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Assessment of Damages Caused by Expansive Soil on Roads Constructed in Addis Ababa

Desalegn Workie and Henok F. Gebregziabher
School of Civil and Environmental Engineering, Addis Ababa University
E-mail address: d0916586141@gmail.com

Abstract

It is often customary to observe many roads in our cities showing different modes of failure, though systematic analyses are rare. This study aims to examine failures of roads constructed on expansive soils in Addis Ababa and provide systematic categorization. The present asphalt road surface conditions need some sophisticated tools to systematically identify pavement distresses which enable stakeholders to take remedial action. Some representative problem-areas in Addis Ababa were carefully selected for geotechnical site investigation of this research. The field exploration consisted of detailed observation and measurement of damaged roads. These road damages have been identified and characterized based on the soil properties and the effects on construction. Secondary data were also used as part of the input for statistical analyses. The field investigations include road damage condition survey and Dynamic Cone Penetrometer test. The identified sources of road damages, according to the detailed investigations, are; longitudinal cracks, with length (L) higher than 100 m and crack width ranging from minor to 50 mm, transverse cracks extended up to edges of road section with major crack width (up to 50 mm), block cracks, rutting, edge cracks, raveling, crocodile cracks which covered a large area, and fully damaged roads on large scale.

Key Words: Pavement Failure, Condition Survey, CBR, Problematic Soil, DCP

1. Introduction

The final performance of roads depends on various factors such as subgrade soil, economy, and the implementing quality of road project construction. Especially the characteristics of foundation soils can have a large effect on road infrastructure. Roads constructed on expansive soils need full attention during design, construction, and operational.

Expansive soils are generally characterized by the presence of clay mineral, montmorillonite (smectite) group. Such soils pose problems in civil engineering works due to their inability to withstand large surfaces. The expansive nature of clay is less near a ground surface where the profile is subjected to seasonal and environmental changes. Clay exhibits a greater increase in volume as it absorbs more water. Expansive soils also shrink as it dries, leading to formation of fissures in the soil (Nelson and Miller1992). These fissures help water penetrate to deeper layers. This action produces a cycle of shrinkage & swelling that causes the soil to undergo a considerable amount of volume change (Day 1999; Patrick; Snethen 1976). This movement result in structural damages especially in lightweight structures such as one & two-story buildings, side-walks, warehouses, retaining walls, driveways, basements, pipelines and foundations (Chen, 1988).

Even if the economic impact has not yet been studied in detail, significant damages to lightweight structures like irrigation systems, water lines, sewer lines, buildings, roads, and other structures are observed due to the existence of expansive soil. As a result, the country invests billions of Birr annually, to repair these damages. However, there are limited studies on the behavior of road subgrade (expanding road platform) that is evident from the damages of pavements mainly due to the uplift forces and heave following wetting of the soil.

Thus, early identification and understanding of such soil behaviors are important in order to avoid costly problems. Engineering problems due to expansive soils have been reported in various countries all across the globe, costing millions of dollars due to severe damages of structures. These damages are most common, especially in arid and semi-arid regions Tibebu (2015).

Damages on-road structures are usually manifested through distresses like rutting, longitudinal and transversal cracks, block cracks, edge failure, corrugation, bulge, shoving, etc. The number of damages can be extended even to the extent of the failure of one or whole structures by decreasing the structural safety of a building, road, or any infrastructure. In some cases, maintenance and repair costs may also exceed the original cost of construction and causes an additional financial burden on concerned bodies. In general, the damage will result in economic loss for clients and the country at large (Tibebu 2015).

The purpose of this study is to examine the causes of failures of roads constructed on expansive soils of central parts of Ethiopia where expansive soil is prevalent (Alemayehu and Yohannes 1986, Tseganeh et al., 2019, Gebremedhin and Gebregziabher 2022). The present asphalt road surface condition needed some sophisticated tools to systematically identify pavement distresses which enable stakeholders to take remedial actions. Having a good understanding of the causes of the failure helps in taking proper remedial measures like revising designing methods, construction methods, and maintenance of roads that can be considered appropriate for the area. This in turn helps the road authority, end users in particular and the whole of the country at large by reducing the maintenance and vehicle running costs.

