites and vermiculites, promotes the formation of cracks (Holtz and Kovacs, 1981) [2]. A high plasticity index (PI) and low shrinkage limit indicate a high potential for shrinkage and swelling. In soils having PI more than 35%, excessive shrinkage can be expected (Daniel, 1992) [3] and the chemistry of the pore fluid also affects crack formation. It is known that surface tension affects the air-water-solid contacts inside the soil and generates negative pore-water pressures in the unsaturated soil (Carol J. Miller et al., 1998) [4]. The matrix suction may result in soil contraction, and ultimately soil shrinkage and cracking. There is a phenomenon called self-healing that occurs in some types of clays, which plays an important role in desiccation studies as it is beneficial in waste containment because of the decrease in hydraulic conductivity of the clay liners. The basic criterion for a soil to be used as a liner is that it should have hydraulic conductivity less than 10^{-7}cm/sec (EU Landfill Directive-European Council, 1999) [5]. For the fabrication of a liner in arid sites (Daniel and Wu, 1993) [6] suggested the use of clayey sand with low hydraulic conductivity and low shrinkage values. The coefficient of permeability (K) represents the soil's ability to permit passage to water through the soil. This, in turn, indicates the ability of the soil to change matric suction as a result of environmental changes (Fredlund and Rahardjo, 1993) [7].

2 Material and Testing Procedure

2.1 Soils

Three types of soils, namely red earth soil, dump yard soil and black cotton soil were selected. Red earth and black cotton soil were collected from locations nearby to NIT-Warangal campus premises and dump yard soil was collected from dumping yard location near Rampur in Warangal. Sieve analysis is performed to determine the distribution of coarser, larger-sized particles and the hydrometer method is used to determine the distribution of finer particles as per IS 2720 Part IV (1985) [8]. Atterberg's limits such as liquid limit, plastic limit and shrinkage limit were estimated as per IS 2720 Part V (1985) [9] and Part VI (1972) [10] respectively. Optimum moisture content (OMC) and corresponding maximum dry density (MDD) were also being reckoned through standard proctor compaction test as per IS 2720 Part-VII (1980) [11]. Free swell index test conformed to IS 2720 Part XL (1977) [12] was performed for quantitatively assessing the swelling potential of soil. All index properties of soil are listed in Table 1.

2.2 Chemicals

Organic chemicals such as Ethylenediaminetetraacetic acid (EDTA), Dichloromethane (DCM) and Humic acid were accounted for in this study. Inorganic chemicals such as Hydrochloric acid (HCl) and Sodium Hydroxide (NaOH) were also taken into account for evaluating the effect of varying pH on cracking characteristics and hydraulic conductivity of the soil. All chemicals were diluted to 9% concentration for testing purpose after preparing a 1N stock solution of each chemical except humic acid.

Table 1. Index properties of soils used

PARAMETERS	RED EARTH	BLACK COTTON	DUMP YARD
Gravel (%)	6	0	2
Sand (%)	27	30	54
Silt (%)	41	39	10
Clay (%)	26	31	34
Soil Classification	CI	CH	SC
Liquid Limit (%)	38	61	84
Plastic Limit (%)	21	21	24
Plasticity Index	17	40	60
Shrinkage Limit (%)	19.32	11.67	18.14
Maximum Dry Density (g/cc)	1.8	1.68	1.77
Optimum Moisture content (%)	19.7	19.6	17.5
Free Swell Index	5	90	240

2.3 Experimental Scheme and Sample Preparation

The desiccation test and hydraulic conductivity tests were conducted on soils compacted at seven different pH (2, 4, 5, 6, 7, 8, 10), three organic chemicals and two alkalides. The reason for not opting higher pH was that usually in a landfill, waste is lying in acidic condition. For these tests, using cylindrical oedometers ring, soil samples were prepared to diameter 6cm and thickness 2 cm. Soil, sieved by 425µ was mixed at optimum moisture content with different pH solutions and organic-inorganic chemical solutions and was compacted in the mould to the required maximum dry density (Day 0). CIF is defined as the time-variable ratio of the surface crack area (A_c), to the total surface area of the sample (A_t).

