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Discussion document

Cement stabilization of road pavement materials: Laboratory testing programme Phase 1

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Abstract:

The introduction of the SABS EN 197-1 (SANS 50197-1) specification for cements in South Africa resulted in a change in the range of cements available for material stabilization for road layers. An investigation was carried out to assess the impact of seven of the available cements on two typical South African construction materials. Chemical analyses of the two materials showed no incidences of unusual components that would lead to specific problems during cement stabilization of the materials.

There is no doubt that both conditioning time and material temperature during the early stages of hydration of the cement affect the compacted density and unconfined compressive strength and indirect tensile strength (these three are obviously interrelated) negatively. However, comparison with one documented example indicates that the current cements probably have an equal or even lesser effect in this regard than the older cements.

No dominant trends relating to the behaviour of the different cements could be isolated during the project. It is clear, however, that the combination of cement type and material under the expected construction conditions will affect the density and strength of material obtained in the field. On this basis, all potential construction materials that are to be stabilized should be tested with the cements likely to be used on the proposed project and under the expected ambient conditions to identify the expected allowable construction time and the combination which provides the longest workability/ construction time should be selected.

Keywords:

Cement stabilization, specification, cement properties, EN 197-1

Proposals for implementation:

Workshop findings

Related documents:

CR-2001/68

Signatures:				
Language Editor	**Technical Review**	**Prog Manager**	**Info Centre**	**Director**

TERMS OF REFERENCE

CSIR Transportek, in collaboration with VKE, Soillab and Frank Netterberg, was contracted by the Cement and Concrete Institute to investigate the influence of the new SABS EN 197-1 cement specifications on the use of cement as a road material stabilizer.

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1. INTRODUCTION

1.1. Background

Current documentation used to assist engineers in South Africa with the design and construction of cement-stabilized layers for roads[1,2] is primarily based on SABS 471 requirements[3] (and to a lesser extent on SABS 626, 831 and 1466) and does not adequately account for the new range of cements introduced with the EN 197-1 specification[4].

An association of CSIR Transportek, Frank Netterberg and VKE (Soillab) was appointed by C&CI to investigate the impact of the new range of cements manufactured under the SABS EN-197-1 specification on the design and construction of pavement layers stabilized with cement, with a view to updating TRH 13 and providing guidelines to users on the selection of the new cement types for use and the most practical techniques of construction using these cements. An important aspect to be investigated was whether or not the new cements adversely affect stabilization in hot weather.

This report (Phase 1) discusses the results of an initial laboratory testing programme including limited interpretation and draws preliminary conclusions. Significantly more interpretation is considered to be possible if more time and funding should become available.

1.2. Terms of Reference and Objectives

The Terms of Reference for the project were to identify the impact of the new range of cements since the original TRH 13[1] was released in draft form in 1986, on the behaviour and performance of cement-stabilized road materials.

The main objectives of the project are to:

- Compare the chemical and physical properties of the current generation of cements with those on which TRH13 was based.
- Identify the implications of the range of cements that is being produced under the EN197-1 specification on road stabilization practice.
- Evaluate the rate and the process of strength development of stabilized materials resulting from the use of the new range of cements.

- Make recommendations on the specification and use of cement for stabilization of road materials.

In the project proposal, the project was divided into three tasks as follows:

Task 1

This task involved a survey carried out by a short pro-forma questionnaire of the industry to evaluate any changes in the cement production process, known changes in chemistry, changes in quality assurance testing, and any other aspects regarded as important during preparation of the questionnaire, resulting from the new cement specification.

Task 2

The information obtained from Task 1, together with the new specifications for cement, was to be evaluated in terms of the theoretical chemical reactions affecting the soil stabilization process. This was to be backed up with limited laboratory testing in an attempt to determine whether there are any notable differences between the current and the old range of cements. This testing was to be dependent on the viability of obtaining cement representative of the previous specification, and assumed that certain producers of cement had not changed their source materials or production process significantly.

Task 3

The final task of this proposal will evaluate the strength gain paths of different cements on a range of typical road construction materials and emulsion-treated soil and relate the two, seven, and 28-day strengths of the new specifications to traditional stabilization specifications and construction procedures/timing.

The final output will be a document that can be used in conjunction or as an addendum to TRH 13 until the current version of TRH 13 is upgraded. The results will also be widely publicised using the normal C&CI and CSIR channels, local technical periodicals and journals where appropriate.

Approval to carry out Tasks 1 and 2 was received from C&CI in July 2001. Based on the findings of these, Task 3 may or may not need to be redefined and would commence in the next financial year.

Task 1 was carried out and reported in CR-2001/68[5]. This report summarises the first phase of testing (Task 2) based on the findings and recommendations of the above report.

2. THE MATERIALS

2.1. Introduction

Phase 1 of this investigation identified the need to test 5 different materials typically used as stabilized layers in roads in order to identify the differences in reaction between the SABS EN197-1 cement types (now SANS 50197-1) and the different materials. As the logistics and cost of testing this number of materials was beyond the scope of the project at the time, two materials representing typical materials were selected for preliminary testing. These were to include a dolerite with a plasticity index of 10 to 15 per cent and one with a plasticity index of less than 6 per cent[5]. The test methods used were those in TMH1[6] or in NASAWC[7] unless otherwise indicated.

In order to classify the materials fully various physical, chemical, mineralogical and classification tests were carried out on each material according to the method shown:

- Grading: TMH1, methods A1(a) and A6
- Atterberg limits and bar linear shrinkage: TMH1, methods A2, A3, A4
- Cone liquid limit: BS 1377: 1975, method 2
- Maximum Dry Density (MDD) and optimum moisture content (OMC): TMH1, method A7
- California Bearing Ratio (CBR) and swell at 3 efforts: TMH1, method A8
- Saturated paste conductivity and pH: TMH1, method A21T with pH on same paste
- pH (KCl) and pH (water): NASAWC, methods 2, 3
- Cation exchange capacity and exchangeable cations: NASAWC, method 12 on < 2mm fraction
- Organic carbon (Walkley-Black): NASAWC, method 34 on <2mm fraction
- Organic impurities: TMH1, method B6 on <4.75 mm fraction
- X-ray Diffraction (XRD) analysis on crushed < 37.5 mm sample and < 0.002-mm fractions including clay treatments
- Acid-soluble sulfate: BS 1377:1975, method 9, crushed < 2mm, no correction
- X-ray Fluorescence (XRF) analysis including major elements, H_2O+, CO_2, Loss on Ignition (LOI) on crushed < 37.5 mm sample
- Minor and trace elements: ICP-MS
- Amorphous silica: Eggimann *et al*[8] on the fraction < 0.425 mm

- Initial consumption of cement (ICC) and Initial consumption of lime (ICL) (constant pH and after 28 days): improved CSIR/DoT method on whole grading crushed < 19 mm
- Methylene blue adsorption (MBA): SABS 1243: 1994 and New Zealand Standard 4407: 1991 on fraction < 0.075 mm

2.2. Weathered dolerite (CCI 1)

A highly weathered dolerite (Weinert Pick and Click Index[9] = 10) was identified and sampled by Gautrans during a routine regravelling operation. The material was obtained from a borrow pit on the farm Rietspruit (Mr Piet Botha) in the Vereeniging District near Road P243-1. The material was removed from the borrow pit using a back-actor. About 8 m^3 were delivered to Soillab where it was scalped through a 37.5-mm sieve, carefully mixed, and riffled to provide as representative samples for testing as was possible. The fraction coarser than 37.5 mm was discarded.

The material was a light olive brown (Munsell 2.5Y 5/6) when dry and dark brown (Munsell 10YR3/6) when wet, relatively fine, sandy gravel (residual dolerite). Individual particles were light brown, but showed obvious plagioclase and pyroxene with significant brown iron oxide staining when broken. The particles were soft and could mostly be broken between the fingers.

As the material was used for regravelling unsealed roads in the area, no relevant performance history was available.

2.3. Weathered norite (CCI 2)

Difficulty was experienced with the location of low-plasticity dolerite gravel. A number of material sources was tested but none had plasticity indices less than 6 per cent. Eventually, a sample of dark grey speckled white (Munsell 10YR 4/1) when dry and black (Munsell 10YR 2/1) when wet, weathered (Weinert Pick and Click classification[9] of 6 to 7) norite, which was identified as non-plastic, was obtained from a borrow pit supplying selected layers and subbase to the N4 Bakwena Highway. The borrow-pit was located near the Hernick Mine outside Brits and the material was used for 20 to 30 km of selected layers (natural) and two 150 mm thick stabilized layers using 2.5 per cent CEM II B-V 32.5 cement. The material was relatively friable (it was ripped and dozed in the borrow pit) and although it contained fragments of hard almost unweathered material, it was

easily worked in the borrow pit by ripping. Significant oversize material (> 37.5 mm) needed to be removed during the sample preparation for testing and was discarded.

It was noted during construction in early December that there was a rapid set when used with a recycler and the material could be easily scuffed with a boot after compaction. However, after returning from the Christmas break, material unsatisfactorily compacted prior to the break was so hard that it could not be picked, and was left in the road. (The Engineer on site did not investigate this effect further.)

2.4. Test results

The test results obtained on the two raw material samples are summarised in Tables 2.1 and 2.2.

The results of X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis are summarised in Table 2.2. The Council for Geoscience (CGS) carried out the XRD and XRF analyses on whole material samples, while the minus 0.002 mm fraction was analysed by XRD using clay treatments by the Institute for Soil, Climate and Water, (ISCW) of the Agricultural Research Council (ARC).

Table 2.1: Properties of weathered dolerite (CCI 1) and norite (CCI 2) gravels

Property	Sample CCI 1 Dolerite	Sample CCI 2 Norite	Tested by
Grading analyses:			
% passing 37.5 mm	100	100	Soillab
% passing 26.5 mm	97	92	"
% passing 19.0 mm	97	88	"
% passing 13.2 mm	96	72	"
% passing 4.75 mm	89	57	"
% passing 2.00 mm	46	47	"
% passing 0.425 mm	16	15	"
% passing 0.075 mm	8	7	"
% passing 0.027 mm	4		'
% passing 0.002 mm	2		"
Grading Modulus	2.30	2.31	"
Liquid Limit (%)	36	39	"
Plasticity Index (%)	7	16	"
Bar linear shrinkage (%)	3.0	7.0	"
Cone Liquid Limit (%) (BS 1377)	38	39	"
Plasticity Index (%) (BS 1377)	12	16	
Linear Shrinkage (%) (BS 1377)	6.0	8.0	
Density and strength:			
Mod AASHO Max Dry Density (MDD) (kg/m^3)	2142	2449	Soillab
Mod AASHO optimum moisture content (OMC) (%)	9.3	6.3	"
CBR at 100% MDD (%)	96	148	"
CBR at 98% MDD (%)	74	111	"
CBR at 97% MDD (%)	65	96	"
CBR at 95% MDD (%)	50	72	"
CBR at 93% MDD (%)	38	55	"
CBR at 90% MDD (%)	24	37	"
Classification:			
AASHTO M145	A-2-4	A-2-6	
Unified	SW	SW	
TRH 14	G6	G6	
Chemical analyses:			
ICL (1 h) (%)	6.0	2.0	Soillab
ICL (28 days) (%)	10.0	3.0	"
pH at end of ICL (1 h)	12.46	12.95	"
pH	7.98	8.37	"
Electrical conductivity (Sm^{-1})	0.006	0.010	"
Cation exchange capacity (me/100g)	20.12	4.43	"
Exchangeable cations (me/100g)	20.6	11.3	"
Na^+ (me/100g)	0.31	0.07	"
K^+ (me/100g)	0.10	0.04	"
Ca^{++} (me/100g)	9.72	6.82	"
Mg^{++} (me/100g)	10.44	4.37	"
Organic carbon (%)	0.07	0.05	ARC
pH (water)	8.62	9.01	"
pH (KCl)	7.01	7.68	"
Amorphous silica (%)	1.6	1.6	CGS
Acid soluble sulfate (BS 1377) (%)	0.014	0.015	Soillab
Methylene Blue Adsorption (SABS)	0.20	0.25	"
Methylene Blue Adsorption (NZS)	0.50	0.75	"
Powerlime was used for the ICL testing.			

Table 2.2: Results of X-ray diffraction and XRF analyses on dolerite and norite gravels

Property	Dolerite (CCI 1)	Norite (CCI 2)
XRD Mineralogy (whole sample) (%) (CGS)		
Plagioclase	68	12
Clinopyroxene	12	0
Orthopyroxene	0	72
Quartz	5	4
Smectite	16	6
Calcite	0	2
Talc	0	4
XRD Clay Mineralogy (< 0.002 mm) (%) (ISCW, ARC)		
Smectite	50	28
Kaolinite	18	9
Talc	0	34
Feldspar	32	29
XRF analysis (mass %) (CGS)		
SiO_2	51.53	50.08
TiO_2	0.87	0.14
Al_2O_3	14.52	5.35
Fe_2O_3	11.23	10.58
MnO	0.17	0.20
MgO	8.76	22.73
CaO	8.60	5.93
Na_2O	1.83	0.60
K_2O	0.36	0.14
P_2O_5	0.11	0.02
Cr_2O_3	0.10	0.31
L.O.I	2.13	4.30
Total	100.21	100.35
H_2O^-	3.76	0.65
Trace elements (mg/1000g) (CGS)		
As	<10	<10
Ba	305	71
Ce	<10	<10
Co	53	83
Cr	469	1938
Cu	108	7
Ga	17	7
Hf	<5	<5
Mo	<2	2
Nb	<2	<2
Ni	287	421
Pb	<5	<5
Rb	9	<5
Sc	25	24
Sr	148	83
Ta	<5	<5
Th	<5	<5
U	<3	<3
V	179	86
W	<3	<3
Y	21	<3
Zn	65	62
Zr	64	16
Note: The XRD analyses are “normalised” semi-quantitative analyses and not quantitative		

2.5. Discussion

The aim during the sampling was to obtain two basic crystalline materials, one with a low plasticity index (< 6 per cent) and one with a moderate to high plasticity index (10 to 15 per cent). It is interesting to note that despite a number of preliminary tests on samples of the raw materials from the sites, confirming that the dolerite had a plasticity index of about 10 per cent and the norite was non to slightly plastic, the actual bulk samples collected for the project indicated respective plasticity indices of 7 and 16 per cent. Each of these is one percentage point higher than the original objective, although the two materials have reversed their respective roles.

The plasticity index results are supported by the methylene blue adsorption results, but the ion exchange capacities and ICLs indicate that the dolerite is more clayey. The semi-quantitative X-ray diffraction and XRF results on the whole sample, however, indicate that the dolerite contains more active clays and would be expected to have a higher plasticity index. Although the samples were tested in one laboratory, the time of soaking, the degree and time of mixing and many other factors during the Atterberg limits test can affect the liquid limit and plasticity index considerably[10]. The test results have been checked to ensure that the samples were not interchanged, and in fact the two materials were sampled and tested a number of months apart. This may have resulted in testing by different operators resulting in reproducibility as well as repeatability problems.

There does not appear to be anything unusual about the properties in Table 2.1 and 2.2 except for the somewhat high pH of 9.0 of the norite and the amorphous silica content of 1.6 per cent of both materials. The pH suggests that there may be traces of Na_2CO_3 – a known cement accelerant – and the amorphous silica content may be sufficient (if uncorrected for clay minerals) to cause rapid hardening by reaction with $Ca(OH)_2$ released by the hydration of the cement. However, the electrical conductivity (EC) of 0.01 S/m of the norite indicates that the total very soluble salt content (i.e. including any Na_2CO_3 is less than about 0.01 per cent. Similarly, the very low ECs of both materials indicate that there are no water-soluble components present, which might convey unusual properties on the materials.

Both materials would be regarded as suitable for stabilization to a C3 or C4 class of material for use as a subbase (C3) and selected subgrade (C4) for a heavily trafficked road and as a base (C3) for a low volume road. However, the very high ICL of 6 per cent for the dolerite might make it suspect as far as durability is concerned.

3. THE CEMENTS

3.1. General

After a number of discussions among the cement producers, the following cement types were selected for use in the investigation (Table 3.1). These were selected to cover a wide range of cements and were based on the individual properties and/or type of extender of specific cements.

Table 3.1: Cements used

Number	Cement type	Source	Brand	Specific characteristics
1	CEM I 42.5	PPC Hercules	OPC	High C_3A content
2	CEM I 42.5	Lafarge Lichtenburg	Duratech	Mod C_3A content
3	CEM II A-M (L) 42.5	Lafarge Lichtenburg	Powercrete	Limestone cement
4	CEM II A-M (S) 42.5	Holcim Roodepoort	High Strength Cement	Slag cement
5	CEM II B-V 32.5	Holcim	All Purpose Cement	Flyash cement
6	CEM II A-L 32.5	PPC Slurry	Surebuild	Limestone cement
7	CEM III A 32.5	NPC	Eagle Pro	Blastfurnace cement
Note: Both of the blastfurnace slag cements used conventional slags and not Corex slags				

It should be noted that although brand names of the cements supplied are provided in this table, these are liable to change and some have already been changed. The cement type is thus the primary identification criterion through this report. The cements were all analysed to provide a comprehensive selection of standard test results. The routine testing was carried out by the individual producers, but testing for properties with results that are more susceptible to operator and technique variability was all carried out by PPC Group Laboratory Services, Jupiter. The following test results were requested for the cements:

Standard chemical tests

- Lime saturation factor (LSF on clinker only)
- CaO and MgO on clinker and final cement (free CaO was determined but not free MgO)
- Acid-soluble SO_3
- Loss on ignition
- Insoluble residue
- H_2O+, CO_2, reactive CaO, reactive SiO_2, Cl^-, alkalis
- XRF and XRD analyses
- Modified Bogue phase composition of clinker

.

Standard physical tests

- Coarse particles
- Specific surface
- Compressive strengths (2, 7, 28 days)
- Initial and final setting times
- Soundness
- Methylene blue adsorption MBA (limestone).

3.2. Details of cements

Details relating to each of the cements used in this project are as follows:

PPC

- CEM I 42,5 Hercules (moderate C_3A content)
- CEM II A-L 32,5 Slurry (Limestone cement)

Holcim

Two CEM II cements were provided by Holcim, having strength grades of 42.5 and 32.5 MPa and containing respectively slag and flyash, both from the Roodepoort factory and using the same clinker from Dudfield. These were

- CEM II A-M (S) 42,5 (Slag cement)
- CEM II B-V 32,5 (Fly ash cement)

Lafarge

A CEM I with a moderate C_3A content and a limestone-based CEM II cement from the Lafarge Lichtenburg factory were tested. Both were grade 42.5 products.

- CEM I 42,5 (Moderate C_3A content)
- CEM II A-M (L) 42,5 (Limestone cement)

NPC

A CEM III cement from the Durban plant using blastfurnace slag as the extender was supplied by NPC.

- CEM III A 32,5 (Blastfurnace cement)

A summary of all of the test results (tested according to SANS EN 197-1) on these cements is provided in Table 3.2.

Table 3.2: Summary of cement properties as provided by cement manufacturers in comparison with SANS EN 197-1

Identification code	**SABS EN 197-1**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Producer **Factory**	**(SANS 50197-1)** **Specification**	**PPC** **Hercules**	**Lafarge** **Lichtenburg**	**Lafarge** **Lichtenburg**	**Holcim** **Roodepoort**	**Holcim** **Roodepoort**	**PPC** **Slurry**	**NPC** **Durban**
Property		**CEM I 42.5**	**CEM I 42.5**	**CEM II A-M (L) 42.5**	**CEM II A-M(S) 42.5**	**CEM II B-V 32.5**	**CEM II A-L 32.5**	**CEM III A 32.5**
Fineness (Blaine (m^2/kg)		425	302	355	429	377	365	366
Density (g/ml)		3.13	3.21	3.17	3.15	2.80	3.08	
Soundness (mm)	= 10	1	3	1	0	1	0	
Initial setting time (min)	= 60 or 75	175	70	115	181	205	165	200
Final Setting time (max)		205			319	331	205	255
ISO 2-day strength (MPa)	= 20 (42.5)	24.3	15.9	19.0	19.3	13.5	15.6	10.3
ISO 7-day strength (MPa)	= 16 (32.5)	38.5	39.8	-	39.5	26.4	28.6	24.7
ISO 28-day strength (MPa)	= 32.5 or 42.5	50.4	57.9	53.7	57.9	44.5	39.2	53.7
Carbon content (%)					0.31	0.36		
Moisture content (%)			-	-	0.9	0.8		
Free lime content (%)			-	-	1.4	1.2		
Insoluble residue (%)	= 5		0.57	-	1.0	21.4		0.2
Loss on ignition (%)	= 5		2.04	3.66	1.8	2.1		0.51
Chloride (%)	= 0.10		0.01	0.01				
SO_3 (%)	= 3.5		1.47	1.88				1.6
Chemical Analysis								
SiO_2		21.6	20.49	19.91	24.75	31.50	21.4	28.74
Al_2O_3		4.2	4.64	4.61	6.03	13.55	3.9	8.89
Fe_2O_3		2.0	2.65	2.65	2.20	2.86	2.06	1.66
CaO		61.2	64.16	63.29	58.94	47.06	60.9	48.66
MgO		4.5	2.24	-	3.61	1.67	2.5	6.98
K_2O		0.55	0.11	0.10	0.62	0.64	0.54	0.66
TiO_2		0.35	0.41	0.38	0.27	0.04	0.39	
Mn_2O_3		1.16	0.32	0.29	0.63	0.47	0.29	0.47
Na_2O		0.08	0.11	0.11			0.09	
SO_3		2.77	1.19	1.74			1.56	
LOI		1.20	1.62	3.45			6.12	
TOTAL		99.7	97.94	96.43	97.05	97.79	99.8	95.97
Extender (%)				10.5 limestone	15 slag	30 flyash	12 limestone	53 GGBS

Note: During the project the SABS EN 197-1 was redefined as SANS 50197-1. The older nomenclature is, however, used throughout this report.

3.3. Testing carried out on clinkers and cements by PPC

Cement properties that are subject to operator and technique variations were all determined by PPC in order to minimise possible variations. These results are summarised in Table 3.3 and 3.4 and the full results, XRD charts and particle size analysis results are provided in Appendices A and B.

Table 3.3: Chemical properties and particle size parameters of all cements determined by PPC Group Laboratory Services (courtesy E Auger)

Cement	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Property (mostly %)	**PPC CEM I 42.5**	**Lafarge CEM I 42.5**	**Lafarge CEM II A-M (L) 42.5**	**Holcim CEM II A-M (S) 42.5**	**Holcim CEM II B-V 32.5**	**PPC CEM II A-L 32.5**	**NPC CEM III A-S 32.5**
SiO_2	21.6	20.9	20.6	24.5	30.2	21.4	28.7
Al_2O_3	4.20	4.75	4.86	6.00	11.40	3.90	9.50
Fe_2O_3	2.00	2.81	2.72	2.06	2.61	2.06	1.52
Mn_2O_3	1.16	0.33	0.34	1.01	0.71	0.29	0.47
TiO_2	0.35	0.47	0.45	0.39	0.68	0.39	0.82
CaO	61.2	64.4	62.7	57.3	47.8	60.9	48.3
MgO	4.5	2.5	2.5	3.9	2.0	2.5	7.1
P_2O_5	0.10	0.04	0.10	0.05	0.19	0.02	0.03
SO_3	2.77	0.80	1.93	2.74	2.04	1.56	2.71
Cl	0.02	0.01	0.01	0.02	0.01	0.01	0.00
K_2O	0.55	0.1	0.1	0.59	0.6	0.54	0.7
Na_2O	0.08	0.13	0.11	0.1	0.12	0.09	0.32
LOI	1.2	2.2	3.6	1.78	1.7	6.12	0.06
Total	**99.73**	**99.44**	**100.02**	**100.44**	**100.06**	**99.78**	**100.23**
Insoluble Residue	1.74	0.54	0.91	1.91	8.88	2.37	2.26
Free CaO	1.3	2.83	2.06	1.58	1.33	1.27	1.3
CO_2	0.6	1.1	2.2	0.7	0.5	4.5	0.1
Acid soluble sulfate	2.69	0.82	1.82	2.34	2.04	1.47	1.29
Reactive CaO	55.2	59.5	56.6	51.7	43.2	48.1	45.8
Reactive SiO_2	19.9	20.4	19.7	22.5	21.3	19	26.4
Max size (µm)	120	164	121	140	89	351	89
d90 (µm)	56	56	48	52	48	70	44
d50 (µm)	20	18	15	19	16	21	16
d10 (µm)	4	2	2	3	2	2	2
d10, d50 and d90 are the maximum particle sizes of 10, 50 and 90 per cent of the particles respectively							

Table 3.4: Chemical and calculated composition of cement clinkers determined by PPC Group Laboratory Services (courtesy E Auger) and Lafarge (clinkers 2 and 3)

Cement	1	2 & 3	4 & 5	6	7	
Property (%)	PPC Hercules clinker	Lafarge Lichtenburg clinker	Holcim Dudfield clinker	PPC Slurry clinker	NPC clinker	Normal (Fulton 2001) Clinker
SiO_2	21.30	22.12	22.50	22.70	21.10	19 - 24
Al_2O_3	3.70	4.42	5.00	4.30	4.70	4 - 7
Fe_2O_3	1.54	2.93	2.61	2.40	2.49	1 - 4
Mn_2O_3	1.42		0.11	0.29	0.15	
TiO_2	0.34		1.70	0.44	0.39	
CaO	64.5	66.0	66.1	66.5	66.2	63 - 68
MgO	5.3	2.1	0.1	2.2	3.0	0.5 - 3.5
P_2O_5	0.10		0.45	0.04	0.06	
SO_3	0.53		0.01	0.56	0.50	
Cl	0.01		0.38	0.01	0.01	
K_2O	0.53	0.12	0.11	0.51	0.77	
Na_2O	0.05	0.12	0.46	0.07	0.29	
LOI	0.31		1.78	0.23	0.57	
Total	**99.63**	**97.81**	**101.28**	**100.25**	**100.23**	
C_3S	61.2		47.9	58.0	56.4	45 - 65
C_2S	14.20		28.00	21.00	17.80	10 - 35
C_3A	5.80	6.78	10.00	8.10	9.10	4 - 10
C_4AF	9.00		8.30	8.20	8.00	5 - 10

3.4. Setting Times at Various Temperatures

In order to determine whether various working temperatures affected the setting times of the cements such that they could influence stabilization construction, a series of determinations of the initial and final setting times at different temperatures was carried out by SOILLAB, Pretoria on each cement. The test method used was SABS 626 (1961: amended 1967). The results are summarised in Table 3.5 and shown graphically in Appendix C.

Table 3.5: Setting times of the cements at various temperatures

CEMENT No Brand Class Strength	1 PPC CEM I 42.5	2 Lafarge CEM I 42.5	3 Lafarge CEM II A-M (L) 42.5	4 Holcim CEM II A-M (S) 42.5	5 Holcim CEM II B-V 32.5	6 PPC CEM II A-L 32.5	7 NPC CEM III A 32.5
SETTING TIMES							
Manufacturers							
IS_{22} (mins)	175	70	115	181	205	165	200
Rating	3	5	4	2	1	5	1
FS_{22} (mins)	205			319	331	205	255
Rating (1)	4			2	1	4	3
Soillab							
IS_{22} (mins)	150	125	175	195	200	190	275
Rating	5	6	4	2	2	3	1
FS_{22} (mins)	245	190	270	305	255	245	330
Rating (1)	5	6	3	2	4	5	1
IS_{35} (mins)	145	120	145	90	180	175	210
Rating	3	4	3	5	2	2	1
FS_{35} (mins)	205	180	230	150	220	230	280
Rating (1)	4	5	2	6	3	2	1
IS_{45} (mins)	130	100	125	70	140	150	170
Rating	4	6	5	7	3	2	1
FS_{45} (mins)	160	160	185	120	180	200	240
Rating (1)	4	4	7	5	3	2	1
Temperature susceptibility $IS_{22} - IS_{45}$ (mins)	20	25	50	125	60	40	105
Rating (2)	1	1	3	6	4	2	5

NOTES:

(1) Ratings are 1 (slowest) to possible 7 (fastest), neglecting differences of up to 5 minutes

(2) Ratings are 1 (least susceptible to possible 7 (most susceptible), neglecting differences of up to 5 mins

(3) Setting times less than 120 minutes are underlined

There is substantial disagreement between the setting times at 22°C of the manufacturers and those of Soillab, the latter being substantially longer. As some of these differences are too great to be ascribed to test reproducibility, it is recommended that they be repeated by another laboratory. It should be noted that the EN 196 equipment is different to the older SABS Vicat equipment. Although some laboratories use automatic measuring equipment, the Soillab tests were done manually. Taking all of this into consideration, a variation of plus/minus 30 per cent between different laboratories could be acceptable.

Also shown in Table 3.5 is a rating of the different cements on the assumption that the slower the set the better for purposes of coil stabilization. Whilst it is realised that setting times simply represent fairly arbitrary consistency limits and that such times do not necessarily accurately represent field conditions when mixed with soil, it is suggested that they should be used as a first approximation in the absence of anything better, especially

as the European Union has increased the minimum setting time for cements for soil stabilization.

A temperature susceptibility index arbitrarily taken as the difference between the initial setting times at 22 and 45°C and a relative rating of the seven cements is also given. The rating is based on the assumption that the smaller the index the better as an all-weather cement for soil stabilization.

It has been suggested that a minimum initial setting time of 120 minutes as required by ENV 13282 be used as a first approximation of acceptability for soil stabilization at any processing temperature. Those initial setting times in Table 3.5 that are less than 120 minutes have therefore been underlined. It should, however, be noted that ENV 13282 is applied in Europe only when EN 197 is not complied with, the conventional EN 197 cements being used predominantly.

If the setting times of the pure cement pastes are an indication of working (processing) time – i.e. the total of mixing and compaction – then neglecting small differences in setting times, the CEM III A cement would appear to be most suitable for soil stabilization: it possessed the longest initial (and generally also the final) setting times. Although it had a high temperature susceptibility, its initial setting time remained the longest. On the basis of the Soillab setting time results, the CEM II B-V 32.5 cement could also be a good choice. However, the test results discussed later indicate that setting time is not the only important criterion.

3.5. Discussion

3.5.1 Chemical and physical properties of cements and clinkers

The test results provided by the manufacturers were summarised in Table 3.2 for comparative purposes. It can be seen that not all of the requested tests were carried out by each laboratory, but the results provided indicate the most important properties.

All of the cements tested complied with the SABS EN 197-1:2000 requirements, the only exceptions being the 28-day strength of the NPC CEM III A 32.5 (53.7 MPa), which was marginally above the specified upper limit (52.5 MPa). Table 3.2 shows the 2-day strength of the CEM III A being less than the specification, but only the 7-day strength is specified for strength class 32.5 cements, which is easily met by cement number 7.

The chemical analyses and particle size distributions of all of the cements carried out by PPC Group Laboratory services were summarised in Table 3.3. No anomalies were noted in any of the chemical analyses on the cements.

