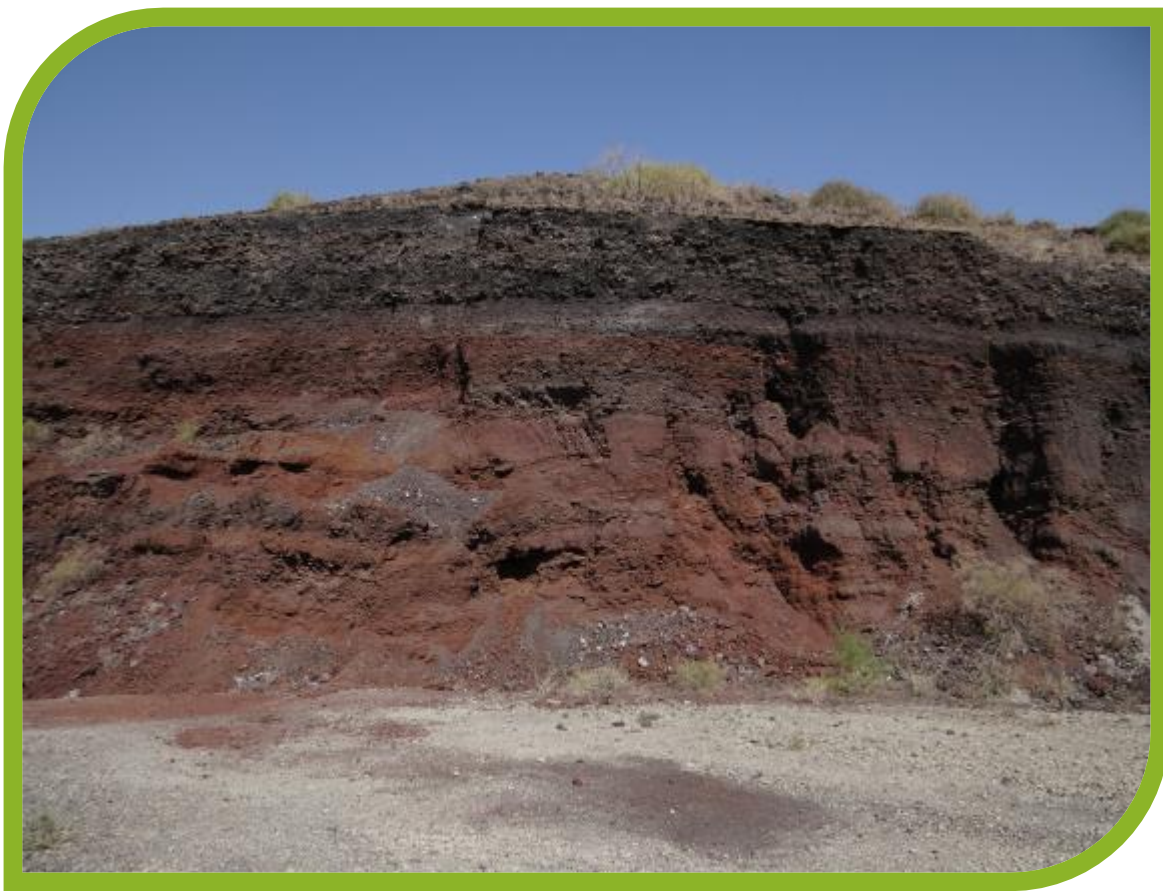


Investigation of the Use of Cinder Gravels in Pavement Layers for Low-Volume Roads

Report Final Project Report



Institution: TRL Ltd

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Cover photo: Excavated cinder material pit in Ethiopia/ Andrew Otto

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Abstract

This report describes the activities carried out in the delivery of the project on the use of cinder gravels, the main findings, the challenges faced, and recommendations for how similar projects might be carried out in the future. The report has also identified areas of further research to be conducted as an outcome of this study. A reluctance to use these materials in the past has stemmed from the view that their properties, in terms of grading and CBR strength, are marginal and highly variable when compared to specifications for road materials. A programme of engineering geological investigation, sampling and laboratory testing illustrates the variability in the engineering properties of cinder gravels and provides recommendations for sampling, selection and appropriate use. Guidelines and recommendations for use of cinder gravels have been produced.

Key words

Low Volume Roads, Guideline, Pavement layers, Scoria, Cinder gravels, Ethiopia

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Research for Community Access Partnership (ReCAP)

Safe and sustainable transport for rural communities

ReCAP is a research programme, funded by UK Aid, with the aim of promoting safe and sustainable transport for rural communities in Africa and Asia. ReCAP comprises the Africa Community Access Partnership (AfCAP) and the Asia Community Access Partnership (AsCAP). These partnerships support knowledge sharing between participating countries in order to enhance the uptake of low cost, proven solutions for rural access that maximise the use of local resources. The ReCAP programme is managed by Cardno Emerging Markets (UK) Ltd.

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Acronyms, Units and Currencies

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AfCAP	Africa Community Access Partnership
AIV	Aggregate Impact Value
ASTM	American Society for Testing and Materials
CBR	California Bearing Ration
EF	Equivalence Factor
ERA	Ethiopian Roads Authority
EMA	Ethiopian Mapping Agency
FACT	10% Fines Aggregate Crushing Test
LAV	Los Angeles Abrasion Value
LL	Liquid Limit
LTPP	Long Term Pavement Performance
LVR	Low Volume Roads
LVSR	Low Volume Sealed Roads
MAIV	Modified Aggregate Impact Value
MDD	Maximum Dry Density
NP	Non-Plastic
OMC	Optimum Moisture Content
PI	Plasticity Index
ReCAP	Research for Community Access Partnership
RRC	Road Research Centre
SSD	Single Surface Dressing
TFV	Ten percent Fines Value
TRL	Transport Research Laboratory
UK	United Kingdom (of Great Britain and Northern Ireland)
UKAid	United Kingdom Aid (Department for International Development)
WA	Water Absorption
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence
%	Percentage
g/cc	Grams/cubic centimetre
km	kilometre
kN	Kilo Newton
m	Metre
mm	Millimetres

µm

Micrometres

Executive summary

The project began on 21st January 2016 and was completed on 28th February 2018. The main objective of the project was to produce a Guideline for the use of cinder gravels in pavement layers for low volume roads, primarily in Ethiopia. The methodology employed included literature reviews, desk studies, field investigations, sampling, laboratory tests, analysis and consultation. The main activities carried out by the project included:

1. Inception phase (including Inception Report, March 2016)

The inception phase began on the 18th of February 2016 and lasted for one calendar month. During this phase, field visits were made to cinder gravel sources, road projects where cinder gravels had been used as subgrade replacement and pavement materials. A review of relevant literature was also carried out.

2. Desk studies (reported in Inception Report and Progress Reports, e.g. PR3 (Nov 2016))

Desk studies comprised an interpretation of aerial photography and the use of Google Earth to identify clusters of cinder cones and related landforms. Cinder cone morphology was assessed from these studies and a list of locations was identified for field investigation. Because materials sampling could only be undertaken from existing borrow areas, Google Earth allowed these locations to be identified and selected for field investigation.

3. Field investigations and sampling (reported in Progress Reports, mainly PR 2 (Sep 2016) and PR 3 (Nov 2016))

Forty-four borrow pits located in cinder cones were visited in order to assess the engineering geological characteristics of the deposit. Samples were taken from 30 of these locations. A total of 56 samples were taken, with up to three being taken from a single borrow pit. Mostly, however, one sample was removed from each pit due to logistical constraints with the transport of multiple bags of samples to the ERA laboratory in Addis Ababa.

4. Pavement investigations (Progress Report 1, Jun 2016)

The oldest known existing road where cinder gravel was used in Ethiopia is Alemegena – Butajira road. Rut depth measurements were taken and test pits excavated. Samples were removed for laboratory testing.

5. Laboratory testing (Progress Reports 2 and 3, mainly)

Laboratory testing was conducted at the Ethiopian Roads Authority Road Research Centre Laboratory at Kality. The tests conducted included Aggregate Impact Value, 10% Fines Aggregate Crushing Test (10% FACT), Specific Gravity and Water Absorption, Atterberg Limits, Maximum Dry Density, California Bearing Ratio, and Particle Size Distribution.

6. Ground truthing (Progress Report 5, Jul 2017)

Analysis of the field and laboratory strength data identified areas where stronger and weaker materials predominated. A total of 15 additional borrow pits were selected, that had not been investigated and sampled under 3 above, to determine whether they also contained stronger or weaker material.

7. XRF and XRD analysis (Progress Report 5, Jul 2017)

X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) analyses were carried out to provide an understanding of the geochemistry of the sampled cinder gravels. The gravels were mainly basaltic. A large content of amorphous “glass” was also present in these materials. Smectite clay was detected in only 3 sites, but the quantities were minimal.

8. Analysis of results and drafting of the Guideline (draft Nov 2017)

Results of field investigations, laboratory testing, ground truthing, and literature surveys were analysed and used to produce the draft Guideline.

9. Preliminary workshop (August 2018)

This was conducted internally between TRL and ERA RRC to discuss the proposed structure and content of the Guideline, its expected size, and focus. The outcome of this workshop led to the structure that was adopted for the Draft Guideline.

10. The stakeholder workshop (Stakeholder Workshop Report, Oct 2017)

The draft Guideline was presented at the Stakeholder Workshop held in Alemgena in Addis Ababa on 26th October 2017. It was well attended. Comments received were used to revise the draft Guideline.

11. Presentation at the Inter-Regional Implementation Meeting

This meeting brought together AfCAP and ASCAP participating countries. It was held in Kampala, Uganda in November 2017. The findings of the project were presented at this meeting. The presentation showed the importance of appropriately using cinder materials in low volume road construction. The presentation was well received.

12. Peer review and finalisation of the Guideline (February 2018)

Following revision of the Guideline after the Stakeholder Workshop, a peer review was conducted. The review comments were addressed and the Final Draft of the Guideline was issued in February 2018.

13. Production of a scientific paper (under technical review with editor)

A scientific paper entitled "Engineering geology of cinder gravel in Ethiopia: prospecting, testing and application to low-volume roads" was prepared and submitted to the Bulletin of Engineering Geology and the Environment journal.

Detailed test results from the project are held with the ERA Road Research Centre (RRC) in Addis Ababa. It was recommended that study sections be demarcated on existing roads and monitored by the RRC. In addition, it was recommended that the new trial sections be constructed in different parts of Ethiopia and monitored by the RRC.

Some cinder gravel sources that have been partially excavated should be fully utilised even if this means the use of explosives to break up welded materials preventing access to suitable materials below. It is recommended that stricter supervision of the extraction of these materials needs to be implemented to ensure the limitation of environmental impact, to enable safe and sustainable use of these materials for future projects and to restore the land to productive use.