$$CIF = \frac{Cracked\ Area\ (A_c)}{Total\ Surface\ Area\ (A_t)} \quad (1)$$

A computer-aided image analysis program was used to determine CIF from photographs of the desiccation process in 4 stages, as shown in figure 1. Firstly, the compacted soil sample was taken and kept in the oven for 24 hours at 70°C temperature (Day 1). Due to this process, the soil sample experienced cracks on the surface. The dried sample was then saturated with the same pH solution or organic-inorganic chemicals for 24 hours (Day 2). After completion of saturation, it was observed the width of cracks in the soil reduced to a significant extent. This could be due to the self-healing property of soil through the swelling process. The saturated sample was again allowed for drying for 24 hours at the same temperature for observing the effect of cycles of wetting and drying on the cracking behaviour of soil (Day 3). At the end of each of the steps, a photograph of the sample was taken and these images were converted to binary images using open source software GIMP 2.0. A MATLAB program was developed for calculating CIF values through analysis of the binary images.

A higher value of the CIF indicates more number of cracks formed in the soil specimen. The closing of cracks mainly depends on the mineralogical composition and self-healing properties of the soil.

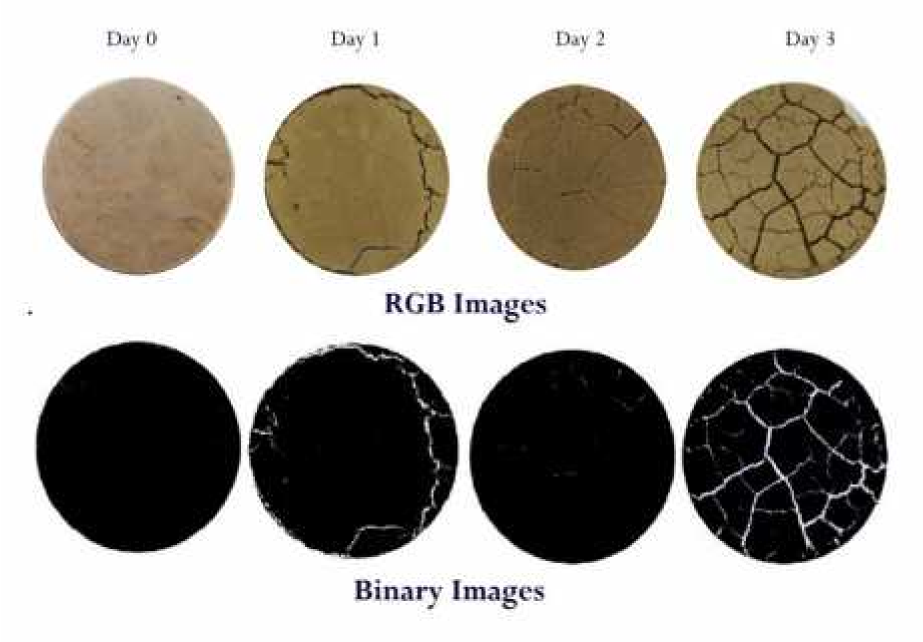

Fig. 1. Images of the desiccated sample at different stages

To understand the influence of variation of pH alongside organic-inorganic chemicals on hydraulic conductivity of desiccated clay liner materials, variable head permeability tests were performed, and the coefficient of permeability was calculated in accordance to IS 2720 Part XVII (1986) [13].

3 Experimental Results and Analysis

3.1 Variation of CIF with Desiccation Cycles

The values of crack intensity factors (CIF) for the three soils (red earth, dump yard soil and black cotton soil) compacted at optimum moisture contents with different pH solutions and saturated with same solutions are presented in Tables 2, 3 and 4.

From the results furnished in Table 2, 3 and 4, it can be observed that the CIF value of the soil during desiccation is increasing and it can be observed from Figure 1, 2 and 3. From Table 1, for red earth soil at pH 7, for the first cycle of desiccation, the CIF value increased from initial value of zero (i.e. on day 0) to 0.598 (i.e. on day 1) whereas during the second attempt of desiccation (i.e. on day 3), the value got increased to 0.806 from 0.088 (i.e., on day 2). Similarly, for dump yard soil, CIF is increased from 2.382 to 5.236 (220%) after the second cycle of desiccation at pH 7.