Chemical analyses of the clinkers used to manufacture the cements were summarised in Table 3.3. These too, showed no anomalies, although the clinker used to manufacture the PPC CEM I that was selected for the project on the basis of its high C_3A content had the lowest C_3A content of the five clinkers tested. The typical Lafarge clinker at the time that the cements were sampled for the project had C_3A contents of 6.8 per cent.

The CEM III material had a sodium oxide equivalent of 0.78 per cent. Various limits are suggested in Lea[11], with a maximum of 0.6 for materials with clinker and calcium sulfate contents exceeding 95 per cent. The limit increases as the amount of extenders increases and for a typical South African CEM III A would probably vary between about 0.9 and 1.1 per cent. It should be noted that the limit applied to alkalis is primarily related to the potential for silica alkali reaction in concrete and is related to both the percentage alkalis in the cement as well as the amount of cement added[12]. This was thus not a cause for concern in terms of soil stabilization due to the lower quantities of cement involved.

3.5.2 Temperature sensitivity of setting times

The investigation into the setting times of the different cements (Table 3.4) was carried out by Soillab and produced mixed results. (These results were used in preference to the results supplied by the manufacturers, as they were incomplete and to minimise operator variability). The initial setting times varied from 125 to 275 minutes (at 22°C) with a general increase from the CEM I to CEM III A cements. The corresponding final setting times varied between 190 and 330 minutes with a similar trend.

As the temperature increased (up to 55°C), both the initial and final setting times reduced significantly (to between 55 and 100 minutes for initial and 95 to 175 minutes for final setting time) with a marked reduction in the differences between the initial and final setting times for the CEM I and grade 42.5 CEM II cements. The differences for the grade 32.5 cements remained relatively constant. The shapes of the curves varied from relatively linear to strongly concave or convex upwards for the different cements. It should be remembered that shade air temperatures greater than 35°C on road construction projects are common in South Africa and high working temperatures in the material being stabilized can thus be expected. However, there is little information available on actual mixing, compaction and curing temperatures and it is recommended that such information be obtained.

It should also be noted that specifications to ensure optimal curing of stabilized materials include early priming[2]. Temperatures under the almost black primes (and later seals) of 50 to 60°C and up to 70°C in the upper base are probably common in South Africa.

Covering with a black surface such as these would set up a very steep temperature gradient and would be regarded as bad practice in concrete work.

As the setting time is supposed to be strongly affected by particle size and gypsum content (in addition to other properties such as clinker content and composition (e.g. C_3A content), and quantity and type of extender), plots of these properties were prepared (Figure 3.1 and 3.2).

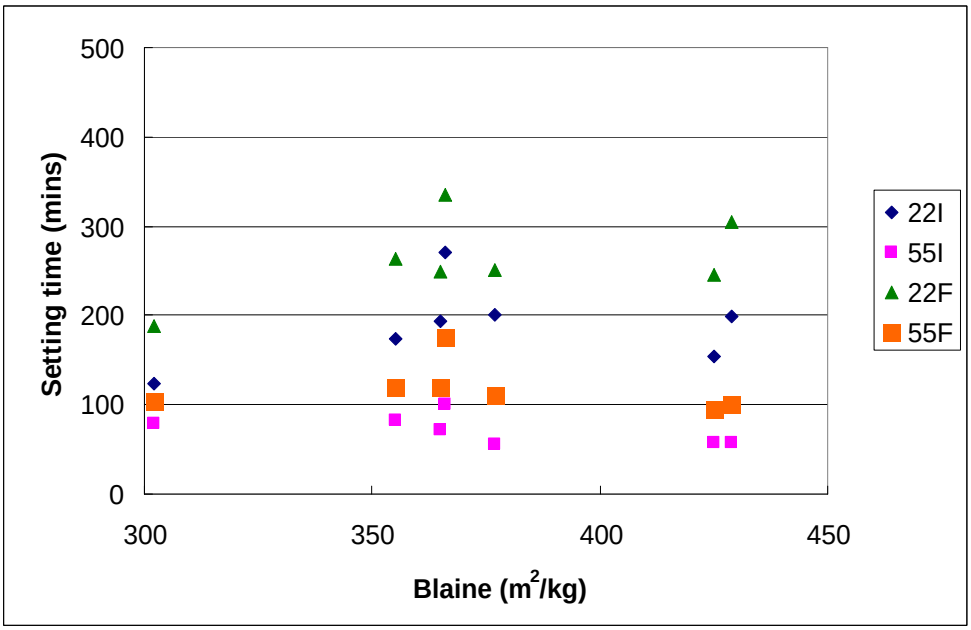

Figure 3.1: Relationship between initial (I) and final (F) setting times at 22 and 55°C and Blaine surface areas

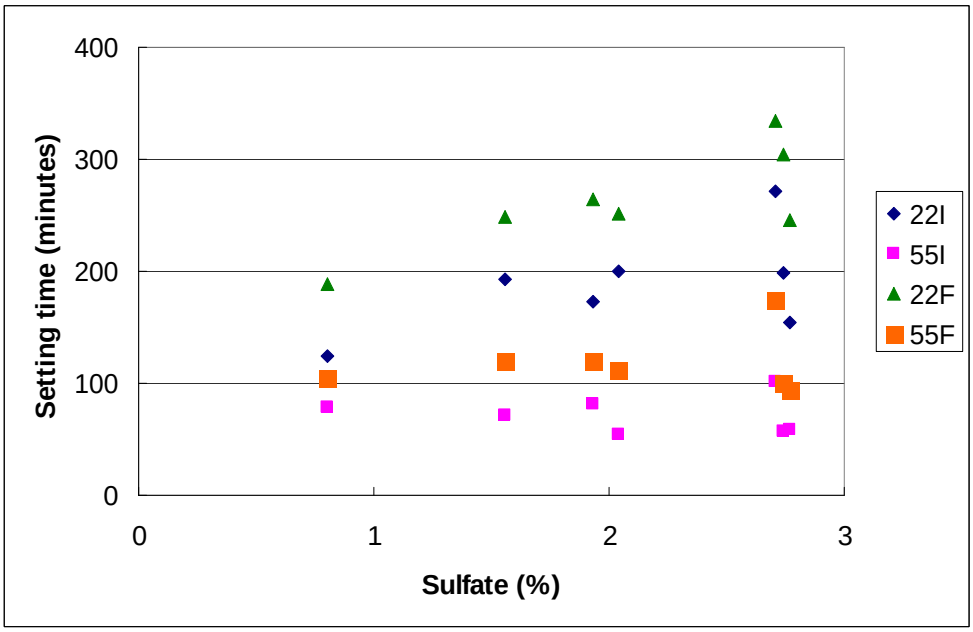

Figure 3.2: Relationship between initial (I) and final (F) setting times at 22 and 55°C and sulfate contents

It is clear that no consistent or good correlations are present, but trend lines fitted to the data showed that there was a general trend for the initial setting time to increase with the Blaine surface area but the final setting time to decrease, irrespective of temperature. The former observation is contrary to expectations. Slightly better, but still poor, relationships were shown with the sulfate content, although the final setting time at 55°C showed a reversed trend. It should be noted that these relationships may be confounded by the inherent properties of the different cement types, but are assessed here purely as alternative soil stabilizers. Figure 3.2 suggests that only the initial setting time is affected by the sulfate content.

If it can be assumed that the setting time relationships are roughly similar for cement stabilization (i.e. soil cement mixtures as opposed to pure cement), it can be concluded that under high temperature construction conditions, compaction after between one and about 1.5 hours, depending on the cement, will result in low densities with their potential accompanying compaction, strength and durability problems. The proposed specification for road stabilizers in Europe (ENV 13282) takes this into account and includes a minimum initial setting time of 120 minutes – double the 60 minutes of EN 197. No final setting time is specified, indicating that initial setting time is recognised as being more relevant for stabilization construction and workability estimation. The setting times of the CEM III cement were the closest to the proposed European standard. Further investigations into the relationship between workability and setting times on treated material should therefore be carried out.

The decreases in both initial and final setting times as temperature increases are clearly illustrated in Figures 3.3 and 3.4. The following conclusions can be drawn:

- Other than cement number 4, the blended cements have longer setting times than the unblended cements at all temperatures.
- Cement number 7 (CEM III A) has the longest setting times of all of the cements
- If figure 3.3 is extrapolated to 10°C for low temperature work, it is suggested that the initial setting times of most of the cements are not significantly increased but those of cements 4 and 7 are greatly affected
- The shape of the curve of cement 4 (CEM II A-M (S) 42.5 differs from the rest – it is concave up whereas the others are generally concave down
- The rate of decrease of setting time (initial and final) of the extended cements increases more than that of the CEM I cements as the temperature increases.

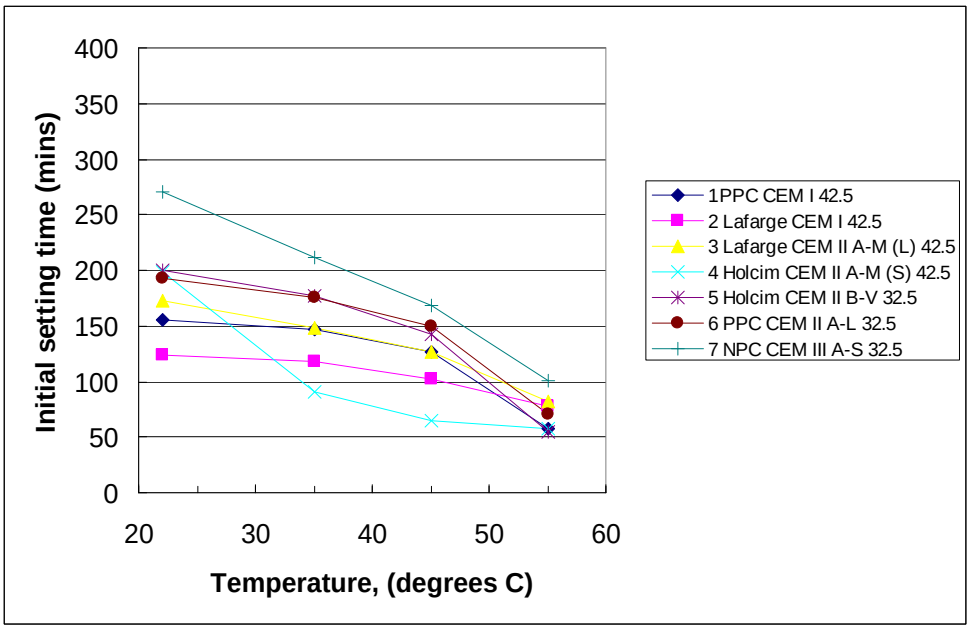

Figure 3.3: Relationship between initial setting times and temperature

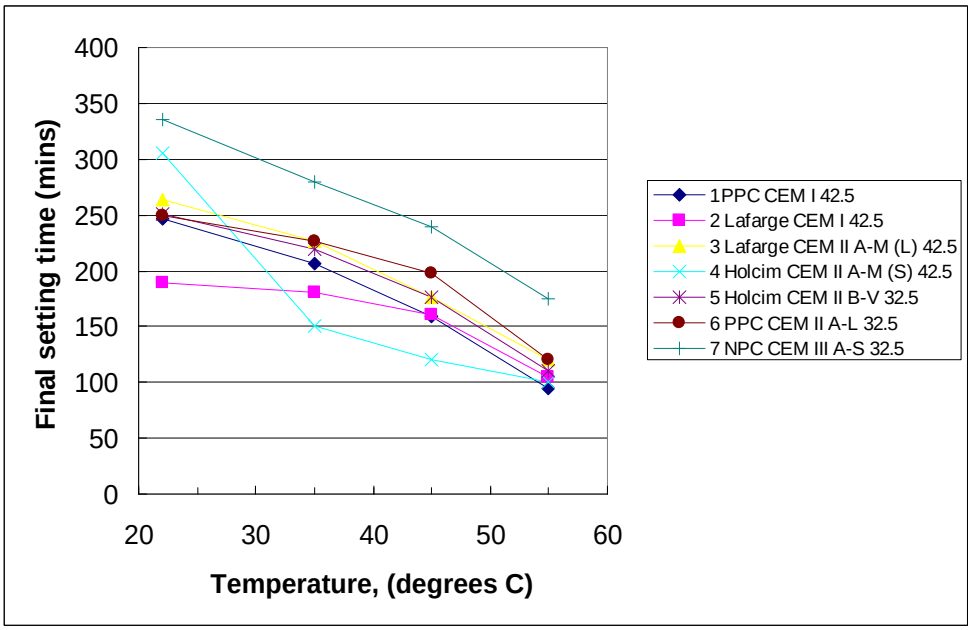

Figure 3.4: Relationship between final setting times and temperature

Figure 3.5 shows a number of setting time parameters plotted for each of the cements. The trends identified earlier are clearly illustrated.

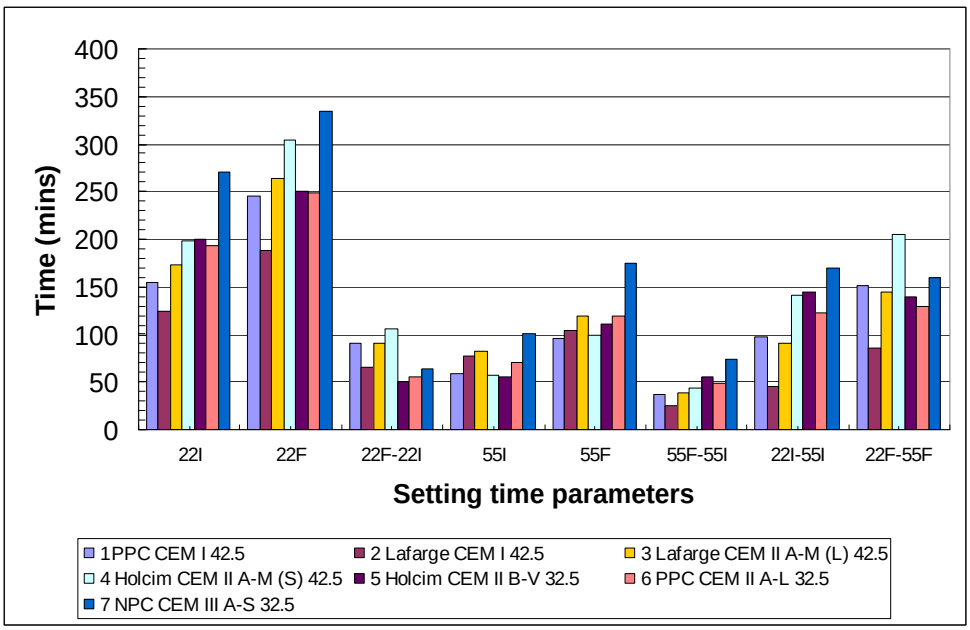

Figure 3.5: Relationship between various setting times and differences between them and cement types.

22I, 22F, 55I and 55F are initial (I) and final (F) setting times at 22 and 55°C

55F-55I, etc are differences between final and initial setting times

4. LABORATORY TESTING OF SOIL-CEMENT MIXES

4.1. General

The primary purpose of this project was to identify whether the new cements behave differently from the previous SABS 471 cements and if so, how this affects the selection of cements for road stabilization and whether special construction techniques are necessary. It was originally suggested that testing should be carried out to investigate[5]:

- Strength
- Workability/compactability
- Effect of compaction delay and mix temperature on density and strength
- Effect of road curing temperature on ultimate strength
- Effect of compaction delay, mixing and curing temperature on durability
- Effect of compaction delay, mixing and curing temperature on carbonation resistance
- Resistance to poor curing.

However, in order to accelerate the project and obtain results that would provide a short-term answer to what cement is best for what purpose and what special construction needs are necessary, the following testing programme was suggested in the short term:

- Representative homogenised samples of two materials to be prepared
- Test using each of the 7 cements provided
- Test all moulds using **3 per cent cement** and compacted at 100 per cent Mod AASHO
- Compact at 2 and 4 hours after hydrating cement, at temperatures of 10, 23 and 40°C
- Cure all specimens for 7 days at 23°C and 100 per cent relative humidity
- Test density, soaked unconfined compressive strength (UCS) and unsoaked indirect tensile strength (ITS) on duplicate samples.

The objectives of this initial work were to assess workability in terms of the densities achieved and the corresponding effects on strength. Based on the results of this testing, the investigation could be subsequently extended to assess specific issues and address any problems identified.

Testing followed the standard TMH1[6] methods as far as possible, except where special circumstances were requested, eg, conditioning time and temperatures. All testing was

carried out on material passing the 37.5 mm sieve, without intentionally breaking the plus 19 mm material down and returning it to the sample as specified in TMH1.

For the purposes of analysis, the cements have been numbered from 1 to 7, with cements 1 and 2 being CEM I 42.5, cements 3 and 4 being CEM II 42.5, 5 and 6 being CEM II 32.5 and 7 being a CEM III 32.5.

The full test results are summarised in Appendix D.

4.2. Initial Consumption of Lime (ICL) and Cement (ICC)

Initial consumption of lime testing (using Powerlime) indicated a definite stabilization of the pH after 1 hour at the pH of a pure lime solution (12.4) for the dolerite but a stabilization near 12.95 for the norite. The ICL value was 6 per cent for the dolerite (CCI 1) and 2 per cent for the norite (CCI 2) although the pH increased slowly from 12.72 to 12.95 for the norite as the lime content increased from 2 to 10 per cent. After 28 days, the ICL was measured as 10 per cent for CCI 1 and 3 per cent for CCI 2, although the equilibration points were not clearly defined.

Each material was tested using up to 10 per cent of each of the cements (Initial Consumption of Cement - ICC) provided for the investigation. The results are summarised in Table 4.1.

Table 4.1: Initial Consumption of Cement (ICC) test results

Cement	pH of pure cement	Dolerite (CCI 1)			Norite (CCI 2)		
		ICC (%)	pH at 10% cement		ICC (%)	pH at 10% cement	
			1 hr	28 days		1 hr	28 days
1 PPC CEM I 42.5	12.47	> 10	12.28	12.11	2	12.82	12.49
2 Laf CEM I 42.5	12.41	10	12.41	12.05	2	12.87	12.30
3 Laf CEM II A-M (L) 42.5	12.40	>10	12.13	11.97	4	12.83	12.28
4 Holcim CEM II A-M (S) 42.5	12.41	10	12.38	12.13	3	12.69	12.44
5 Holcim CEM II B-V 32.5	12.43	> 10	11.78	12.19	3	12.78	12.58
6 PPC CEM II A-L 32.5	12.55	> 10	12.43	12.26	2	12.82	12.74
7 NPC CEM III A 32.5	12.58	> 10	12.38	12.03	5	12.88	12.46

The results for CCI 1 show that the pH of only one of the tests (cement 2) actually reached the pH of the pure cement after one hour, with another (cement 4) being marginally lower. This equates to ICC values of 10 per cent or more. The pH values of the norite after one hour were in a much tighter range than the dolerite in all cases and the ICC was between 2 and 5 per cent. There is thus a significant difference in the results of the ICL and ICC tests (more so for the dolerite), indicating that more cement is required than lime to allow for the initial consumption.

The amount of 3 per cent cement by mass used for the laboratory testing of the soil cements was therefore insufficient to satisfy the ICC of the dolerite by far, more than sufficient for the norite with cements 1, 2 and 6, just sufficient with cements 4 and 5 and insufficient with cement 7. It is normally recommended that, in the case of cemented materials (e.g. the C3 or C4 strength classes aimed at), the ICL must always be satisfied in order to ensure durability, even if the strength is attained with a lesser percentage of stabilizer. However, the interpretation of the ICC, which is a more recent development is uncertain, and a reaction (and hydration) time of more than one hour used for the ICL is probably necessary.

It should be noted that the definition of the end-point in the ICL is not always clear as there are ongoing small changes in the pH at the high pHs involved. The ICL and ICC end points were thus taken at the first lime or cement content where there was an increase in pH of 0.1 or less. The absolute value of the pH was not considered, minimising the effects of Na_2O-equivalent on the pH and the effect of the sulfates and extenders on the binding and release of the alkalis.

4.3. Density

As a general background to this section the concept of maximum dry density and optimum moisture content is introduced. Any soil, as a function of its particle size distribution and to a lesser extent its plasticity has a single moisture content (the optimum moisture content - OMC) at which an equivalent maximum dry density (MDD) is achieved at a particular, constant compaction effort (referred to as Modified AASHO or MAASHO in this report). The addition of cement to the soil typically results in a decrease in the MDD and an increase in OMC.

The strength of the soil-cement mixes was determined by compacting cylinders of soil cement at the same MAASHO effort and OMC and therefore to nominally the MDD.

Changes in the density were determined during the initial stabilized maximum dry density (MDD) testing as well as on all moulds compacted for strength testing. This provided a total of 175 dry density test results after stabilization for the two materials at various temperatures and conditioning times.

4.3.1 Effect of cement type at 23°C

The MAASHO maximum dry density and optimum moisture contents of the untreated materials and the MDD and OMC values determined on the two soils after stabilization with each of the cements are summarised in Table 4.2. In interpreting the data in this table it should be borne in mind that the smaller the decrease in MDD and the smaller the

increase in OMC from that of the unstabilized material, the better. However, any decrease in MDD is by far the most important.

Table 4.2: Effects of different cements on maximum dry density and optimum moisture content at 23°C after 4 hours conditioning (% change in parentheses)

Treatment			Dolerite (CCI 1)		Norite (CCI 2)	
			MDD (kg/m^3)	OMC (%)	MDD (kg/m^3)	OMC (%)
Natural			**2142**	**9.3**	**2449**	**6.3**
Cement						
No.	**Make**	**Type**				
1	PPC	CEM I	2062 (-3.7)	11.3 (+21.5)	2463(+0.6)	7.7 (+22.2)
2	Lafarge	CEM I	2093 (-2.3)	11.2 (+20.4)	2456 (+0.3)	8.0 (+27.0)
3	Lafarge	CEM II A-M(L)	2085 (-2.7)	11.5 (+23.7)	2464 (+0.6)	8.2 (+30.2)
4	Holcim	CEM II A-M(S)	2062 (-3.7)	10.8 (+16.1)	2390 ((-2.4)	9.0 (+42.9)
5	Holcim	CEM II B-V	2132 (-0.5)	10.2 (+9.7)	2448 (0)	7.2 (+14.3)
6	PPC	CEM II A-L	2079 (-2.9)	11.4 (+22.6)	2451 (0)	7.5 (+19.0)
7	NPC	CEM III A	2116 (-1.2)	10.2 (+9.7)	2420 (-1.2)	8.6 (+36.5)
Mean			**2090 (-2.4)**	**10.9 (17.2)**	**2442 (-0.3)**	**8.0 (+27.0)**

The addition of cement reduced the MDD of the dolerite in all cases and increased the OMC as would be expected from cement stabilization of a gravelly sand material. The cements, however, had a far smaller impact on the MDD of the norite but increased the OMC in all cases. The actual changes in MDD varied between -1.2 and -3.7 per cent (mean -2.4 per cent) of the untreated density for CCI 1 and between +0.6 and –2.4 per cent (mean –0.3 per cent) for CCI 2. It should be noted that the test method for stabilized materials requires a standard conditioning period of 4 hours at 23°C. A decrease in MDD of more than about one per cent would exceed the repeatability of the test method and would also exceed the one per cent drop generally allowed for. Similarly, an increase in MDD of up to one per cent is probably within the testing error and should be disregarded. Recent work at Transportek and elsewhere, however, has shown that when this conditioning is carried out at elevated temperatures, even lower densities are obtained.

There are no strong trends between the density decrease and the cement types with the CEM I materials giving similar decreases to those produced by the CEM II cements irrespective of whether they were 32.5 or 42.5 strength class cements. The CEM III A and flyash cement (CEM II B-V 32.5) affected the MDD of the dolerite the least but had the greatest effects of all the cements (although minimal) on the norite.

Figure 4.1 shows plots of the initial and final setting times of each cement (as determined by Soillab) against the effect of the cement on the density of the dolerite and norite.

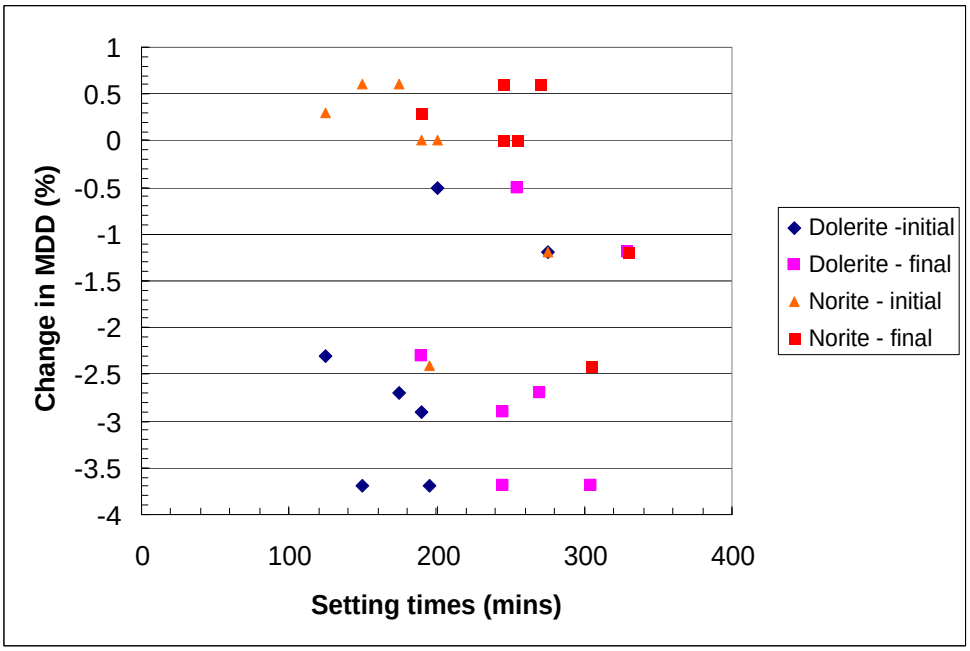

Figure 4.1: Relationship between initial and final setting times at 22°C and change in MAASHO MDD at 23°C

No specific relationships are evident although the trends indicate that as the initial setting times get longer, the MDD of the norite decreases, contrary to expectations. However, it seems that there may be a tendency for the MDD of the dolerite to increase with increase in initial setting time.

It would appear from the limited data available that modification reactions associated with the higher plasticity materials minimise the impact of early cementation, retarding early strength development. Testing of a wider range of materials would be needed to confirm this.

Plots of the initial and final setting time and MDD at 22**°C** against the cement type (number) for the dolerite and norite are provided in Figures 4.2 to 4.4.

Apart from cements 5 (CEM II B-V (32.5) and 7 (CEM III A), there are clear trends that as the initial setting time increases, the MDD decreases. Cement 5 shows an exaggerated increase in density for a negligible decrease in initial setting time while cement 7 shows an increase in density with increased setting time. Similar trends are observed for the final setting time on the dolerite, although that for cement 5 is not as exaggerated. It is notable, however, that only the CEM III has an initial setting time longer than the 4 hour conditioning period used in the standard MDD determination. The trends for the norite are not as well defined and the CEM III A does not follow the expected trend on the norite.