It is reported that changes governing the protection of some of the cones for the extraction of material are under consideration by the Ethiopian Government. This must be undertaken in full consultation with the Environmental Protection Agency and the Geological Survey of Ethiopia. No new borrow pits in virgin cones should be investigated or opened up without official approval.

1 Introduction

1.1 Background

The contract between Cardno Emerging Markets and the Transport Research Laboratory (TRL) for the project entitled ETH2058A: 'Investigation of the use of cinder gravels in pavement layers for Low-Volume Roads' was signed on 21/01/2016. The principal objective of the project was to carry out research to enable the use of cinder gravels (scoria) in low volume roads to be advanced, by determining the range in engineering properties of cinder gravels, evaluating their performance in road pavements already constructed in Ethiopia and thereby developing specifications for their use in future road construction. By doing so, significant cost savings should accrue.

This report describes the activities carried out in the delivery of the project, the main findings, the challenges faced, and recommendations for how similar projects should be carried out in the future. The report has also identified areas of further research to be conducted as an outcome of this study.

Progress reports were produced at key stages of the project. These reports are available on the ReCAP website, with ERA RRC and with TRL.

1.2 Objectives

The principal objective of this project was to improve the understanding of the properties and natural variability of cinder gravels in relation to their use as pavement construction materials in low volume roads and produce a Guideline that would facilitate their wider use, thus leading to potentially significant cost savings in low volume road construction. It was especially important to study cinder deposits outside the vicinity of Addis Ababa and at profile depths not previously achieved in the ERA/TRL cinder gravel study carried out in the 1970s (Newill et al. 1979; Newill and Aklilu 1980; Newill et al. 1987). The main deliverable of this project is the production of a draft Guideline covering the selection, processing and use of cinder gravels.

Other objectives of the project were:

- To carry out further research on the properties of cinder gravels
- Promote capacity building through working with ERA RRC counterparts
- Knowledge exchange through stakeholder workshops

1.3 Scope

The Guideline produced is for use in the design and construction of low volume roads, and in conjunction with the Ethiopian Low Volume Roads Manual Part B, 2017. Some elements of the Guideline will be applicable to the sub-base and capping layers of high volume roads.

2 Inception phase

The activities carried out included consultative meetings between ERA and the TRL team, visits to projects currently using cinder gravels, visits to existing cinder gravel deposits and a literature review.

The field visits made during the Inception phase provided an interesting insight into the range of materials exposed in some of the existing borrow areas. The scoria (cinder) is commonly gravel and cobble-sized (occasionally boulder-sized) and can occur as an amorphous (structureless) mass of welded clasts or as a stratified deposit, often with a matrix of gritty material.

An earlier collaborative project by ERA and TRL was carried out to investigate the location and properties of cinders during the mid-1970s. A final project report was issued by ERA in 1979. Subsequently, papers were published which contained technical details of the materials investigated and the performance of the trials (Newill and Kassaye, 1980, Newill, Robinson and Kassaye, 1987). These early investigations provided valuable knowledge on the use of cinder gravels.

Other laboratory-based studies (Hadera 2015, Ayele et al 2002, Behranu 2009) were also reviewed. The outcomes from these studies provided valuable information on the stabilisation of cinder gravels and were included in the draft Guideline. Literature on the geology and volcanology of Ethiopia was also extensively reviewed and specialists in the field of volcanic products were also consulted.

Currently cinder gravels are used only as subgrade replacement, capping and sub-base materials on very few occasions. They are not being used in the roadbase layer of any roads. Thus, if the behaviour of cinder gravels is understood to allow its use in roadbases of low volume roads, then there is significant potential for road construction cost savings.

The results of these studies were included in the draft Guideline.

3 Field investigations and sampling

The main study areas included cinder cones and related deposits near:

- Debre Zeit/Addis – Adama Expressway
- Bishoftu
- Adama
- Metahara/Fantale (not sampled)
- Tulubolo
- Butajira
- Hawassa
- Assela – Dodola Road
- Shashemene – Dodola Road
- Hosana
- Bahir Dar
- Injibara
- Kunzila

The GPS coordinates of the study locations are included in Annex 1. A map of these locations and other locations where cinder materials occur is shown in Annex 2. Forty-four borrow pits located in cinder cones were visited in order to assess the engineering geological characteristics of the deposit. Samples were taken from 30 of these locations. A total of 56 samples were taken, with up to three being taken from a single borrow pit. Mostly, however, one sample was removed from each pit due to logistical issues concerning the transport of multiple sample bags to the laboratory in Addis Ababa. On average, 3 bags (50 kg each) were taken for each sample. A table showing the field description of materials is shown in Annex 3.

By combining field investigations, laboratory test results and information obtained from literature, a geographical and a geomorphological interpretation of the occurrence of the cinder gravels was carried out. With the exception of deposits around Bahir Dar and Injibara, most cinder gravel deposits occur on the margins and within the Rift Valley. Generally, there is such variability in the engineering geological properties of the cinder gravels that strong geographical variations fail to emerge. Nevertheless, sources of stronger materials were found in the Injibara area, and parts of Butajira and Bishoftu, especially, whereas weaker materials appeared characteristic of Hawassa and Metahara. Steeper-sided, well-defined cones and maars tended to contain stronger materials than flatter cones and other non-conical deposits.

4 Pavement investigations

Major existing roads where cinder gravels have been used include Alemgena-Butajira, Assela – Dodola, Shashemene – Dodola, and the Addis Ababa – Adama Expressway. The oldest of these is the Alemgena - Butajira road, which is currently more than 15 years old. The road consists of a bituminous surfacing, crushed rock base, blended cinder gravel sub-base on one section and weathered basalt sub-base on another. The same sub-base materials were used as capping/subgrade replacement over mainly black cotton soil subgrade.

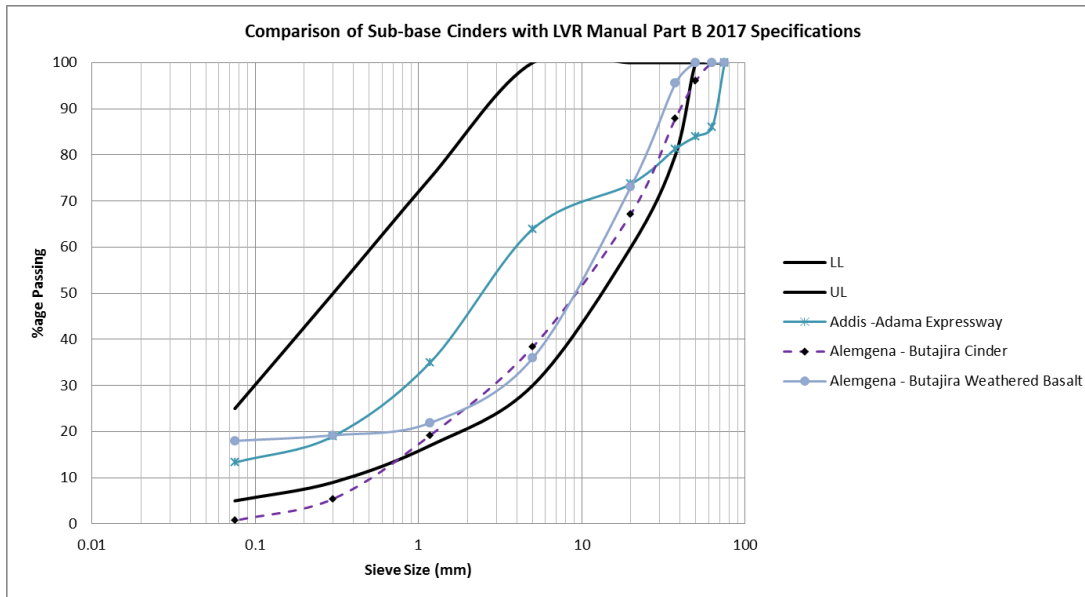
Rut depths were measured on both sections. The mean rut depth recorded on the blended cinder gravel sub-base section was 14 mm and that on the weathered basalt sub-base section was 13 mm. According to the ERA condition rating system, these rut depth values are regarded as “Fair”, thus indicating similar and acceptable performance on both sections. The traffic carried in the heaviest loaded direction was estimated to be 2.7 Mesa i.e. almost three times that normally classified for a low volume road.

Samples of sub-base material were extracted from two sections along the Alemgena – Butajira road. One section had been constructed using weathered basalt sub-base and the other cinder gravel. The test results on these samples are shown in Table 1. It is worth noting that on both sections the Atterberg Limits are above the recommended limits (Liquid Limits of <45 and Plasticity Indices of <16 are the recommended limits in the ERA LVR Manual 2017). The plasticity modulus (PM), which reflects both the quantity of fines and the plasticity of the material of both sections is low. Thus, PM is considered to be more important than Plasticity Index alone. The particle size distribution of the cinder gravel (Figure 1) lacks sufficient fines. The maximum particle size of both the cinder gravel and the weathered basalt is 75 mm.

Table 1 Test results of sub-base materials on Alemgena – Butajira road

Property	Weathered Basalt Sub-base	Blended Cinder Sub-base
MDD (gm/cc)	2.0	1.6
OMC (%)	11.2	21
CBR @ 95% MDD 4-days Soak (%)	32	15
Swell in CBR mould (%)	0.41	0.02
Liquid Limit	50.4	50.4
Plasticity Index	18	26
Linear Shrinkage (%)	6.1	10.4
Specific Gravity (gm/cc)	2.7	2.0
Bulk Gravity (gm/cc)	2.6	1.7
Water Absorption (%)	4.6	15.1
Plasticity Modulus	342	208

Figure 1 Particle size distribution of sub-base materials from Alemgena - Butajira



It is recommended that ERA RRC sets up long-term pavement performance (LTPP) monitoring on sections of the Assela – Dodola and Shashemene – Dodola roads, both currently about 7 years old. This will add to the knowledge base in understanding the behaviour and thresholds for the use for cinder gravels.

5 Laboratory testing

Laboratory testing was conducted at the ERA RRC laboratory at Kality. The tests conducted included:

- Aggregate Impact Value (by BS 812-112 test method),
- 10% Fines Aggregate Crushing Test (10% FACT) (by BS 812-111 test method),
- Specific Gravity and Water Absorption (by ASTM C127 test method),
- Atterberg Limits (by AASHTO T89 test method),
- Maximum Dry Density (by AASHTO T180-D test method – specimens were re-used),
- California Bearing Ratio (by AASHTO T193 test method), and
- Particle Size Distribution (by AASHTO T11 and T27 test methods).

As an indication of the number of test carried out, over 500 pages of laboratory test sheets were used, which are held at the ERA RRC Laboratory in Kality. The ranges of values obtained during laboratory testing are shown in Table 2. Notable are high AIV values, low 10% FACT values, low specific gravities, high water absorption and low maximum dry density values.