In order to achieve the objectives of this research, and identify the causes of damages of road sections in selected parts of Addis Ababa, the following methodologies are used:

- Road damage condition survey;
- In-situ tests using Dynamic Cone Penetrometer tests;
- Laboratory investigation; and'
- Mineralogical test to identify the behavior of the soil.

In addition, secondary laboratory experimental data which were already collected on selected and representative areas of proposed sites were also incorporated in the study. These data were found from the research result of "Investigations on the expansive soils of Addis Ababa" by Alemayehu and Yohannes (1986) which have been evaluated in different layers of soil material, with respect to standards and manuals. Other secondary data are collected from AACRA road maintenance, road asset, and laboratory staff.

2. Road Damage Condition Survey

A condition survey is a detailed assessment and identification of all important data of an existing construction was performed in the eastern and central parts of Addis Ababa, where expansive soils are predominant. At the end of 2021, condition survey data are collected from selected sites from Megenagna to Mekanissa in addition to secondary data from AACRA maintenance staff and their database. The site condition survey has been supported by Dynamic Cone Penetrometer tests.

Road defects could start either from structural, geotechnical/subgrade, or both and are inter-related. Even though, different pavement defects (like pothole, small surface cracks, edge cracks, rough surfaces, eroded surface, peeled off surfaces, rutting, raveling, crocodile cracks, block cracks, longitudinal & transverse cracks etc. are observed in the study area, only defects related to expansive soil cases are assessed (Figure 1).

Some of the representative damages of roads that are associated with the subgrade material and, observed in the study area include:

1. Longitudinal cracks: relatively long (3 – 100m); sometimes extending to edges and crack width to 50mm
2. Transverse cracks extending up to edges of road section with crack width up to 50 mm
3. Block cracks (small to large in size)
4. Rutting
5. Edge cracks
6. Raveling
7. Crocodile cracks which covers large areas
8. Totally damaged roads on large scale

A summary of the quantitative road damage condition survey data where expansive soils are abundant is presented in Table 1.


Longitudinal Cracks

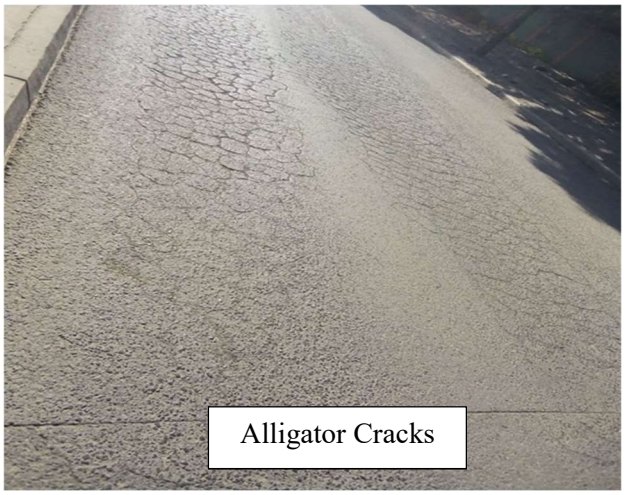

Alligator Cracks



Figure 1 Images of Different Damages of Failed Road Sections

It is also observed that the number of crocodile cracking, which is common in expansive soils, is higher compared to other distresses, while only one transverse cracking is recorded at a single location.

The possible causes of road failures are:

- ❖ Insufficient strength properties of bituminous mixes
- ❖ Movement of overloaded vehicles
- ❖ Bad drainage condition
- ❖ Natural disaster
- ❖ Subgrade soil instability

Since observation of the damaged and undamaged sections of the selected routes do not infer the possibility of the first four possible causes of failure to be realized in the specific failed sections, the Authors of this study have focused on the assessment of subgrade soil properties by performing laboratory and mineralogical tests.