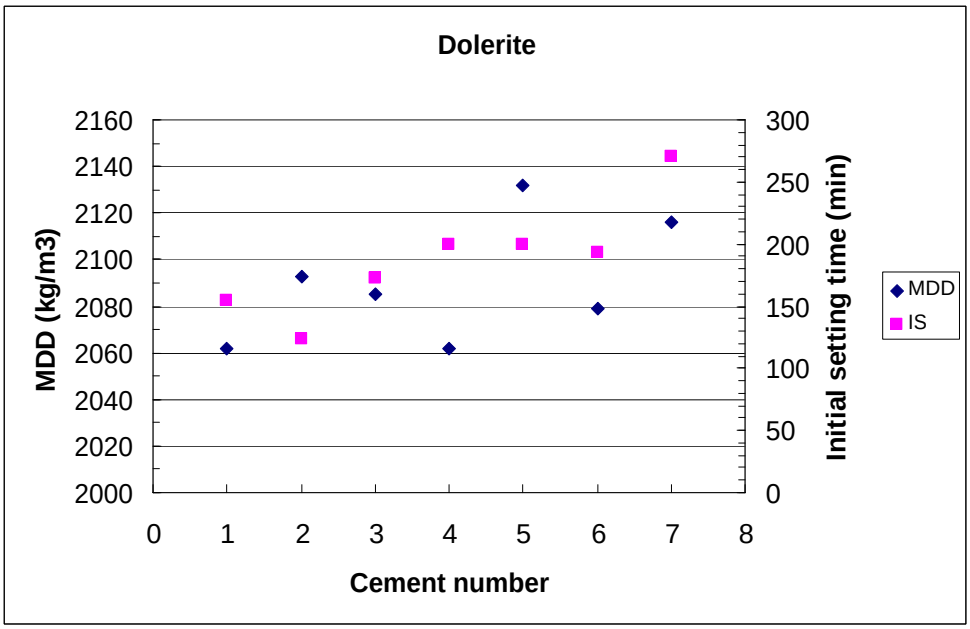

Figure 4.2: Change in MDD of dolerite at 23°C with change in initial setting time at 22°C by cement type

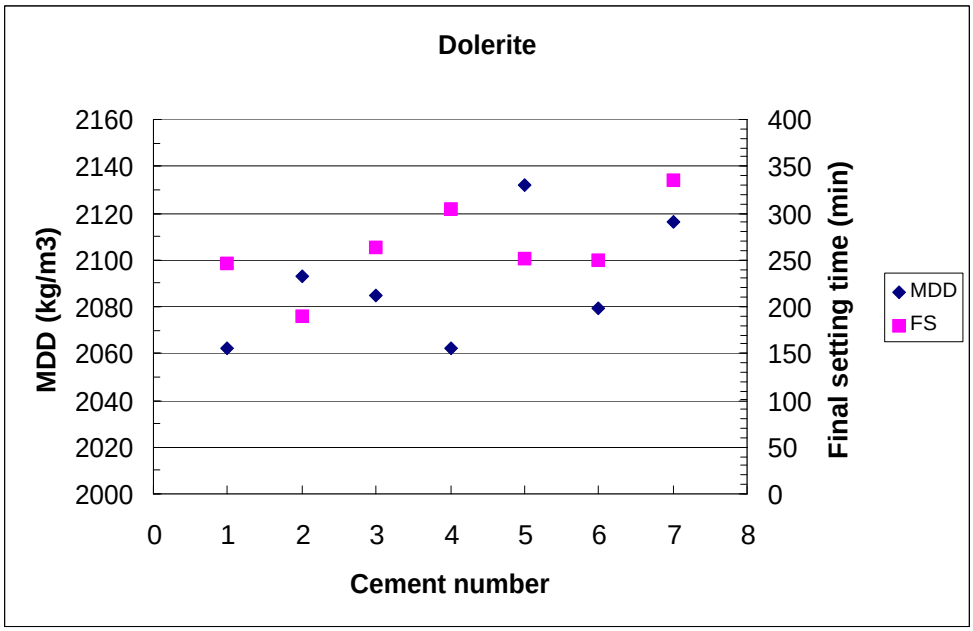

Figure 4.3: Change in MDD of dolerite at 23°C with change in final setting time at 22°C by cement type

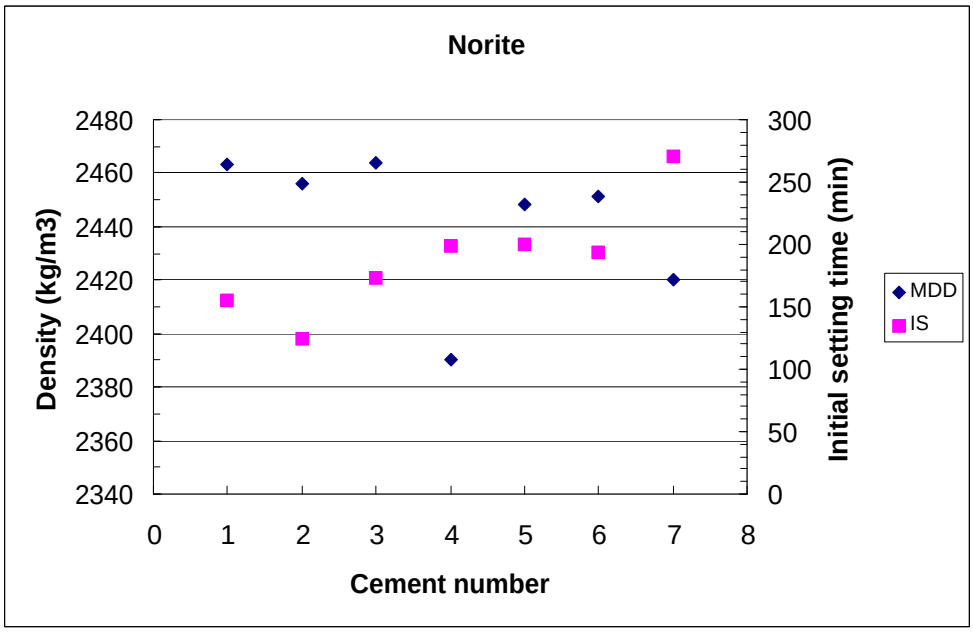

Figure 4.4: Change in MDD of norite at 23°C with change in initial setting time at 22°C by cement type

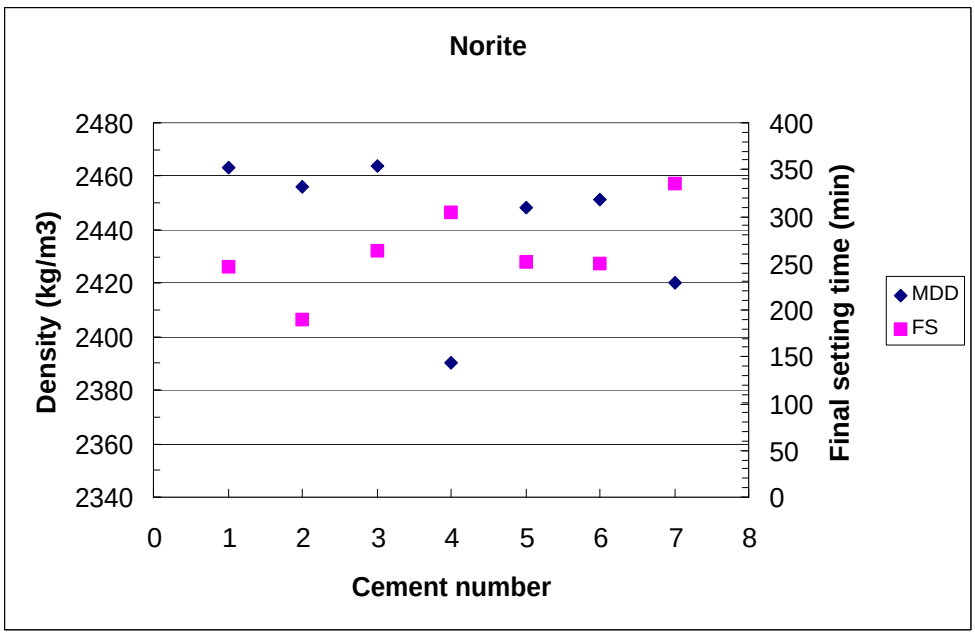

Figure 4.5: Change in MDD of norite at 23°C with change in final setting time at 22°C by cement type

4.3.2 Effect of conditioning temperature

Figures 4.6 and 4.7 show the relationships between the dry density obtained by compacting at MAASHO effort and OMC for the particular cement at the specified conditioning temperatures for the different cement types for the dolerite and norite respectively. The soil and water mixes and the cements were brought to the selected temperature and retained at this temperature (subject to temperatures generated by hydration of the cement) for the conditioning period – the standard 4 hours unless stated otherwise.

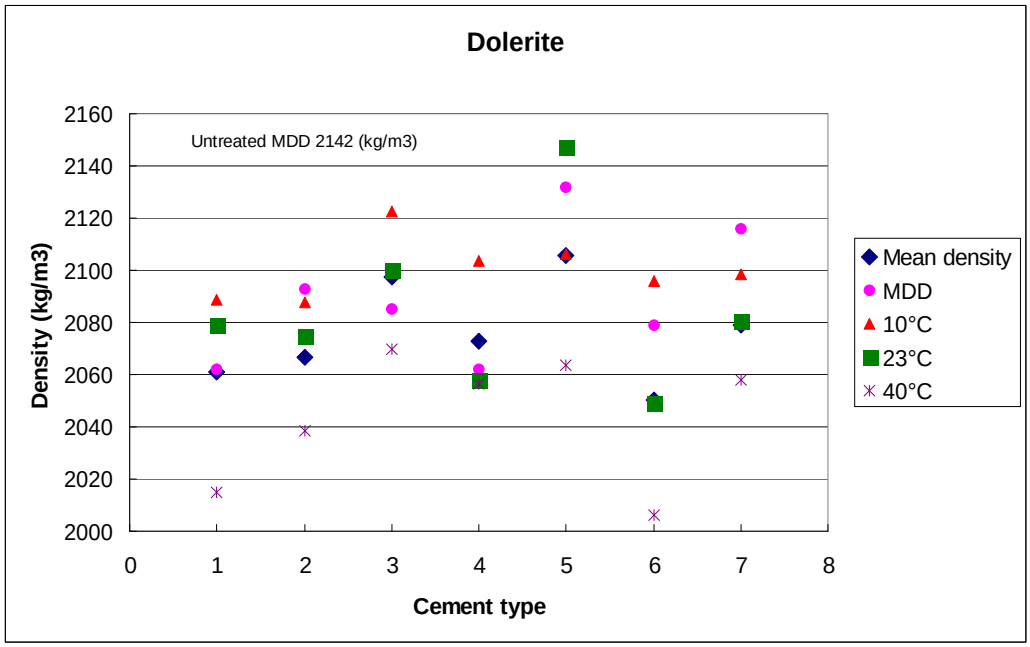

Figure 4.6: Changes of density of dolerite with temperature by cement type in comparison with MDD at 23°C, all at 4h

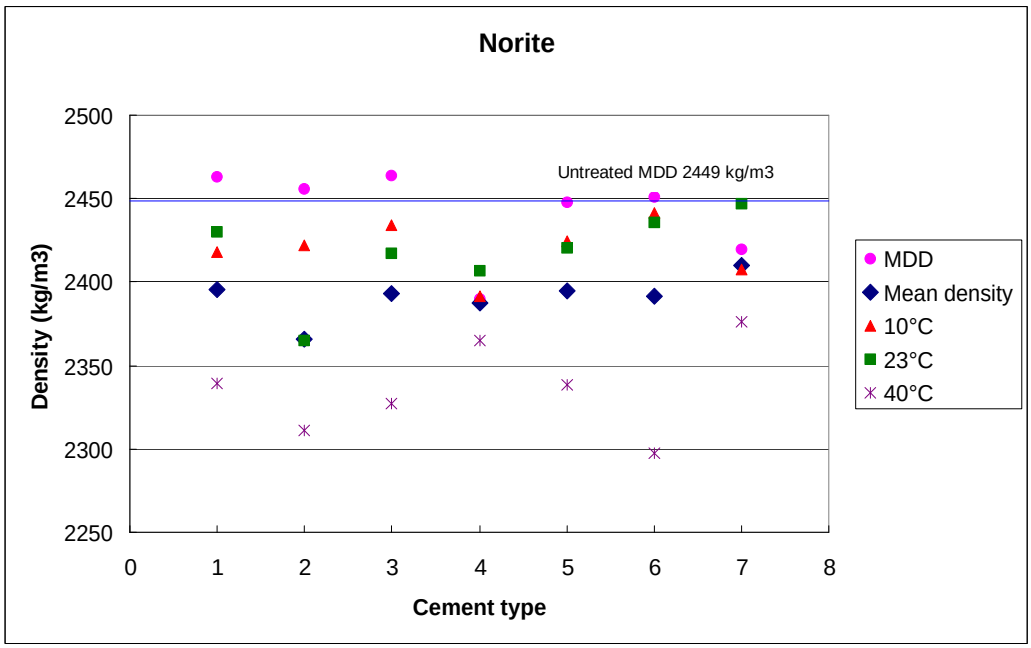

Figure 4.7: Changes of density of norite with temperature by cement type in comparison with MDD at 23°C, all at 4h

The density data used for these plots are the mean of the duplicate results obtained at each temperature for the UCS and ITS testing after both 2 and 4 hours conditioning (i.e. 8 specimens). All testing was carried out on duplicate samples compacted at the OMC for the material and cement using MAASHO compaction effort and where obvious discrepancies between the two strength results were obtained the test was repeated.

These mean results show that a variation in density of up to 6 per cent can be expected for some cements (cements 2 and 6) depending on the material and construction temperature. Cement 2, however, showed a much smaller variation with the dolerite than with the norite. In general the following observations were made:

- The variation from the mean results for the dolerite was smaller than that for the norite. The majority of results for the dolerite were in a tight band of about 40 kg/m^3. The majority of results for the norite lay in a band with a range of about 100 kg/m^3.
- The CEM I cements were more noticeably affected by high temperature than the other cements (except the CEM II A-L 32.5) in the dolerite.
- The mean densities of both dolerite and norite using the two slag cements (4 and 7) were the least sensitive to temperature changes. This could not be attributed to any individual chemical or physical property.
- The flyash cement (No 5) was least affected on average for the dolerite and performed similarly to the other cements with the norite, although the densities of both the norite and dolerite dropped significantly at 40°C.

It should be noted that working at high temperatures resulted in a greater reduction in density than was caused by the different cement types.

4.3.3 Effect of conditioning time

The time between adding the cement to the moist material and between starting and final compaction significantly affects the density that can be obtained. This was realised many years ago and TRH13[1] provides figures showing the effect of this time (Figure 4.8). It was noted that from about three hours, the density is little affected. The basis of the method allowing conditioning of the material for four hours prior to compaction was an attempt to simulate construction conditions on the road[6], but coincidentally this fits in with equilibration of the density at a time of 3 to 4 hours as illustrated in TRH13[1]. This figure relates to granite with a high cement content (8 per cent) and no information regarding other different materials has been located.

It should be noted that the decrease in density in the TRH 13 example is about 9.4 per cent, significantly greater than the maximum decrease recorded after 4 hours delay during this investigation, i.e., 4.9 and 4.5 per cent for the dolerite and norite respectively. The higher cement content used in the TRH 13[1] example may have had some influence on the high result.

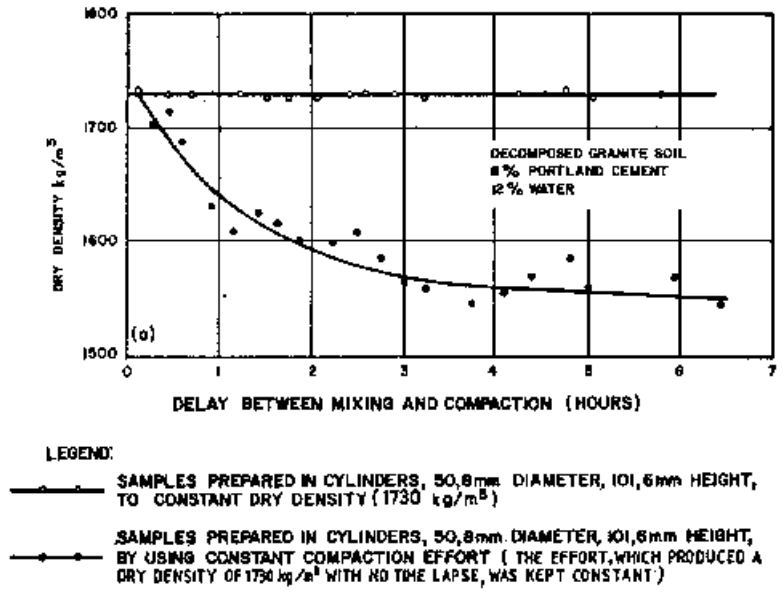

Figure 4.8: TRH 13[1] diagram of effect of delay between mixing and compaction on dry density

The trend towards the increasing use of recycling machines, however, results in the potential for the material (on a well-managed project) to be compacted within one or two

hours after the combination and mixing of water, cement and soil. In these cases, the maximum possible field density is likely to be higher than the laboratory-determined maximum dry density after 4 hours conditioning as a result of the rapid compaction, i.e. reduced delay before compaction.

This effect can have serious implications when determining performance, as the actual compaction may be poor despite the "specified" densities being achieved and durability of the material could be compromised. Where rapid compaction is achieved, this should be simulated during laboratory testing for determination of the MDD for use in quality control testing. This should be taken into account and an MDD simulating the field condition should be determined.

The effect of conditioning time on density is shown in Figure 4.9. The mean compacted densities (at OMC and MAASHO effort) for each material type after 2 and 4 hours conditioning at all temperatures are plotted against the cement type. The mean changes in density in percentage points are shown in Figure 4.10 for easy comparison.

The test results show that in the majority of cases (75 per cent), the compacted density dropped when compaction was delayed for 4 hours compared with compaction after 2 hours. In 25 per cent of the results, the density increased and no reason could be found for this. All testing was carried out in duplicate and the test data were carefully assessed to ensure that no outliers influenced the results. Observations regarding the results were:

- The maximum decrease in compacted density compared with the MDD of the natural material (irrespective of temperature) in the dolerite was 3.8 per cent after 2 hours conditioning, compared with 4.7 per cent after 4 hours conditioning.
- The maximum compacted density decrease (irrespective of temperature) in the norite was 5.6 per cent after 2 hours conditioning, compared with 6.8 per cent after 4 hours conditioning.
- The mean compacted density decreased with conditioning time, although the degree of decrease varied from marginal to strong.
- No consistent pattern related to cement types was evident.

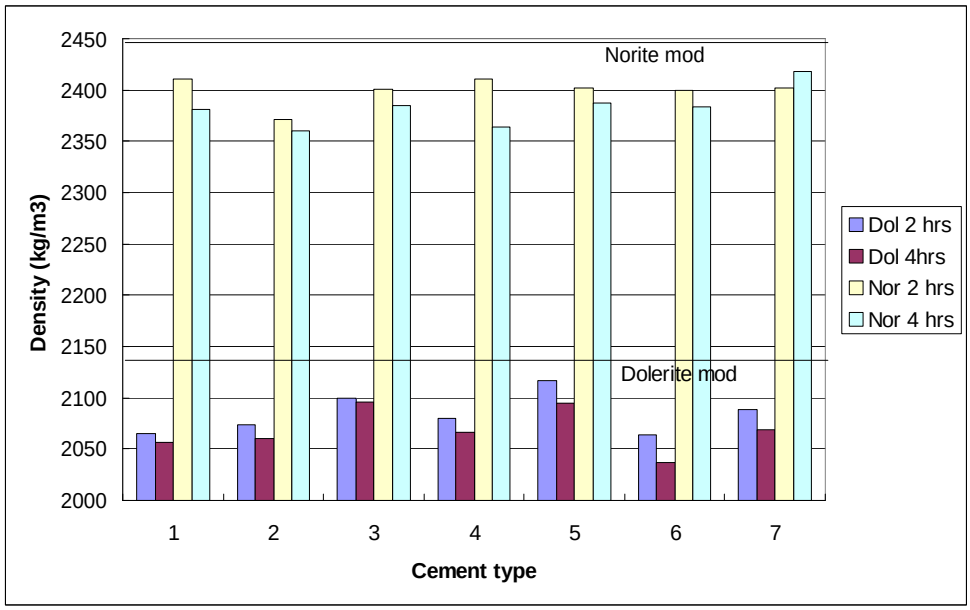

Figure 4.9: Effect of conditioning time on compacted density

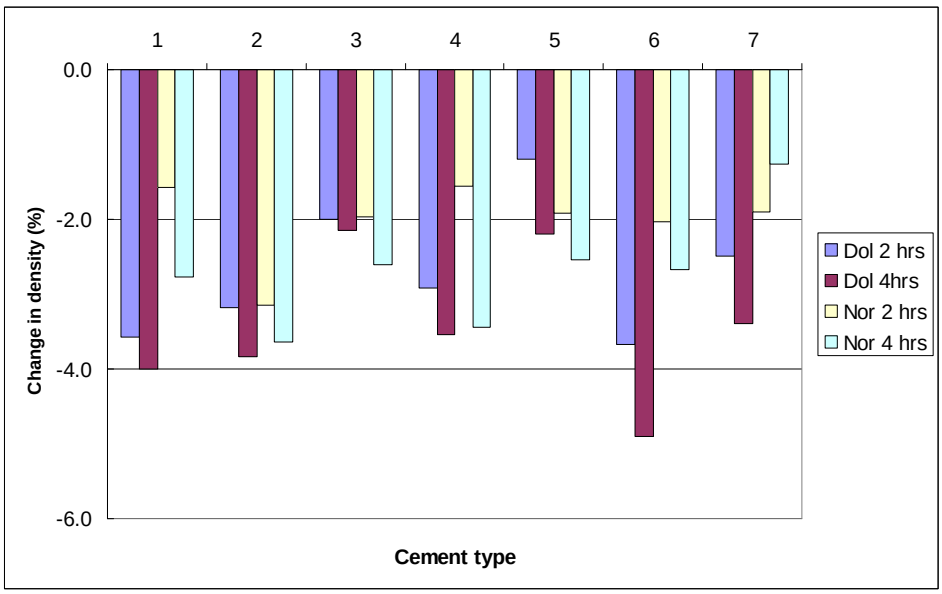

Figure 4.10: Effect of conditioning time on compacted density expressed as change in density (%)

In terms of overall performance, the flyash cement (No 5) was probably marginally better than the others although the CEM III A with norite was least affected by conditioning time. The CEM I 42.5 and CEM II A-L 32.5 cements were generally most affected by delayed compaction times.

4.3.4 Effect of temperature

Although the results of the 10°C and 23°C testing were somewhat erratic, the average effect of all tests on both materials indicated that the densities achieved at 40°C were significantly lower than those at the standard 23°C (see section 4.3.2 and Figures 4.6 and 4.7). Other observations were:

- In general the densities at 23°C were lower than at 10°C but when the conditioning time was 4 hours, the dolerite showed only marginal differences in density.
- At 10°C, the mean density after 4 hours conditioning was almost the same as after 2 hours conditioning. The mean density of the norite after 2 hours conditioning (at 23°C) was higher than that at 10°C but after 4 hours, the density at 23°C was generally less.
- The difference between the density of the norite at 23°C and 40°C was much larger than the differences for the dolerite.
- In all cases the greatest density decrease occurred when the material was compacted at 40°C.
- In most cases the maximum density was achieved at 23°C, although the material treated at 10°C generally had more consistently higher mean densities.
- The CEM II B-V and CEM III A (with blastfurnace slag) were generally the cements with densities least affected by high temperatures on both the dolerite and norite.

4.4. Unconfined compressive strength (UCS)

Unconfined compressive strength testing was carried out on duplicate briquettes of both materials using all seven cements, three conditioning temperatures and two conditioning times at one compactive effort (MAASHO). In all, 84 test results were obtained, each being a mean of two tests. Testing followed the TMH 1 requirements with the normal curing for 7 days in a humidity room at 95 to 100 per cent relative humidity and at a temperature of 22 to 25°C. All specimens were soaked in water for 4 hours prior to testing.

The types of material at which this project was aimed are generally lightly cemented C4 and C3 type materials. Specified strengths for these materials are 750 to 1500 kPa and 1500 to 3000 kPa respectively[1] at 100% MAASHO compaction. It should be noted that strength test results are extremely dependent on the density at the time of testing. In the previous section the impact of cement type, temperature, conditioning delay, etc. on

density was discussed and the impact of this on the strength results should be borne in mind – strengths will be lower at lower densities.

4.4.1 Effect of cement type

A plot (Figure 4.11) of cement type versus the mean UCS (mean of duplicate specimens at all temperatures and conditioning times) showed that for the dolerite, the CEM I cements (numbers 1 and 2) produced lower strengths than the CEM II 42.5 cements (numbers 3 and 4) and the strength thereafter generally decreases as the cement type changed through the CEM II 32.5 (5 and 6) to the CEM III. The CEM III (cement number 7) failed to produce the required strength for a C3 material at an application rate of 3 per cent. The strengths obtained from all of the cements, except the CEM II B-V 32.5 exceeded the upper limit for a C3 material on the norite on the other hand, with the CEM III producing the highest strength of all. It should be noted that the failure of the CEM III to produce the minimum strength of 1500 kPa at 7 days is not necessarily a disadvantage, provided it has other advantages and reaches similar strengths to the other cements at say 28 days. However, assurance of this further strength increase does not need to be known, as strengths are usually only specified at 7 days (or after the equivalent accelerated test).

The variation in measured strength (as a percentage) was significantly less for the norite than for the dolerite.

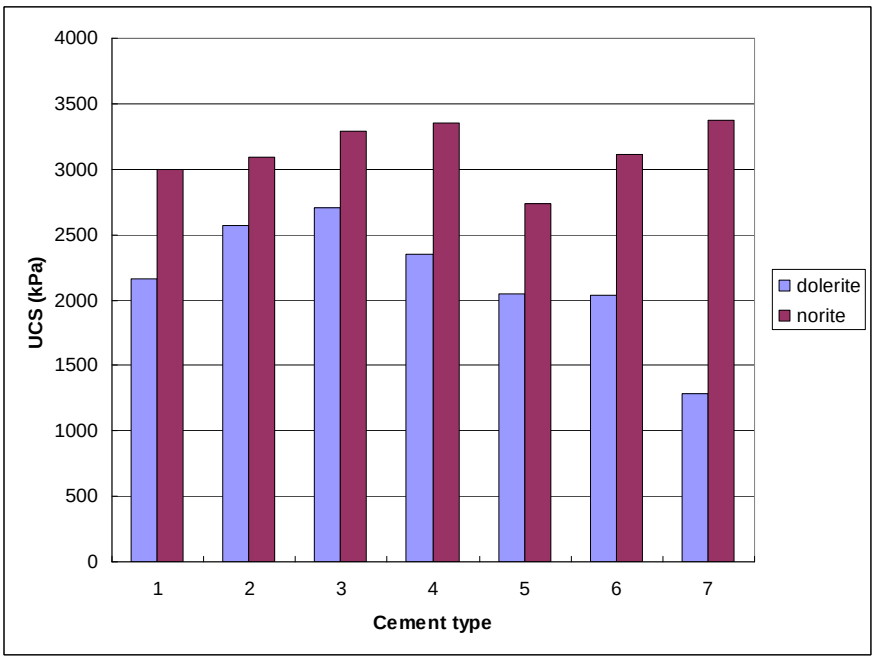

Figure 4.11: Influence of cement type on mean unconfined compressive strength at 7 days with 3% cement

Figure 4.12 shows a plot of the density and UCS versus the cement type. No obvious relationships are seen apart from a tendency for the mean UCS to increase with mean dry density. In order to normalise the density, these data are re-plotted (Figure 4.13) using the ratio of density at testing (only the data from the specimens conditioned at 23°C and for 4 hours were used) to MDD for each cement, i.e. the per cent compaction as normally used. The compactions achieved on each specimen should, of course, be all close to 100 per cent.

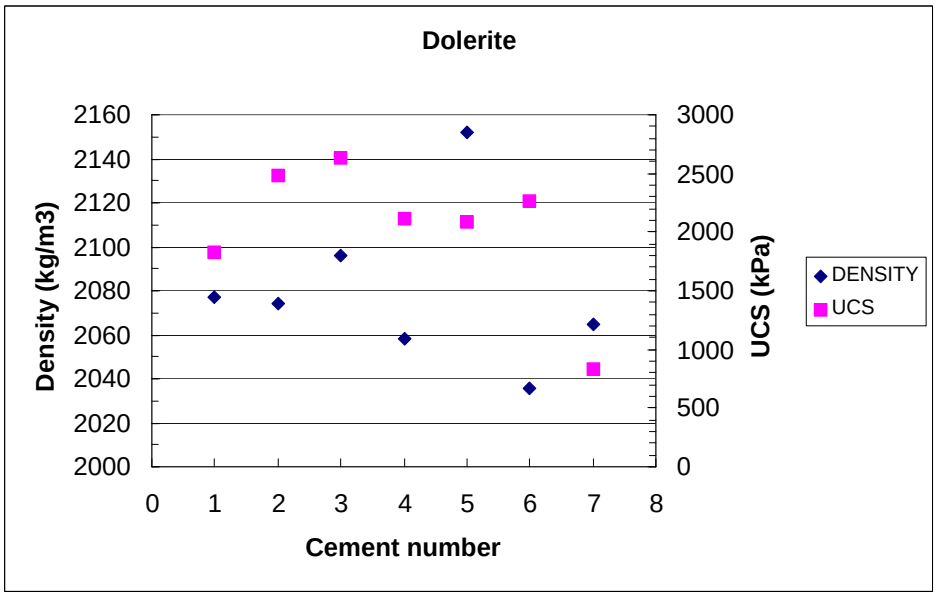

Figure 4.12: Influence of cement type on unconfined compressive strength and density of dolerite

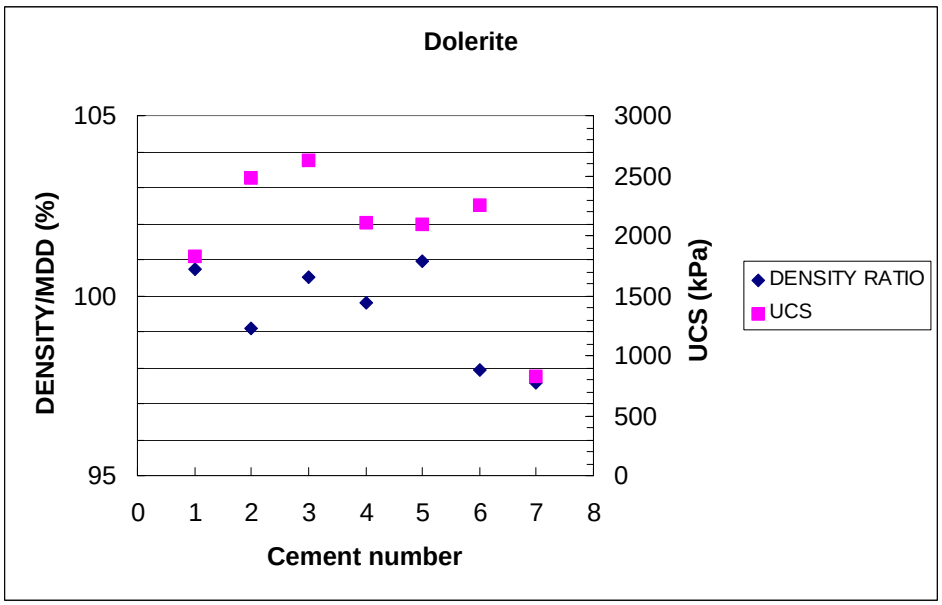

Figure 4.13: Influence of cement type on unconfined compressive strength (at 23°C and 4 h conditioning) and ratio of specimen density to MDD for dolerite

Apart from cements 6 and 7, all of the specimens were within one per cent of MDD. No trends are obvious in these data. Similar plots were produced for the norite and the UCS-density ratio plot is shown in Figure 4.14.

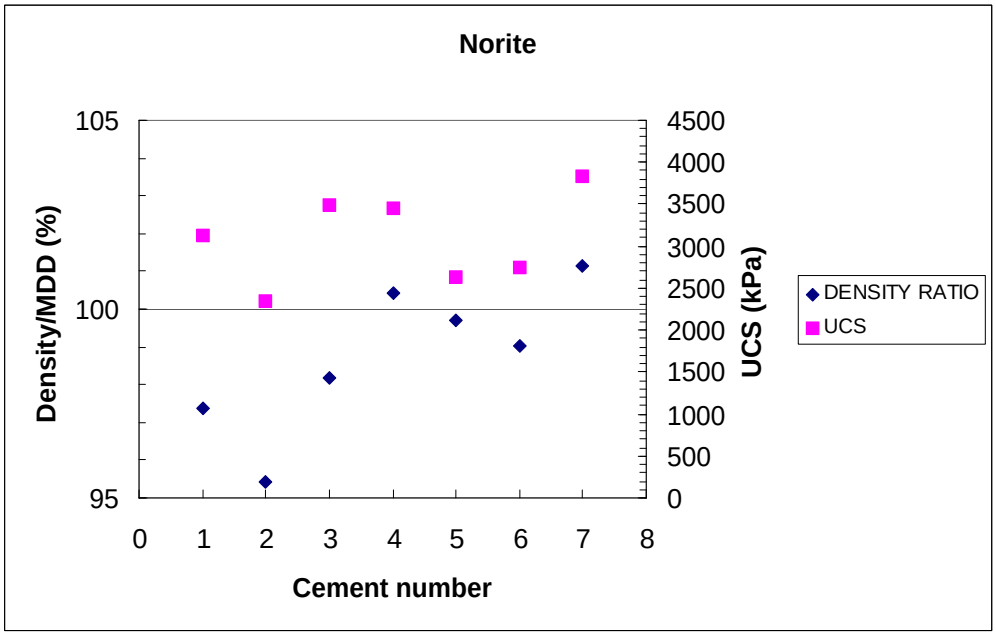

Figure 4.14: Influence of cement type on unconfined compressive strength (at 23°C and 4 h conditioning) and ratio of specimen density to MDD for norite

A much stronger trend is shown for the norite than the dolerite, with the UCS trace almost tracking the density trace point by point. It is, however, doubtful that the UCS pattern is solely the result of changes in density (although a much wider range of densities was obtained than the norite). Cements 3 and 4 have similar strengths but the densities differ by more than 2 per cent.

4.4.2 Effect of conditioning time

Conditioning the specimen material (soil, cement and water) for 4 hours after mixing and before compaction resulted in a reduction of the strength compared with that conditioned for 2 hours in every case (Figure 4.15). The degree of reduction, however, varied from cement to cement and also between the two materials. The UCS of the dolerite was usually relatively less affected than the norite.