Table 2 Summary of results obtained from the laboratory testing programme

Test	Range of Values
Aggregate Impact Value (%)	9-71
Modified Aggregate Impact Value (%)	14-130
10% FACT (kN)	28-64
Apparent Specific Gravity (gm/cc)	1.57-2.62
Saturated Surface Dry Specific Gravity (gm/cc)	1.45-2.44
Bulk Specific Gravity (gm/cc)	1.17-2.33
Water Absorption (%)	5-33
Maximum Dry Density (gm/cc)	1.46 -1.80
California Bearing Ratio – neat cinder gravels (%)	18-148 ¹
California Bearing Ratio – cinder gravels blended ² with other materials (%)	16 - 60

Note 1: These materials may not meet the recommended particle size distribution of the Ethiopia LVR Manual (2017) despite high CBR values.

Note 2: Blended to meet recommended particle size distribution.

Specific Gravity, Water Absorption, and Aggregate Impact Value test results are shown in Annex 4. Maximum Dry Density (MDD), Optimum Moisture Content (OMC) and California Bearing Ratios (CBRs) are shown in Table 3. The method of re-using the specimen for compaction was used in the determination of the maximum dry density and optimum moisture content of neat (unblended) cinder gravel samples. This was to enable a maximum value of dry density to be obtained. For blended cinder gravels, the specimens were not re-used in the determination of the maximum dry density or the optimum moisture content. This is because the MDD and OMC values could be easily obtained for blended material.

Table 3 CBRs of typical neat cinder gravels

Location	Site	Category	CBR (%) @56 blows	MDD (gm/cc)	OMC (%)
Location 3 Butajira-Zway	Site 1	Cat 1	100	1.79	20
	Site 2	Cat 4	48	1.77	18
Location 5 Butajira-Hossana	Site 1	Cat 1	120	1.77	16
Location 6 Tulubolo	Site 1	Cat 1	46	1.50	22
	Site 2	Cat 2	62	1.72	17
Location 7 Tulubolo	Site 1	Cat 1	58	1.75	18
Location 8 Hawassa	Site 1	Cat 1	48	1.50	17
Location 11 Dodola-Assela	Site 1	Cat 1	54	1.46	20
Location 13 Dodola-Shashemene	Site 1	Cat 2	18	1.53	26
Location 14 Adama - Dira	Site 1	Cat 1	41	1.56	22
Location 17 Adama - Dira	Site 1	Cat 1	95	1.70	19
Location 19 Bishoftu	Site 1	Cat 1	148	1.80	16
Location 21 Bishoftu	Site 1	Cat 1	57	1.69	11
Location 23 Bahir Dar	Site 1	Cat 1	67	1.78	21
Location 24 Bahir Dar	Site 1	Cat 1	90	1.77	19
Location 25 Injibara	Site 2	Cat 1	90	1.74	17
Location 27 Kunzila	Site 1	Cat 1	44	1.68	20

Often neat cinder gravels will not meet the particle size distribution requirement of the Ethiopia LVR Manual 2017, and will require blending with finer materials to improve the grading and aid compaction. This could result in lower CBR values in some cases, if the grading requirement is to be achieved. The PI of the materials used for blending with cinder gravels varied between 6 and 29 (for those that showed plasticity). Results of trial blends are shown in Table 4. To obtain material of roadbase quality, additional blending with crushed rock may be required. Results of such a trial blend are shown in Table 5. Note that it is possible to obtain a non-plastic (plasticity not detectable on material passing the 0.425 mm sieve) material even after blending with another material that is evidently plastic (i.e. material that yields a value of PI).

Table 4 Typical characteristics of cinder gravels blended with fine materials

Location	Blend Ratio (%Cinder/% Blending Material)	Soaked CBR @56 blows (%)	CBR at OMC @56 blows (%)	PI of Blend	% Passing 425µm Sieve	Plasticity Modulus
Location 5 Butajira-Hossana	80/20	40	70	13	25	325
	90/10	16	35	NP	17	0
Location 7 Tulubolo	80/20	30	70	NP	34	0
	90/10	12	65	NP	37	0
Location 11 Dodola-Assela	80/20	30	55	NP	41	0
	90/10	50	75	NP	38	0
Location 22 Tuludimptu	75/25	25	-	23	18	414
Location 23 Bahir Dar	80/20	13	45	NP	33	0
	90/10	15	15	NP	17	0
Location 25 Injibara	80/20	16	35	NP	30	0
	90/10	13	60	NP	17	0

Table 5 Cinder gravel blended with fine materials and crushed stone

Characteristic	Neat Cinder	50%/20%/30% Blend
Plasticity Index	None Plastic	None Plastic
Soaked CBR @ 56 blows	46	55 – 60%
CBR at OMC @ 56 blows	55	80 – 85%
Base Grading Envelope	B (after reprocessing)	B
AIV/MAIV	40/55	N/A

Nearly all the cinder materials were non-plastic. Only Locations 6 and 13 (see Annex 1) contained plastic material. The characteristics of these materials are shown in Table 6. The materials were probably from older cinder deposits that had had time to weather and the samples were collected from this weathered zone of the deposits.

Table 6 Samples from cinder gravel borrow pits exhibiting plasticity

Location	Site	LL	PI	% Passing 425µm Sieve	Plasticity Modulus
Location 6 Tulubolo	S1	74	39	8	312
	S2	66	41	14	574
Location 13 Shashemene - Dodola	S1	47	21	23	483
	S2	47	26	36	936

Particle size distributions are shown in Figures 2 to 4. Prior to compaction Figure 2, the cinder gravels lack fines and upon repeated compaction (Figure 3) the fines content increases as the material is broken down. The fines content was also improved (Figure 4) by blending with finer materials taken from adjacent deposits in the borrow pits.

Figure 2 The particle size distribution of typical cinder gravels before compaction

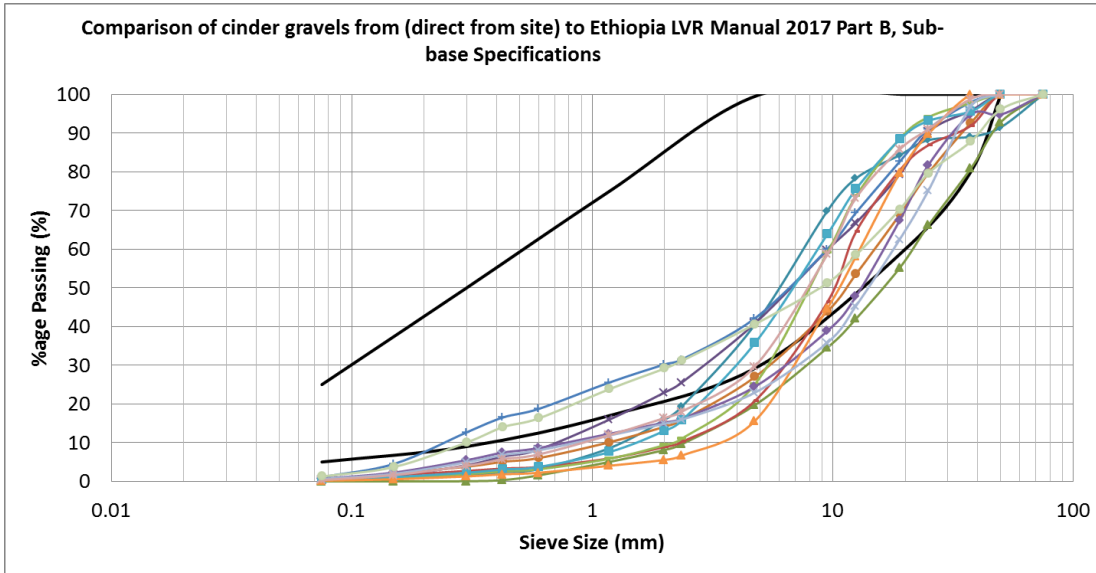


Figure 3 The particle size distribution of typical cinder gravels after compaction

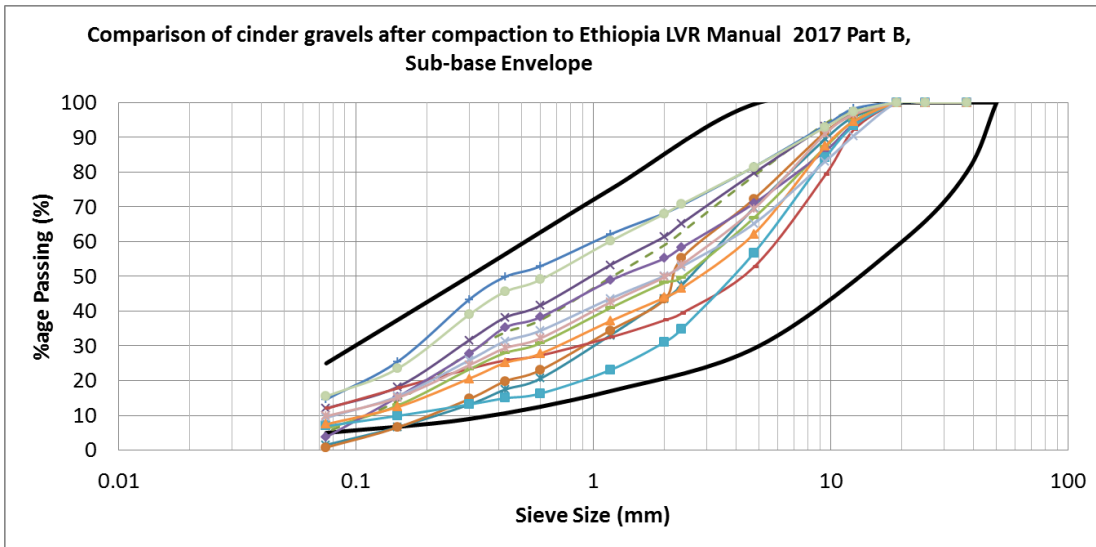
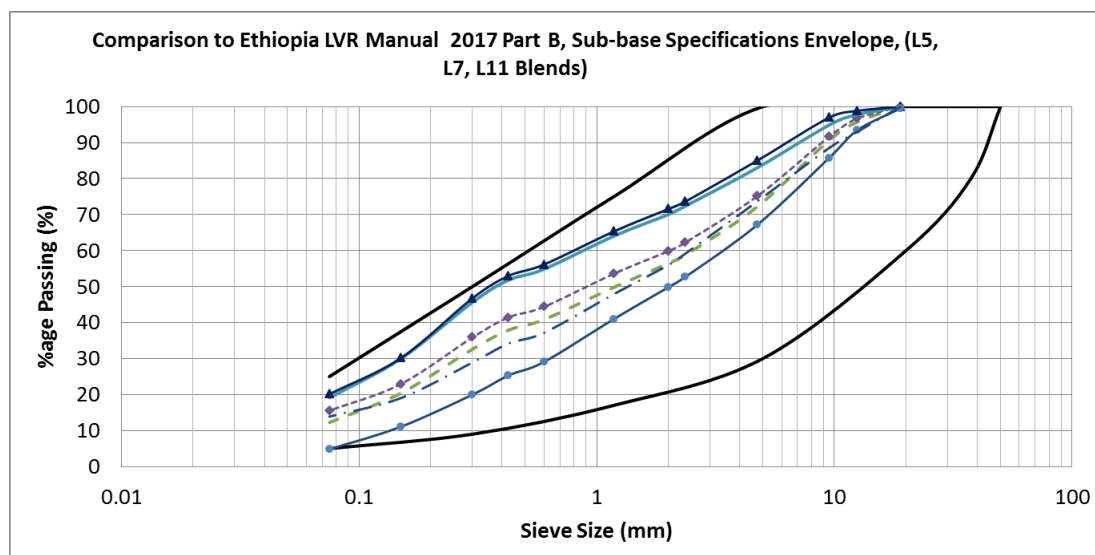


Figure 4 Particle size distribution of cinder gravels blended with plastic fines from the same cone



The 10% FACT values were tested for a few samples. The values are shown in Table 7. The values are significantly lower than for other materials (e.g. most basalt rock is greater than 130 kN). Nevertheless, these materials are being used in lower pavement layers on the roads observed without any apparent problems.