For black cotton soil also, CIF is increased from 2.567 to 5.964 (232%) after the second cycle of desiccation. These values clearly indicate that the rate of increase in the CIF value is increasing with the number of desiccation attempts. This is mainly because the cracks formed in the first desiccation attempt remained as weaker zones even after saturation period and the cracks reopened and progressed easily with drying for the second time of desiccation.

Table 2. CIF values for red earth soil at different pH

pH	Stage of testing (day)			
	Initial soil (0)	On drying (1)	On wetting (2)	On drying (3)
2	0	0.208	0.082	0.282
4	0	0.272	0.106	0.322
5	0	0.306	0.165	0.482
6	0	0.354	0.098	0.511
7	0	0.598	0.088	0.806
8	0	0.622	0.094	1.454
10	0	0.623	0.111	1.896

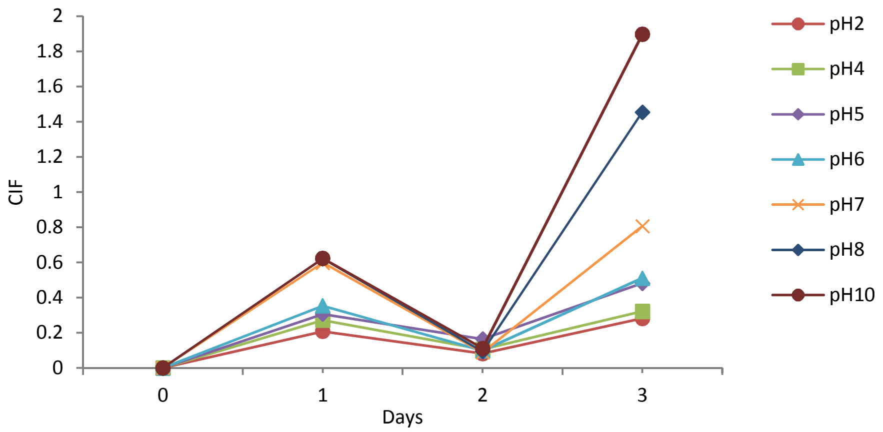

Fig. 2. Variation of CIF for red earth soil with the stage of drying and saturation

It is evident from Figure 1, 2 and 3 that CIF values are minimum for red earth soil and maximum for black cotton soil for all type of pH solution. This observation is mainly because when the soil sample which is compacted at a particular moisture content, during the drying process the matric suction produced on the surface of soil sample may increase the tensile stresses and cause more negative pore pressures, thus leading to cracks in the soil sample. It was observed that the applied W-D cycles resulted in significant rearrangement of specimen structure: the initially homogeneous and non-aggregated structure was converted to a clear aggregated-structure with obvious interaggregate pores after the second W-D cycle.

Table 3. CIF values for dump yard soil at different pH

pH	Stage of testing (day)			
	Initial soil (0)	On drying (1)	On wetting (2)	On drying (3)
2	0	0.548	0.094	2.668
4	0	0.478	0.222	3.785
5	0	1.696	0.287	3.847
6	0	1.852	0.036	4.949
7	0	2.382	0.165	5.236
8	0	2.411	0.201	5.988
10	0	3.598	0.231	7.016

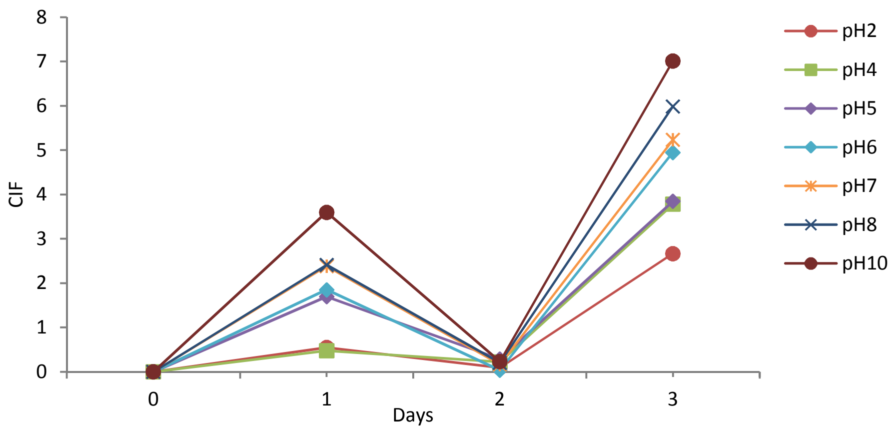

Fig. 3. Variation of CIF for dump yard soil with the stage of drying and saturation