Table 1 Summary of Road Condition Survey

Route name	Number of Recorded Damage for Respective Type					
	Raveling	Alligator cracking	Rutting	Longitudinal cracking	Transverse cracking	Fully damaged
From Megenagna to Bole	4	5	3	3	1	0
From Japan Embassy to RR (near Safeway supermarket)	2	2	1	5	0	0
From Lem Hotel to Anbessa Garage	0	0	0	0	0	7
From 24 to Megenagna Derartu building	0	1	0	0	0	0
From Golagol to Ednamall	0	2	0	0	0	0
From Japan Embassy to RR (near East African Aviation)	1	1	0	0	0	0
From AMCE through Ebziabherab church to 138	2	6	0	3	0	0
From Sealite Mihret to Shola Tsehay real estate	0	1	0	1	0	0
From 127 junction to 181	0	0	0	0	0	2
From Bole Bulbula to Medhanealem church	0	5		2	0	1
Bole Michael bridge	1	0	0	1	0	1

Route name	Number of Recorded Damage for Respective Type					
	Raveling	Alligator cracking	Rutting	Longitudinal cracking	Transverse cracking	Fully damaged
Bole RR to Ruanda Embassy	1	2	0	1	0	0
From Bole Medhanealem T junction to RR (Ayat hospital)	3	1	1	4	0	0
From Alem building to Bole Medhanealem church	0	0	0	1	0	0
Atlas to Shala	0	0	1	0	0	0
Stadium to Getahun Beshah building	3	0	2	0	0	0
St. Gebriel Hospital to 24 Taxi mazoria	0	0	0	1	0	0
From Golagol to SAS120	1	2	0	0	0	0
From Say cake to Atlas Hotel	0	0	0	4	0	0
From AMCE through Ebziabherab church to 148	0	0	2	0	0	0

3. Laboratory Investigations

3.1 Sampling and Testing Methods

With the aim of proving if damages are associated with the expansive behavior of the subgrade soil, laboratory tests are conducted on samples taken from six different locations to determine the engineering properties of the subgrade materials. The sampling locations are.

1) Bole Road (near Commercial School Alumina Association)
2) Old Airport
3) Near Civil Aviation Radio Transmission Station
4) In front of Auto Manufacturing Company of Ethiopia (AMCE)
5) In the compound of St. Yared Church (Nifas Silk)
6) In the compound of Ethiopian Building Construction Authority (EBCA)

Table 2 Laboratory Test Results for Selected Sites in the Study Area

Location	Depth (m)	Color	Specific gravity	Natural moisture content	Unit weight (kPa)	Dry unit weight	Liquid limit	Plasticity Index I_p	Free swell	Swelling Pressure (kPa)	Activity
AMCE	1.2	Black	2.63	38.6	18.4	13.3	102	78	130	125	1.6
	2	Grey	2.6	32.6	18.5	13.9	123	93	120	125	1.3
Bole Road	1	Black	2.65	32.4	17.9	13.5	110	75	150	188	1.3
	2	Grey	2.64	34.8	18.3	13.6	108	76	140	220	1.4
Civil Aviation	1.2	Black	2.66	36.7	18.2	13.3	94	72	130	157	1.6
EBCA	1	Black	2.69	30.2	18.2	14	101	75	140	251	1.5
	3	Grey	2.48	34.8	18	13.4	87	72	90	90	1.8
Old Airport	1	Black	2.78	39.3	18.2	13.1	98	68	140	140	1.4
Yared Church	1	Black	2.69	40	17.6	12.6	114	89	125	94	1.5
	2	Grey	2.56	32	17.7	12.6	107	82	170	188	1.8

The laboratory tests are conducted in accordance with standard methods of testing road construction materials; namely, American Association of State Highway & Transportation

Officials (AASHTO), American Society for Testing and Materials (ASTM), Ethiopian Road Authority (ERA) Manual, and Addis Ababa City Road Authority (AACRA) manuals.

3.2 Results of Identification Tests

Laboratory tests for the determination of specific gravity, moisture content, total unit weight, dry unit weight, Atterberg Limits, free swell, swelling pressure, and activity are carried out for the collected soil samples. The corresponding results are summarized in Table 2. For ease of evaluation, the activity values are plotted on the activity chart as shown in Figure 2.

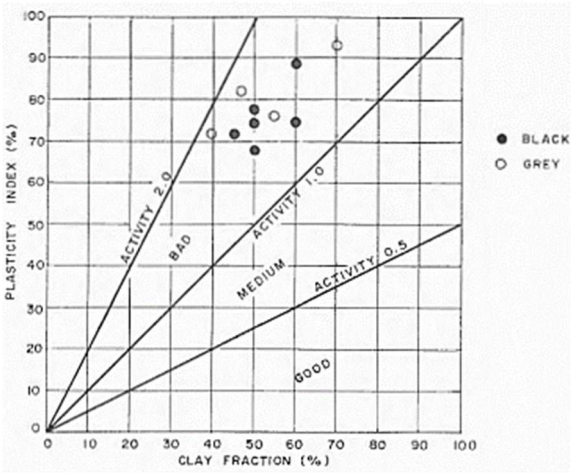


Figure 2. Activity Chart with Values from the Corresponding Sites

Based on the finding, it is observed that all samples are composed of inorganic clays with high plasticity, with activity values between 1 & 2. This indicates that a soil belongs to “bad” category with regards to expansiveness.

