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Influence of Soil Properties on Cracking of Earth Dams in Sri Lanka

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ABSTRACT. Earth is the common material used for the construction of most of the dams in Sri Lanka. Earth dams have the ability to withstand considerable amount of foundation settlement with little deformation. Even though they have the ability to withstand settlements most of the earth dams in Dry Zone of Sri Lanka experience longitudinal cracking during prolong dry periods. These cracks close during the rainy season and reappear in the next dry period. The main aim of the present study was to determine the causes for cracking of these dams. Four dams from Anuradhapura and three dams from Hambanthota districts were selected for the study. Soil samples were taken down to a 30 cm depth from the dams having no cracks, low, medium and high intensity of cracks during the dry season. Soil properties such as particle size distribution, atterberg limits, organic matter content, moisture content of air-dried samples and clay mineralogy were determined. Clay contents of the collected soil samples were in the range from 8% to 56%. Cracking intensity significantly correlated with clay percentage and moisture content of the air-dried samples. Clay fraction was dominated by smectite and kaolinite in samples collected from the cracked dams. The results demonstrated that cracking of dams are due to presence of swelling type clays with the total clay content exceeding 20%. Therefore presence of smectite clays in significant quantities appears to be the major cause for the cracking of the earthen dams in dry zone of Sri Lanka. The moisture content of air- dried soil can be used as an indicator of presence of smectite clays in soils.

INTRODUCTION

Most of the dams in Sri Lanka are constructed using the earth. This is due to factors such as availability of suitable material, relatively low height of the dams and economy. Moreover, the foundation requirements for earth fill dams are less stringent than that for the other types of dams. They are most suited for different foundation conditions and more economical than the other commonly used materials (Arthur, 1973). Most of the earth dams in the Dry Zone of Sri Lanka develop longitudinal cracking during prolong dry periods. These cracks normally disappear during the rainy season and reappear in the next dry spell.

The onset of cracking depends on the mineralogy of the soil, climatic conditions such as temperature and rainfall, and surface vegetation cover. However, high temperatures alone do not produce wide deep cracks if the high temperatures occur during wet season. Wide deep cracks are associated with soils having high plasticity and high temperatures during dry seasons when the water table is deep

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(Morris *et al.* 1992). The amount of water absorbed by the clay mixtures increases with increasing smectite content and relatively large amount of water absorbed by the smectite-rich mixtures reflects the greater surface area and interlayer swelling characteristics of the smectite (Likos and Lu, 2002). Therefore, the amount of water absorbed by the air-dried samples can be used to get a rough estimate of the amount of available swelling type clay present in a soil. The objective of the present study was to identify the causes of dam cracking of some selected earthen dams in Anuradhapura and Hambanthota districts in Sri Lanka.

MATERIALS AND METHOD

The study area

The study areas are located in the Anuradhapura district near to the Anuradhapura city and Hambanthota district near to the Thissamaharama city. Geologically, the areas belong to the Vijayan complex (Cooray, 1984). The Anuradhapura and Hambanthota locations belong to Agro Ecological regions DL1 and DL5, respectively (Panabokke, 1996). All the locations are in the dry zone with mean annual rainfall less than 1500 mm and mean annual temperature between 22.5^{0}C - 27.5^{0}C. Four dams from Anuradhapura and three dams from Hambanthota districts were selected for the study.

Table 1. Dam site, sample number, sampling location and crack intensity for selected dam sites.