Table 4. CIF values for black cotton soil at different pH

pH	Stage of testing (day)			
	Initial soil (0)	On drying (1)	On wetting (2)	On drying (3)
2	0	0.536	0.105	2.999
4	0	0.88	0.298	3.568
5	0	1.778	0.321	4.645
6	0	2.074	0.045	5.905
7	0	2.567	0.184	5.964
8	0	2.634	0.225	6.785
10	0	2.765	0.258	6.806

Therefore, the cracking behavior of soils mainly depends on the moisture content and rate of evaporation within the soil mass. (Miller et al., 1998) [4]. Cracks which are generated in the first cycle of desiccation, they are not closed completely after saturation. Hence after the first cycle when soil is saturated and dried again leads to an increase in the crack. CIF values at day 2 (i.e., after saturation) reduced remarkably indicating the self-healing of soil.

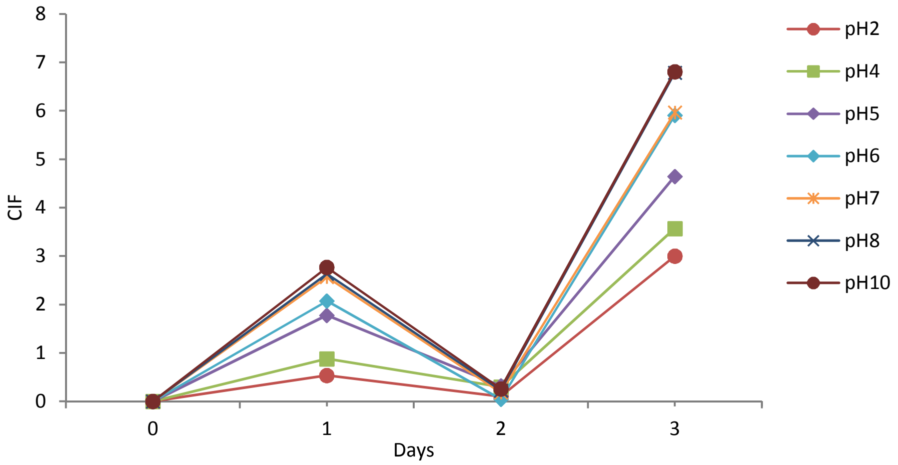

Fig. 4. Variation of CIF for Black Cotton soil with the stage of drying and saturation

3.2 Variation of CIF with pH

From Figure 5, it can be observed that the CIF value increased when the pH of the solution varies from acidic to basic. This can be due to the fact liquid limit of the soil decreases as the soil gets acidic resulting in the reduction of plasticity index and hence the cracking of the soil is decreased (M.H.T. Rayhani et al., 2007) [14]. In acidic condition, the leaching of alumina, silica and iron occurs which erodes the lattice structure of clays and releases undissolved fragments for the migration with the leachate. These undissolved fragments form precipitation and fill the cracks as seen in SEM images (Amulya M et al., 2015) [15]. Hence closing of the crack starts and overall crack width decreased resulting in decrease in CIF. While in the basic condition, the dissolution of alumina, silica and iron starts while forming hydroxides which in turn get dissolved and corrode the cracks furthermore and results in an increase in crack width increasing CIF values. (Singh N.N. et al., 2015) [16]. It was observed that most of the cracking occurred in the initial 18-hour time period. Upon the second cycle of drying, the crack features (width, thickness, etc.) have progressed significantly compared to that of the first cycle. In the first cycle the cracking pattern was observed to be linear with small branches whereas in the second cycle the pattern of polygon network.