Table 7 Results of 10% FACT

Location	Category	10% FACT (kN)
Location 1 Alemgena - Butajira	1	51
Location 3 Butajira-Ziway	1	35
Location 7 Tulubolo	1	33
Location 19 Bishoftu	1	28
Location 22 Tuludimptu	1	46
Location 23 Bahir Dar	5	64
Location 30 Injibara	5	32

6 Ground truthing

The main phase of investigation in 2016 did find some geographical trends in material strength. Injibara and some of the deposits in Butajira and Bishoftu yielded generally stronger materials than other locations, such as Hawassa. Although there was considerable variability, it was decided to collect further samples to see if these trends could be repeated. Google Earth imagery was used to identify locations where additional samples (from previously unsampled deposits) would be taken in Bishoftu and Injibara/Bahir Dar. This exercise was undertaken in 2017.

Bishoftu

A total of six locations were identified in the Bishoftu area from the imagery and an additional site was located during the fieldwork itself. Table 8 summarises the field descriptions of material strength at the ground truthing locations in the Bishoftu area and allows comparison with the AIV test data in each case.

Table 8 Field descriptions and laboratory tests from Bishoftu ground truthing sites

Ground truthing location	Field description of strength	Average AIV%
GT1	Very weak to moderately weak	56
GT2	Moderately weak to very strong (maar rim)	11
GT3 black GT3 red	Moderately weak to very strong Very weak to weak	54 45
GT4	Strong to very strong	25
GT5	Moderately weak to strong	44
GT6A	Moderately strong to very strong	42
GT6B	Very weak to strong (highly variable)	28

Note: the field description of strength referred to in this table is based on standard engineering geological field techniques (see Progress Report No 5).

Generally, the field descriptions indicated material varying between moderately weak to very strong. This supports the interpretation made following the main phase of fieldwork and testing. There was good correspondence between the visual strength and the test results, and the only anomaly is ‘GT3 red’ where the visual strength of the material was very weak to weak and the AIV was 45%.

As can be seen from Table 8 above, according to the average AIV values, the materials are generally representative of stronger rather than weaker materials. Based on the AIV test results, samples GT2, GT4, and GT6B could probably be suitable for use as base course and others could probably qualify for sub-base.

Injibara/Bahir Dar

Table 9 shows the results of the field descriptions and the laboratory tests for samples taken from the Injibara and Bahir Dar ground truthing sites

Table 9 Field descriptions and laboratory tests from Injibara/Bahir Dar ground truthing sites

Ground truthing location	Field description of strength	Average AIV%
GT7	Strong to very strong gravel on maar slope surface – indicative of strong gravels at depth. below 1-3m of residual soil. NB sample taken of dozed material only (materials dozed out of way to provide space for crusher plant using imported igneous material), but sample assumed to be derive from original site material	45
GT8	Residual soil only, any gravels too deep to be seen/sampled	No sample taken
GT9	Not visited	No sample taken
GT10	Deep residual soils formed on maar slopes – no gravel exposure, though occasional weathered gravel on slope surface – moderately weak to strong – indicative of strong gravels at depth.	No sample taken
GT11	Weak to very weak. Borrow area located in unconfirmed linear volcanic landform, either a lava flow or part of an ancient maar	46 (red/brown) 36 (dark grey)
GT12	Deep residual soils exposed on maar side slopes. No gravel identified	No sample taken
GT13	Non-vesicular basalt gravel, probably strong (lower slopes of maar rim) – indicative of strong gravel at depth	No sample taken
GT14	Not visited	No sample taken
GT15	Strong to very strong (new location in Bahir Dar area)	25
U11 black U11 red	Weak to moderately strong Very weak to weak	37 50

In Injibara, a number of the ground truthing locations contained gravels that appeared to be non-vesicular and strong on the surface, but there was insufficient exposure to collect samples. These locations are on

the rims of maars and not cinder cones *per se*. Of the two locations in the Injibara area where samples were taken, one (GT7) was on the rim of a maar and the other (GT11) was in a volcanic landform yet to be defined. The material at GT7 was described in the field as being strong in engineering geological terms. Upon testing, this material was found to have an AIV of 45%. The material at GT11 was described in the field as being weak in engineering geological terms. Upon testing, this material was found to have an AIV of 36-46%.

In Bahir Dar Location U11 (Table 9) was described in the field as being composed of very weak to weak and weak to moderately strong material, although average AIVs of 37-50% were obtained, indicating strong material. This is clearly an anomaly between the field and laboratory data and probably reflects the significant variability in materials. At GT15 (Table 9) the material was described as strong to very strong in the field and yielded average AIVs of 31%. This confirms the good quality of this material in an area that is generally composed of material with mixed strength.

7 XRD and XRF analysis

X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses were undertaken by X-Ray Minerals Ltd, UK, as the relevant equipment at the Geological Survey of Ethiopia had broken down (Progress Report No 4). The tests were conducted on 36 samples in order to study the mineralogy and chemical composition of cinder gravel samples (Tables 10 and 11). Results were averaged for each of the geographical cluster areas (Table 12). The average alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) versus silica (SiO_2) contents correspond to predominantly basaltic materials. The geochemistry of the samples did not vary greatly between cluster areas; however, there are some important differences. In the XRF data, these relate to the high MgO values for Injibara, Bahir Dar and Butajira, which correspond with their high forsterite contents (forsterite is the magnesium-rich end-member of the olivine mineral group), and the low Al_2O_3 and high Fe_2O_3 values for Hawassa. In the XRD data, important mineralogical differences include high and low values for plagioclase at Bishoftu and Injibara respectively, high forsterite values at Butajira, Bahir Dar and Injibara (referred to above), high pyroxene values at Bahir Dar and Injibara, the very high value for haematite (Fe_2O_3) at Hawassa and the presence of nepheline at Bahir Dar. Nepheline is a feldspathoid mineral typically found in silica-undersaturated igneous rocks. Compared with other areas, a high average goethite content was recorded in samples from Asasa. Goethite is an iron hydroxide derived from the weathering of other iron-rich minerals.

Ferromagnesian minerals (represented by pyroxene and forsterite) and calcium-rich varieties of plagioclase feldspar are particularly vulnerable to chemical weathering, while sodium-rich plagioclase is moderately susceptible. Samples with high contents of ferromagnesian minerals or plagioclase, such as those from Bahir Dar, Injibara and Bishoftu, may be less weathered, and therefore potentially stronger. Samples with high haematite and goethite contents, such as those from Asasa and Hawassa, might represent more weathered materials that are potentially weaker. The Bahir Dar and Injibara materials were among the strongest in AIV tests, and those from Injibara were the strongest according to the geological field description. Hawassa samples were found to be the weakest in both AIV tests and field descriptions. Therefore, there is an apparent indirect relationship between mineralogy and strength through the effects of chemical weathering.

To conclude, XRF major element geochemistry does not appear to control the strength of the cinder gravel. The XRD data, however, may provide some insight into the weathering state of cinder gravel, and therefore its likely strength characteristics. The total clay, and in particular the expansive clay, content is of considerable significance to the engineering behaviour of the material and, from the limited data available, it would appear that material extracted from below the weathered horizon contains negligible expansive clay. However, blending operations, whereby the plasticity of the cinder materials is increased through the addition of fines, need to be careful not to introduce any expansive clays from the weathered horizon.

Table 10 XRF analysis results

Element Oxide	Minimum Quantity (% by weight)	Maximum Quantity (% by weight)	No. of sites
SiO ₂	40.65	51.10	36
Al ₂ O ₃	13.81	17.79	
Fe ₂ O ₃	10.56	17.23	
MgO	2.71	12.70	
CaO	3.12	10.83	
TiO ₂	1.39	4.31	
Na ₂ O	0.22	4.28	
K ₂ O	0.09	2.01	
P ₂ O ₅	0.16	0.84	
Mn ₂ O ₃	0.17	0.29	
BaO	0.02	0.12	
SO ₃	0.01	0.09	
Loss of mass on ignition	0.00	9.28	

Table 11 XRD analysis results

Mineral	Minimum Quantity (% by weight)	Maximum Quantity (% by weight)	No. of sites
Amorphous	13.2	73.6	36
Plagioclase	5.3	48.0	36
Pyroxene	1.4	36.3	36
Forsterite	0.0	23.3	35
Hematite	0.0	24.0	24
Kaolinite	0.0	21.3	4
Illite/smectite	0.0	30.0	3
Nepheline	0.0	13.1	2
Goethite	0.0	2.4	2
Zeolite	0.0	9.7	1
Magnetite	0.0	2.4	1
Ilmenite	0.0	2.1	1

Table 12 Average percentage major element and mineral content of cinder gravel samples for each geographical cluster from XRF and XRD