District	Dam Site	Sample No.	Sampling Location	Crack Intensity
Anuradhapura	Rambewa	RAM-1	Bund Top	Low
		RAM-2	Up Stream	Low
Anuradhapura	Nachchaduwa	NAC-1	Down Stream	No
		NAC-2	Down Stream	No
Anuradhapura	Gonewa	GON-1	Bund Top	No
		GON-3	Up Stream	High
Anuradhapura	Udiyankulama	UDI-1	Down Stream	High
		UDI-2	Down Stream	High
Hambanthota	Pahala Andarawewa	AND-3	Down Stream	Medium
		AND-6	Bund Top	No
Hambanthota	Aluththarama	ALU-1	Up Stream	No
		ALU-2	Up Stream	Low
Hambanthota	Bandagiriya	BAN-3	Bund Top	Medium
		BAN-4	Bund Top	Medium

Sample collection

The selected dams represented different cracking intensities. Disturbed samples were collected from each bund down to a depth of 30 cm, at least from two locations in each dam. If the sampling locations were either upstream or downstream, top 15 cm of the soil layer was removed before sampling.

Soil properties

The soils were air-dried and riffled using a riffle box until the required reduction has been achieved. Particle size distribution were determined using dry sieving and hydrometer analysis proposed by Head (1992) and described in clause 9 of BS 1377: Part 1: 1990. Three replicates of each soil were used to determine the atterberg limits as described by Head (1992) and the method given in clause 4 and 5 of BS 1377: Part 1: 1990. Liquid limit was determined using the cone penetrometer. Each soil was filled into the cup and the cone penetration for 5s was measured and the gravimetric moisture content of the sample was obtained. This was repeated at least five times and the gravimetric moisture content for the cone penetration of 20mm was estimated using a graphical technique. Plastic limit was determined by forming a 3 mm thread and determining the gravimetric moisture content at the time of crumbling (Head, 1992). The plasticity index was obtained as the difference between the liquid and the plastic limits. Clay activity was calculated using the ratio between plasticity index and clay percentage. The organic matter content of the samples was determined by the loss on ignition method (Ben-Dor and Banin, 1989). The moisture contents of air-dried soils were determined by placing the samples in an oven at 105 ^{0}C, until the samples gain constant weight as described by the method in clause 3 of BS 1377:Part 1: 1990.

Mineralogical analysis

Mineralogy of the dam materials were investigated in the clay fraction which was separated. Prior to separation of clay fraction, soils were pretreated for the removal of soluble salts and organic matter (Kunze and Dixon, 1986). The soluble salts were removed by washing the sample with distilled water and 30% hydrogen peroxide was used to remove organic matter. After saturating the soil sample with 1 M NaCl to facilitate dispersion, clay fraction (< 2μm) was separated by sedimentation (Gee and Bauder, 1986). Three clay slides from each clay fraction after saturation with K, Mg and glycerol were prepared to obtain X-ray diffractograms.

Clay fractions were saturated with K and Mg by washing with 1M KCl, and mixture of 0.5M magnesium acetate / 0.5M $MgCl_2$ respectively. K and Mg saturated clay samples were mounted onto glass slides dissolved with acetone. Glycerol solvated samples were obtained by adding few drops of glycerol onto the Mg-saturated clay slide. The slides were kept in a $CaCl_2$ desecrtor until analysis. X-ray diffraction test was carried out by the Siemens D 5000 diffractrometer (manufactured in Germany, 1991 model) operated at the potential of 40 kV and the amperage of 30 mA, producing Cu $K\alpha$ radiation at a wave length of 1.54 Å equipped with Ni filter and silicon monochromator. The samples were made using a continuous scanning technique between 3^0 2θ and 35^0 2θ and a scan speed of 0.02 ^{0} 2θ per minute. Crystalline phases were identified using the Powder Diffraction File (JCPDF, 1997).

Statistical Analysis

Correlation between crack intensity and individual soil properties were studied using Spearman's correlation coefficients (Siegel and Castellan, 1988). The scores were given to the cracking intensity as shown in Table 2.

Table 2. Crack intensity score.

Maximum Depth / (mm)	Maximum Width / (mm)	Crack Intensity Score
0	0	1
< 10	< 25	2
10-500	25-200	3
>500	>200	4

RESULTS AND DISCUSSION

Results obtained from mechanical analysis, atterberg limit tests, moisture content of the air-dried samples, and organic matter content of the samples are given in Table 3.