The results reflect the density-strength relationships, with similar trends evident. It is clear that small differences in density are reflected in relatively high differences in strength, particularly for the norite. Cements 4 and 7 produce the best results (high strengths with small variations resulting from conditioning and density) on the norite while cements 4 and 6 seem to be most effective on the dolerite. This is not in agreement with the density results where other cements had smaller variations in density.

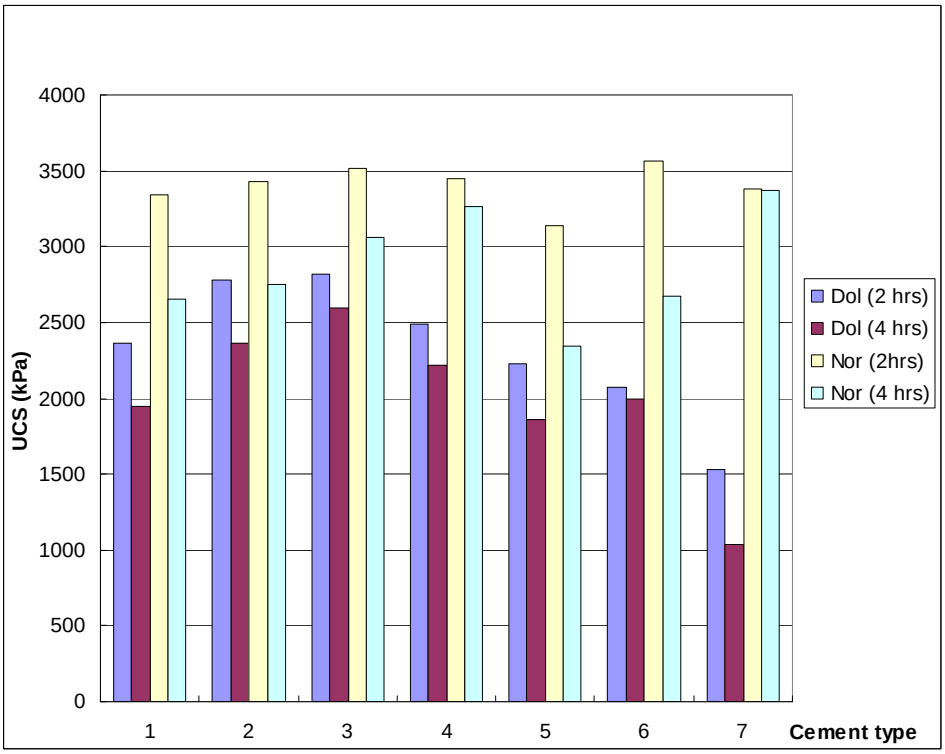

Figure 4.15: Influence of conditioning time on mean unconfined compressive strength

4.4.3 Effect of temperature

Figure 4.16 summarises the mean strength of the materials (the 2 and 4 and D and N labels indicate conditioning time in hours and material types – dolerite and norite). The mean strengths were determined from the duplicate specimens using all cements. The laboratory conditioning temperatures are assumed to represent the temperatures of the soil-cement during mixing and compaction on the road.

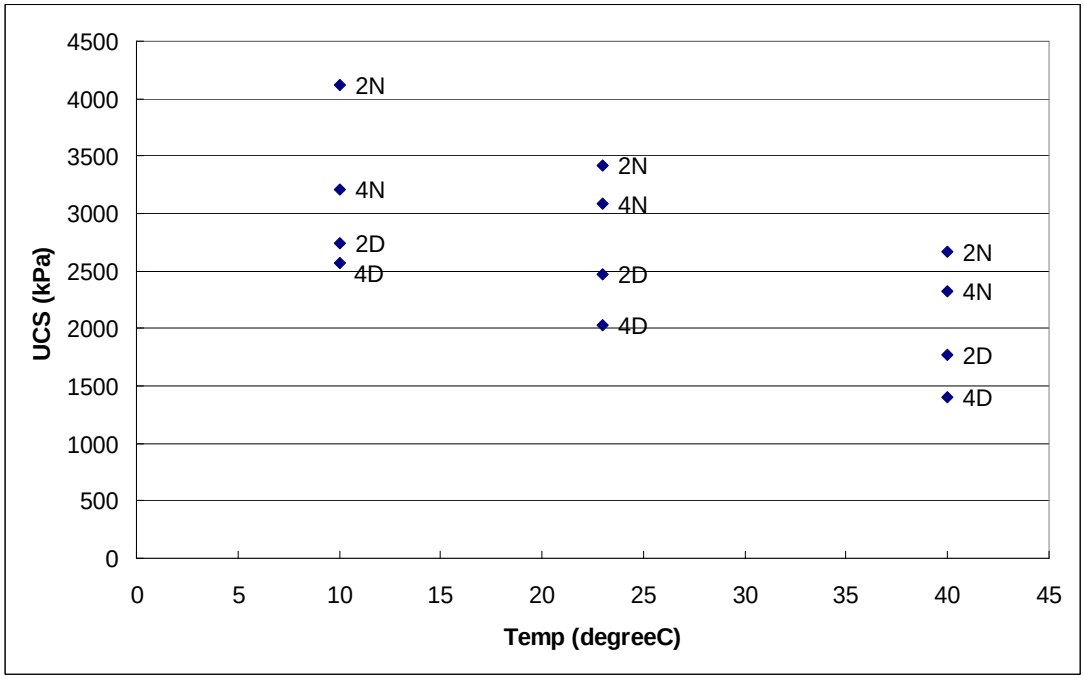

Figure 4.16: Influence of conditioning temperature on mean (of all cements) unconfined compressive strength

The significant decrease in mean strength as conditioning temperature increases is clearly illustrated, bearing in mind the accompanying decrease in compacted density and concomitant reduction in strength. It is, however, not possible with the data avaialble to quantify the proportion of strength lost through density reduction.

As a first generalised approximation, it appears that the effect of conditioning temperature on UCS may in many cases be linear over the range of interest, with a temperature coefficient of about –40 kPa/°C. Thus, if the strength at a particular conditioning time and temperature is known, it may be possible to estimate the strength for any other conditioning time.

As a second generalised approximation, let it be assumed tha a further two-hour delay causes a reduction in UCS of about 500 kPa. For example, if a UCS of 3500 kPa is obtained at 23°C after a two hour delay, the effect of a four hour delay at 40°C would be to reduce the UCS to about 2300 kPa – a very substantial effect. This relationship is of course only roughly valid for this set of data, but may point the way towards a method of estimating the magnitude of these effects in a particular case.

The general trend of decrease in strength is illustrated further in Figures 4.17 and 4.18 in relation to the conditioning time and cement types. It should be noted, however, that not

all of the specimens showed this trend and the duplicate test results were individually assessed during the laboratory testing to ensure that these outlying trends were correct.

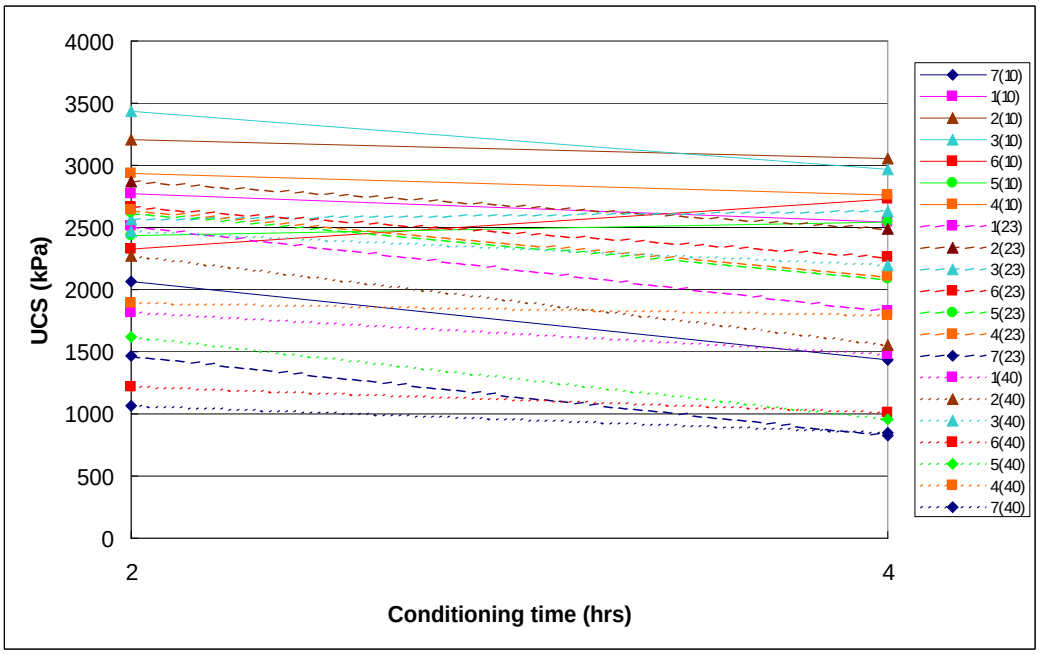

Figure 4.17: Influence of conditioning temperature on unconfined compressive strength of dolerite (by conditioning time and cement type). (Note that the first number in the legend is the cement number and the second is the temperature.)

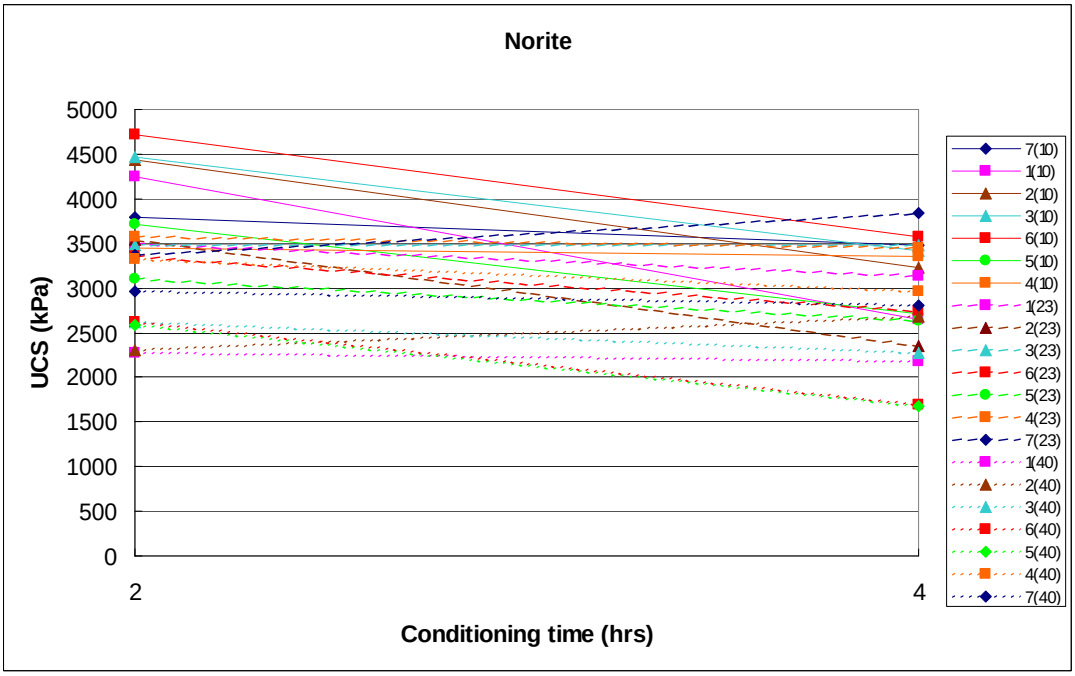

Figure 4.18: Influence of conditioning temperature on unconfined compressive strength of norite (by conditioning time and cement type)

Figures 4.19 and 4.20 summarise these results in terms of the cement types.

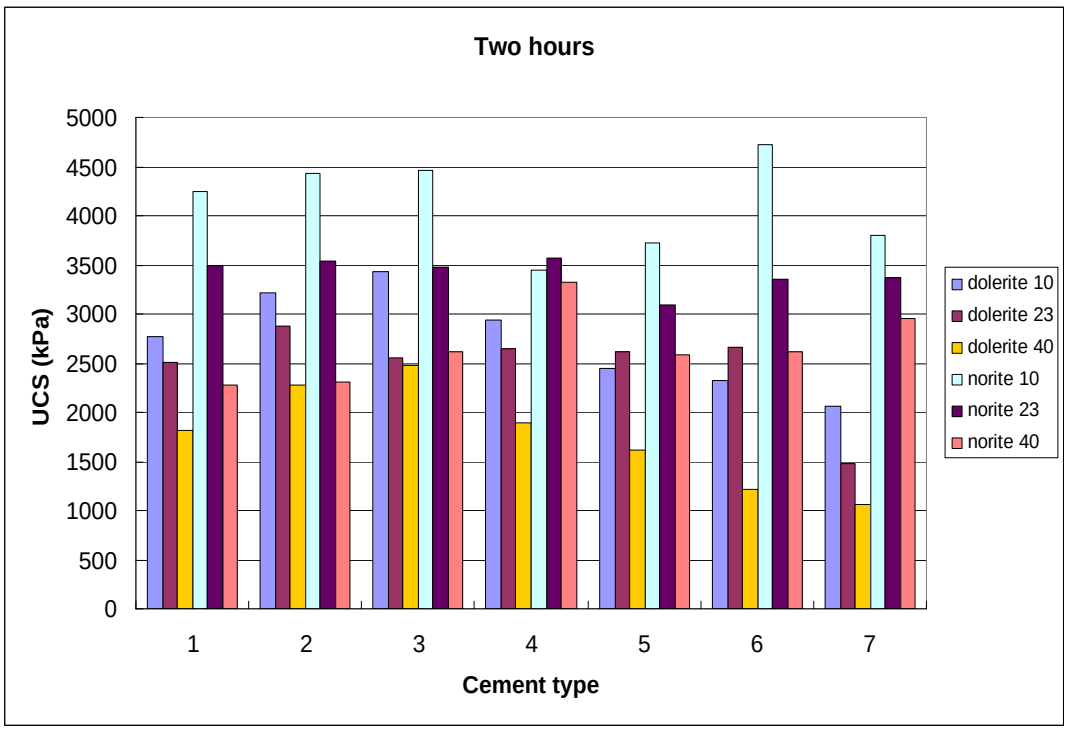

Figure 4.19: Influence of conditioning temperature after conditioning for 2 hours on unconfined compressive strength (by cement type)

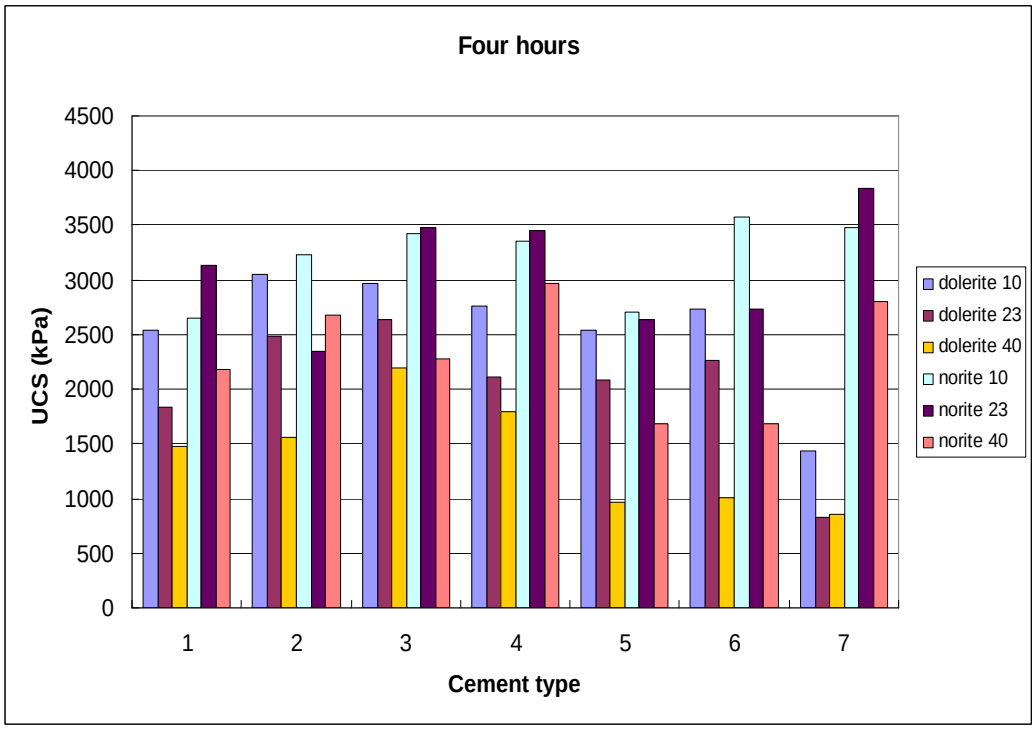

Figure 4.20: Influence of conditioning temperature after conditioning for 4 hours on unconfined compressive strength (by cement type)

It is clear that the strengths produced by certain of the cements are affected to a greater degree by conditioning time and material than others, e.g. cement number 4 was least affected on the norite while cement number 5 was strongly affected on the dolerite by time and temperature. There are, however, no fixed trends and a cement type (cement 7 - CEM III A) that was affected strongly by conditioning time and temperature reacted poorly with the dolerite for instance but produced the highest overall strengths for the norite.

4.5. Indirect tensile strength (ITS)

COLTO specifies minimum limits for the indirect tensile strength of cemented materials. These are set at 200 kPa for C4 and 250 kPa for C3 materials at 100 per cent Mod AASHO density. It is the belief of the authors that the tensile strength affects the durability and performance of stabilized materials more than the compressive strength.

Testing of the indirect tensile strength was carried out using the standard TMH 1 method, except that the maximum particle size used was 37.5 mm and the conditioning times and temperatures were varied as for the unconfined compressive strength testing. As specified in TMH 1, no soaking of the specimens was carried out prior to testing.

4.5.1 Effect of cement type

A plot of the cement type versus the mean ITS (at all temperatures and conditioning times) indicated that for the dolerite, the CEM I cements produced marginally lower or similar strengths to the CEM II 42.5 and the strength thereafter generally decreased as the cement type changed through the CEM II 32.5 and the CEM III cements (Figure 4.21). Cement 4 (CEM II A-M(S) 42.5) produced the highest strength on the norite. Other than this the trend shown for the dolerite was mostly reversed with the norite.

Only 2 cements produced the required ITS for a C3 material (250 kPa) and 3 cements for a C4 (200 kPa) on the dolerite. The CEM II A-L 32.5 and CEM III A failed to produce the required strength for a C4 material at 3 per cent cement. The tensile strengths obtained from all the cements, except one (CEM II A-M 42.5) achieved the limit for a C3 material on the norite on the other hand, with the CEM III A producing the second highest strength.

Both materials produced significant variations in measured strength as discussed later. The relative effects of the different cements on the ITS of the dolerite and norite were in some cases dissimilar to those of the UCS.

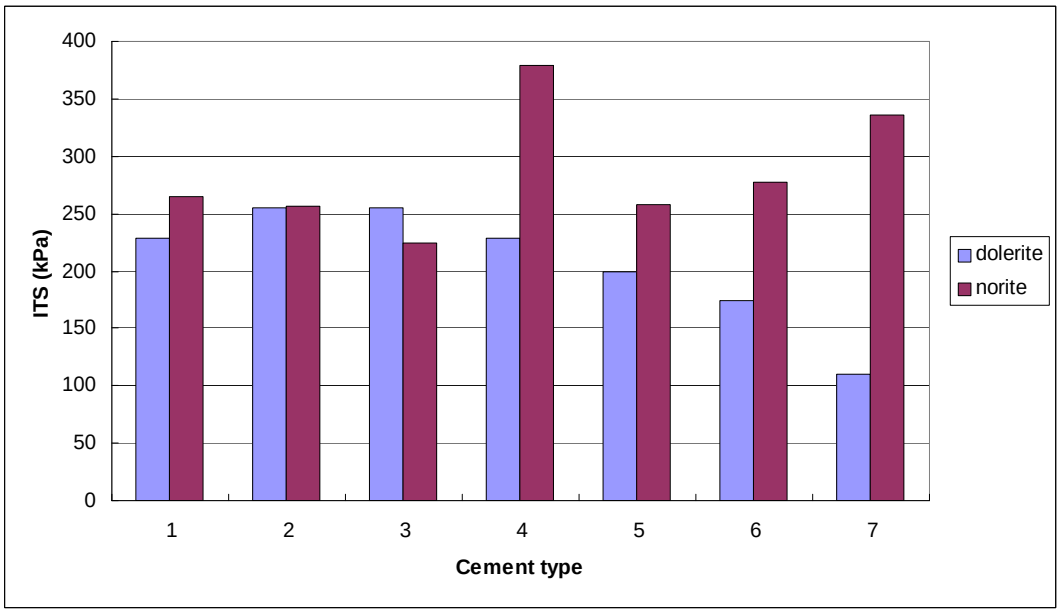

Figure 4.21: Influence of cement type on mean indirect tensile strength

Plots of the density, density/MDD ratio (i.e. per cent relative compaction) and ITS versus the cement type for the dolerite and norite are shown in Figures 4.22 to 4.25.

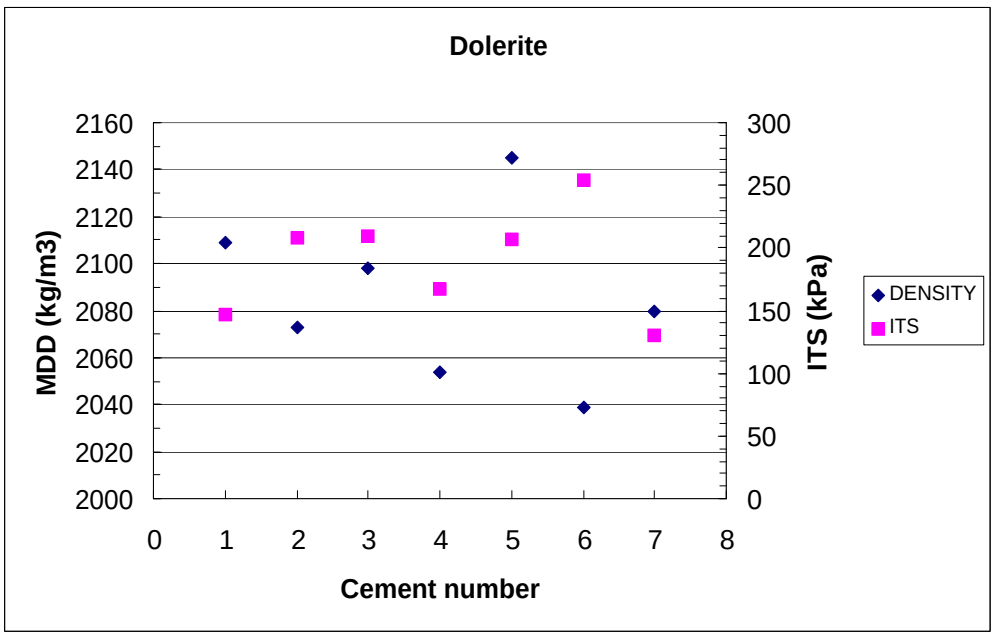

Figure 4.22: Influence of cement type on indirect tensile strength and density of test specimens of dolerite (at 23°C and 4 h conditioning)

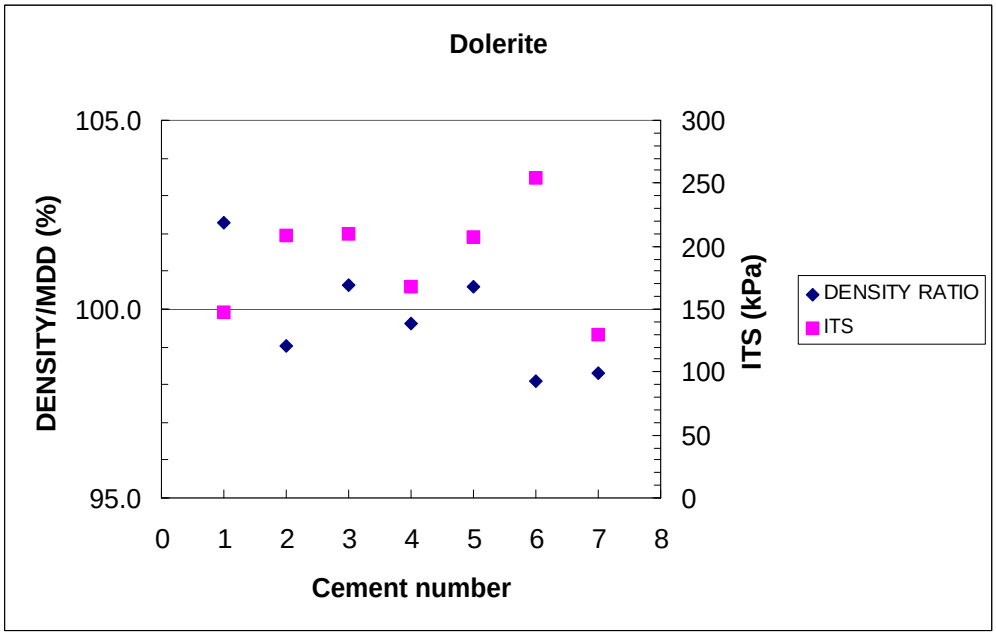

Figure 4.23: Influence of cement type on indirect tensile strength and ratio of density of test specimens to MDD of dolerite (at 23°C and 4 h conditioning)

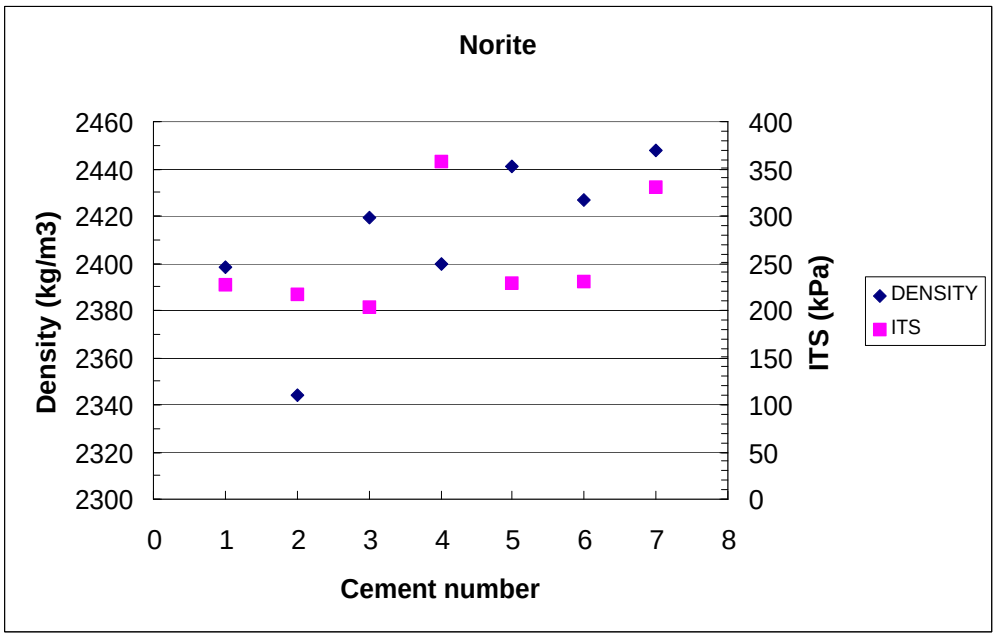

Figure 4.24: Influence of cement type on indirect tensile strength and density of test specimens of norite (at 23°C and 4 h conditioning)

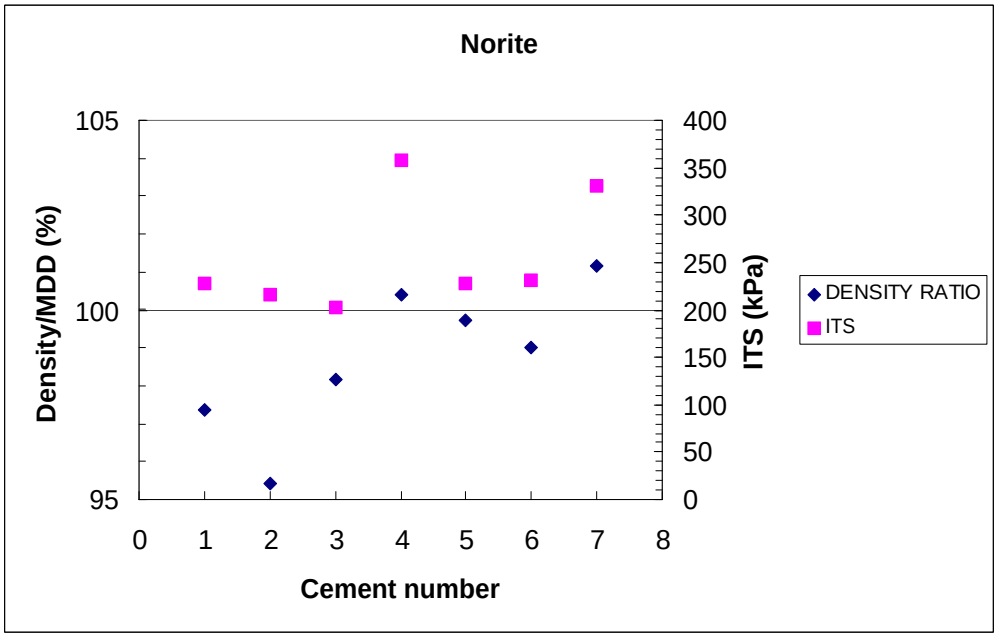

Figure 4.25: Influence of cement type on indirect tensile strength and ratio of density of test specimens to MDD of norite (at 23°C and 4 h conditioning)

The density and ITS plots show little correspondence except for the norite, but a much better relationship is seen when the density is expressed as the ratio of specimen density to MDD, i.e. relative compaction. The ITS is therefore seen to be more closely related to the density of the test specimen than the UCS. It is, however difficult to discriminate between the change in ITS related to the density and that related to the cement type. The MDD used in these plots is of course the MDD for 3 per cent of the particular cement after 4 h conditioning at 23°C.

It is for this reason that trends related to individual cements are investigated in this report. The validity of taking the mean results of all tests at differing temperatures and conditioning times to indicate these trends may be questioned. As the findings attempt to replicate the behaviour of stabilized materials under full-scale site conditions, including temperature and time variations, the trends obtained are, however, considered valuable.

4.5.2 Effect of conditioning time

Conditioning the specimen material (soil, cement and water) for 4 hours after mixing of the cement and water and before compaction resulted in a reduction of the mean indirect tensile strength compared with that conditioned for 2 hours in almost every case (Figure 4.26). The CEM III A specimens showed a small increase for the dolerite and a negligible increase for the norite compared with the generally more significant decrease obtained with all the other cements. The degree of reduction for the other cements, however, varied from cement to cement although a greater reduction was generally obtained for the

norite than for the dolerite. Apart from the effect on the CEM III A cement, the relative effect of conditioning on the ITS parallels the effect on the UCS almost exactly.