		Butajira	Alemgena-Tuludimptu	Tulubolo	Hawassa	Asasa	Adama-Dera	Bishoftu	Bahir Dar	Injibara
XRF Major Element	Na ₂ O	2.92	2.27	2.25	2.86	3.22	3.04	3.26	2.44	2.43
	MgO	8.35	7.71	6.82	5.77	3.53	5.94	5.73	9.16	11.72
	Al ₂ O ₃	15.33	15.51	16.27	13.87	17.12	16.31	16.43	15.49	14.39
	SiO ₂	46.96	47.00	45.64	44.58	48.62	49.21	48.91	45.50	44.20
	P ₂ O ₅	0.52	0.42	0.60	0.72	0.56	0.50	0.48	0.42	0.39
	SO ₃	0.05	0.04	0.02	0.06	0.03	0.03	0.03	0.03	0.01
	K ₂ O	1.05	0.82	0.82	0.70	1.27	1.08	1.45	1.24	1.19
	CaO	9.50	9.80	10.03	8.98	7.25	8.52	8.91	9.63	9.29
	TiO ₂	2.40	1.86	2.14	4.29	2.43	1.74	1.94	1.71	1.54
	Mn ₂ O ₃	0.20	0.20	0.19	0.28	0.24	0.22	0.21	0.23	0.23
	Fe ₂ O ₃	11.96	11.62	11.93	16.77	12.23	11.33	11.11	11.58	12.09
	BaO	0.07	0.05	0.04	0.06	0.05	0.04	0.08	0.07	0.07
	Loss on Ignition	0.50	2.20	2.80	0.25	3.00	1.70	1.00	2.00	2.10
	Na ₂ O + K ₂ O	3.97	3.09	3.07	3.56	5.00	4.11	4.71	3.68	3.62
XRD Mineral Phase	Total clay ¹	0.00	7.50	1.50	0.00	1.67	0.20	0.67	1.60	0.33
	Plagioclase	27.67	24.50	30.50	39.00	37.00	36.00	44.33	25.40	21.67
	Pyroxene	12.33	13.50	25.00	16.00	9.33	8.20	15.67	28.80	29.33
	Forsterite	12.67	8.50	8.00	4.00	1.67	4.40	4.67	13.60	16.33
	Haematite	0.00	7.50	7.50	20.50	8.67	7.20	8.00	7.60	6.33
	Goethite	0.67	0.00	0.00	0.00	13.33	0.00	0.00	0.00	1.33
	Nepheline	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.60	0.00
	Amorphous	44.00	38.50	27.50	18.50	41.33	43.80	27.00	20.20	24.67

8 The Draft Guideline

Site investigation activities carried out in respect to engineering geology and geomorphology, laboratory tests, literature, and study of existing roads were used to draft the Guideline.

The chapters included in the Guideline are:

1. Introduction
2. Pyroclastic Materials
3. Future Extraction
4. Engineering Properties of Cinder Gravels
5. Cinder Gravels for Subgrade Replacement and Capping
6. Cinder gravels for Sub-base Layer
7. Cinder Gravels for Roadbase Layer
8. Cinder Gravels for use in Bituminous Surfacing

9. Cinder Gravels as Gravel Wearing Courses
10. Processing of Cinder Gravels
11. Other Uses of Cinder Gravels
12. Recommendations
13. Bibliography
14. Map of the Locations of Cinder Gravel Deposits in Ethiopia

A summary of the key recommendations in the Guideline are:

1. For initial selection of cinder gravels for further suitability testing, the cut-off values proposed are: base layer AIV<40 (MAIV<60), sub-base and capping layer AIV<55 (MAIV<90). Water absorption (on particles larger than 4.75 mm) of cinder gravels intended for use in the base course should not be more than 12%.
2. Before carrying out any laboratory determination of maximum dry density and optimum moisture content on cinder gravels, conduct Atterberg Limit tests.
3. For neat non-plastic cinder gravels determination of the Maximum Dry Density and optimum moisture content should be carried out by the method of re-using the specimen.
4. For neat cinder gravels that contain plastic fines, or for cinder gravels that are blended with fines (whether plastic or non-plastic), carry out determination of maximum dry density and optimum moisture content by using separate specimens (usual method).
5. Because of the low quantity of fines in cinder gravels (including blended materials), plasticity index alone is not a good measure of the influence of plasticity on expected pavement performance; it is recommended that plasticity modulus is used. The recommended maximum plasticity modulus (based on maximum plasticity index for sub-base and maximum percentage passing the 425µm sieve for the sub-base envelope) for sub-bases is therefore 360 in regions classified as wet tropical, 720 in seasonally wet tropical and 1200 in arid and semi-arid regions.
6. Reworking of cinder gravels sometimes improves both the particle size distribution and the CBR. However, in some cases, it can lead to a marked reduction in CBR. This should be assessed by laboratory testing before application in the field.
7. For most pavement layers, the required properties can be achieved by blending with plastic fines, or crushed stone, or both. Cement and lime stabilisation should only be considered in the case of design traffic levels of 0.5-1.0 million equivalent standard axles.
8. The minimum 4-day soaked CBR of the base layer for traffic classes LV2, LV3 and LV4 is recommended to be reduced from 65% to 55%. For dry areas (Weinert Number less than 4), and where appropriate drainage measures (sealed shoulders and crown height greater than 0.75 m) have been undertaken, it is recommended that the design roadbase CBR should be based on the values measured at optimum moisture content.
9. For capping and sub-base layers, the maximum allowable particle size is recommended as 75 mm (the layer thickness should be at least 150 mm for this to be acceptable).
10. For base course layers, cinder gravels with low water absorption should be used. The bituminous prime application rates recommended are: MC70 at 1.0 litre per square metre and for MC30 at 1.5 litres per square metre. MC70 is the preferred prime.
11. For use in gravel roads, gravel loss is reduced if the cinder gravel is blended with plastic fines to meet the materials specifications in the Ethiopian Low Volume Roads Manual Part B 2017. Even if the grading coefficient is not achieved but the shrinkage product is achieved, a reduction in gravel loss can be expected.

9 The stakeholder workshop

The Ethiopian Roads Authority, through its Research and Development Directorate and with support of the Africa Community Access Partnership (AfCAP), organized a workshop on the “Investigation of the Use of Cinder Gravels in Pavement Layers for Low Volume Roads”. This was focused particularly on the draft Guideline prepared as part of the project. The workshop was held on 26th October 2017 at the Alemgena Training Centre facility of the Ethiopian Roads Authority (ERA), near Addis Ababa. The Deputy Director General of ERA, Engineering Operations, Ato Mohammed Abdurrahman, delivered a welcome address and opening remarks for the workshop. A short briefing on AfCAP and its research activities was delivered by Eng. Nkululeko Leta, Deputy Team Leader- Infrastructure Research Manager for ReCAP. The workshop was attended by many stakeholders’ representatives, including consultants, contractors, association of professional engineers, regional authorities, universities, academic institutions, ERA partners, relevant ERA directorates and departments and Geological Survey of Ethiopia. In general, the workshop was highly interactive.

The following main topics were presented:

- Geological Background,
- Sampling,
- Testing,
- Discussion of XRF and XRD Analysis,
- Draft Guideline: Prospecting and Sampling,
- Draft Guideline: Testing Materials, Specifications and Applications (Capping, Sub-base, and Gravel Roads),
- Draft Guideline: Testing Materials, Specifications and Applications (Roadbase Layer, Stabilisation, Surfacing), and
- Sustainable Use of cinder gravels.

The presentations were made jointly by Dr. Gareth Hearn (Project Team Leader) and Ato Deribachew Mezgebu (ERA Highway Research Team Leader, Road Research Centre). The discussion sessions were chaired by Eng. Nkululeko Leta (Deputy Team Leader- Infrastructure Research Manager for ReCAP). Finally, the closing remarks of the workshop were delivered by Engineer Hirut (Director of South Region Contract Management Directorate).

10 Summary of comments from the peer review of the Draft Guideline

The outcome of the peer review of the draft Guideline was provided to the Consultant on 31 January 2018. Overall, the peer reviewer’s comments were very positive. The main points that were raised by the reviewer for further action are summarised below:

- The method of laboratory re-use of sample materials requires further explanation
- More discussion is required on quality control during rolling to achieve the required gradings
- Further discussion is required on the relationship between CBR, compactive effort (i.e. density) and performance
- Comment on the use of cinder gravels in pozzolanic reactions (NB the Consultant did consider this while drafting the text but decided it was not the subject of the draft Guideline, so it was omitted)
- Unsealed shoulders can lead to problems with expansive subgrades
- The use of vibration amplitude and frequency variations during compaction should be explained.

These comments were well-received and have been considered in the preparation of the final draft Guideline.

11 Scientific Paper

A scientific paper entitled "Engineering geology of cinder gravel in Ethiopia: prospecting, testing and application to low-volume roads" has been prepared and submitted to the Bulletin of Engineering Geology and the Environment journal.

The paper is currently under editorial review, and its Abstract is as follows:

Expansion of the rural road network in Ethiopia requires the availability of low-cost materials for road construction, including capping layer and subgrade improvement, subbase, base course, gravel wearing course and bituminised surface treatment. A reluctance to use these materials in the past has stemmed from the view that their properties, in terms of grading and CBR strength, are marginal and highly variable when compared to international specifications for road works. A programme of engineering geological investigation, sampling and laboratory testing illustrates the variability in the engineering properties of cinder gravels and provides comparisons between field descriptions of material strength and laboratory test results. The geographical variability in cinder gravel geochemistry and engineering properties is described and comparisons are made with cinder cone morphology, leading to the conclusion that maars and steep-sided, well-defined cones tend to yield the better materials. The performance of trial sections of road constructed using cinder gravel as subbase has been assessed and combined with the results of laboratory testing to develop a Guideline for the wider use of the material in roadworks, either directly or through processes of blending, alternative compaction methods and cement stabilisation to yield a product that can be considered as 'fit for purpose' for a range of uses in low-volume and high-volume road construction.

12 Capacity building and knowledge exchange

12.1 Capacity building

Capacity building was carried out at all the main stages of the project. This included the stages of sampling, ground truthing, laboratory testing, analysis of test results, drafting of the guideline, and dissemination. Significant periods of time were spent in the field with ERA RRC counterparts during sampling and ground truthing discussing the geology of Ethiopian volcanism and the range of materials produced, and the manner in which they were deposited, as a means of explaining the selection of samples for laboratory testing. The rationale for the laboratory tests and methods was developed in conjunction with the laboratory team. Results obtained were analysed jointly with our counterparts.

In August 2017, one of the ERA RRC counterparts should visited the TRL offices in UK. During the visit, the counterpart was exposed to the processes involved in XRF and XRD testing and analysis. Further joint analysis of laboratory test results and drafting of the Guideline was carried out.

The counterparts were also trained in preparing presentations in standard formats acceptable to wide audiences and one of the counterparts presented several sections of the Guideline at the Stakeholder Workshop. Finally, the scientific paper discussed in Chapter 11 was co-authored with counterparts from ERA RRC.