Table 3. Clay (%), organic matter content (%), moisture content of air-dried samples (%), atterberg limits (%), clay activity and crack intensity for selected dam materials.

Sample No.	Clay (%)	OMC (%)	MC - Air Dried (%)	Atterberg Limits (%)			Clay Activity	Crack Intensity
				LL	PL	PI		
RAM-1	41.0	4.1	6.9	53.0	21.0	32.0	0.8	2
RAM-2	40.0	3.9	6.7	52.0	20.0	32.0	0.8	2
NAC-1	15.0	2.1	2.6	28.0	16.0	12.0	0.8	1
NAC-2	8.0	1.9	1.6	26.0	15.0	11.0	1.4	1
GON-1	20.0	3.1	3.5	34.0	16.0	18.0	0.9	1
GON-3	56.0	4.3	10.7	56.0	18.0	38.0	0.7	4
UDI-1	26.0	2.6	4.9	46.0	18.5	27.5	1.1	4
UDI-2	27.5	3.4	5.6	48.0	17.0	31.0	1.1	4
AND-3	46.0	5.5	6.6	54.0	22.0	32.0	0.7	3
AND-6	17.5	3.3	3.3	34.5	17.0	17.5	1.0	1
ALU-1	32.0	4.2	3.1	38.0	17.5	20.5	0.6	1
ALU-2	40.0	4.2	6.3	43.5	17.0	26.5	0.7	2
BAN-3	35.0	2.5	4.3	37.5	17.0	21.5	0.6	3
BAN-4	33.0	3.4	3.5	33.5	17.0	16.5	0.7	3

(OMC= Organic matter content, MC= Moisture content, LL= Liquid limit, PL= Plastic limit, PI= Plasticity index)

The clay contents of the samples were ranging from 8 to 56% and their moisture contents of air-dried samples ranged from 1.6 to 10.7%. For all the samples tested the moisture content of air-dried samples were less than 3.5% of dams with no cracks and above 3.5% for dams with cracks (Table 3). The highest recorded value of

10.7% moisture content was recorded for the GON-3 sample which showed high intensity of cracking.

The results of the Spearman correlation coefficients (r_s) of cracking intensity with individual soil properties are presented in Table 4. Moisture contents of the air-dried samples showed a significant relationship (r_s = 0.65) with cracking intensity. Moisture content of air-dried samples can be used as an indicator to find out the tendency of soil for cracking during dry seasons. A significant positive correlation (r_s = 0.55) was observed between cracking intensity and clay content of the dam materials. High clay contents in dam materials increases the probability of producing cracks in earth dams. There were no significant correlations of crack intensity with organic matter percentage and clay activity (Table 4).

Table 4. Spearman correlation coefficients of crack intensity with soil properties.

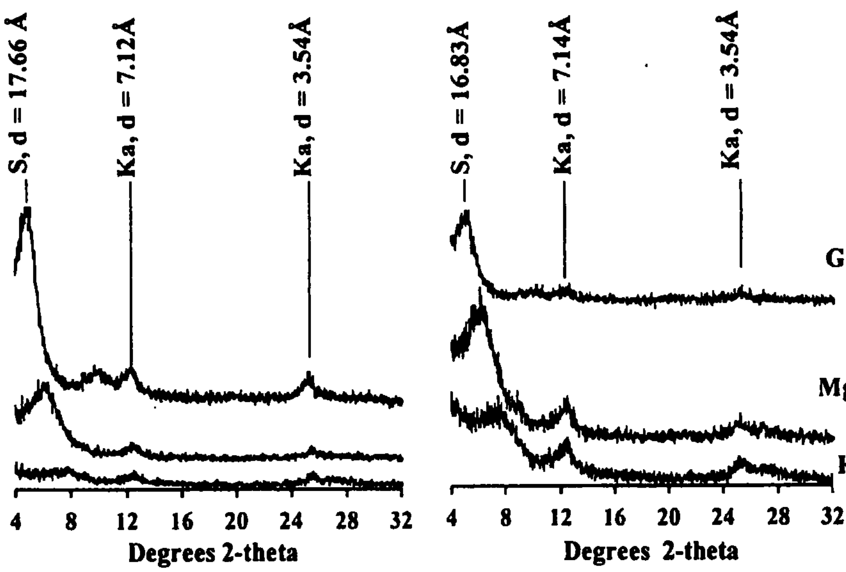
Variable	Spearman correlation (r_s)
Clay Content / (%)	0.55 (0.04)
Organic Matter Content / (%)	0.30 (0.29)
Moisture Content Air-Dried / (%)	0.65 (0.01)
Plasticity Index / (%)	0.64 (0.01)
Clay Activity	-0.01 (0.73)