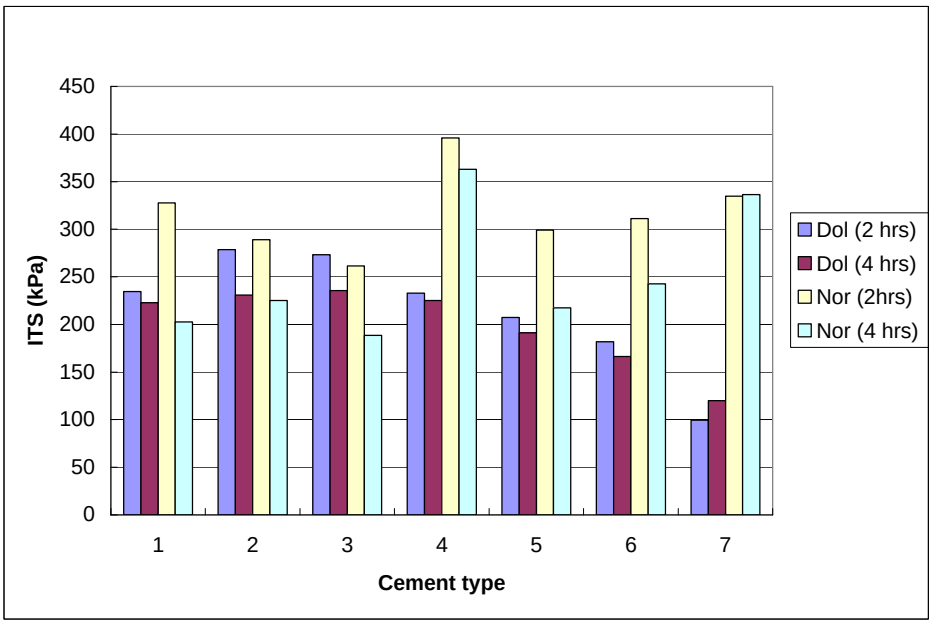

Figure 4.26: Influence of conditioning time on mean indirect tensile strength

4.5.3 Effect of temperature

Figure 4.27 summarises the mean strength of the materials (the 2 and 4 and N and D labels indicate conditioning time in hours and material types – dolerite and norite).

The significant decrease in mean strength as conditioning temperature (assumed to be that of mixing and compaction) increases is clearly illustrated and follows a similar trend to that for the UCS (Figure 4.16). This is illustrated further in Figure 4.28 for dolerite in relation to the conditioning time and cement types. The norite results were similar except that fewer cements increased in tensile strength after 4 hours conditioning.

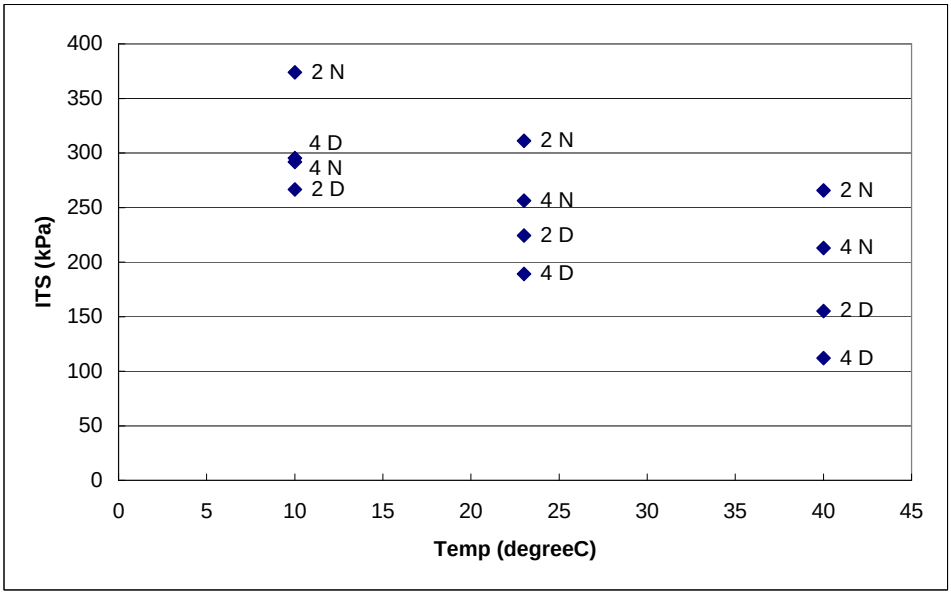

Figure 4.27: Influence of conditioning temperature on mean indirect tensile strength of all cements

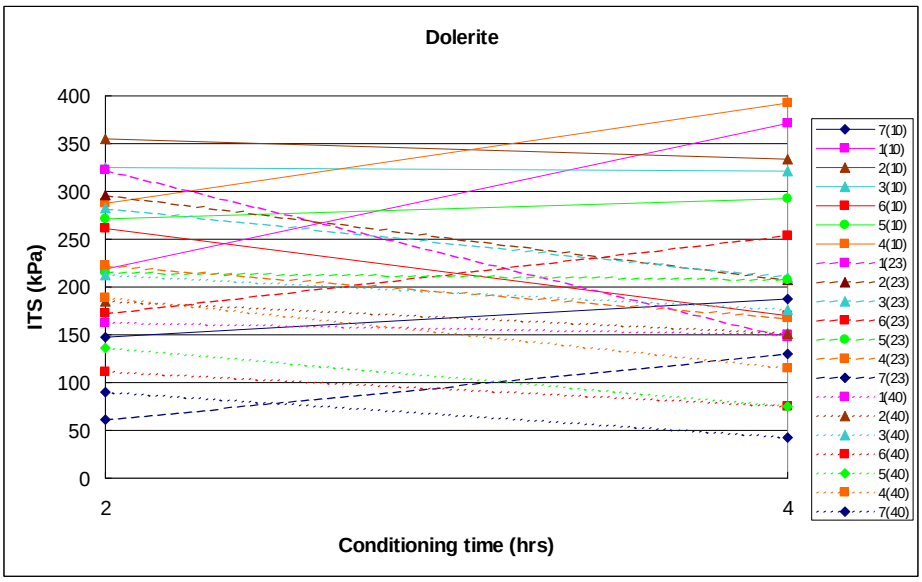

Figure 4.28: Influence of conditioning temperature on indirect tensile strength of dolerite (by conditioning time and cement type)

As a rough generalised first approximation it seems that the temperature coefficient for ITS is about –5 kPa/°C and the loss of ITS about 50 kPa for a further two hour delay.

Figures 4.29 and 4.30 identify the above trends by cement type.

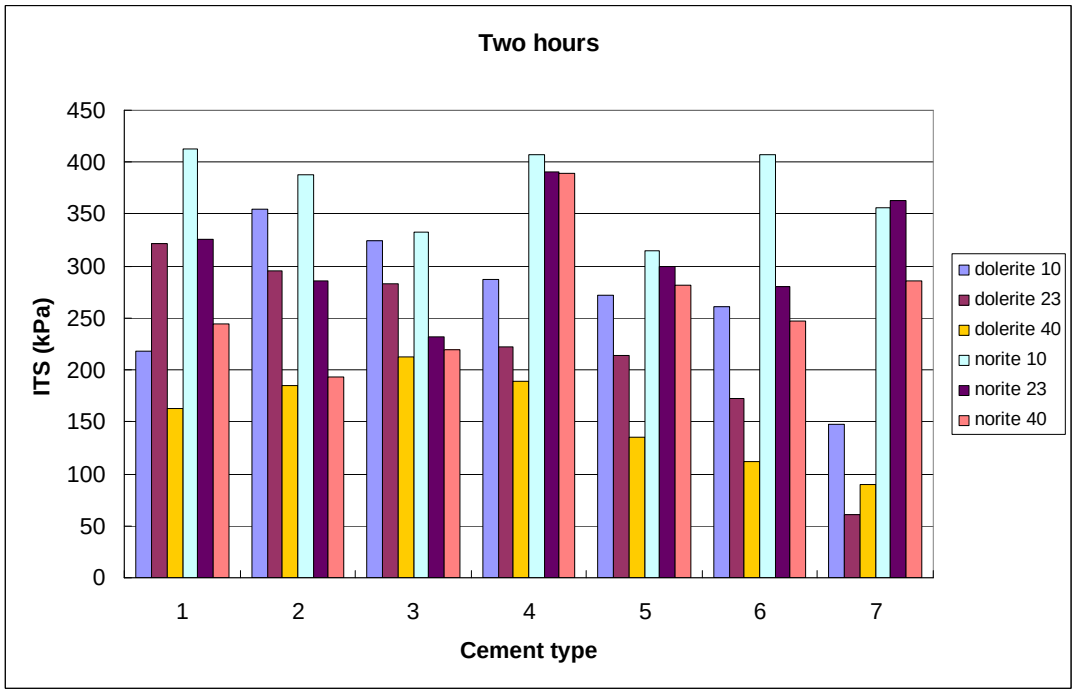

Figure 4.29: Influence of conditioning temperature after conditioning for 2 hours on indirect tensile strength (by cement type)

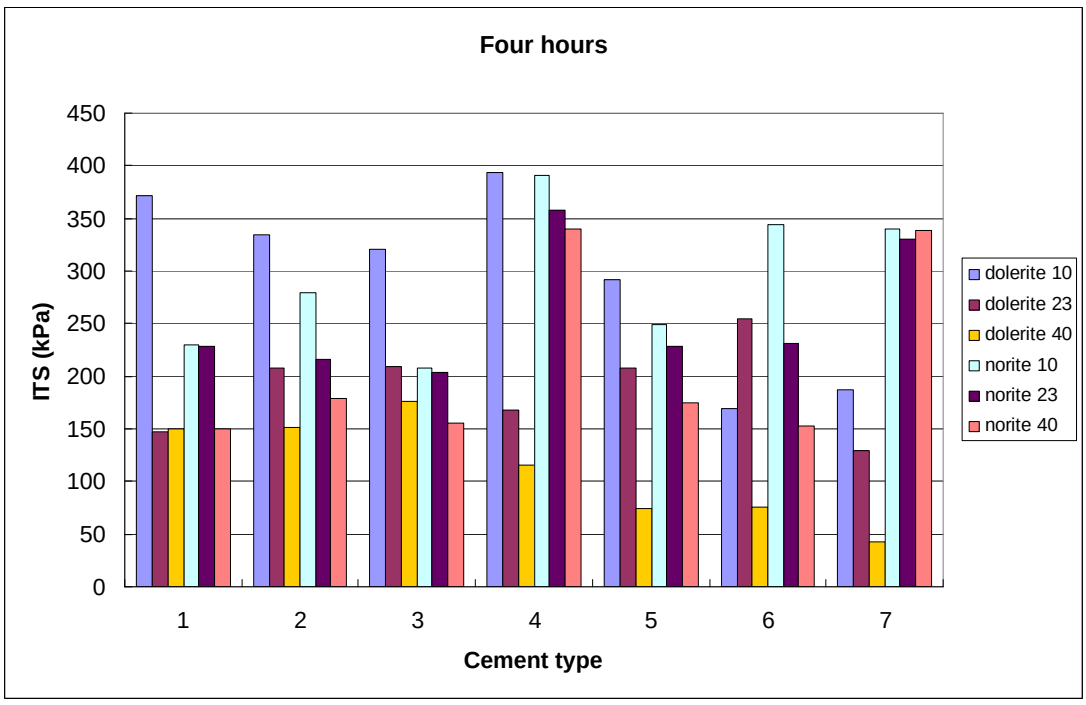

Figure 4.30: Influence of conditioning temperature after conditioning for 4 hours on indirect tensile strength (by cement type)

It is clear that the tensile strengths produced by certain of the cements are affected to a greater degree by conditioning time and material than others. There are, however, no fixed trends and a cement (CEM III A) that was affected strongly by conditioning time and temperature reacted poorly with the dolerite for instance but produced some of the best results for the norite. The results show some significant differences from the UCS behaviour (see Figures 4.19 and 4.20), with more severe decreases being evident for some cements. The effect of temperature on the CEM III A with the norite after 4 hours conditioning was negligible and the conditioning time only had a small overall effect on the ITS. Again the contribution of the lower densities to the reduced indirect tensile strengths cannot be quantified from the data available.

4.6. Discussion

4.6.1 Density and strength

Based on the limited number of materials tested, it appears that different materials behave very differently when cement stabilized depending on their composition, the cement types used and the construction conditions.

The earlier analyses indicated that both conditioning time and temperature have a significant impact on density and strength. A wide range of densities and strengths, well outside the conventional acceptance limits for construction control, was achieved depending on the conditioning temperature and time, as well as the cement type.

An assessment of the impact of cement type on compacted density (Figure 4.31) using the mean results of the densities of all strength test (UCS and ITS) specimens carried out at the standard temperature (23°C) and conditioning (4 hours) conditions indicates that for the dolerite all cements showed a decrease in mean density compared with the unstabilized MDD but three of the samples had densities higher than the stabilized MDD for that cement. The norite on the other hand had only two stabilized MDDs less than the natural MDD but the mean compacted densities achieved during strength testing at standard conditions of six of the seven cements were less than the MDD for those cements. The effect of density changes on the measured strengths cannot be quantified from the data available.

In interpreting Figure 4.31, it should be borne in mind that the smaller the loss of maximum densities or compacted dry densities from the MDD of untreated material, the better.

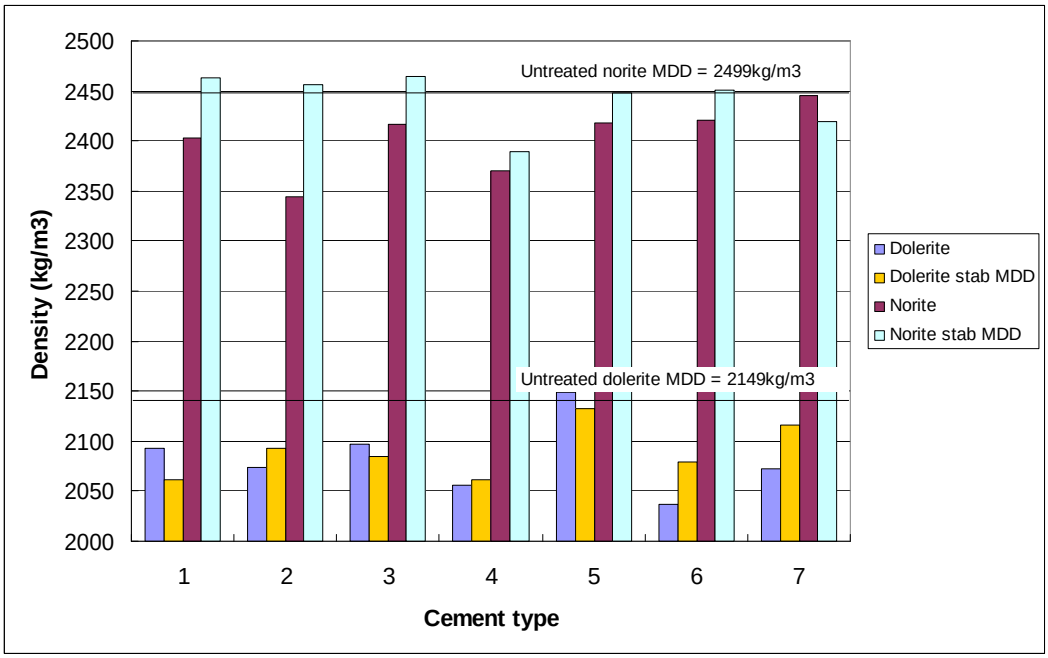

Figure 4.31: Impact of cement type on compacted density in comparison with maximum dry density after 4 h conditioning at 23°C

From the testing carried out, little relationship between the cement type, material type, conditioning time or temperature was obvious. Factors such as cement chemistry and physical properties may play an important role.

4.6.2 Unconfined compressive and indirect tensile strength

Plots of the relationship between the unconfined compressive strength and indirect tensile strength against the cement types are shown in Figures 4.32 and 4.33 for the dolerite and norite respectively. This comparison ignores the effect of variations in compacted density of the specimens on the strength data.

Apart from one “outlier” for the norite (cement number 3), the trends between the two strength measurements are very comparable. It thus appears that the strengths are more (or equally) affected by the cement types than by the compacted densities at which they are tested.

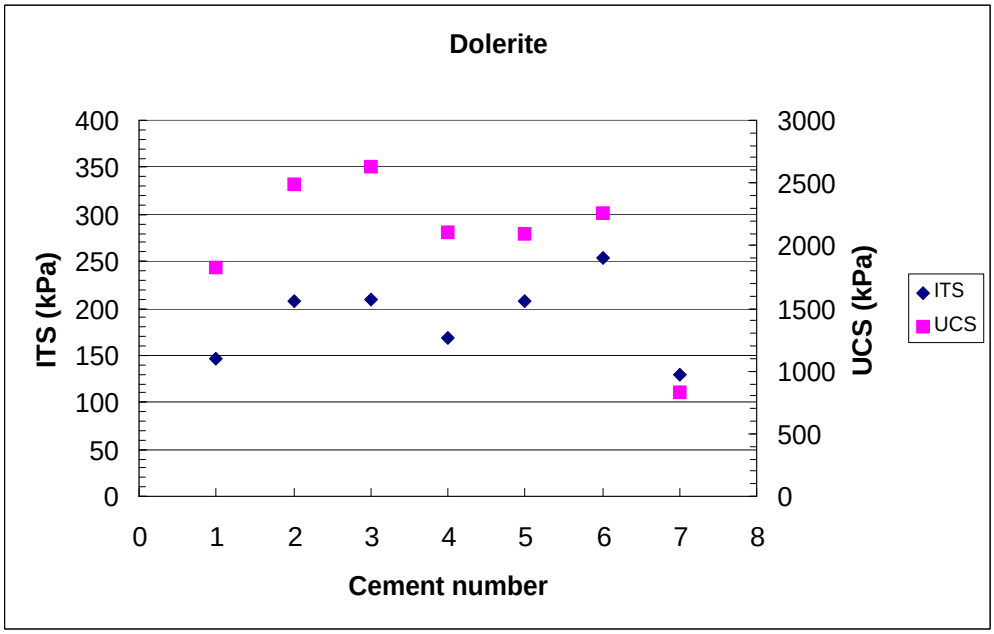

Figure 4.32: Impact of cement type on UCS and ITS after 4 h conditioning at 23°C and 7 days curing for dolerite

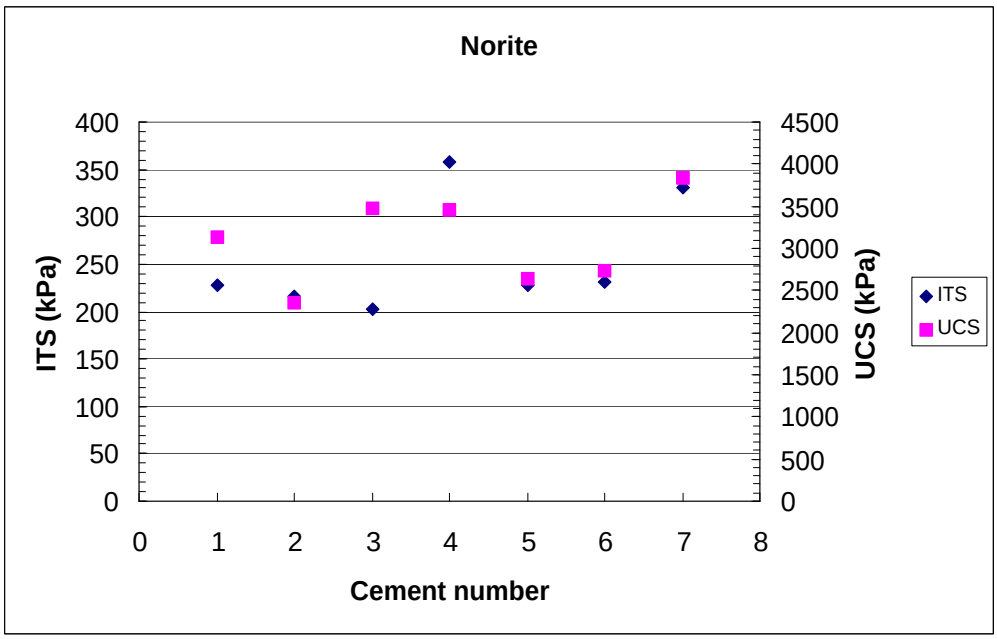

Figure 4.33: Impact of cement type on UCS and ITS after 4 h conditioning at 23°C and 7 days curing for norite

4.6.3 Sulfate contents

The sulfate contents of the cements varied between 0.8 (this value, determined by PPC Group Laboratory Services, appears low - the Lafarge analysis on this cement yielded a value of 1.19 per cent) and 2.77 per cent SO_3, all well within the upper limit of 3.5 or 4.0 per cent specified for the different strength classes in EN 197. The sulfate in the clinker

varied between 0.45 and 0.56 per cent, indicating that the majority of the sulfate in the cement originated from the gypsum added to control the setting rate. As discussed earlier, there was little correlation between the setting rates and the sulfate contents of the cements.

4.6.4 Alumina content

The alumina contents of the cements lie in the range 3.9 to 11.4 per cent with only the cements containing flyash and slag being higher than 6 per cent (alumina contents are meaningless in these cements). These results compare favourable with typical analyses of a range of European CEM I cements, which have alumina contents of 4.1 to 6.2 per cent[11].

4.6.5 Particle size

The Blaine surface area measurements varied between 302 and 429 m^2/kg with a mean of 374 m^2/kg. Although surface area is no longer specified in EN 197-1, this is considerably higher than the old SABS 471 minimum specification of 225 m^2/kg for Portland cement and even higher than the minimum of 325 m^2/kg for rapid hardening cement. It is interesting that this does not appear to have been offset by an increase in sulfate content, and yet the setting times seem to have been retarded. It should be noted that the limits prescribed in SBS 471 were for Portland cement and rapid-hardening portland cement and are essentially meaningless when referring to blended cements.

4.6.6 General

Based on the testing of two chemically similar geological materials, there seems to be little relationship between any individual cement property and the hardening characteristics when used to stabilize the materials. It would thus appear that combinations of properties seem to interact with each other to affect the setting and hardening characteristics.

5. ALLOWABLE CONSTRUCTION TIMES

It is usual for limitations to be placed upon the total period of time permitted for the construction of a stabilized layer and/or separately for mixing and compaction.

In the case of cemented layers, COLTO, Section 3503, Item (i)[2] requires that the "maximum continuous period allowed from the time the stabilizing agent comes into contact with the layer being stabilized until the completion of compaction" is 8 hours for ordinary portland cement and/or approved portland cement blends and 10 hours for slaked and unslaked lime. A maximum of 48 hours is permitted for lime modification only. The "starting time shall be the median time taken to complete the spreading of the stabilizing agent".

It is understood that a maximum of 6 hours is now required by SANRAL for cements, as recommended in TRH 13[1], whilst Marais[13] recommended 4 hours. COLTO does not place separate restrictions on the mixing and compaction times but both TRH13[1] and Marais[13] recommend a maximum of 2 hours for compaction and finishing.

Australian practice[14] goes further and provides a method for the prior laboratory determination of the permitted maximum working time for a particular combination of soil and cement by determining the rate of decrease in MDD and UCS with time:

> "The nominated working time for any proposed mix shall be the lesser of the working time for the maximum dry density and unconfined compressive strength.
>
> The working time for maximum dry density is defined as 'the time measured from the commencement of the addition of the stabilizing agent to the compaction of the stabilized material, which corresponds to 97 % of the mean value of three determinations of maximum dry density, for samples compacted one hour after incorporation of the stabilising agent'.
>
> All samples shall be cured in a loose condition in airtight containers at 23°C ± 2°C.
>
> The working time for unconfined compressive strength is defined as the time measured from the commencement of the addition of the stabilizing agent to the compaction of the stabilized material, which corresponds to 80% of the mean value of three determinations of UCS, for samples compacted one hour after incorporation of the stabilizing agent.

> All samples shall be cured in a loose condition in airtight containers at 23°C ± 2°C.
>
> This working time is a function of the materials and also the ambient conditions and allowance should be made for temperature and humidity."

It is also stated that most general purpose cements have working times of less than 3 hours and that the availability of blended cements with long working times has rendered the use of retarders obsolete.

A similar procedure is followed by the roads department of the Australian state of Victoria[15] except that they base their working time only on the UCS, for which a figure of 90 per cent is used instead of that of 80 per cent as used by Austroads.

Apart from the above statement that allowance should be made for temperature and humidity no guidance on hot weather stabilization is known to the writers. In contrast, the problems associated with concrete work in hot weather have been well studied and COLTO places restrictions on placing and compacting time for both structural and paving concrete in hot weather. For example (Clause 7107), in the case of paving concrete, the normal maximum time of 2.5 hours permitted for compacting and finishing after mixing has to be decreased by half an hour for every 5°C by which the concrete temperature is above 20°C, and "paving operations shall cease when the concrete temperature as discharged at the paver exceeds 32°C". There are no such restrictions anywhere on hot weather stabilization of which the writers are aware and it is believed that several cases of premature distress have been at least partly due to this.

Whist insufficient information is available to determine the working time according to Australian practice, it does provide a means for the relative rating for workability of the soil-cements tested (Tables 5.1 and 5.2). Results from this investigation are only available for the MAASHO MDD at 4 hours and the MAASHO dry density and UCS at 2 and 4 hours. Whilst not a true MDD, the dry density determined by compacting the UCS specimens at the same effort and moisture content as the MDD should be reasonably close to the MDD determined after the same delay and can therefore be used as a proxy for it. The results at 2 hours have therefore been taken as the standard instead of one hour and 98 per cent of the density and 90 per cent of the UCS at 2 hours used to allow somewhat for this relaxation. No attempt has been made to determine the actual working time from only two points, but only qualitatively whether it is greater or less than 2 hours.

A slightly subjective relative rating for the tests carried out has also been given for the two materials at each temperature.

The comparison between the MDD (determined at 4 hours) and the dry density at 23°C at 4 hours provides a rough check on the quality of the work: these figures should ideally all be close to 100 per cent. Only two results differed significantly from 100 per cent. This means that their densities and strengths achieved in the laboratory were all too low. No attempt has been made to correct these effects. Some of the other results at 23°C should also be reviewed in this light.

Table 5.1: Working times for dolerite

CEMENT	A	B	C	D	E	F	G
10°C							
Density @ 4h/2h (%)	100.5	98.6	98.1	97.6	97.3	99.3	98.1
Time to 98.0% (h)	> 2	>2	2	< 2	< 2	>2	2
UCS @ 4h/2h (%)	95	94	117	70	92	87	104
Time to 90% (h)	>2	>2	> 2	« 2	> 2	< 2	> 2
Working time (h)	> 2	> 2	2	« 2	< 2	< 2	2
Rating at 10°C	1	2	3	7	6	5	4
23°C							
Density @ 4h/2h (%)	100.1	99.8	99.2	99.0	100.7	100.2	100.3
Time to 98.0% (h)	> 2	> 2	>2	>2	> 2	> 2	> 2
UCS @ 4h/2h (%)	87	80	85	57	73	103	80
Time to 90% (h)	< 2	< 2	< 2	« 2	« 2	> 2	< 2
Working time (h)	< 2	< 2	< 2	« 2	« 2	> 2	< 2
Rating at 23°C	2	5	3	7	6	1	4
40°C							
Density @ 4h/2h (%)	97.8	99.1	98.7	99.0	100.0	99.0	97.8
Time to 98.0% (h)	2	> 2	> 2	> 2	> 2	> 2	2
UCS @ 4h/2h (%)	69	95	83	80	81	89	59
Time to 90% (h)	« 2	> 2	< 2	< 2	< 2	2	« 2
Working time (h)	« 2	> 2	< 2	< 2	< 2	2	« 2
Rating at 40°C	6	1	4	5	3	2	7
MDD/density at 23°C and 4h (%)	101.0	100.0	101.3	101.4	100.0	99.7	99.3

Table 5.2: Working times for norite

CEMENT	A	B	C	D	E	F	G
10°C							
Density @ 4h/2h (%)	99.8	100.6	100.5	101.5	100.2	98.4	98.1
Time to 98.0% (h)	> 2	>2	> 2	> 2	> 2	>2	2
UCS @ 4h/2h (%)	73	97	76	92	62	77	104
Time to 90% (h)	<2	>2	< 2	> 2	« 2	< 2	> 2
Working time (h)	< 2	> 2	< 2	> 2	« 2	< 2	2
Rating at 10°C	6	1	3	2	7	5	4
23°C							
Density @ 4h/2h (%)	98.4	98.5	98.9	100.1	97.4	100.0	100.8
Time to 98.0% (h)	> 2	> 2	>2	>2	< 2	> 2	> 2
UCS @ 4h/2h (%)	66	97	82	114	89	100	85
Time to 90% (h)	« 2	> 2	< 2	> 2	< 2	> 2	< 2
Working time (h)	« 2	> 2	< 2	> 2	< 2	> 2	< 2
Rating at 23°C	7	3	6	1	5	2	4
40°C							
Density @ 4h/2h (%)	100.9	97.6	99.0	101.1	98.9	100.6	98.8
Time to 98.0% (h)	> 2	< 2	> 2	> 2	> 2	> 2	> 2
UCS @ 4h/2h (%)	116	89	65	95	96	87	65
Time to 90% (h)	> 2	< 2	« 2	> 2	> 2	< 2	« 2
Working time (h)	> 2	< 2	« 2	> 2	> 2	< 2	« 2
Rating at 40°C	1	5	6	2	3	4	7
MDD/density at 23°C and 4h (%)	103.1	99.3	99.8	99.0	100.0	101.8	101.1

In the case of the dolerite, at 10°C only two cements yielded working times in excess of 2 hours. At 23°C only one cement had a working time of more than 2 hours, whilst those for two of the cements were much less than 2 hours. At 40°C only one cement had a time in excess of 2 hours and two cements had times of much less than 2 hours.

In the case of the norite, at 10°C only one cement yielded a working time in excess of 2 hours. At 23°C, two cements yielded times of more than 2 hours. At 40°C three cements yielded times in excess of 2 hours whilst two cements had times of much less than 2 hours.

Although this simplistic analysis has severe limitations, it does seem that the following tentative conclusions can be drawn for the materials tested:

1 No single cement performed best in all cases, even for one material. One cement was best or second best at all three temperatures on the norite. However, the same cement was the worst or one of the worst with the dolerite.
2 At 10°C, one cement performed well (best or second best and a working time in excess of 2 hours) with both materials.
3 At 23°C (assumed average conditions), one cement performed well (best or second best and with a working time in excess of 2 hours) with both materials.

4 At 40°C no single cement performed well (working time of 2 hours or more) with both materials.

5 It is recommended that actual working times in the field be determined on these two and on other materials.

6 There seems to be some correlation between the initial and final setting times of the cement at the nearest temperature with its working time (the slower the set, the better in the case of the dolerite but not with the norite).

7 A system similar to that used in Australia to predict the working time of any material cement combination should be developed for use in South Africa and implemented until sufficient experience and information allows more conclusive recommendations to be made.