To further understand the effect of organic-inorganic chemicals, NaOH and HCl as inorganic chemical solutions were used to see the variation in extreme acid-base condition. Cracking characteristics of soils (red earth, dump yard soil and black cotton soil)

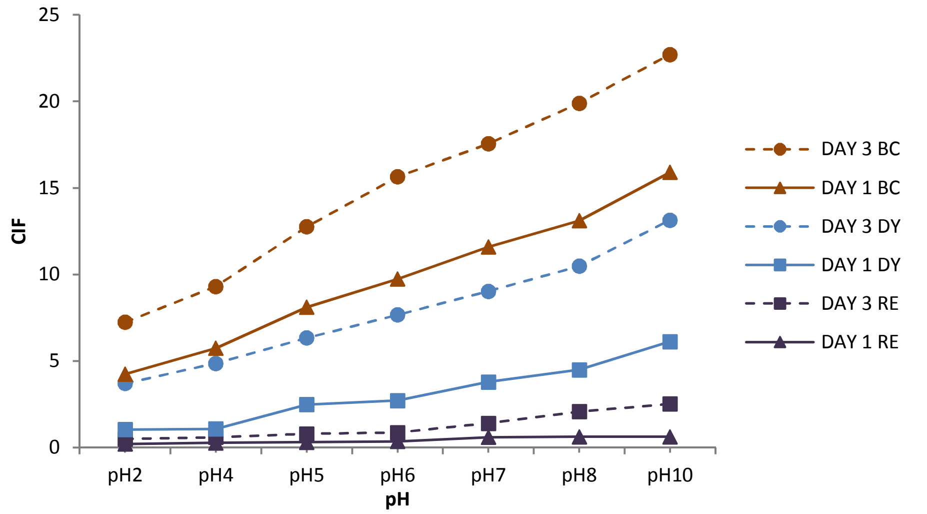

Fig. 5. Variation of CIF for red earth (RE), dump yard (DY) and black cotton (BC) soil with pH after desiccation

Table 5. CIF values for soils with different organic-inorganic chemicals

Stage of testing (day)	CIF				
	HCl	DCM	EDTA	Humic	NaOH
(a) Red earth soil					
Initial soil (0)	0	0	0	0	0
On drying (1)	0.178	0.738	0.269	0.487	1.423
On wetting (2)	0.047	0.102	0.041	0.146	0.197
On drying (3)	0.356	1.128	0.476	0.953	2.112
(b) Dump yard soil					
Initial soil (0)	0	0	0	0	0
On drying (1)	0.207	3.505	0.673	2.748	3.118
On wetting (2)	0.088	0.378	0.213	0.211	0.289
On drying (3)	0.971	6.275	1.391	5.487	7.648
(c) Black cotton soil					
Initial soil (0)	0	0	0	0	0
On drying (1)	0.239	3.895	0.735	3.111	3.727
On wetting (2)	0.089	0.421	0.233	0.228	0.305

On drying (3)	1.186	6.982	1.968	6.101	7.945

is shown in Table 5. It can be observed from the following table that CIF values are minimum for HCl and maximum for NaOH for all three types of soils which is also evident from fig. 5 which shows similar variation when all soils were subjected to varying pH. CIF values for organic chemicals are lying in between HCl and NaOH owing to their natural acidic-basic behaviour. Since DCM is nearly neutral when mixed with water at room temperature; it is showing more CIF then EDTA (acidic in nature) and Humic acid. Among organic chemicals, DCM is showing maximum CIF and EDTA is showing minimum CIF; while for humic acid, CIF is lying in-between; supporting the explanation that as the solution becomes acidic and CIF value decreases substantially.

3.3 Variation of Permeability with pH

The values of Hydraulic conductivity for the three soils (red earth, dump yard soil and black cotton soil) compacted at optimum moisture contents with different pH solutions and saturated with same solutions in terms of uncracked permeability constant (K_0) and cracked permeability constant (K_1) are presented in Table 6. From Table 6, it can be observed, for an uncracked sample as acidity increases permeability increases. This could be because of the increase in acidity attributing to the decrease in the thickness of Diffuse Double Layer (DDL), resulting in flocculation of the clay particles. Flocculated and dispersed structures have different hydraulic conductivities. The thickness of the DDL can influence the soil structure, resulting in permeability changes. Hence as solution acidity is increasing, there is enormous loss in DDL thickness, and increase in hydraulic conductivity. While in the basic condition also; permeability is increasing with the increase in basicity confirming that the increase in chemical concentration results in higher permeability in soils. (Seracettin Arasan, 2010) [17]. While for cracked soil permeability is mostly depending on how much the soil specimen is cracked. For higher CIF values of sample, higher permeability constant is observed. Permeability ratio is observed to be increasing as the pH of the soil is changing from acidic to basic. With an increase in acidity, the liquid limit of the soil decreases and hence plasticity index of the soil is also reduced. Hence permeability ratio is increasing with the increase in soil plasticity and as well as varying from acidic to basic condition.