There is no clear distinction between black & grey soils regarding plasticity and activity, which can be misleading for inexperienced engineers, while a higher values of recorded swelling pressure for all samples also indicate the possibility of road damage for relatively smaller traffic load.

3.3 Tests for Determination of Degree of Expansiveness

3.3.1 Mineralogical Identification

For mineralogical identification, X-Ray Diffraction technique was utilized. To quantify these variations, a semi-quantitative clay mineral estimation method was used. This method is used as most peaks are sharp and rather symmetrical indicating well crystallized minerals. As the samples used for the X-Ray diffraction tests are not treated with chemical, existing standard value of mineral inter-planar spacing as given by Beavers & Jones (1964) are used for identifying the various minerals. The amount of montmorillonite for each testing location is presented in Table 3.

Table 3 Degree of Expansiveness Based on the Swelling Potential for the Teste Samples

Location	Depth (m)	Color	Amount of montmorillonite (%)	Plasticity Index I_p	Swelling Potential S	Degree of Expansion
AMCE	1.20	Black	50	78.00	14.9	Very high
	2.00	Grey	45	93.00	18.3	Very high
Bole road	1.00	Black	46	75.00	14.1	Very high
	2.00	Grey	78	76.00	14.4	Very high
Civil Aviation	1.20	Black	75	72.00	13.4	Very high
EBCA	1.00	Black	49	75.00	14.1	Very high
	3.00	Grey	60	72.00	13.4	Very high
Old Airport	1.00	Black	50	68.00	12.5	Very high
Yared church	1.00	Black	87	89.00	17.5	Very high
	2.00	Grey	50	82.00	15.9	Very high

3.4 Swelling Potential Determination

The swelling potential of the samples is calculated according to the empirical formula of Anderson and Thompson (1969).

$S = 0.23I_p - 3.12$

where

S = Swelling potential

I_p = Plasticity Index.

The values of swelling potential calculated and presented in Table 3 are compared with the classification scheme given by Anderson and Thompson (1969). Accordingly, all soil samples have very high degree of expansion.

The other soil investigation data results are collected from the Akaki Kality and Jemo 2 sites conducted for sub-grade material characterization and strength improvement. These sites are also poor sub-grade and black cotton expansive soils. The engineering material property laboratory test results are summarized in Table 4.

Table 4 Laboratory Test Result for Samples from Akaki and Jemo Sites

Location	Depth (m)	Natural Moisture content	Liquid limit	Plastic limit	Plasticity index	Free swell	Specific gravity
AkakiKality		27	102	48	54	140	2.6
Jemo	1.5	28.2	152	39	113	130	2.51
	3	43	103	56	47	120	2.76

3.5 Test Results from Dynamic Cone Penetrometer (DCP) Test

Our country's previous practice shows that dynamic cone penetration (DCP) tests are widely conducted on bridge design. Although, the DCP test is very quick and easy to conduct, the test result is used with other field and laboratory test results. In this study, DCP tests are used to determine the material strength of road profiles for the selected sites. The test results of the existing road section sub-grade CBR value are relatively large. This is due to the modified nature of the soil during the construction and service period. The CBR value of expansive soils or weak and unsuitable soils in the natural condition is very small (less than 5%). On the other hand, the CBR values of good materials give larger values (Table 5).