6. CONCLUSIONS

Seven cements covering a wide range of products produced in South Africa were investigated as part of this investigation. All of the cements complied with the specifications, although those containing limestone and flyash extenders had high loss on ignition and insoluble residues respectively, as a result of the extenders.

The seven cements were found to vary widely in initial setting times between 70 and 275 minutes at 22°C and 70 and 170 minutes at 45°C. Some are highly temperature susceptible losing up to 25 minutes in initial set over the temperature range 22 to 45°C.

The initial and final setting times at 22°C show some slight tendency to increase with increasing sulfate content, but the setting times at 55°C appear to be independent of sulfate content. There was also some, even poorer tendency for the initial setting time at 22°C to increase with the Blaine surface area, but for the final setting time at 55°C to decrease slightly.

Significant laboratory testing was carried out on the treatment of two materials with essentially the same chemical but different physical properties with the seven different cements. Chemical and mineralogical analyses of the two materials showed no incidences of unusual components that would lead to specific problems during cement stabilization of the materials. However, the high ICL and ICC of the dolerite suggest that the 3 per cent cement used in the testing programme, although generally sufficient for strength purposes, would provide insufficient durability in the long term.

There is no doubt that both conditioning time and material temperature during the early stages of hydration of the cement affect the compacted density and unconfined compressive strength and indirect tensile strength (these three are obviously interrelated) negatively. However, comparison with one documented example indicates that the current cements probably have an equal or even lesser effect in this regard than the older cements.

In the case f the dolerite, there was a clear tendency for the MDD at 4 hours 23°C to increase with increasing initial and final setting times at 22°C. In the case of the norite a slight inverse tendency was apparent. The effect of higher temperatures was more important than that of the cement type.

No dominant trends relating to the behaviour of the different cements could be isolated during the project. It is clear, however, that the combination of cement type and material

under the expected construction conditions will affect the density and strength of material obtained in the field. On this basis, all potential construction materials that are to be stabilized should be tested with the cements likely to be used on the proposed project and under the expected ambient conditions to identify the expected allowable construction time and the combination which provides the longest workability/ construction time should be selected.

7. RECOMMENDATIONS

It is recommended that:

- A few of the characterisation tests on the two materials should be repeated
- Further investigations into the relationship between workability (probably demonstrated through the CBR test) and setting times should be carried out. A system similar to that used in Australia should be developed for local use.
- The results of tests from a non-plastic material (weathered granite) should be added to the current data to clarify any relationships that may exist.
- Any soil to be used for stabilization should be tested following the normal material design procedures as well as assessing the temperature and time sensitivity of the density and strength according to the Australian practice, using the cement types that are economically available at the site. The construction techniques and temperatures should also be simulated as closely as possible.
- The effect of cement, conditioning time and temperature on durability should be assessed. This should include tests such as the wet/dry brushing test, carbonation resistance and ultimate (say 56 day) strength at constant density.
- Actual mixing, compaction and curing temperatures encountered in practice should be measured together with air temperatures in the sun and shade.
- Consideration should be given to reducing the strength grade and increasing the setting times for stabilization cements, similar to the ENV 13282 requirements for road stabilization cements.
- Actual working times should be determined on the dolerite and norite materials as well as a range of other materials.
- Road authorities and their consultants should determine the workability of each proposed mix in terms of the effect of time and temperature on MDD and UCS and/or ITS.
- This report summarises the data obtained from the test programme and includes limited interpretation from which a number of conclusions are drawn. Using sophisticated statistical analyses, it is considered that significantly more could be obtained from this data and it is recommended that this be carried out when funding permits.

8. REFERENCES

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APPENDIX A

SUMMARY OF CEMENT TESTING BY PPC

APPENDIX A: SUMMARY OF CEMENT TESTING BY PPC

NPC, Dudfield, Hercules and Slurry clinkers

*Corrections : CaO-free lime-0.7*SO_3 & SiO_2-IR*

Sample No.	Sample Reference	SiO_2	Al_2O_3	Fe_2O_3	Mn_2O_3	TiO_2	CaO	MgO	P_2O_5	SO_3	Cl	K_2O	Na_2O	LOI	Total	IR	F.CaO	LSF	SR	AM	C_3S	C_2S	C_3A	C_4AF	Acid Soluble Sulfate
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
1021200821	NPC/clinker 28/11/02	21.1	4.7	2.49	0.15	0.39	66.2	3.0	0.06	0.50	0.01	0.77	0.29	0.57	100.3	0.04	3.37	93.6	2.72	1.94	56.4	17.8	9.1	8.0	0.50
1030201521	Dudfield clinker 08/01/03	22.5	5.0	2.61	0.11	0.51	66.1	1.7	0.07	0.45	0.01	0.38	0.11	0.46	100.0	0.13	2.18	89.6	2.73	2.03	47.9	28.0	10.0	8.3	0.45
1030201524	Hercules clinker 09/01/03	21.3	3.7	1.54	1.42	0.34	64.5	5.3	0.10	0.53	0.01	0.53	0.05	0.31	99.7	0.29	2.01	94.5	3.03	1.38	61.2	14.2	5.8	9.0	0.53
1030201526	Slurry clinker 10/01/03	22.7	4.3	2.40	0.29	0.44	66.5	2.2	0.04	0.56	0.01	0.51	0.07	0.23	100.4	0.16	0.88	92.3	3.04	1.78	58.0	21.0	8.1	8.2	0.56

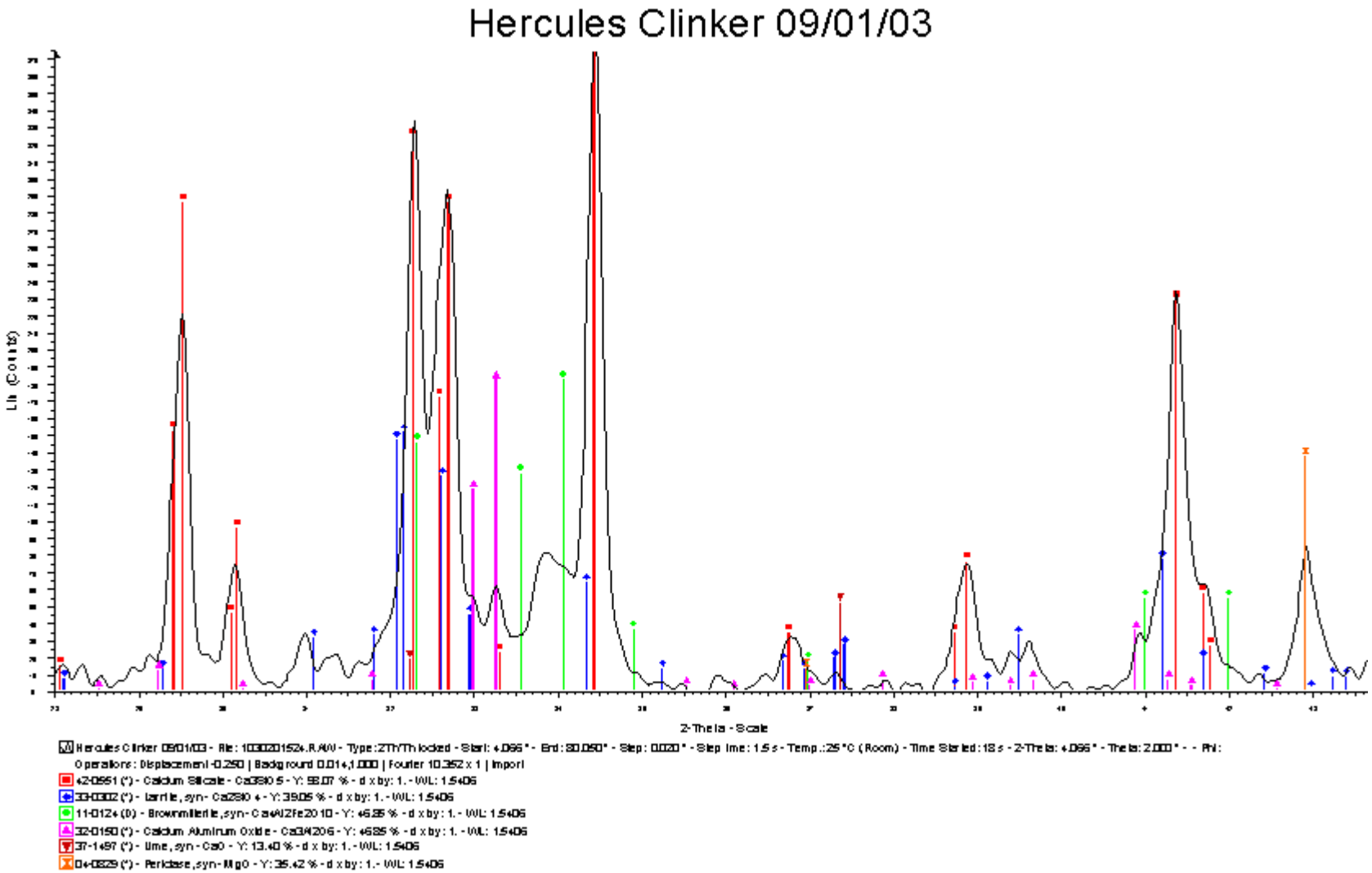
NPC, Dudfield, Hercules and Slurry cements

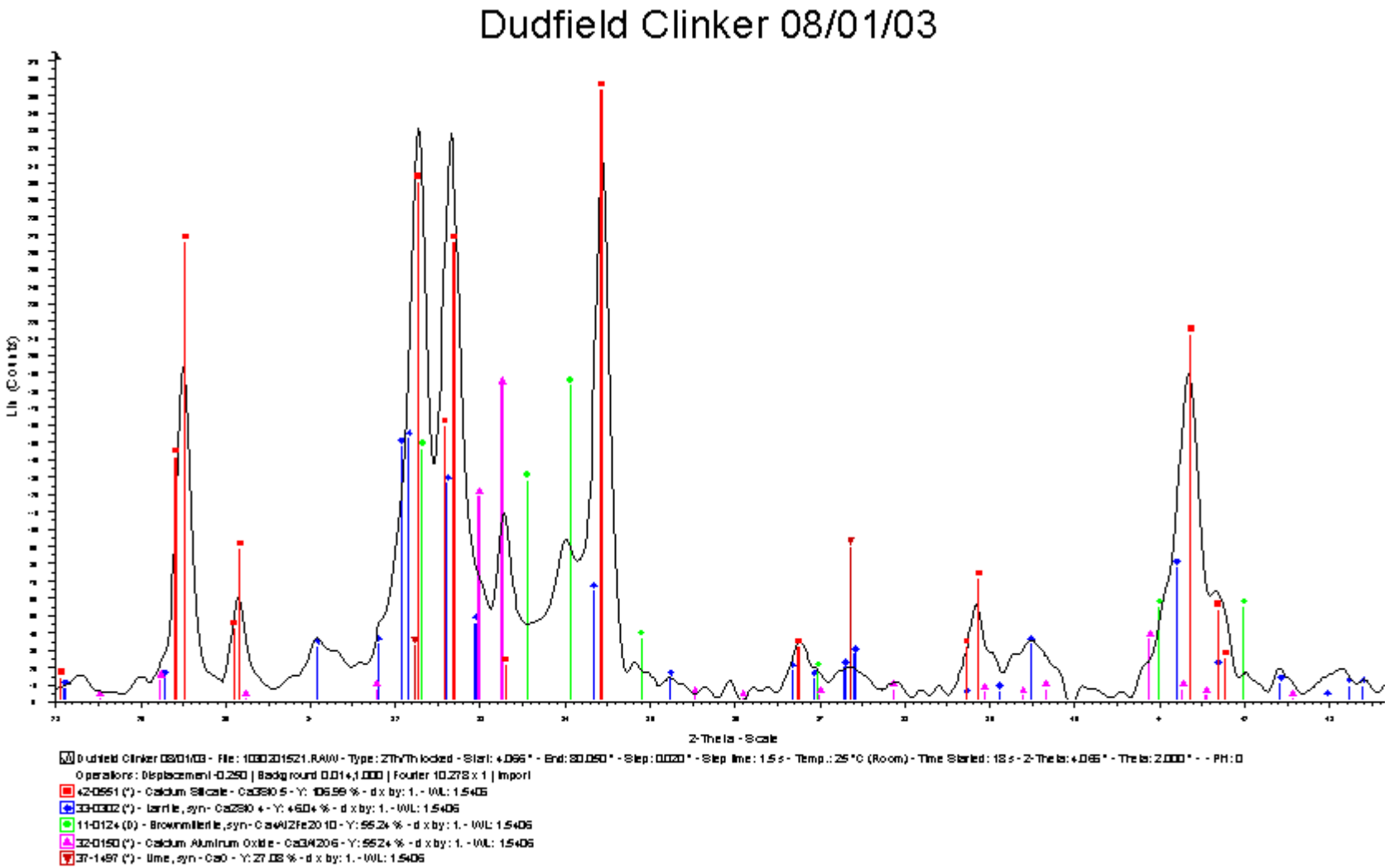
Sample No.	Sample Reference	SiO_2	Al_2O_3	Fe_2O_3	Mn_2O_3	TiO_2	CaO	MgO	P_2O_5	SO_3	Cl	K_2O	Na_2O	LOI	Total	IR	F.CaO	CO_2	Acid Soluble Sulfate	Reactive CaO	Reactive SiO_2
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%		
1021200820	NPC/Cem111AS 28/11/02	28.7	9.5	1.52	0.47	0.82	48.3	7.1	0.03	2.71	0.00	0.70	0.32	0.06	100.2	2.26	1.30	0.1	1.29	45.8	26.4
1030201522	High Strength 08/01/03	24.5	6.0	2.06	1.01	0.39	57.3	3.9	0.05	2.74	0.02	0.59	0.10	1.78	100.4	1.91	1.58	0.7	2.34	51.7	22.5
1030201523	All purpose 08/01/03	30.2	11.4	2.61	0.71	0.68	47.8	2.0	0.19	2.04	0.01	0.60	0.12	1.70	100.1	8.88	1.33	0.5	2.04	43.2	21.3
1030201525	H/OPC 09/01/03	21.6	4.2	2.00	1.16	0.35	61.2	4.5	0.10	2.77	0.02	0.55	0.08	1.20	99.7	1.74	1.30	0.6	2.69	55.2	19.9
1030201528	S/Surebuild 23/01/03	21.4	3.9	2.06	0.29	0.39	60.9	2.5	0.02	1.56	0.01	0.54	0.09	6.12	99.8	2.37	1.27	4.5	1.47	48.1	19.0

0.0 Means not detected by X-Ray at this level and does not imply zero %

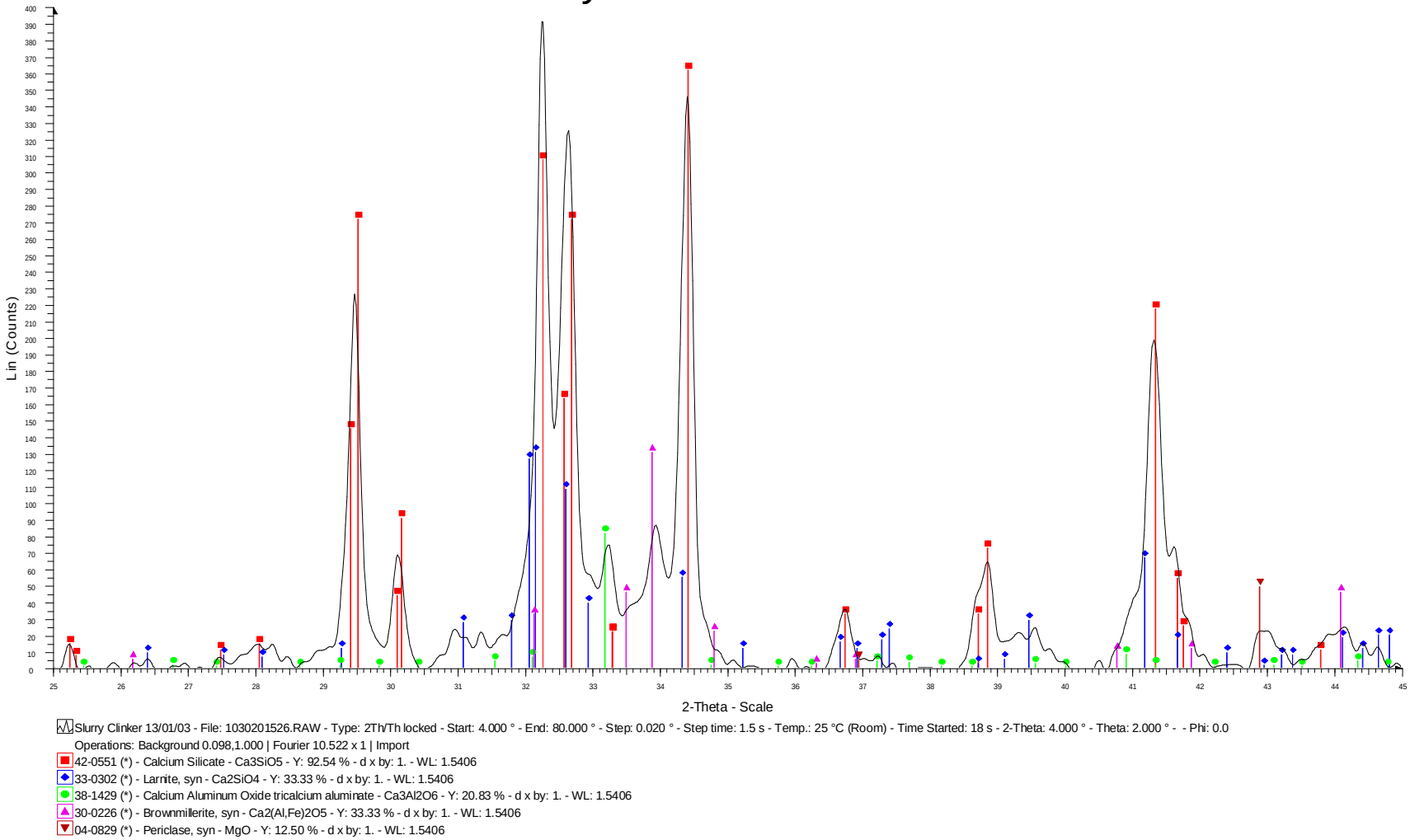
Sample No.	Sample Reference	SiO_2	Al_2O_3	Fe_2O_3	Mn_2O_3	TiO_2	CaO	MgO	P_2O_5	SO_3	Cl	K_2O	Na_2O	LOI	Total	IR	F.CaO	CO_2	Acid soluble SO_3	Reactive SiO_2	Reactive CaO
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
1040120139	Lafarge Powercrete cem II (A-M(L)) 42.5	20.6	4.86	2.72	0.34	0.45	62.7	2.5	0.10	1.93	0.01	0.10	0.12	3.6	101.1	0.51	2.05	2.2	1.82	19.7	55.6
1040120140	Lafarge Durabetch cem I 42.5	20.9	4.75	2.81	0.33	0.47	64.4	2.5	0.04	0.80	0.01	0.10	0.13	2.2	99.4	0.54	2.83	1.1	0.82	20.4	55.5

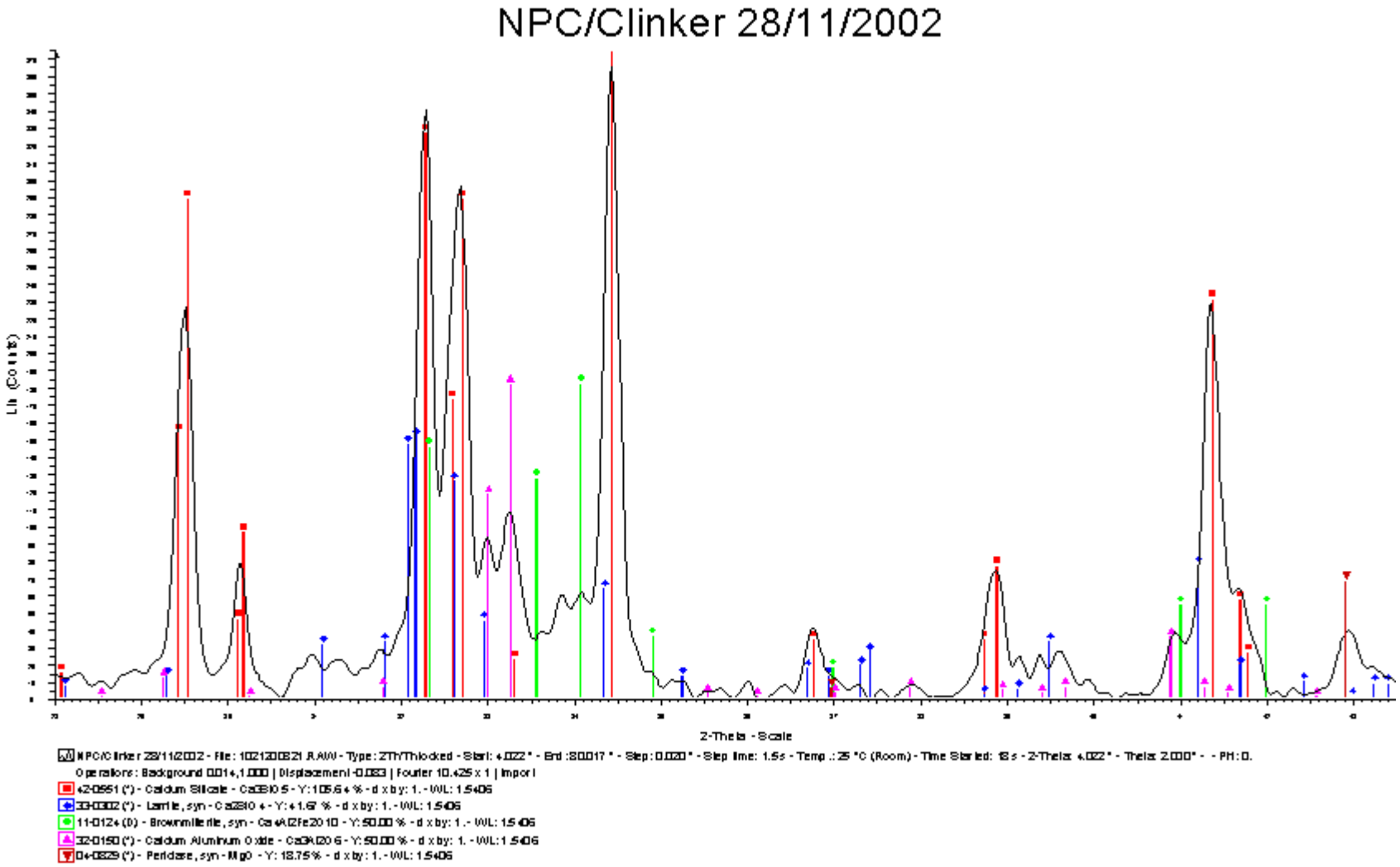
0.0 Means not detected by X-Ray at this level and does not imply zero %


Hercules Clinker 09/01/03
Lin (Counts)
2-Theta - Scale
Hercules Clinker 09/01/03 - File: 103020152A.RAW - Type: 2Th/Th locked - Start: 4.066 ° - End: 80.050 ° - Step: 0.020 ° - Step time: 1.5 s - Temp.: 25 °C (Room) - Time Started: 18 s - 2-Theta: 4.066 ° - Theta: 2.000 ° - - Phi:
Operations: Displacement -0.250 | Background 0.014,1.000 | Fourier 10.352 x 1 | Import
42-0551 (*) - Calcium Silicate - Ca3SiO5 - Y: 58.07 % - d x by: 1. - WL: 1.5406
33-0302 (*) - Larnite, syn - Ca2SiO4 - Y: 39.05 % - d x by: 1. - WL: 1.5406
11-0124 (D) - Brownmillerite, syn - Ca4Al2Fe2O10 - Y: 46.85 % - d x by: 1. - WL: 1.5406
32-0150 (*) - Calcium Aluminum Oxide - Ca3Al2O6 - Y: 46.85 % - d x by: 1. - WL: 1.5406
37-1497 (*) - Lime, syn - CaO - Y: 13.40 % - d x by: 1. - WL: 1.5406
04-0829 (*) - Periclase, syn - MgO - Y: 35.42 % - d x by: 1. - WL: 1.5406

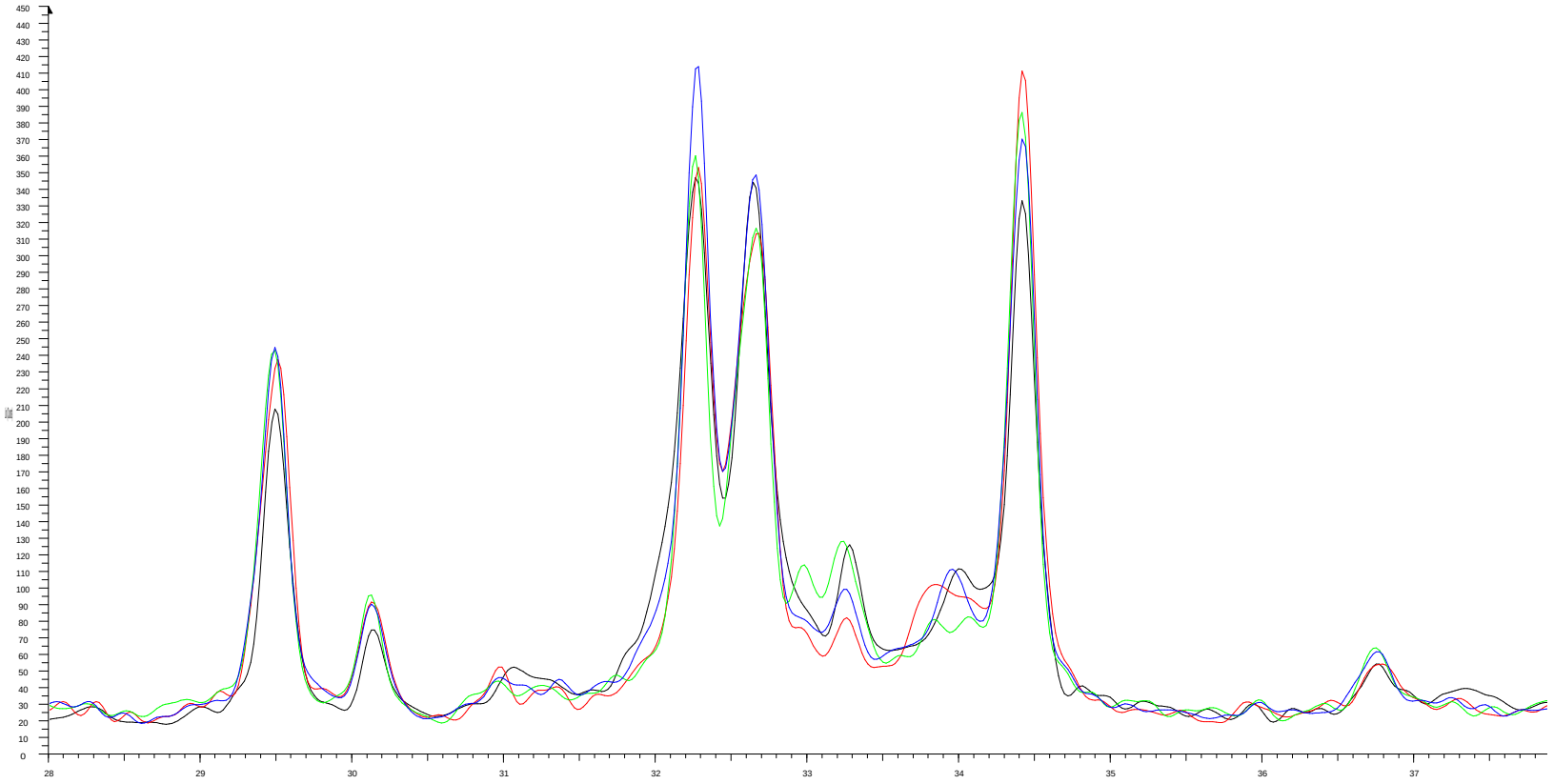

Dudfield Clinker 08/01/03
Lin (Counts)
2-Theta - Scale
Dudfield Clinker 08/01/03 - File: 1030201521.RAW - Type: 2Th/Th locked - Start: 4.066 ° - End: 80.050 ° - Step: 0.020 ° - Step time: 1.5 s - Temp.: 25 °C (Room) - Time Started: 18 s - 2-Theta: 4.066 ° - Theta: 2.000 ° - - PH: 0
Operations: Displacement -0.250 | Background 0.014,1.000 | Fourier 10.278 x 1 | Import
42-0551 (*) - Calcium Silicate - Ca3SiO5 - Y: 106.59 % - d x by: 1. - WL: 1.5406
33-0302 (*) - Larnite, syn - Ca2SiO4 - Y: 46.04 % - d x by: 1. - WL: 1.5406
11-0124 (D) - Brownmillerite, syn - Ca4Al2Fe2O10 - Y: 55.24 % - d x by: 1. - WL: 1.5406
32-0150 (*) - Calcium Aluminum Oxide - Ca3Al2O6 - Y: 55.24 % - d x by: 1. - WL: 1.5406
37-1497 (*) - Lime, syn - CaO - Y: 27.08 % - d x by: 1. - WL: 1.5406