Table 6. Variation of permeability with pH

(a) Red earth soil			
pH	**K_0 (10^{-7} cm/s)**	**K_1 (10^{-7} cm/s)**	**K_r**
2	0.351	2.011	5.73
4	0.322	2.991	9.29
5	0.301	3.369	11.19
6	0.289	3.428	11.86

7	0.288	3.525	12.24
8	0.291	4.072	13.99
10	0.312	4.447	14.25
	(b) Dump yard soil		
2	0.663	4.896	7.38
4	0.609	7.312	12.01
5	0.569	8.210	14.43
6	0.546	8.355	15.30
7	0.544	8.601	15.80
8	0.551	9.945	18.05
10	0.614	11.851	19.30
	(c) Black cotton soil		
2	1.492	18.099	12.13
4	1.369	26.909	19.66
5	1.279	30.321	23.70
6	1.228	30.842	25.11
7	1.224	31.726	25.92
8	1.244	36.546	29.38
10	1.286	40.051	31.14

3.4 Variation of Permeability in the Presence of Organic-Inorganic Chemicals

Values of uncracked permeability constant (K_0) and cracked permeability constant (K_1) of soil with different organic-inorganic chemicals is presented in Table 7. From Table 7, it can be seen that irrespective of acid and base permeability is increasing with chemicals. Permeability of cracked sample is significantly higher than the uncracked sample and permeability ratio is higher for black cotton soil and lesser for red earth soil while for dump yard soil, it is lying in between earlier two.

Table 7. Variation of permeability of soil with organic-inorganic chemicals

(a) Red earth soil			
Chemical	$\mathbf{K_0}$ (10^{-7} cm/s)	$\mathbf{K_1}$ (10^{-7} cm/s)	$\mathbf{K_r}$
HCl	0.366	2.768	7.56
Dichloromethane	0.289	3.429	11.87
EDTA	0.299	2.433	8.14
Humic	0.342	2.877	8.41
NaOH	0.360	5.465	15.18
(b) Dump yard soil			

HCl	0.692	6.753	9.76
Dichloromethane	0.546	8.337	15.26
EDTA	0.565	5.886	10.42
Humic	0.646	7.111	11.00
NaOH	0.591	13.325	22.55
	(c) Black cotton soil		
HCl	1.556	24.882	16.00
Dichloromethane	1.228	30.851	25.12
EDTA	1.271	21.907	17.24
Humic	1.454	25.883	17.81
NaOH	1.205	49.187	40.82

4 Conclusions

The desiccation cracking and hydraulic conductivity of the selected locally available soils are controlled by soil properties like plasticity index and clay content. The crack intensity factor (CIF) values are observed to be more for soils having high plasticity index values. All soils have shown an increase in the CIF value with the increase in the number of desiccation attempts. In acidic condition, CIF values of soil are decreasing with a decrease in pH and in basic condition, CIF values are increasing with the increase in pH. Hydraulic conductivity of soil is increasing for an uncracked sample and decreasing for cracked sample in acidic condition with a decrease in pH. While in basic condition both cracked and uncracked permeability is increasing with the increase in pH. In the case of organic chemicals, CIF value is increasing with desiccation cycles and significantly affecting the cracks developing in the soil. Hydraulic conductivity is increasing with increasing chemical concentration and plasticity of the soil. The values of permeability ratios increased with an increase in plasticity index of the soils. In all the cases with different pH and organic chemicals, red earth soil showed minimum values of CIFs, hydraulic conductivities and also permeability ratios; hence red earth soil should be chosen as a liner material among selected locally available soils.

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