* Values in parenthesis are significant probabilities

X-ray diffractograms of Rambewa samples were shown in Fig. 1(a) and (b). A peak near 14Å in the Mg-saturated sample and shift of the 14 Å peak to 18 Å following solvation with glycerol (Mg-gly) indicate the presence of smectite (JCPDF No. 13-135). A peak at 7.1 Å in K-saturated, Mg-saturated and Mg-Glycerol solvated sample signifies the presence of kaolinite.

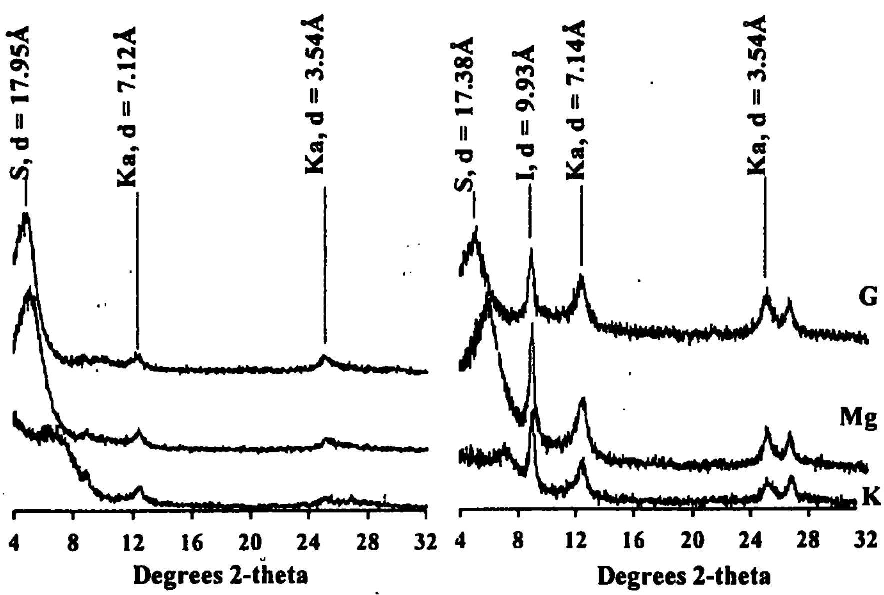
X-ray diffraction pattern similar to Rambewa was observed in Nachchaduwa sample 1 (Fig. 2a). The smectite and kaolinite are the dominant clay minerals present in Nachchaduwa site. In addition to smectite and kaolinite, presence of illite was indicated by the peak at 9.93 Å (JCPDF No. 43-685) in Nachchaduwa sample 2 (Fig. 2b). The clay percentages of the Nachchaduwa samples were only 15% and 8% (Table 2). Though both Rambewa and Nachchaduwa samples indicate the presence of smectite, only Rambewa, which is having high clay percentage, i.e., 40%, had cracking in the dam (Table 2).