12.2 Knowledge exchange

The purpose of knowledge exchange is to disseminate the findings of the study to a wider regional or international audience to enable them to benefit from the project findings. The scientific paper discussed in Chapter 11 will go a long way in achieving this objective. In addition to that, the findings of the project were presented in the Inter-Regional Implementation Meeting (IRIM) held in Kampala, Uganda in November 2017. This facilitated the dissemination of the study findings to participants from the AfCAP and AsCAP countries. This was particularly useful to attendees from Uganda, Kenya and Tanzania where cinder materials occur to a limited extent. Further dissemination will be conducted in upcoming international conferences.

13 Challenges faced

The main challenge faced was the prolonged period of laboratory testing of materials. This occurred as a result of insufficient equipment being available for the amount of testing required, particularly, a shortage of CBR moulds. In addition, there was frequent breakdown of the automatic compaction machine. These factors contributed to lengthy delays in the testing programme.

Construction of the new RRC facilities is in progress, and this should alleviate the likelihood of similar problems occurring in the future.

14 Recommendations for future research projects

Guidelines reflect current knowledge. They are meant to be live documents, which can be updated from time to time when new knowledge becomes available. Future improvements to the Guideline produced under this project can be achieved by the Ethiopian Roads Authority through its Road Research Centre as follows:

1. Select existing roads where cinder gravels have been used in different pavement layers. Sections for monitoring should be selected and marked out on these roads and routine performance measurements carried out. One such section of importance that should be included in the study is the Durbate town section near Bahir Dar City. This is the only known existing road where cinder gravel has been used in the roadbase layer. Another road that should receive special attention is the Tulubolo – Kella road (first 2 km at Tulubolo Town). This is because a cinder gravel sub-base has been laid directly over black cotton soil and no deformation defects have yet been observed. Other roads where monitoring should continue are Alemgena-Butajira, Assela –Dodola, Shashemene – Dodola, and Combel village.
2. Construct trial sections where cinder gravels of varying quality are used. The locations for the trials could be based on the current research areas where samples were taken and tested, and where quantities are large. The AIV and water absorption are good indicators of particle quality that should be assessed in the trials. As with all research trials, a thorough design supported by materials testing and monitoring should be carried out to ensure that the results are reliable and can be applied with confidence.
3. It is possible that the use of surface geophysical testing may enhance the process of materials prospecting. It would be advantageous for ERA to discuss what might be achievable with an Ethiopian specialist and perhaps carry out some trials.

When more evidence is gathered through the above recommendations, then the Guideline could be turned into a standalone manual, or be wholly incorporated in the next revision of the LVR Manual, or remains as a guideline. The decision will have to be made by ERA after more evidence is gathered.

15 Conclusions

The study has demonstrated that most deposits of cinder gravels can be used in the construction of low volume roads. However, the nature of the cinder material is such that successful exploitation of the material requires changes to be made in site investigation activities, sampling and laboratory testing procedures. This Guideline also recommends changes to some specifications for the use of cinder gravels. These are based on the results of previous research and from experience in their use in current projects in the road sector in Ethiopia.

The recommendations for additional testing and blending of these gravels may be more onerous than the usual testing routine but the benefits from using this material resource, which is abundant in parts of Ethiopia, has the potential for having a major impact on road provision and aiding the development of rural areas.

Locating cinder gravel deposits

The surface indicators for locating cinder deposits appear to make it easier to locate this type of materials than other types of natural gravels. Most deposits are to be found within volcanic cones, which give the clearest surface evidence of the location of these materials. However, predicting the type (quality) of material that lies within them either from their location or shape is difficult due to the extreme variability of the material contained within the cones. General guidance for locating the most likely useable deposits is included in the draft Guideline, but the variable nature of cinder material makes it very difficult to predict material quality and consistency from the surface.

Site investigation

The variability of cinder gravels is due to the method of their formation, as described in the Guideline. Weak and relatively strong materials can be found within the same cone. Multiple trial pitting is recommended to locate the best materials, especially for cones from which materials have not yet been excavated. The accurate estimation of particle strength in trial pit profiles is an essential part of their evaluation. Reinstatement of test-pitting excavations is mandatory.

On-site tests for evaluating materials sources

Preliminary on-site testing (geological methods) was carried out during this study to make an initial approximate assessment of the quality and properties of the material present in the borrow areas. This approach is also recommended for future routine investigations. It is designed to reduce the need for the transportation and laboratory testing of samples that are unlikely to be suitable for the desired purpose as well as for identifying the different material types present at the same site, which could be used in combination (e.g. for blending). A portable AIV apparatus should be used to help streamline the sampling and laboratory testing.

Laboratory testing

Some cinder gravels display unusual results when using standard laboratory tests. The Guideline makes recommendations on the best way of dealing with cinder gravels that behave differently in these tests if, for example, the maximum dry density value is difficult to determine or, as in some cases, continues to increase within the normal testing limits.

Application of the results

Tests on many of the deposits investigated indicated that cinder gravels can be used in road construction projects in their natural or blended state. Procedures that can be used both on site and during laboratory testing, which are designed to assess and enable their use, are described in the Guideline. These include effecting changes to the particle size distribution, Atterberg Limits and CBR. As a result of these procedures, some of the materials investigated can be used in each of the structural layers of the pavements of low volume roads.

Cinder materials have also been used in surfacing trials as a graded-aggregate bituminous seal. The recommended spray rates for the use of the porous materials in graded aggregate surfacing are given.

In circumstances where materials of greater strength are required but unavailable locally, an alternative option is to stabilise (with lime or cement) the cinder gravel, although this option should be considered only as a last resort as the costs are considerably greater than using neat or blended material.

Trial sections

At the beginning of any project utilising cinder gravels, a trial section of at least 200 m should be used to determine blending proportions on site, compaction regimes that produce the required dry density and particle size distribution, and the amount of compaction water required. This trial section should be removed and reconstructed with the correct proportions and procedures determined through the trials.

Borrow area management

It is evident from this study, that the extraction of cinder material from many borrow areas has not been well managed. This is partly due to extraction by local contractors and villagers for housing and other

projects, but it is also evident that excavation of larger quantities of material has also not been well managed in some cases. The result is that many parts of the countryside are left scarred with numerous borrow areas not re-instated and quarries in cones left unworkable, and in some areas potentially dangerous. Some sources that have been partially excavated should be blasted under controlled conditions to allow further use of the material. It is recommended that stricter supervision of the extraction of these materials needs to be implemented to limit extent ensure the limitation of environmental impact, to enable safe and sustainable use to be made of these materials for future projects and to restore the land for productive use.

It is reported that changes governing the protection of some of the cones from extraction of materials is under consideration by the Ethiopian Government. We recommend that the RRC should liaise with the Environmental Protection Agency and the Geological Survey of Ethiopia and request the relevant Ethiopian Government institution to involve all stakeholders in deciding which cones should be protected. Further to this, no new borrow pits in virgin cones should be investigated or opened up without official approval.

16 References

- Ayele A, Tadesse E, Segni G, Dessie K, and Berhanu G, 2002. Thesis: Stabilization of Cinder Gravels with Volcanic Ash and Cement. Addis Ababa, Ethiopia: Addis Ababa University.
- Berhanu G, 2009. Stabilizing cinder gravels for heavily trafficked base course. Journal of EAEA, 26: 23-29.
- ERA, 2017. Low volume roads manual, Ethiopian Roads Authority, Addis Ababa.
- Hadera Z, 2015. The potential use of cinder gravel as a base course material when stabilised by volcanic ash and lime. MSc thesis submitted to the University of Addis Ababa, Ethiopia.
- Newill D, Duffell C G, Black R E, Gulilat G, 1979. Investigations of Cinder Gravels in Ethiopia 2. Road Trials. JRRP Report No. 12, Ethiopian Roads Authority, Addis Ababa.
- Newill D, Aklilu K, 1980. The location and engineering properties of volcanic cinder gravels in Ethiopia, 7th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Accra, Ghana, 1-7 June 1980: 21-32.
- Newill D, Robinson R, Aklilu K, 1987. Experimental Use of Cinder Gravels on Roads in Ethiopia. 9th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Lagos, Nigeria: 467-488