Slurry Clinker 13/01/03

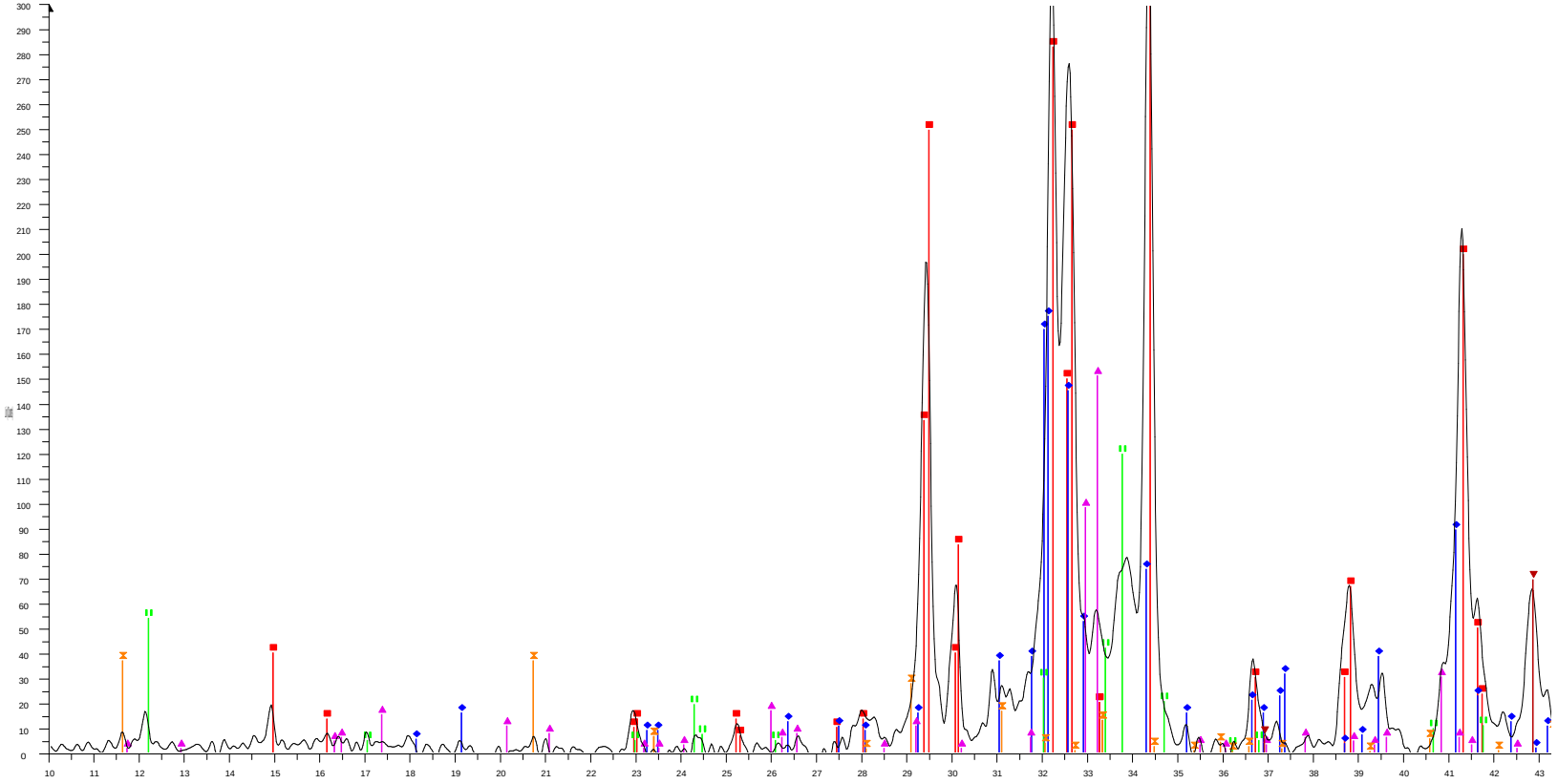



NPC/Clinker 28/11/2002
Lin (Counts)
2-Theta - Scale
NPC/Clinker 28/11/2002 - File: 102120021.RAW - Type: 2Th/Thlocked - Start: 4.022 ° - End: 80.017 ° - Step: 0.020 ° - Step time: 1.5s - Temp.: 25 °C (Room) - Time Started: 18 s - 2-Theta: 4.022 ° - Theta: 2.000 ° - - PH: 0.
Operations: Background 0.014,1.000 | Displacement -0.083 | Fourier 10.425 x 1 | Import
42-0551 (*) - Calcium Silicate - Ca3SiO5 - Y: 105.64 % - d x by: 1. - WL: 1.5406
33-0302 (*) - Larnite, syn - Ca2SiO4 - Y: 41.67 % - d x by: 1. - WL: 1.5406
11-0124 (D) - Brownmillerite, syn - Ca4Al2Fe2O10 - Y: 50.00 % - d x by: 1. - WL: 1.5406
32-0150 (*) - Calcium Aluminum Oxide - Ca3Al2O6 - Y: 50.00 % - d x by: 1. - WL: 1.5406
04-0829 (*) - Periclase, syn - MgO - Y: 18.75 % - d x by: 1. - WL: 1.5406

Superimposed Clinker Diffractograms



H/OPC 09/01/03



H/OPC 09/01/03 - File: 1030201525.RAW - Type: 2Th/Th locked - Start: 4.000 ° - End: 80.000 ° - Step: 0.020 ° - Step time: 1.5 s - Temp.: 25 °C (Room) - Time Started: 18 s - 2-Theta: 4.000 ° - Theta: 2.000 ° - - Phi: 0.00 ° - -
Operations: Background 0.014,1.000 | Fourier 10.278 x 1 | Import

42-0551 (*) - Calcium Silicate - Ca3SiO5 - Y: 100.88 % - d x by: 1. - WL: 1.5406

33-0302 (*) - Larnite, syn - Ca2SiO4 - Y: 53.01 % - d x by: 1. - WL: 1.5406

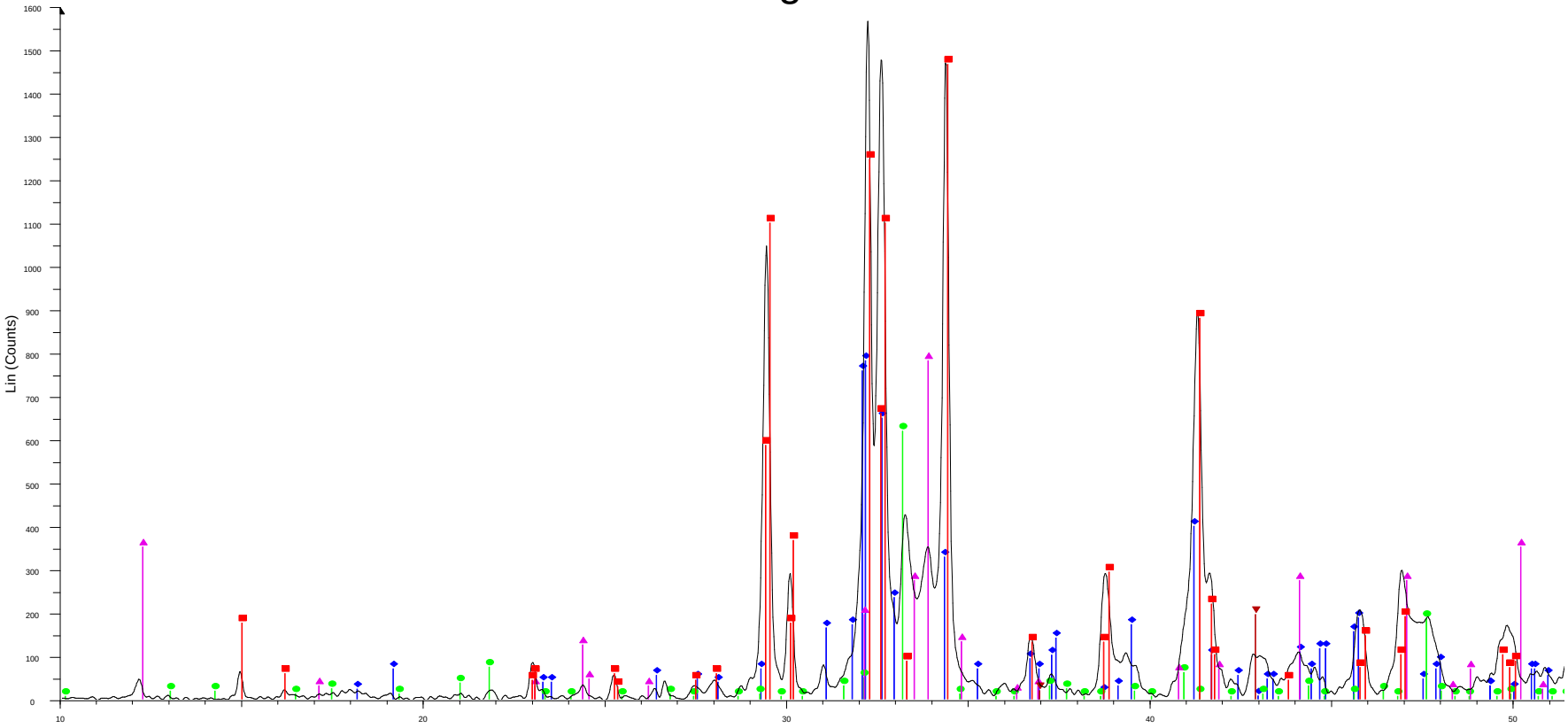
30-0226 (*) - Brownmillerite, syn - Ca2(Al,Fe)2O5 - Y: 36.24 % - d x by: 1.0021 - WL: 1.5406

32-0150 (*) - Calcium Aluminum Oxide - Ca3Al2O6 - Y: 45.79 % - d x by: 1. - WL: 1.5406

04-0829 (*) - Periclase, syn - MgO - Y: 20.98 % - d x by: 1. - WL: 1.5406

33-0311 (*) - Gypsum, syn - CaSO4·2H2O - Y: 11.13 % - d x by: 1. - WL: 1.5406

Lafarge Duratech



Lafarge Duratech - File: 1040100140.RAW - Type: 2Th/Th locked - Start: 4.000 ° - End: 80.000 ° - Step: 0.020 ° - Step time: 1.5 s - Temp.: 25 °C (Room) - Time Started: 18 s - 2-Theta: 4.000 ° - Theta: 2.000 ° - - Phi: 0.00 ° - -
Operations: Background 0.014,1.000 | Fourier 9.863 x 1 | Import

42-0551 (*) - Calcium Silicate - Ca3SiO5 - Y: 93.75 % - d x by: 1. - WL: 1.5406

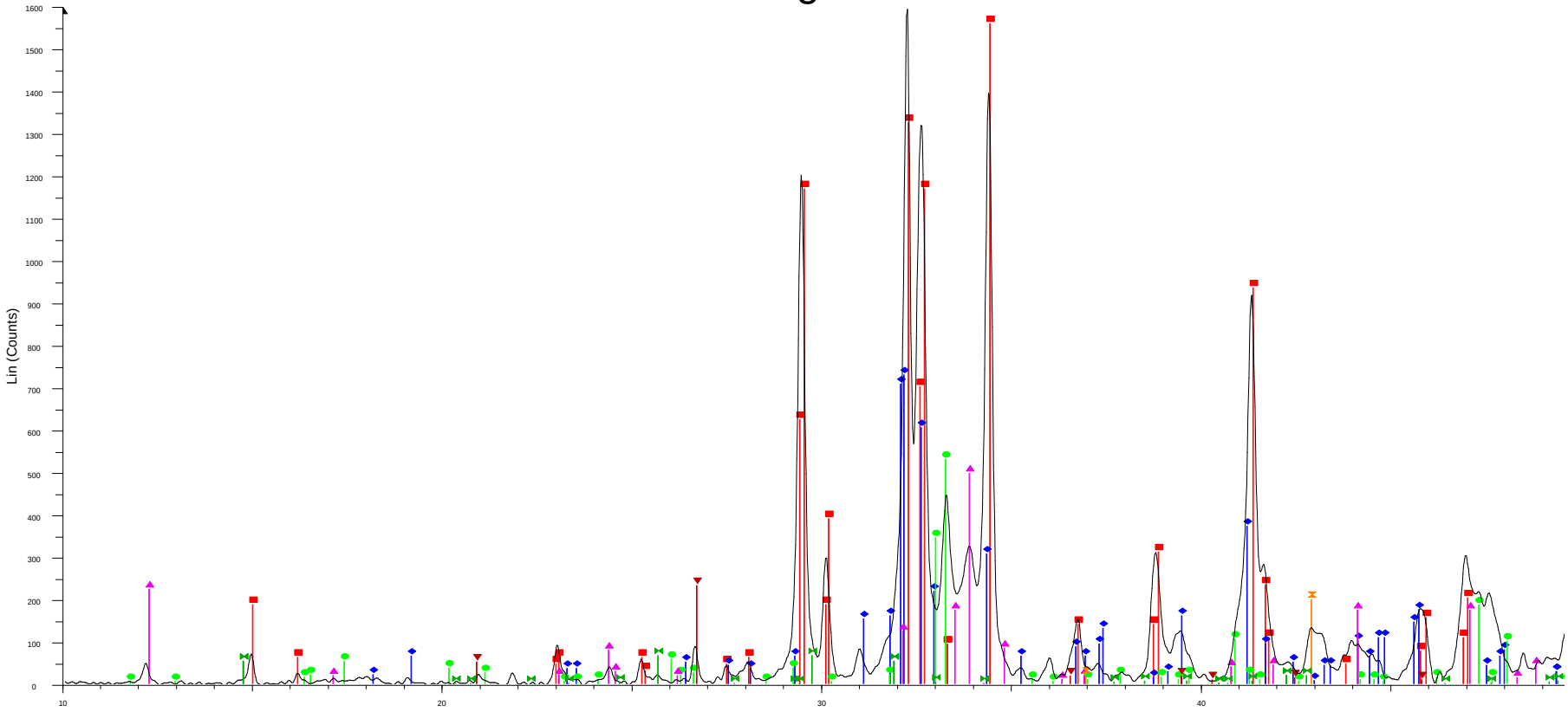
33-0302 (*) - Larnite, syn - Ca2SiO4 - Y: 50.00 % - d x by: 1. - WL: 1.5406

38-1429 (*) - Calcium Aluminum Oxide tricalcium aluminate - Ca3Al2O6 - Y: 39.58 % - d x by: 1. - WL: 1.5406

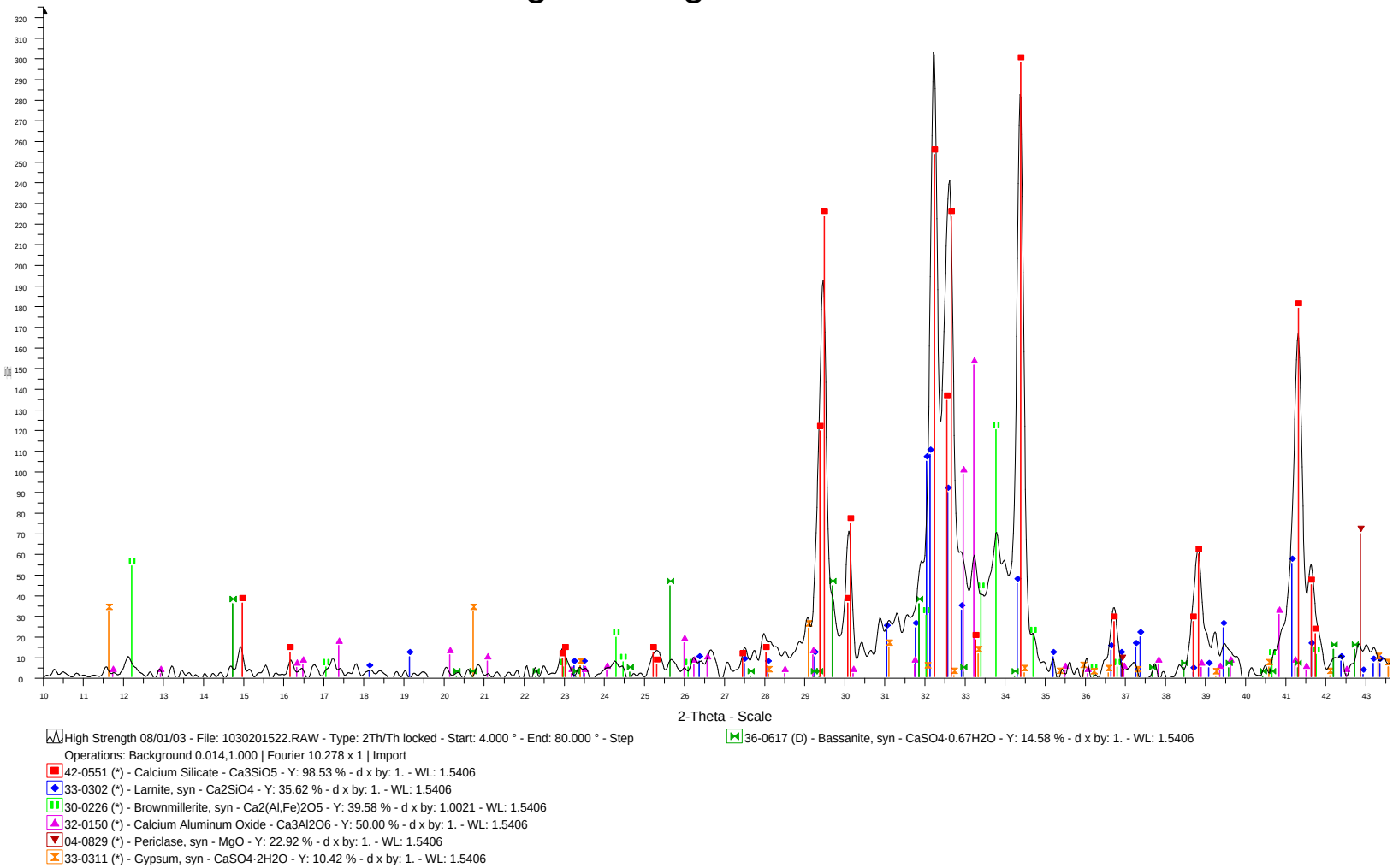
30-0226 (*) - Brownmillerite, syn - Ca2(Al,Fe)2O5 - Y: 50.00 % - d x by: 1. - WL: 1.5406

04-0829 (*) - Periclase, syn - MgO - Y: 12.50 % - d x by: 1. - WL: 1.5406

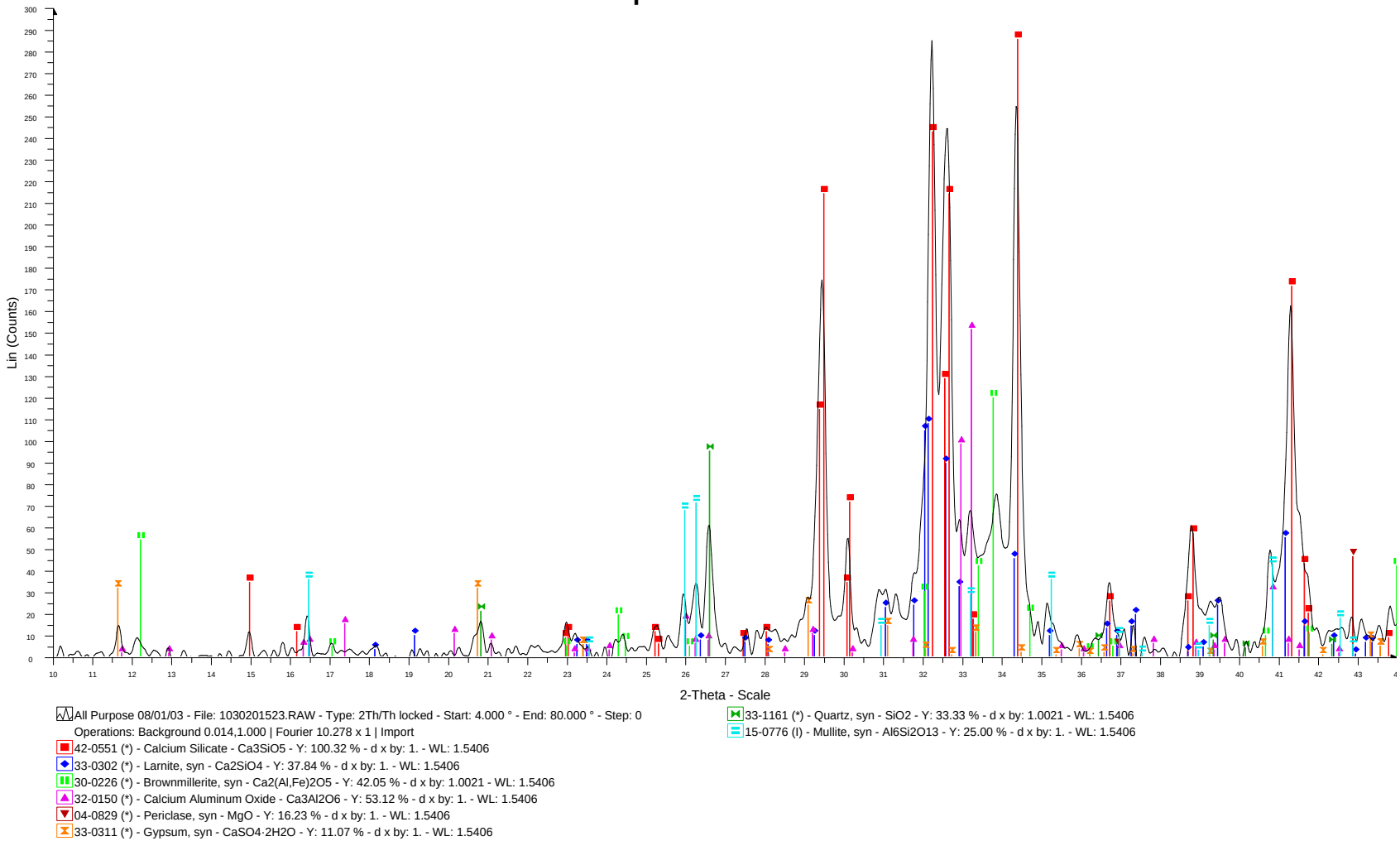
Lafarge Powercrete



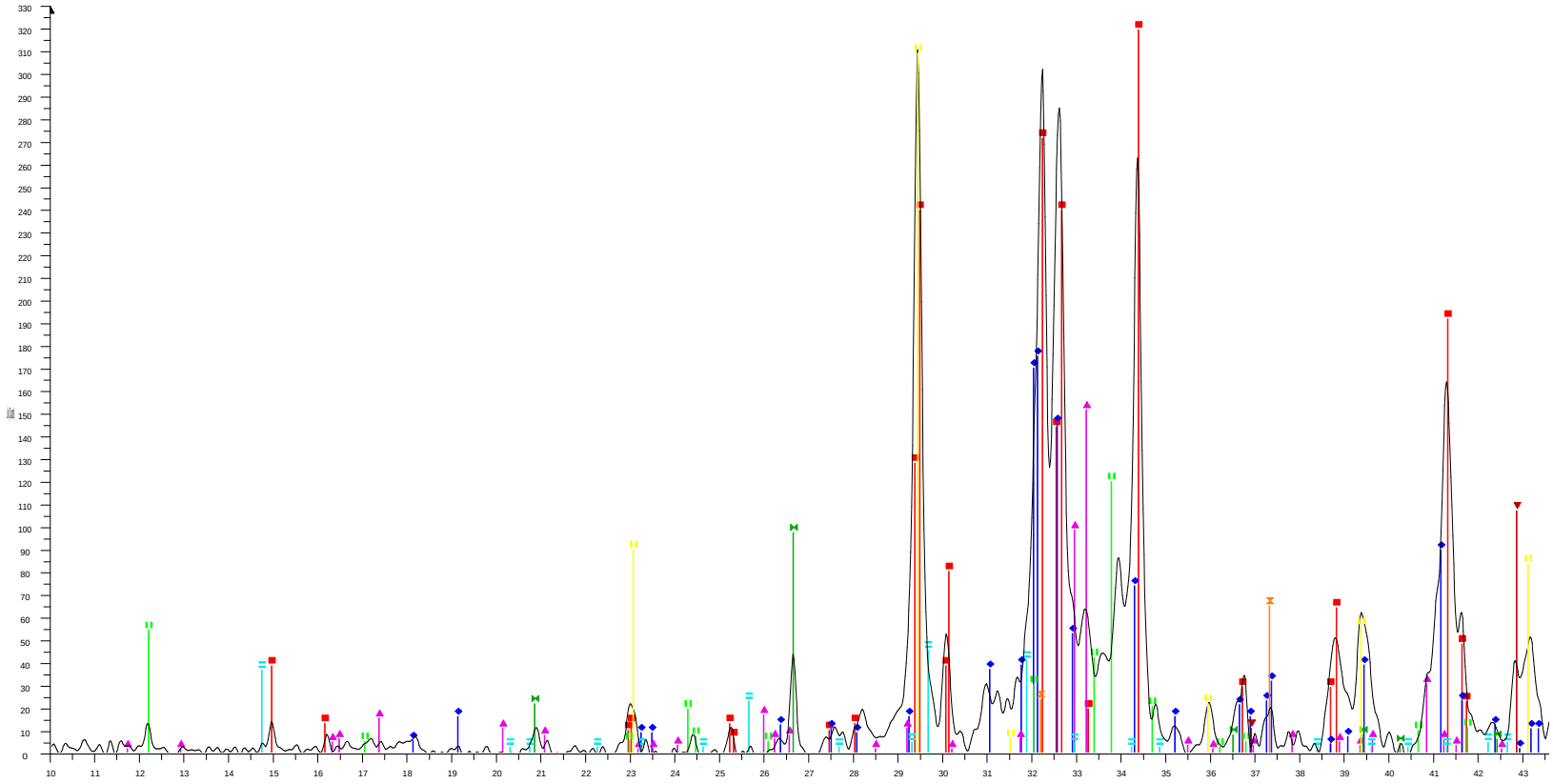
High Strength 08/01/03



All Purpose 08/01/03



S/Surebuild 23/01/03



S/Surebuild 23/01/03 - File: 1030201528.RAW - Type: 2Th/Th locked - Start: 4.022 ° - End: 80.017 ° - Step:
Operations: Displacement -0.083 | Background 0.014,1.000 | Fourier 10.278 x 1 | Import

42-0551 (*) - Calcium Silicate - Ca3SiO5 - Y: 102.86 % - d x by: 1. - WL: 1.5406

33-0302 (*) - Larnite, syn - Ca2SiO4 - Y: 56.41 % - d x by: 1. - WL: 1.5406

30-0226 (*) - Brownmillerite, syn - Ca2(Al,Fe)2O5 - Y: 38.57 % - d x by: 1.0021 - WL: 1.5406

32-0150 (*) - Calcium Aluminum Oxide - Ca3Al2O6 - Y: 48.72 % - d x by: 1. - WL: 1.5406

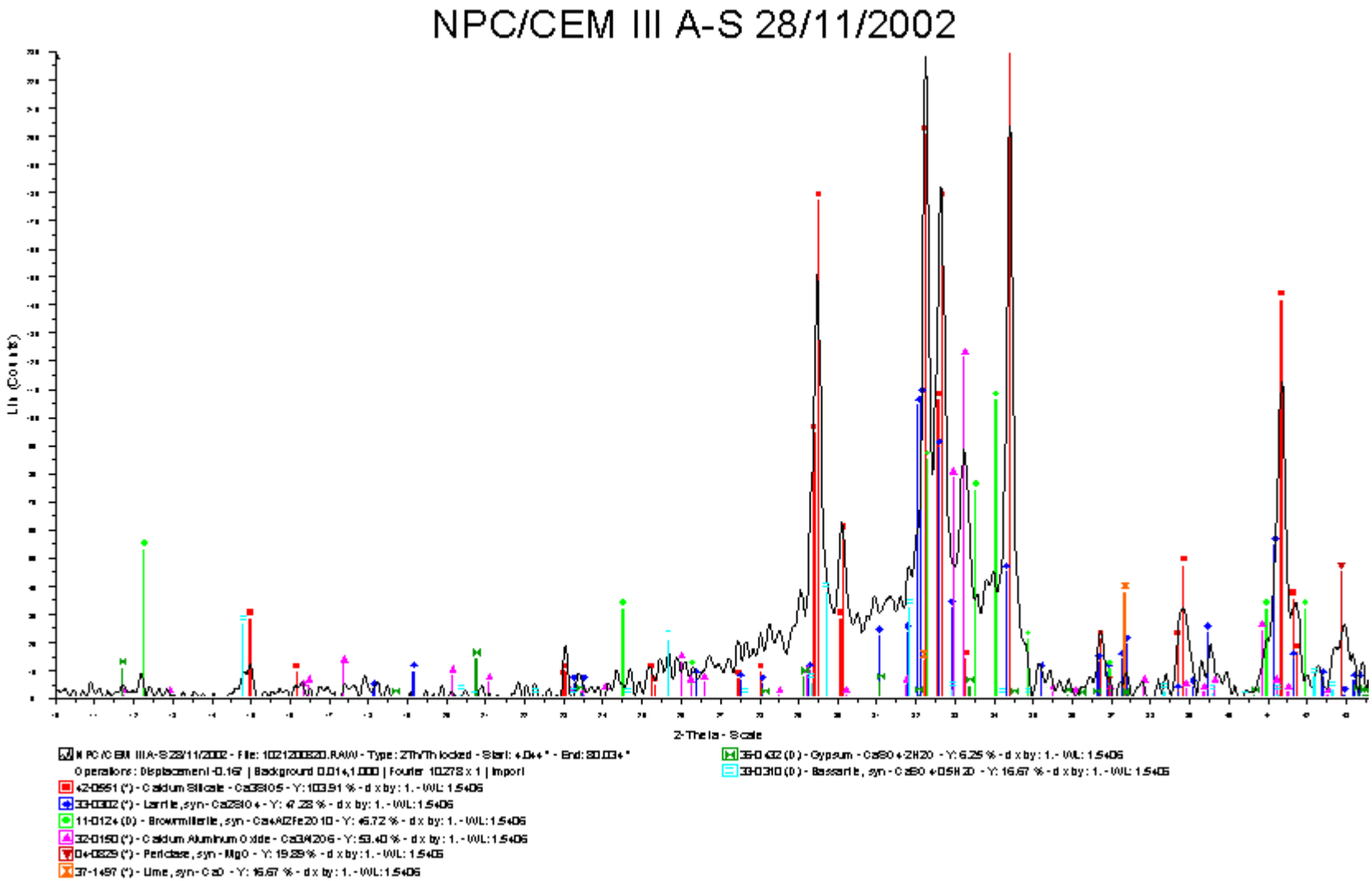
04-0829 (*) - Periclase, syn - MgO - Y: 34.41 % - d x by: 1. - WL: 1.5406

37-1497 (*) - Lime, syn - CaO - Y: 20.83 % - d x by: 1. - WL: 1.5406

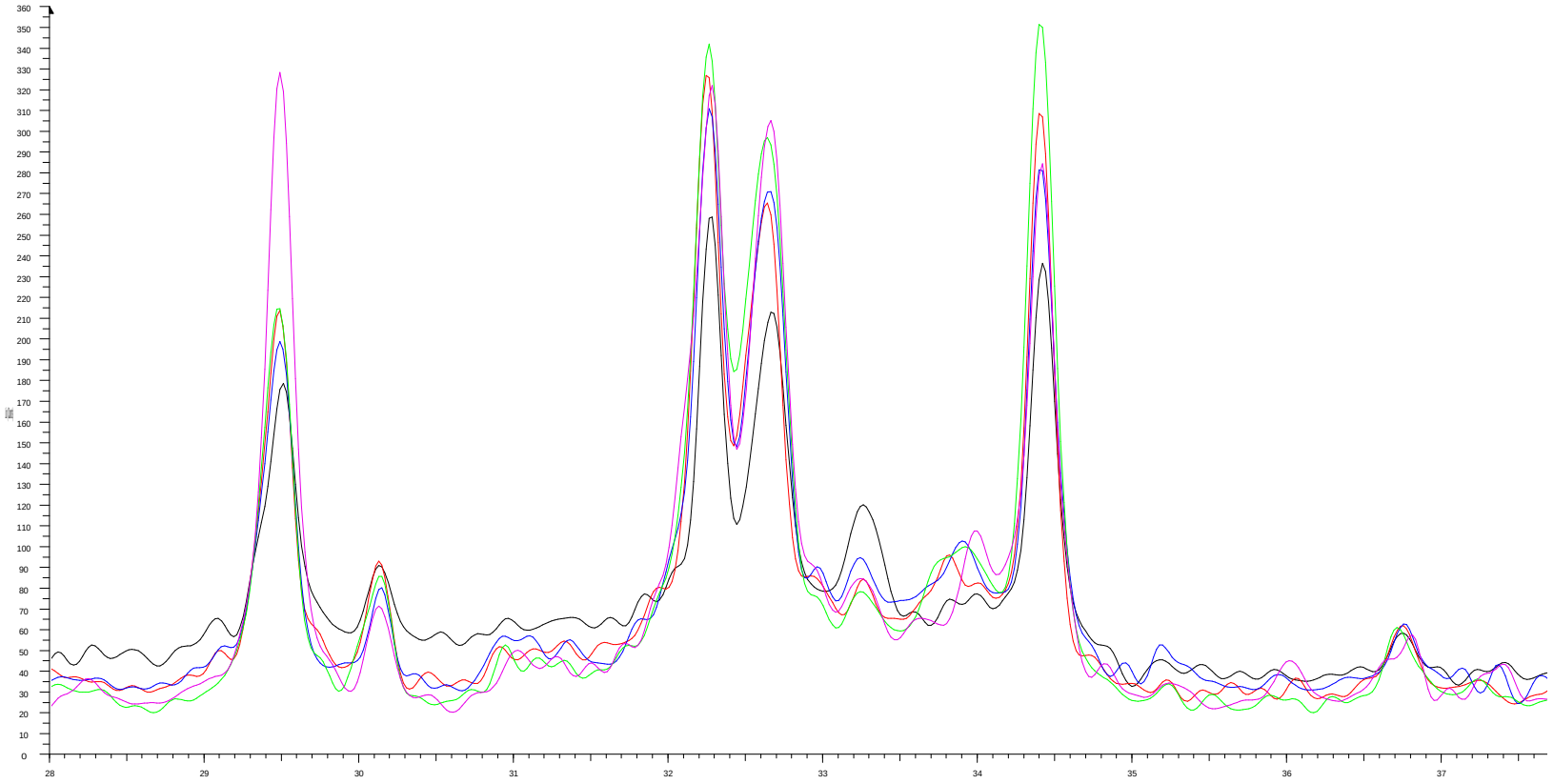
33-1161 (*) - Quartz, syn - SiO2 - Y: 31.25 % - d x by: 1. - WL: 1.5406