Table 5 Correlation of CBR and DCP Index

DCP index Mm/blow[A]	CBR (%)	DCP index Mm/blow[A]	CBR (%)	DCP index Mm/blow[A]	CBR (%)	DCP index Mm/blow[A]	CBR (%)
<3	100	22-23	9	52	3.5	92-96	1.8
3	80	24-26	8	53-54	3.4	97-101	1.7
4	60	27-29	7	55	3.3	102-107	1.6
5	50	30-34	6	56-57	3.2	108-114	1.5
6	40	35-38	5	58	3.1	115-121	1.4
7	35	39	4.8	59-60	3.0	122-130	1.3
8	30	40	4.7	61-62	2.9	131-140	1.2
9	25	41	4.6	63-64	2.8	141-152	1.1
10-11	20	42	4.4	65-66	2.7	153-166	1.0

DCP index Mm/blow[A]	CBR (%)	DCP index Mm/blow[A]	CBR (%)	DCP index Mm/blow[A]	CBR (%)	DCP index Mm/blow[A]	CBR (%)
12	18	43	4.3	67-68	2.6	167-183	0.9
13	16	44	4.2	69-71	2.5	184-205	0.8
14	15	45	4.1	72-74	2.4	206-233	0.7
15	14	46	4.0	75-77	2.3	234-271	0.6
16	13	47	3.9	78-80	2.2	272-324	0.5
17	12	48	3.8	81-83	2.1	>324	<0.5
18-19	11	49-50	3.7	84-87	2.0		
20-21	10	51	3.6	88-91	1.9		

[A] for DCP index in units of in/blow divided by 25.4

The expansive nature of the representative soils was high with a CBR value of less than 4% and needs special attention during design, construction, and operation stage of any infrastructure.

From laboratory test data results, the CBR values of original expansive soil are less than 2%. For example, according to AACRA lab test results (test method AASHTO T-193) the CBR values of Akaki Kality expansive soil for 10, 30, and 65 blows are 1%, 1.3 %, and 1.5% respectively.

4. Conclusions

In this research, the conditions of different road sections in Addis Ababa are surveyed, where the road shows various types of damages. On top of the site investigations, representative soil samples are collected from around the failure areas to perform laboratory tests to identify the causes of failures.

The road condition surveys indicated that most of the damages are longitudinal and alligator cracks, which are mostly related to subgrade problems and soil expansiveness. The longitudinal cracks of length (L) larger than 100 m and crack width up to 50 mm, sometimes extending to edges are observed during the study.

According to the data, all samples are found to be inorganic clays (expansive) of high plasticity and bad activity (between 1 and 2), having a very high degree of expansiveness and high swelling pressure. This shows that the material is unstable or problematic foundation material or subgrade and can possess a large potential to cause damages if not properly treated. Based on the Dynamic Cone Penetrometer test results and the CBR value of the unmodified soil sample for selected samples, (performed as per AASHTO test standard T- 193). CBR values ranging from 1% to 4%, is less than the minimum code requirement, necessitating treatment of soil or replacement. Most damages happened where there are poor drainage systems. Road damages ranged from minor to large and covered all types of roads (collectors to main roads and ring roads as well).

5. Recommendation and Suggestions

Depending on the results of the paper, the following tasks are suggested to all concerned bodies to mitigate or minimize the degree of causes of damage to the road.

- Addis Ababa City Roads Authority should have updated and well-organized research supported data, like representative laboratory test soil property of Addis Ababa roads, condition survey data.
- Drainage system design and utility line installation give special attention to the construction of roads.
- The Addis Ababa City Road Authority has to create opportunities to involve both in maintenance and construction to develop the competitive spirit and efficiency of local contractors in road construction work.

- The road maintenance deserves much more emphasis than is usually placed on it in order to protect the investment that has been made on our road system and a maintenance program should be collected be chalked out by the concerned stakeholders well ahead to undertake maintenance work in a timely manner according to the priorities determined according to the conditions of the ground and the funds available.
- Funds required for proper and timely maintenance of the failed section of this road should be provided to the organizations/contractors concerned and also organizations/contractors should have an adequate number of professionals, technical and skilled personnel. In addition, sufficient equipment and machinery are important to undertake maintenance work speedily and effectively.
- Generally, all parties have to take responsibility for risks that happen pre-and-post of road construction work which can reduce the factors which affect the failure of roads.
- Finally, concerned sector shall give more attention and assess in-depth for all parts of Addis Ababa road with sufficient sample area.

6. Recommendation for Further Studies

The Authors recommend for further studies on road drainage system design and implementation problems in the study area, with due considerations of the effects of seasonal variations. Studies shall also be conducted about the economic impact of road pavement failure due to expansive soil all over the country. Furthermore, assessment of causes of road damage studies in conjunction with high way and structural engineer shall be performed.

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