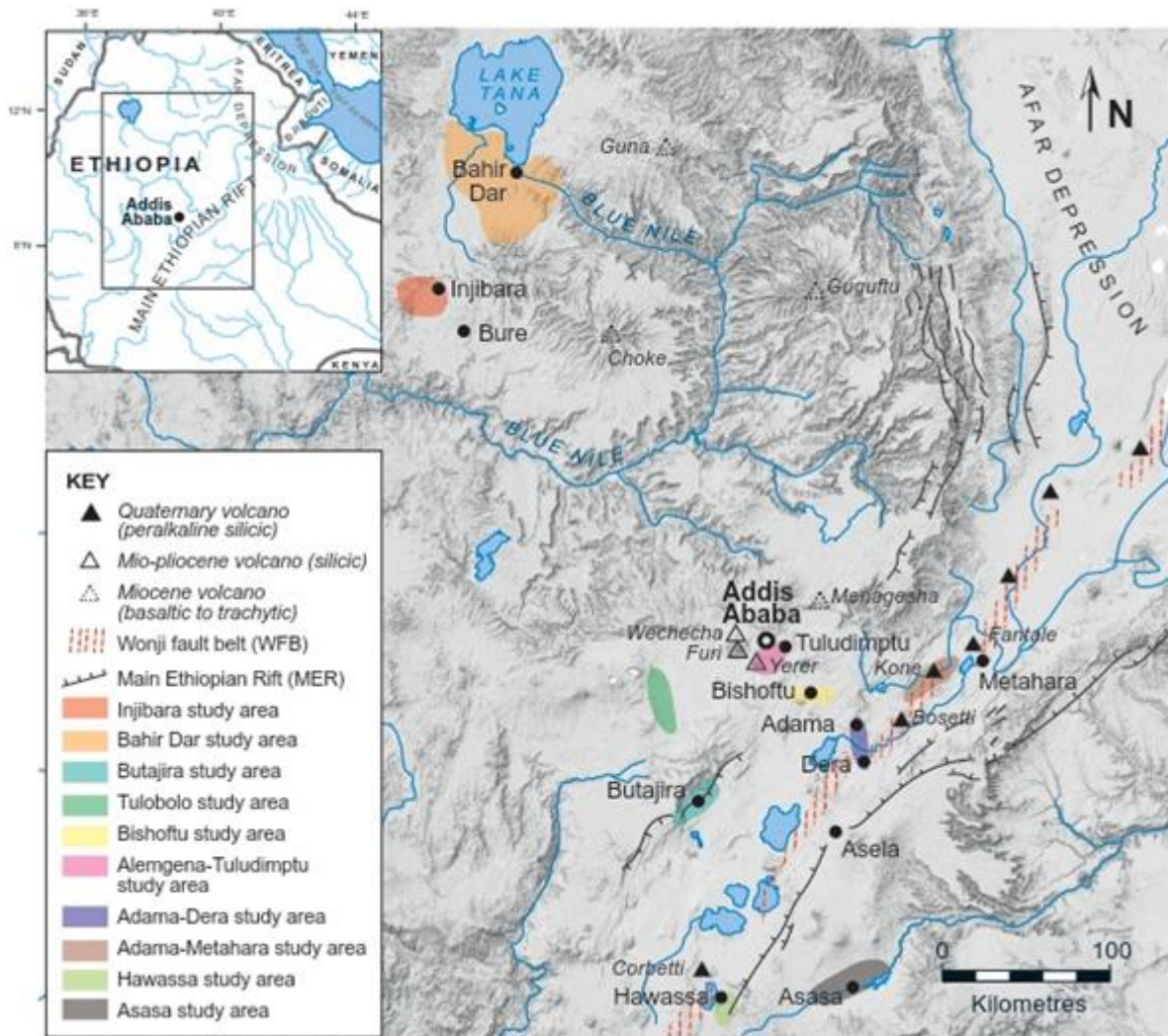
Annex 1 Location of study sites

Location	Site	Category	GPS Coordinates
Location 1 Alemgena-Butajira Rd 122km from Addis Ababa	Site 1	Cat 1	438925 / 904439
	Site 2	Cat 1	438848 / 904167
	Site 3	Cat 3	438913 / 904440
Location 2 Alemgena-Butajira Rd 30km from Addis Ababa	Site 1	Cat 1	462330/ 978155
	Site 2	Cat 1	
Location 3 Butajira-Zway	Site 1	Cat 1	437310 / 901285
	Site 2	Cat 4	437268 / 901189
Location 4 Butajira-Hossana Rd	Site 1	Cat 1	432042 / 895488
Location 5 Butajira-Hossana	Site 1	Cat 1	429064 / 891320
Location 6 Tulubolo	Site 1	Cat 1	401900 / 974047
Location 7 Tulubolo	Site 1	Cat 1	414722 / 955767
	Site 2	Cat 5	414722 / 955767
	Site 3	Cat 4	414556/ 955775
Location 8 Hawassa	Site 1	Cat 1	444591 / 780598
Location 9 Hawassa	Site 1	Cat 1	443911 / 776512
Location 10 Hawassa (Rubbish Dump)	Site 1	Cat 3	445940 / 778241
Location 11 Dodola-Assela	Site 1	Cat 1	529599 / 800549
Location 12 Dodola	Site 1	Cat 1	540358 / 799821
Location 13 Dodola-Shashemene	Site 1	Cat 2	490564 / 778928
	Site 2	Cat 2	490439 / 778938
Location 14 Adama - Dira	Site 1	Cat 1	536528 / 913537
Location 15 Adama -Dira	Site 1	Cat 3	535374 / 933089
Location 16 Adama -Dira	Site 1	Cat 1	533575 / 937332
Location 17 Adama -Dira	Site 1	Cat 1	532500/ 938460
Location 18 Adama -Dira	Site 1	Cat 1	532319/ 938514
	Site 2	Cat 1	532334 / 938481
Location 19 Bishoftu	Site 1	Cat 1	502495 / 970384
Location 20 Bishoftu	Site 1	Cat 1	507806 / 970503
Location 21 Bishoftu	Site 1	Cat 1	503507 / 968115
Location 22 Tuludimptu	Site 1	Cat 1	479478 / 979044
Location 23 Bahir Dar	Site 1	Cat 1	320321/ 1281924

	Site 2	Cat 1	320314/ 1282004
	Site 3	Cat 4	320409/ 1281865
Location 24 Bahir Dar	Site 1	Cat 1	312409/ 1284975
Location 25 Injibara	Site 1	Cat 1	275622/ 1210523
	Site 2	Cat 1	275538/1210569
	Site 3	Cat 2	275506/1210538
Location 26 Gondar Rd	Site 1	Cat 4	331955/ 1287559
	Site 2	Cat 1	331947 / 1287552
	Site 3	Cat 1	331834 / 1287598
Location 27 Kunzila	Site 1	Cat 1	283462/ 1310777
Location 28 Injibara	Site 1	Cat 1	264588 / 1210015
Location 29 Injibara	Site 1	Cat 1	273412 / 1210050
Location 30 Kessa	Site 1	Cat 5	277404/ 1206101
GT1 Adama	Site 1	Cat 1	501288/966687
GT2 Akaki	Site 1	Cat 1	499212/ 969211
GT3 to the east of the Expressway at Bishoftu	Site 1	Cat 1	503329/ 970708
GT4 South of Bishoftu	Site 1	Cat 1	500708/ 965388
GT5 ENE from Bishoftu	Site 1	Cat 1	510557/ 971752
GT6A Western outskirts of Bishoftu	Site 1	Cat 1	495831/ 965899
GT6B Western outskirts of Bishoftu	Site 1	Cat 1	490762/ 963583
GT7 To west of Injibara	Site 1	Cat 1	266276/ 1210177
GT11 South of Addis Kidame	Site 1	Cat 1	270491/ 1223888
GT15 South of Bahir Dar	Site 1	Cat 1	319306/ 1276716
U1 Bishoftu	Site 1	Cat 1	502139/ 970113
U2 Bishoftu	Site 1	Cat 1	501937/ 967163

U3 Bishoftu	Site 1	Cat 1	503823/ 968257
U4 Bishoftu	Site 1	Cat 1	503772/ 964197
U5 Adama- Awash Road	Site 1	Cat 1	533967/ 940037
U6 Adama- Awash Road	Site 1	Cat 1	582105/ 978803
U7 Adama- Awash Road	Site 1	Cat 1	578106/ 976591
U8 Adama- Awash Road	Site 1	Cat 1	578021/ 976043
U9 Adama- Awash Road	Site 1	Cat 1	5753111/ 973612
U10 Adama- Awash Road	Site 1	Cat 1	560913/ 963508
U11 Red Bahir Dar	Site 1	Cat 1	305120/ 1266257
U11 Black Bahir Dar	Site 1	Cat 1	305120/ 1266257
Key			
Cat 1: Non-plastic cinder gravels			
Cat 2: Plastic cinder gravels			
Cat 3: Fine-grained (sandy) non-plastic cinder gravel			
Cat 4: Very fine-grained blending material (yellow)			
Cat 5: Very tough non-plastic cinder limited quantity			
GT: Ground truthing location			
U: Visited location but not sampled			

Annex 2 Locations of cinder deposits



Annex 3 Summary of table of field strengths

Area	Site	Geology	Geomorphology	Air photo interpretation	Dimensions (m)			Cone slope (°)	Crater / summit dia (m)	Dip of beds (°)	Field Strength (Geological Description)	
					Base length	Base width	Height				Field	Ave strength plus AIV%
Butajira	1	Hol. Wonji basalt & pyroclastics	Crater rim, possibly tuff ring or maar	Side of a crescentic-shaped crater -part of a larger complex	580	430	17	-	410	Not known/none		
	3	Hol. Wonji basalt & pyroclastics	Possible collapsed inner cone rim	Complex & multiple event, central cone, several cone collapses & lava flow	860	860	45	-	400	0-20		
	4		Base of cone rim	Small, steep-sided cone with collapse to the north	460	400	47	-	120	Up to 30		
	5		Base of cone/dome	Very small steep sided cone without vent. On side of a much larger volcano	360	220	18	-	NA	-		
Alemgena-Tuludimptu	2	Plio. welded -unwelded pyroclastics	Very subtle dome, i.e. not a cone		NA	NA	NA	-	NA	10-25	47	
	22	Akaki Unit Basalt, more vesicular & oxidised than Bishoftu Basalt	Much of original topography removed by excavation, cone without crater		770	630	66	20	NA	25-30		
	U13	Welded and unwelded pyroclastic flow	Dome, most of topography excavated					-	NA	Inclined	NA	
Tulubolo	6	Olig.-Mio. Tarmaber-Megezez Fm Chefedonsa pyroclastic deposits	Slope of apparent 'lava dome'		735	400	50	<25	NA	20-25		
	7		Slope of apparent 'lava dome'		500	500	17	-	NA	30	40	

Hawassa	8	Hol. Hawasa-Butajira Basalt	Topography removed by excavation	Partial remnant of an ancient crater				-	-	15-20, max 35	48	
	9		Most of topography removed by excavation. Formed on summit of low plateau/'dome'	Very indistinct low-amplitude 'cone' with apparent collapse & lava flow. Same as 8	380 (Estimated)	250 (Estimated)	16 (Estimated)		NA	Variable steep	44	
	10		Two main areas of raised ground (low amplitude ridges), collapsed & rafted blocks. Remnants of a much larger crater				30 (Estimated)	-	NA	-		
Asasa	11	Chilano ignimbrites and trachytes	Partially collapsed, isolated cone above plain.		650	490	60	-	260 (Estimated)	> nat slope		
	12		Cone without crater, occupying higher ground		550	475	60	-	110	> nat slope	25	
	13	Mio.-Plio. Nazaret & Dino Fm welded ignimbrite			416	380	17	<15	NA	15-20		
	U14	Ginidhir plateau basalt over Nazaret Group stratoid silicics	Cone, most of topography excavated, occupies raised ground		260 (Estimated)	170 (Estimated)	10 (Estimated)	-	NA	-	NA	
Adama-Dera	14	Hol. Wonji basalt & pyroclastics	Cone without crater		600	450	50	-	NA	28		
	15	As 14, Dera Sodore Unit-poorly-welded ash, ignimbrite, rhyolite lava & pumice	Cone, lava flow from base, cone collapse		600	400	54	26	NA	28		
	16		This is a collapsed cone with an extended 'ridge' into which the borrow pit is excavated, i.e. not into the cone. The whole feature is located on a subtle elongate dome. Located in Wonji cone field.	Very rounded, old cone with small ridge line to the side (SW) and collapsed rim to the NE. No evidence of lava, therefore extremely old. Surrounded by apparent subtle perimeter of raised ground.	500	500	30	18-20	200	26	50	
	17		Possibly located within collapsed cone material	Distinct steep-sided cone with vent collapsed to the SE. Small extension ridge to the SW. Probably a very eroded remnant of a one multiple feature. Some minor workings evident at 18	400	400	47	33-35	130	35	37	
	18		Located on a spur from the main cone of 17		NA	NA	20 ridge	25	NA	25	32	
	U5		Lower slopes of cone with crater collapse. Fault scarp across cone		800	800	60	23-29	330	23		
	Bishoftu		19	Cone with possible collapsed crater, located in the vicinity of the Debre Zeit maar field		290	290	25	-	70 summit	Parallel to slope	43