Presence of smectite in relatively small quantities in Nachchaduwa dam materials may not result any cracks in dams. Moisture retention in soils is an indirect indication of predominant type of clay minerals present in soils. Higher moisture content of air-dried samples was recorded in Rambewa (6.8%) than that of Nachchaduwa samples (2.6% and 1.6%) (Table 2). This further signifies the presence of smectite in Rambewa samples in large quantities, consequently producing cracks in dams during long dry spells.



(a) (b)

Fig. 1. X-ray diffractograms of the clay fraction (< 2μm) of Rambewa samples (a. RAM-1 and b. RAM-2). [Ka = Kaolinite, S = Smectite, K= K-saturated, Mg = Mg-saturated, G= glycerol-solvated].



(a) (b)

Fig. 2. X-ray diffractograms of the clay fraction (< 2μm) of Nachchaduwa samples (a. NAC-1 and b. NAC-2). [Ka = Kaolinite, S = Smectite, I = Illite, K= K-saturated, Mg= Mg-saturated, G= glycerol-solvated].

There was no evidence for presence of expanding type clay minerals in GON-1 (Fig. 3a). The absence of cracks on this dam relates with the non-availability of swelling type clays, which was confirmed by both XRD analysis and low moisture content of 3.5% air-dried sample (Table 2). The XRD pattern of GON-3 (Fig. 3b) indicates the presence smectite, illite and kaolinite. The high clay content (56%) and presence of swelling type clays were the reasons for having high intensity cracks in GON-3 sample. High moisture content of air-dried sample also indirectly signifies the presence of 2:1 swelling type clays.

The X-ray diffractogram of Udiyankulama sample 1 showed high background in Mg- and K-saturated samples obscuring the low angle peaks (Fig. 4a). However, 17Å peak of the glycerol solvated sample of UDI-1 confirms the presence of smectite. Other clay minerals present in UDI-1 were illite and kaolinite (Fig. 4a). High background scatter obscured the low angle peaks in UDI-2 sample (Fig. 4b). A shifted smectite peak at 8.37 Å can be observed in glycerol-saturated sample of UDI-2 confirming the presence of smectite (Moore and Reynolds, 1997). Accordingly UDI-2 is having clay minerals of smectite, illite and kaolinite. Presence of 2:1 swelling type clay is also confirmed by the relatively high moisture content of air-dried samples of 4.9% and 5.6% of UDI-1 and UDI-2, respectively (Table 3).

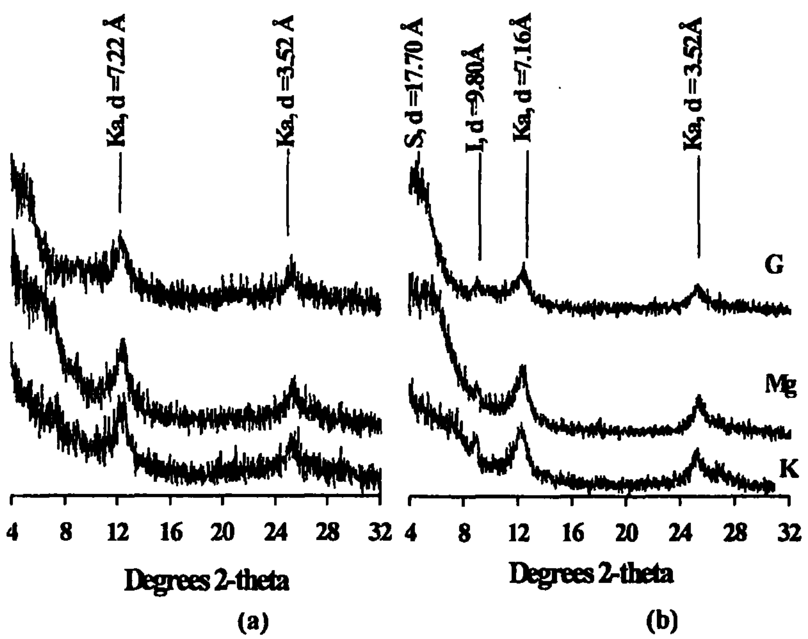


Fig. 3. X-ray diffractograms of the clay fraction (< 2μm) of Gonewa samples (a. GON – 1 and b. GON–3). [Ka = Kaolinite, S = Smectite, I = Illite K= K-saturated, Mg= Mg-saturated, G= glycerol-solvated].

The clay minerals of smectite, illite and kaolinite were present in AND-3 (Fig. 5a). Consequently the bund top shows cracks during dry periods. Absence of swelling type clays in AND-6 was confirmed by the XRD pattern (Fig. 5b) and low moisture content of air-dried sample (Table 2). The 14 Å peak of Mg-saturated sample which did not shift to 17 Å in glycerol solvated sample in AND–6 was due to the presence of non-swelling type clays, i.e., chlorite or vermiculite.

The XRD pattern for ALU-1 and ALU-2 (Fig. 6a and b) showed the presence of only non-swelling type clays, i.e., illite and kaolinite. The ALU-1 showed no cracking while ALU-2 showed low-cracking intensity during prolong dry spells. High clay content (40%) in ALU-2 seemed to be the reason for low cracking in this earth dam.

The X-ray diffractograms of Bandagiriya sample 3 (BAN-3) and 4 (BAN-4) were shown in Fig. 7a and 7b. High background scatter obscured low angle peaks in BAN-3. However, the presence of smectite was evident by the 8.4 Å peak in glycerol solvated pattern. Bandagiriya sample 4 indicates the smectite peaks (Fig. 7b). The dominant clay minerals in both BAN-3 and BAN-4 are smectite, illite and kaolinite, consequently giving medium-intensity cracks during dry spells.

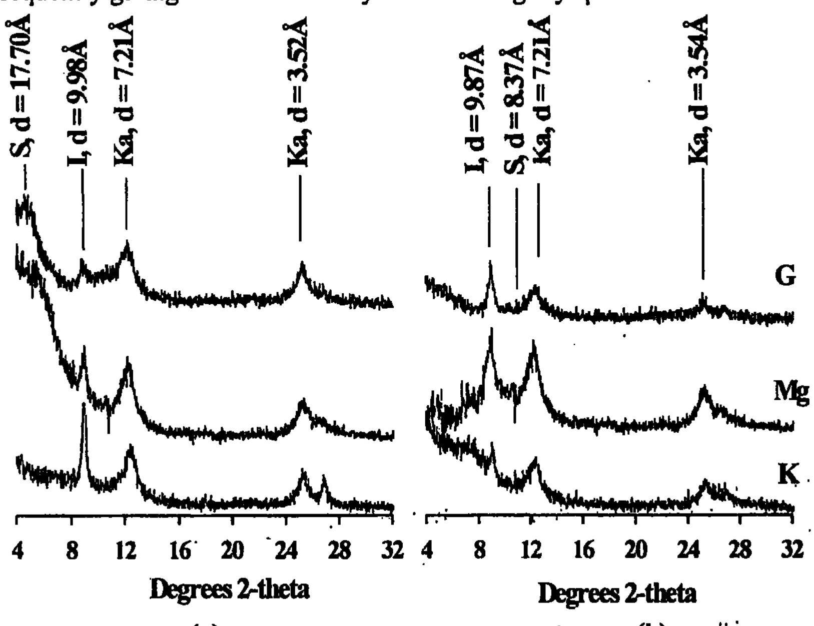
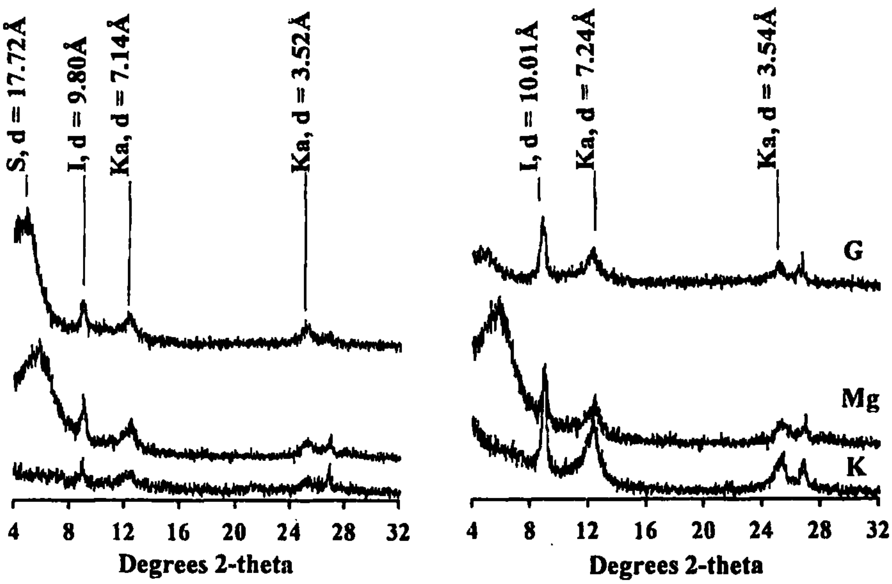