Bahir Dar	20		Elongate dome, original topography removed, located in the vicinity of the Debre Zeit maar field		220	125	10	-	NA	-	71		
	21		Possibly located on an ancient rim segment, i.e. very little remains of the original feature, located in the vicinity of the Debre Zeit maar field				16	15-17		20-25	9		
	U1	Plio. Bofa basalt	Cone next to No 19 with a circular flat summit		282	305	20	-	106	-	NA		
	U2		Cone with collapsed crater, occupying raised ground (dome?). Near maar field		444	465	20	10	Crater collapse.	25-30	NA		
	U3		Opposite side of ridge to No 21, near Debre Zeit maar field				16	15		-	NA		
	U4		Cone remnant near Debre Zeit maar field		800	800	25	15-20	530	10-15	NA		
	GT1											56	
	GT2												
	GT3Grey											54	
	GT3Red											45	
	GT4											25	
	GT5												
	GT6A	Hol. Wonji scoria cones and fallout deposits										42	
	GT6B											28	
23	Quat. basalt	Cone, crater breached at southern end	Steep-sided, elongate 'coiled' rim with flat vent surface	640	728	14	-	375	35				
24		Much of original topography excavated, cone without crater	Crescent-shaped, steep-sided half-cone. Appears extremely old	700	300		18-35	NA	33	29			
26		Original topography completely removed		Very dissimilar to all others. Landscape comprises mesas & buttes, possible plugs, but no cones	263	223		15-20		20-25			
27					150	93		10-15		10-15	47		
U11	Quat. Basalt	Crater with filled and lava flows from cone to NW		390	390	15	30-35	200 summit	-	NA			

	GT15	Quat. scoria									25	
Injibara	25	Quat. basalt	Lower slope of probable ancient volcano or maar		475	475	106	15	475	0-10	25	
	28	Olig. Tarmaber Gussa Fmtn alk basalt & trachyte	Cone with possible crater, lava flow, adjacent maar and tuff ring	Elongated NNW-SSE, double vented, southerly vent collapsed	300	475	20	28	collapse	18	34	
	29		Breached cone with crater, cones & craters nearby	Very steep-sided, crater open to the WNW, large and the side walls are irregular. Apparent small vent within the main vent, judged to be very old. Elongated WNW-ESE	1130	1150	80	-	500	-	34	
	30		Possible small segment of ancient rim				20	20		20	40	
	U12	Oligo.-Mio. Tarmaber Gussa Fmtn – alk basalt, trachyte	Broken rim of ancient maar or tuff ring		1170	1170	30	-	350	-		
	GT7	Lower Tertiary Upper Basalt										
	GT10	Quat. Pyroclasts (olivine basaltic cones & crater rims)										
	GT11 Grey	Olig.-Mio. Tarmaber-Gussa Fmtn										
GT11 Red										36		
Adama-Metahara	U6	Pleist. – sub-recent basalts	Cone with subtle crater. Extensive lava flow from base		450	350	20	25	150	22		
	U7		Surrounded by other cones and recent lava flows. Possibly part of a widespread deposit from remote source.		NA	NA	NA	30	NA	10	NA	
	U8	Hol. Aphyric basalt	About 50% of rim remains after explosion & lava flow		380	380 (Estimated)	10	35 (Estimated)	250 (Estimated)	35	NA	
	U9	Pleist. unwelded tuff & pumice	Cone, all of original topography removed by excavation		170	150		-		-	NA	
	U10	Pleistocene to sub-Recent basalt and Dino ignimbrite	Possibly two coalescing cones, no crater(s)		500	310	35	30	NA	30		

Annex 4 AIV, Specific Gravity, and Water Absorption Results

Location	Site	Category	AIV-Dry (%)	MAIV-Dry (%)	Apparent Specific Gravity (gm/cc)	Surface Dry Gravity (gm/cc)	Bulk Gravity (gm/cc)	Water Absorption (%)
Location 1 Alemgena-Butajira Rd 122km from Addis Ababa	Site 1	Cat 1	37	54	2.10	1.90	1.74	10
	Site 2	Cat 1	44	68	1.90	1.75	1.57	12
	Site 3	Cat 3	57	96	2.10	1.95	1.79	9
Location 2 Alemgena-Butajira Rd 30km from Addis Ababa	Site 1	Cat 1	44	57	2.09	1.92	1.67	12
	Site 2	Cat 1	48	75	2.49	1.94	1.50	26
Location 3 Butajira-Zway	Site 1	Cat 1	37	59				
	Site 2	Cat 4	39	65	2.30	2.10	1.92	9
Location 4 Butajira-Hossana Rd	Site 1	Cat 1	38	55	2.25	2.02	1.88	9
Location 5 Butajira-Hossana	Site 1	Cat 1	39	57	2.37	2.09	1.89	11
Location 6 Tulubolo	Site 1	Cat 1	39	57	2.19	1.92	1.70	13
	Site 2	Cat 2	38	56	2.09	1.87	1.67	12
Location 7 Tulubolo	Site 1	Cat 1	40	55	2.30	1.96	1.70	15
	Site 2	Cat 3	57	96	2.50	2.20	1.99	10
Location 8 Hawassa	Site 1	Cat 1	48	75	1.64	1.53	1.35	13
Location 9 Hawassa	Site 1	Cat 1	44	68	2.00	1.85	1.66	11
Location 10 Hawassa (Rubbish Dump)	Site 1	Cat 3	62	106				
Location 11 Dodola-Assela	Site 1	Cat 1	54	94	1.57	1.45	1.25	16
Location 12 Dodola	Site 1	Cat 1	25	35	2.38	2.03	1.86	12
Location 13 Dodola-Shashemene	Site 1	Cat 2		51				
Location 14 Adama - Dira	Site 1	Cat 1	17	28	2.16	1.90	1.68	13
Location 15 Adama -Dira	Site 1	Cat 3	40	58	2.10	1.97	1.81	8
Location 16 Adama -Dira	Site 1	Cat 1	50	79	1.76	1.58	1.35	17
Location 17 Adama -Dira	Site 1	Cat 1	37	53	2.00	1.87	1.74	8
Location 18 Adama -Dira	Site 1	Cat 1	32	45	2.25	2.00	1.79	11
Location 19 Bishoftu	Site 1	Cat 1	43	70	2.17	1.97	1.81	9
Location 20 Bishoftu	Site 1	Cat 1	71	130	1.90	1.55	1.17	33
Location 21 Bishoftu	Site 1	Cat 1	9	14	2.62	2.44	2.33	5
Location 22 Tuludimptu	Site 1	Cat 1	37	53	2.41	2.02	1.80	14
Location 23 Bahir Dar	Site 1	Cat 1	23	30	2.30	2.09	1.92	9

	Site 3	Cat 5	27	37	2.19	2.05	1.94	6
Location 24 Bahir Dar	Site 1	Cat 1	29	41	2.05	1.88	1.72	10
Location 25 Injibara	Site 2	Cat 1	25		2.17	1.97	1.81	9
Location 26 Gondar Rd	Site 2	Cat 1	50	78	2.10	1.83	1.58	16
	Site 3	Cat 1	36	54	1.60	1.49	1.27	18
Location 27 Kunzila	Site 1	Cat 1	47	72	2.08	1.77	1.48	20
Location 28 Injibara	Site 1	Cat 1	34	49	2.00	1.86	1.69	10
Location 29 Injibara	Site 1	Cat 1	34	47	2.30	1.97	1.71	15
Location 30 Kessa	Site 1	Cat 5	40	59	2.34	2.09	1.90	10
U11 Red Bahir Dar	Site 1	Cat 1	50					
U11 Black Bahir Dar	Site 1	Cat 1	37					
GT1 Nazaret	Site 1	Cat 1	56					
GT2 Akaki	Site 1	Cat 1	11					
GT3 Black Nazaret	Site 1	Cat 1	54					
GT3 Red Nazaret	Site 1	Cat 1	45					
GT4 Adama	Site 1	Cat 1	25					
GT5 Adama	Site 1	Cat 1	44					
GT6A Akaki	Site 1	Cat 1	42					
GT6B Akaki	Site 1	Cat 1	28					
GT7 Bure	Site 1	Cat 1	45					
GT11 Black Bahir Dar	Site 1	Cat 1	36					
GT11 Red Bahir Dar	Site 1	Cat 1	46					
GT15 Bahir Dar	Site 1	Cat 1	25					
GT16	Site 1	Cat 1	31					

Apparent Specific Gravity, Gsa. The volume measurement only includes the volume of the aggregate particle; it does not include the volume of any water permeable voids. The mass measurement only includes the aggregate particle. Apparent specific gravity is intended to only measure the specific gravity of the solid volume; therefore, it will be the highest of the aggregate specific gravities. It is formally defined as the ratio of the mass of a unit volume of the impermeable portion of aggregate (does not include the permeable pores in aggregate) to the mass of an equal volume of gas-free distilled water at the stated temperature.

Bulk Saturated Surface Dry (SSD) Specific Gravity. Volume measurement includes the overall volume of the aggregate particle as well as the volume of the water permeable voids. The mass measurement includes the aggregate particle as well as the water within the water permeable voids. It is formally defined as the ratio of the mass of a unit volume of aggregate, including the weight of water within the voids filled to the extent achieved by submerging in water for approximately 15 hours, to the mass of an equal volume of gas-free distilled water at the stated temperature.

Bulk Specific Gravity (Bulk Dry Specific Gravity), Gsb. The volume measurement includes the overall volume of the aggregate particle as well as the volume of the water permeable voids. The mass measurement only includes the aggregate particle. Since it includes the water permeable void volume, bulk specific gravity will be less than apparent specific gravity. It is formally defined as the ratio of the mass of a unit volume of aggregate, including the water permeable voids, at a stated temperature to the mass of an equal volume of gas-free distilled water at the stated temperature.

Annex 5 Selected site photographs



General view of cone



Benched excavation into consistently-dipping scoria



Beds dipping slightly steeper than ground slope



Well-stratified basalt and scoria gravel



Site 1 material internal structure (slightly vesiculated)



Vesiculated scoria



Typical variability in deposits of predominantly vesiculated scoria

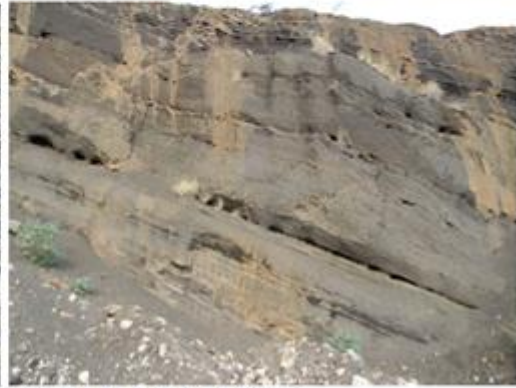




Site/Sample 1 collection



Basalt and scoria gravel



Steeply dipping, stratified deposits