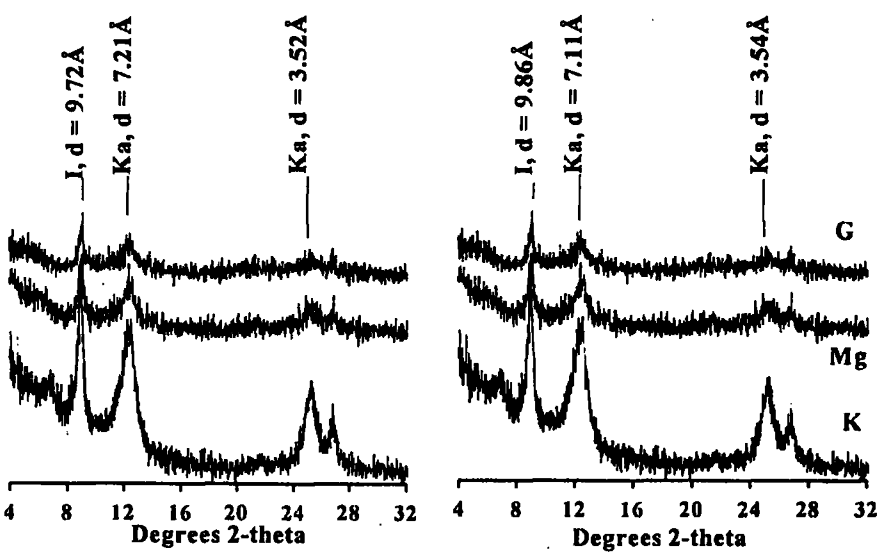
Fig. 4. X-ray diffractograms of the clay fraction (< 2μm) of Udiyankulama samples (a. UDI–1 and b. UDI–2). [Ka = Kaolinite, S = Smectite, I = Illite, K= K-saturated, Mg= Mg-saturated, G= glycerol-solvated].

Vertisols are the clay-rich soils that shrink and swell with changes in moisture content. The clay content of more than 35 % and the predominance of expanding type clays, especially smectite, are the requisites for a Vertisol (Buol *et al.*, 1989). The characteristic feature of Vertisols is development of cracks on soil profiles during the dry season, due to the shrinkage of the 2:1 expanding clays. Many engineering problems are associated with these soils due to shrinking and swelling ability of the soils. The type location for Vertisols in Sri Lanka is in Tunnakkai on the border between Mullatiu and Mannar districts (Panabokke 1996). Cracks up to 12 cm wide are formed when the soils dries out. With increasing clay content, these cracks become more pronounced (Panabokke, 1996). Alfisols is the widespread soil order found in dry zone of Sri Lanka. The clay minerals in Alfisols are mainly kaolinite, followed by illite and smectite (Panabokke, 1996; Jayawickrama, 1993; Tampoe, 1989). Smectite is found in tropical environments where leaching is limited (Allen and Hajek, 1989). Therefore, the presence of smectite in soils of these dam sites, which are located in DL1 and DL5 are quite possible. It is also possible to produce cracks on these dam materials when smectite is present in larger quantities. Presence of smectite may not result cracking on dams unless the clay percentages are large enough to exhibit the shrinking effect. According to this study, severe cracking was observed only when the clay content was above 20% with then presence of swelling type clays.



(a) (b)

Fig. 5. X-ray diffractograms of the clay fraction (< 2μm) of Pahala Andarawewa samples (a. AND–3 and b. AND–6). [Ka = Kaolinite, S = Smectite, I = Illite, K= K-saturated, Mg= Mg-saturated, G= glycerol-solvated].



(a) (b)

Fig. 6. X-ray diffractograms of the clay fraction (< 2μm) of Aluththarama samples (a. ALU–1 and b. ALU–2). [Ka = Kaolinite and I = Illite, K= K-saturated, Mg= Mg-saturated, G= glycerol-solvated].

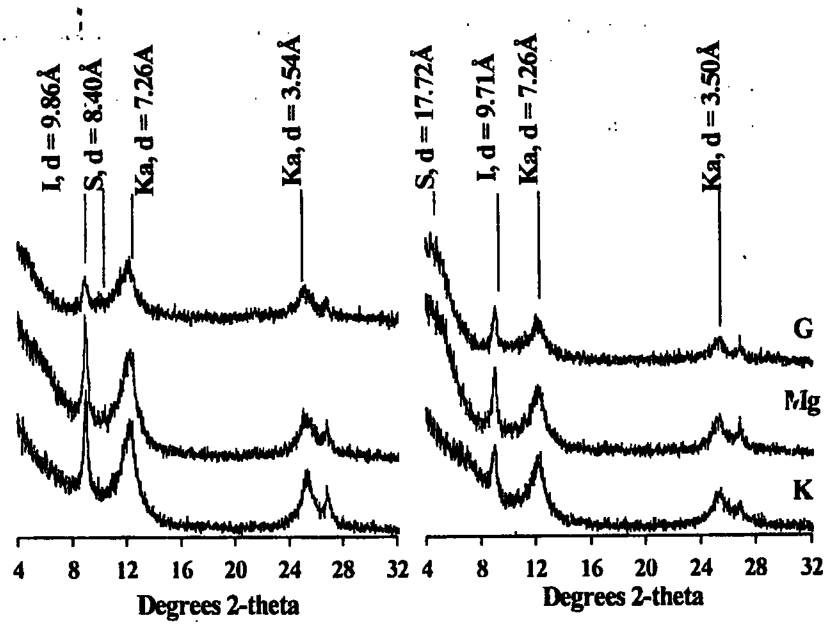


Fig. 7. X-ray diffractograms of the clay fraction (< 2μm) of Bandagiriya samples (a. BAN–3 and b. BAN – 4). [Ka = Kaolinite, S = Smectite, I = Illite, K= K-saturated, Mg= Mg-saturated, G= glycerol-solvated].

CONCLUSIONS

Presence of swelling clays and high clay contents in dam materials seems to be the main contributor for the cracking of dams in the studied sites. Significant correlations of cracking intensity of dams were observed with clay percentage, plasticity index and moisture content of air-dry samples. The cracking effect was exhibited only when soils had high amount of clay percentage together with 2:1 expanding clays. Moisture content of the air-dried samples was less than 3.5% for all soils from non-cracking dams and above 3.5% for all cracking dams. There was no significant relationship between cracking intensity and clay activity for the tested samples. Organic matter content of the most cracking soils was high but it also did not indicate any significant relationship with cracking intensity.

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