41-0224 (I) - Bassanite, syn - CaSO4·0.5H2O - Y: 14.58 % - d x by: 1. - WL: 1.5406

24-0027 (D) - Calcite - CaCO3 - Y: 99.56 % - d x by: 1. - WL: 1.5406


NPC/CEM III A-S 28/11/2002
Lin (Counts)
2-Theta - Scale
NPC/CEM III A-S 28/11/2002 - File: 10212008S0.RAW - Type: 2Th/Th locked - Start: 4.004 ° - End: 80.004 °
Operations: Displacement -0.167 | Background 0.014,1.000 | Fourier 10.278 x 1 | Import
42-0551 (*) - Calcium Silicate - Ca3SiO5 - Y: 103.91 % - d x by: 1. - WL: 1.5406
33-0302 (*) - Larnite, syn - Ca2SiO4 - Y: 47.23 % - d x by: 1. - WL: 1.5406
11-0124 (D) - Brownmillerite, syn - Ca4Al2Fe2O10 - Y: 46.72 % - d x by: 1. - WL: 1.5406
32-0150 (*) - Calcium Aluminum Oxide - Ca3Al2O6 - Y: 53.40 % - d x by: 1. - WL: 1.5406
04-0829 (*) - Periclase, syn - MgO - Y: 19.29 % - d x by: 1. - WL: 1.5406
37-1497 (*) - Lime, syn - CaO - Y: 16.67 % - d x by: 1. - WL: 1.5406
33-0432 (D) - Gypsum - CaSO4·2H2O - Y: 6.25 % - d x by: 1. - WL: 1.5406
33-0310 (D) - Bassanite, syn - CaSO4·0.5H2O - Y: 16.67 % - d x by: 1. - WL: 1.5406

Superimposed Cement Diffractograms



APPENDIX B
PARTICLE SIZE DISTRIBUTIONS

PPC CEM I 42.5

PROCESS SERVICES

Particle Size Analysis

PPC

Result: Analysis Report

Sample Details

Sample ID: 1030201525
Sample File: 30201525
Sample Path: C:\SIZERS\DATA\
Sample Notes: LIMS Sample No 1030201525
HOPC
09/01/2003

Run Number: 13
Record Number: 2

Measurement Date: 27 2 2003 11:42PM
Analysis Date: 27 2 2003 11:42PM
Result Source: Analysed

System Details

Range Lens: 300RF mm
Presentation: 3$$D
Analysis Model: Polydisperse
Modifications: None

Beam Length: 2.40 mm
Fraunhofer

Sampler: MS17

Obscuration: 15.7 %
Residual: 1.059 %

Result Statistics

Distribution Type: Volume
Mean Diameters:
D [4, 3] = 26.81 um

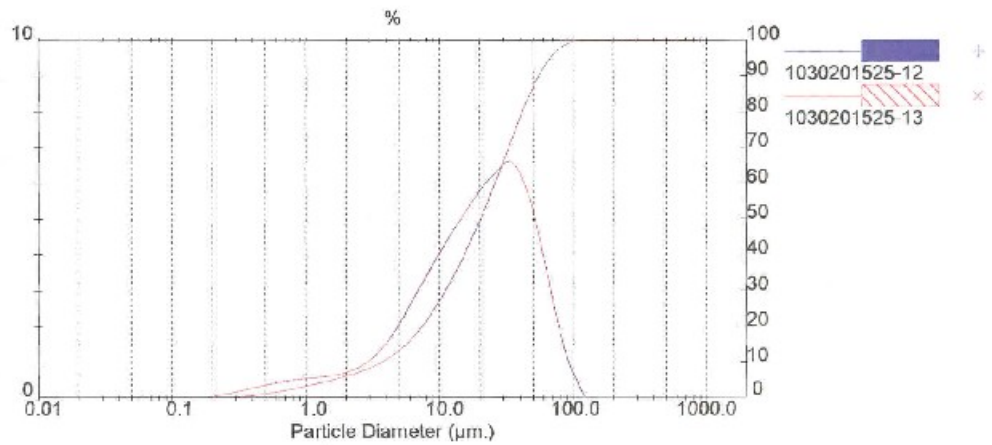
Concentration = 0.0154 %Vol
D (v, 0.1) = 3.76 um
D [3, 2] = 6.51 um

Density = 1.000 g / cub. cm
D (v, 0.5) = 20.37 um
Span = 2.549E+00

Specific S.A. = 0.9216 sq. m / g
D (v, 0.9) = 55.69 um
Uniformity = 7.963E-01

Size_Low (um)	In %	Size_High (um)	Under%
0.05	0.00	0.06	0.00
0.06	0.00	0.07	0.00
0.07	0.00	0.08	0.00
0.08	0.00	0.09	0.00
0.09	0.00	0.11	0.00
0.11	0.00	0.13	0.00
0.13	0.00	0.15	0.00
0.15	0.00	0.17	0.00
0.17	0.02	0.20	0.02
0.20	0.06	0.23	0.08
0.23	0.10	0.27	0.18
0.27	0.15	0.31	0.33
0.31	0.21	0.36	0.54
0.36	0.26	0.42	0.80
0.42	0.32	0.49	1.12
0.49	0.38	0.56	1.51
0.56	0.43	0.67	1.94
0.67	0.48	0.78	2.42
0.78	0.51	0.91	2.93
0.91	0.54	1.06	3.47
1.06	0.56	1.24	4.03
1.24	0.59	1.44	4.62
1.44	0.62	1.66	5.24
1.68	0.66	1.95	5.90
1.95	0.73	2.28	6.63
2.28	0.83	2.65	7.45
2.65	0.97	3.09	8.43
3.09	1.18	3.60	9.61
3.60	1.46	4.19	11.06
4.19	1.80	4.88	12.86
4.88	2.20	5.69	15.06
5.69	2.64	6.63	17.69

Size_Low (um)	In %	Size_High (um)	Under%
6.63	3.05	7.72	20.77
7.72	3.52	9.00	24.30
9.00	3.95	10.48	28.25
10.48	4.33	12.21	32.61
12.21	4.75	14.22	37.36
14.22	5.13	16.57	42.49
16.57	5.49	19.31	47.98
19.31	5.83	22.49	53.82
22.49	6.13	26.20	59.94
26.20	6.35	30.53	66.32
30.53	6.60	35.56	72.92
35.56	6.42	41.43	79.33
41.43	5.90	48.27	85.24
48.27	5.06	56.23	90.29
56.23	3.97	65.51	94.26
65.51	2.80	76.32	97.06
76.32	1.72	88.91	98.78
88.91	0.83	103.58	99.60
103.58	0.34	120.67	100.00
120.67	0.00	140.58	100.00
140.58	0.00	163.77	100.00
163.77	0.00	190.80	100.00
190.80	0.00	222.28	100.00
222.28	0.00	258.95	100.00
258.95	0.00	301.68	100.00
301.68	0.00	351.46	100.00
351.46	0.00	409.45	100.00
409.45	0.00	477.01	100.00
477.01	0.00	555.71	100.00
555.71	0.00	647.41	100.00
647.41	0.00	754.23	100.00
754.23	0.00	878.67	100.00



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Malvern, UK
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Mastersizer S long bed Ver. 2.19
Serial Number: 32418-12

02 Sep 03 10:5

LAFARGE CEM I 42.5

PROCESS SERVICES

Particle Size Analysis

PPC

Result: Analysis Report

Sample Details

Sample ID: 1040100140
Sample File: 40100140
Sample Path: C:\S ZERS\DATA\
Sample Notes: LIMS Sample No 1040100140
Lafarge Curatech Cem I 42.5

Run Number: 9
Record Number: 2

Measurement Date: 15 1 2004 09:04PM
Analysis Date: 15 1 2004 09:04PM
Result Source: Analysed

System Details

Range Lens: 300RF mm
Presentation: 3SSD
Analysis Model: Polydisperse
Modifications: None

Beam Length: 2.40 mm
[Fraunhofer]

Sampler: MS17

Obscuration: 18.2 %
Residual: 0.645 %

Result Statistics

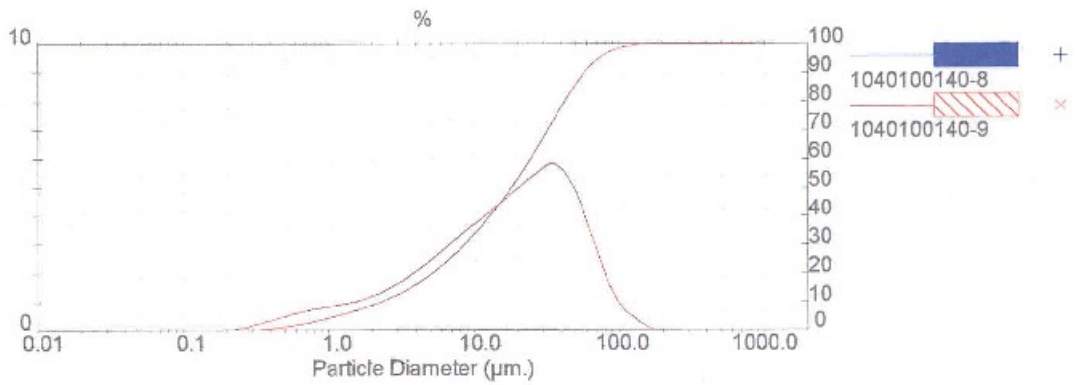
Distribution Type: Volume
Mean Diameters:
D [4, 3] = 25.10 um

Concentration = 0.0145 %Vo
D (v, 0.1) = 2.23 um
D [3, 2] = 5.20 um

Density = 1.000 g / cub. cm
D (v, 0.5) = 18.00 um
Span = 3.059E+00

Specific S.A. = 1.1534 sq. m / g
D (v, 0.9) = 57.29 um
Uniformity = 9.785E-01

Size_Low (um)	In %	Size_High (um)	Under%	Size_Low (um)	In %	Size_High (um)	Under%
0.05	0.00	0.06	0.00	6.63	3.12	7.72	27.84
0.06	0.00	0.07	0.00	7.72	3.39	9.00	31.23
0.07	0.00	0.08	0.00	9.00	3.66	10.48	34.89
0.08	0.00	0.09	0.00	10.48	3.92	12.21	38.82
0.09	0.00	0.11	0.00	12.21	4.19	14.22	43.01
0.11	0.00	0.13	0.00	14.22	4.46	16.57	47.47
0.13	0.00	0.15	0.00	16.57	4.75	19.31	52.22
0.15	0.00	0.17	0.00	19.31	5.03	22.49	57.25
0.17	0.00	0.20	0.00	22.49	5.30	26.20	62.56
0.20	0.01	0.23	0.01	26.20	5.56	30.53	68.11
0.23	0.08	0.27	0.09	30.53	5.79	35.56	73.90
0.27	0.16	0.31	0.24	35.56	5.69	41.43	79.59
0.31	0.25	0.36	0.50	41.43	5.30	48.27	84.89
0.36	0.35	0.42	0.85	48.27	4.61	56.23	89.50
0.42	0.45	0.49	1.30	56.23	3.69	65.51	93.19
0.49	0.55	0.58	1.85	65.51	2.70	76.32	95.89
0.58	0.64	0.67	2.49	76.32	1.80	88.91	97.68
0.67	0.72	0.78	3.21	88.91	1.10	103.58	98.78
0.78	0.79	0.91	4.00	103.58	0.64	120.67	99.43
0.91	0.85	1.06	4.85	120.67	0.41	140.58	99.83
1.06	0.91	1.24	5.75	140.58	0.17	163.77	100.00
1.24	0.98	1.44	6.72	163.77	0.00	190.80	100.00
1.44	1.04	1.65	7.75	190.80	0.00	222.28	100.00
1.68	1.14	1.95	8.89	222.28	0.00	258.95	100.00
1.95	1.27	2.28	10.16	258.95	0.00	301.68	100.00
2.28	1.42	2.65	11.58	301.68	0.00	351.46	100.00
2.65	1.61	3.09	13.19	351.46	0.00	409.45	100.00
3.09	1.81	3.60	15.00	409.45	0.00	477.01	100.00
3.60	2.04	4.19	17.05	477.01	0.00	555.71	100.00
4.19	2.29	4.88	19.34	555.71	0.00	647.41	100.00
4.88	2.56	5.69	21.89	647.41	0.00	754.23	100.00
5.69	2.83	6.63	24.73	754.23	0.00	878.67	100.00



Malvern Instruments Ltd.
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Mastersizer S long bed Ver. 2.19
Serial Number: 32418-12

15 Jan 04 12:23

LAFARGE CEM II A-M(L) 42.5

PROCESS SERVICES

Particle Size Analysis

PPC

Result: Analysis Report

Sample Details

Sample ID: 1040100139
Sample File: 40100139
Sample Path: C:\SIZERS\DATA\
Sample Notes: LIMS Sample No 1040100139
Lafarge Powerecrete Cement II 42.5

Run Number: 3
Record Number: 2

Measurement Date: 15 1 2004 06:37PM
Analysis Date: 15 1 2004 06:37PM
Result Source: Analysed

System Details

Range Lens: 300RF mm
Presentation: 3$$D
Analysis Model: Polydisperse
Modifications: None

Beam Length: 2.40 mm
[Fraunhofer]

Sampler: MS17

Obscuration: 17.0 %
Residual: 1.262 %

Result Statistics

Distribution Type: Volume
Mean Diameters:
D [4, 3] = 20.89 um

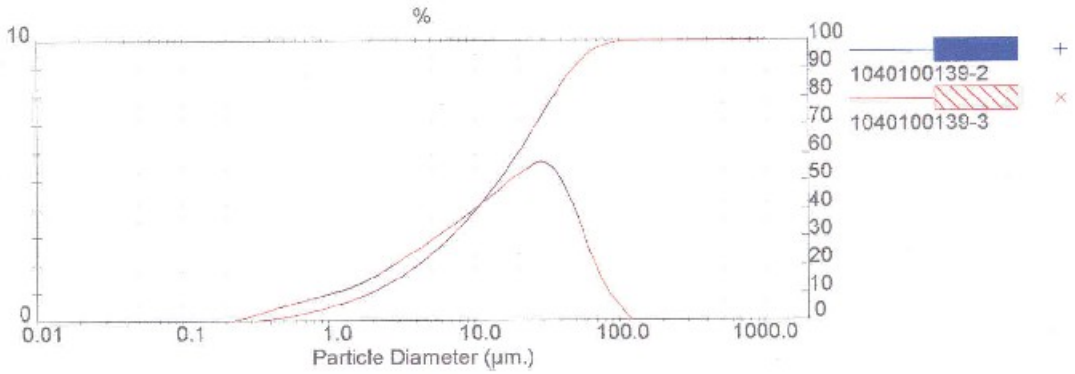
Concentration = 0.0121 %Vol
D (v, 0.1) = 1.92 um
D [3, 2] = 4.85 um

Density = 1.000 g / cub. cm
D (v, 0.5) = 14.85 um
Span = 3.136E+00

Specific S.A. = 1.2900 sq. m / g
D (v, 0.9) = 48.48 um
Uniformity = 9.943E-01

Size_Low (um)	In %	Size_High (um)	Under%
0.05	0.00	0.06	0.00
0.06	0.00	0.07	0.00
0.07	0.00	0.08	0.00
0.08	0.00	0.09	0.00
0.09	0.00	0.11	0.00
0.11	0.00	0.13	0.00
0.13	0.00	0.15	0.00
0.15	0.00	0.17	0.00
0.17	0.00	0.20	0.00
0.20	0.01	0.23	0.01
0.23	0.09	0.27	0.10
0.27	0.17	0.31	0.27
0.31	0.27	0.36	0.54
0.36	0.37	0.42	0.92
0.42	0.48	0.49	1.39
0.49	0.59	0.58	1.98
0.58	0.68	0.67	2.66
0.67	0.78	0.78	3.44
0.78	0.86	0.91	4.30
0.91	0.93	1.06	5.26
1.06	1.03	1.24	6.31
1.24	1.16	1.44	7.47
1.44	1.28	1.68	8.75
1.68	1.44	1.95	10.18
1.95	1.62	2.28	11.80
2.28	1.82	2.65	13.62
2.65	2.03	3.09	15.65
3.09	2.24	3.60	17.89
3.60	2.47	4.19	20.35
4.19	2.69	4.88	23.04
4.88	2.92	5.69	25.96
5.69	3.16	6.63	29.12

Size_Low (um)	In %	Size_High (um)	Under%
6.63	3.40	7.72	32.52
7.72	3.65	9.00	36.17
9.00	3.91	10.48	40.08
10.48	4.17	12.21	44.25
12.21	4.45	14.22	48.70
14.22	4.73	16.57	53.42
16.57	5.00	19.31	58.42
19.31	5.25	22.49	63.67
22.49	5.46	26.20	69.12
26.20	5.63	30.53	74.75
30.53	5.51	35.56	80.27
35.56	5.13	41.43	85.40
41.43	4.48	48.27	89.88
48.27	3.82	56.23	93.71
56.23	2.58	65.51	96.29
65.51	1.50	76.32	97.79
76.32	1.12	88.91	99.11
88.91	0.67	103.58	99.78
103.58	0.22	120.67	100.00
120.67	0.00	140.58	100.00
140.58	0.00	163.77	100.00
163.77	0.00	190.80	100.00
190.80	0.00	222.28	100.00
222.28	0.00	258.95	100.00
258.95	0.00	301.68	100.00
301.68	0.00	351.48	100.00
351.48	0.00	409.45	100.00
409.45	0.00	477.01	100.00
477.01	0.00	555.71	100.00
555.71	0.00	647.41	100.00
647.41	0.00	754.23	100.00
754.23	0.00	878.67	100.00



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Mastersizer S long bed Ver. 2.19
Serial Number: 32418-12

15 Jan 04 12

Holcim CEM II A-M (S) 42.5

PROCESS SERVICES

Particle Size Analysis

PPC

Result: Analysis Report

Sample Details

Sample ID: 1030201522
Sample File: 3020152?
Sample Path: C:\SIZERS\DATA\
Sample Notes: LIMS Sample No 1030201522
High Strength
06/11/2003

Run Number: 13
Record Number: 2

Measurement Date: 27.2.2003 11:21PM
Analysis Date: 2/ 2.2003 11:21PM
Result Source: Analysed

System Details

Range Lens: 300RF mm
Presentation: 3$9D
Analysis Model: Polydisperse
Modifications: None

Beam Length: 2.40 mm
[-raunhofer]

Samples: MS17

Obscuration: 16.6 %

Residual: 0.951 %

Result Statistics

Distribution Type: Volume
Mean Diameters:
D [4, 3] = 24.37 um

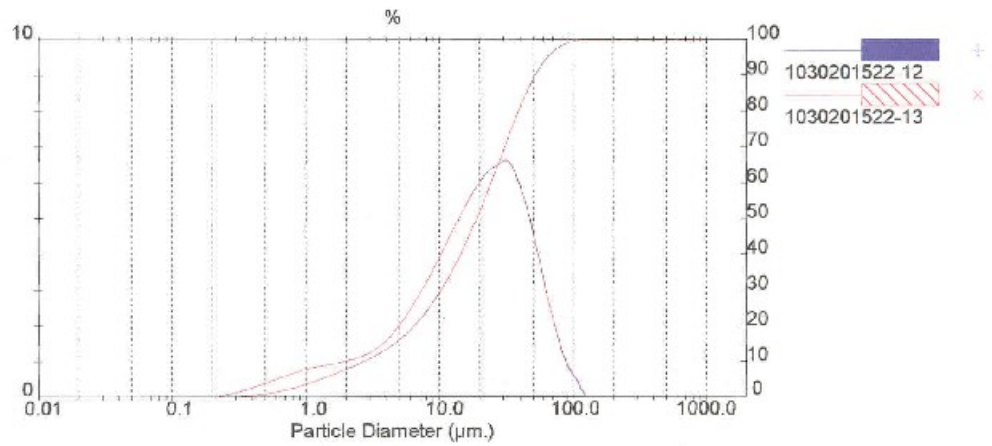
Concentration = 0.0151 %Vol
D (v, 0.1) = 2.72 um
D [3, 2] = 5.98 um

Density = 1.000 g / cub. cm
D (v, 0.5) = 19.19 um
Span = 2.606E+00

Specific S.A. = 1.0041 sq. m / g
D (v, 0.9) = 52.74 um
Uniformity = 6.165E-01

Size_Low (um)	In %	Size_High (um)	Under%
0.05	0.00	0.06	0.00
0.06	0.00	0.07	0.00
0.07	0.00	0.08	0.00
0.08	0.00	0.09	0.00
0.09	0.00	0.11	0.00
0.11	0.00	0.13	0.00
0.13	0.00	0.15	0.00
0.15	0.00	0.17	0.00
0.17	0.00	0.20	0.00
0.20	0.01	0.23	0.01
0.23	0.06	0.27	0.07
0.27	0.12	0.31	0.18
0.31	0.18	0.36	0.37
0.36	0.26	0.42	0.63
0.42	0.35	0.49	0.98
0.49	0.44	0.58	1.41
0.58	0.53	0.67	1.94
0.67	0.62	0.78	2.56
0.78	0.70	0.91	3.26
0.91	0.77	1.06	4.04
1.06	0.84	1.24	4.87
1.24	0.89	1.44	5.76
1.44	0.93	1.68	6.69
1.68	0.96	1.95	7.67
1.95	1.03	2.28	8.70
2.28	1.10	2.65	9.80
2.65	1.20	3.09	11.00
3.09	1.34	3.60	12.35
3.60	1.53	4.19	13.88
4.19	1.79	4.88	15.67
4.88	2.10	5.69	17.77
5.69	2.47	6.63	20.23

Size_Low (um)	In %	Size_High (um)	Under%
6.63	2.87	7.72	23.10
7.72	3.31	9.00	26.41
9.00	3.75	10.48	30.20
10.48	4.25	12.21	34.47
12.21	4.78	14.22	39.25
14.22	5.25	16.57	44.51
16.57	5.71	19.31	50.22
19.31	6.09	22.49	56.31
22.49	6.36	26.20	62.67
26.20	6.51	30.53	69.18
30.53	6.59	35.56	75.77
35.56	6.15	41.43	81.92
41.43	5.40	48.27	87.31
48.27	4.41	56.23	91.73
56.23	3.32	65.51	95.05
65.51	2.28	76.32	97.33
76.32	1.42	88.91	98.76
88.91	0.80	103.58	99.56
103.58	0.41	120.67	99.97
120.67	0.03	140.58	100.00
140.58	0.00	163.77	100.00
163.77	0.00	190.80	100.00
190.80	0.00	222.28	100.00
222.28	0.00	258.95	100.00
258.95	0.00	301.68	100.00
301.68	0.00	351.46	100.00
351.46	0.00	409.45	100.00
409.45	0.00	477.01	100.00
477.01	0.00	555.71	100.00
555.71	0.00	647.41	100.00
647.41	0.00	754.23	100.00
754.23	0.00	878.67	100.00



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Mastersizer S long bed Ver. 2.19
Serial Number: 32418-12

02 Sep 03 10:5

Holcim CEM II B-V (32.5)

PROCESS SERVICES

Particle Size Analysis

PPC

Result: Analysis Report

Sample Details

Sample ID: 103C201523
Sample File: 30201523
Sample Path: C:\SIZERS\DATA\
Sample Notes: LIMS Sample No 103C201523
All Purpose
08/01/2003

Run Number: 7
Record Number: 3

Measurement Date: 27.2.2003 11:33PM
Analysis Date: 27.2.2003 11:33PM
Result Source: Analysed

System Details

Range Lens: 300RF mm
Presentation: 3$3D
Analysis Model: Polydisperse
Modifications: None

Beam Length: 2.40 mm
Fraunhofer

Sampler: MS17

Obscuration: 16.5 %
Residual: 0.986 %

Result Statistics

Distribution Type: Volume
Mean Diameters:
D [4, 3] = 20.80 um

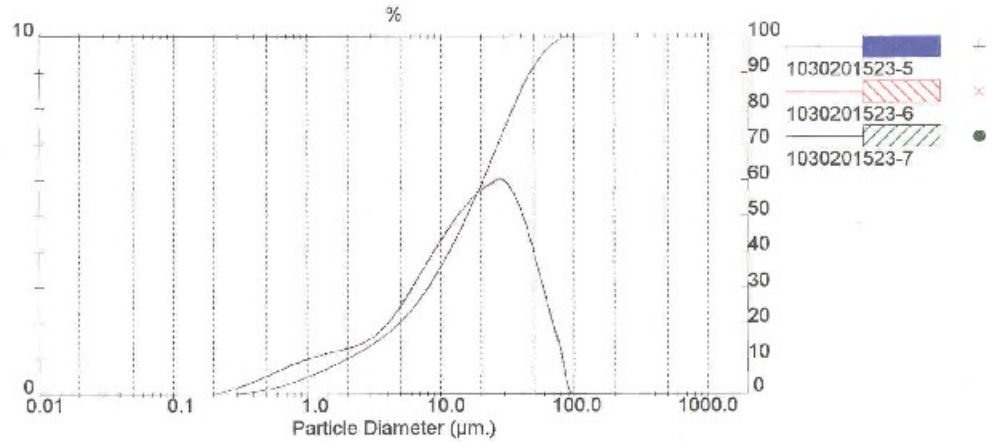
Concentration = 0.0123 %Vol
D (v, 0.1) = 1.59 um
D [3, 2] = 4.69 um

Density = 1.000 g / cub. cm
D (v, 0.5) = 15.75 um
Span = 2.868E+00

Specific S.A. = 1.2270 sq. m / g
D (v, 0.9) = 47.17 um
Uniformity = 6.841E-01

Size_Low (um)	In %	Size_High (um)	Under%
0.05	0.00	0.06	0.00
0.06	0.00	0.07	0.00
0.07	0.00	0.08	0.00
0.08	0.00	0.09	0.00
0.09	0.00	0.11	0.00
0.11	0.00	0.13	0.00
0.13	0.00	0.15	0.00
0.15	0.00	0.17	0.00
0.17	0.00	0.20	0.00
0.20	0.03	0.23	0.03
0.23	0.09	0.27	0.12
0.27	0.16	0.31	0.29
0.31	0.25	0.36	0.53
0.36	0.34	0.42	0.88
0.42	0.45	0.49	1.32
0.49	0.56	0.58	1.88
0.58	0.67	0.67	2.54
0.67	0.78	0.78	3.33
0.78	0.88	0.91	4.21
0.91	0.98	1.06	5.19
1.06	1.06	1.24	6.25
1.24	1.13	1.44	7.38
1.44	1.19	1.68	8.58
1.68	1.25	1.95	9.83
1.95	1.32	2.28	11.15
2.28	1.41	2.65	12.56
2.65	1.52	3.09	14.08
3.09	1.69	3.60	15.77
3.60	1.93	4.19	17.70
4.19	2.23	4.88	19.93
4.88	2.59	5.69	22.51
5.69	2.99	6.63	25.51

Size_Low (um)	In %	Size_High (um)	Under%
6.63	3.40	7.72	28.91
7.72	3.82	9.00	32.73
9.00	4.23	10.48	36.96
10.48	4.60	12.21	41.56
12.21	4.95	14.22	46.52
14.22	5.27	16.57	51.78
16.57	5.53	19.31	57.31
19.31	5.74	22.49	63.05
22.49	5.89	26.20	68.94
26.20	5.99	30.53	74.94
30.53	5.75	35.56	80.71
35.56	5.32	41.43	86.03
41.43	4.61	48.27	90.64
48.27	3.70	56.23	94.34
56.23	2.79	65.51	97.13
65.51	1.89	76.32	99.02
76.32	0.98	88.91	100.00
88.91	0.00	103.58	100.00
103.58	0.00	120.67	100.00
120.67	0.00	140.58	100.00
140.58	0.00	163.77	100.00
163.77	0.00	190.80	100.00
190.80	0.00	222.28	100.00
222.28	0.00	258.95	100.00
258.95	0.00	301.68	100.00
301.68	0.00	351.46	100.00
351.46	0.00	409.45	100.00
409.45	0.00	477.01	100.00
477.01	0.00	555.71	100.00
555.71	0.00	647.41	100.00
647.41	0.00	754.23	100.00
754.23	0.00	878.67	100.00



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Mastersizer S long bed Ver. 2.19
Serial Number: 32418-12

02 Sep 03 10:5

PPC CEM II A-L (32.5)

PROCESS SERVICES

Particle Size Analysis

PPC

Result: Analysis Report

Sample Details

Sample ID: 1030201528
Sample File: 30201528
Sample Path: C:\S ZERS\DATA\
Sample Notes: LIMS Sample No 1030201528
S/Surebuild
23/01/2003

Run Number: 7
Record Number: 2

Measurement Date: 27 2 2003 11:56PM
Analysis Date: 27 2 2003 11:58PM
Result Source: Analysed

System Details

Range Lens: 300RF mm
Presentation: 3$$D
Analysis Mode: Polydisperse
Modifications: None

Beam Length: 2.40 mm
[Fraunhofer]

Sampler: MS17

Obscuration: 18.2 %
Residual: 1.237 %

Result Statistics

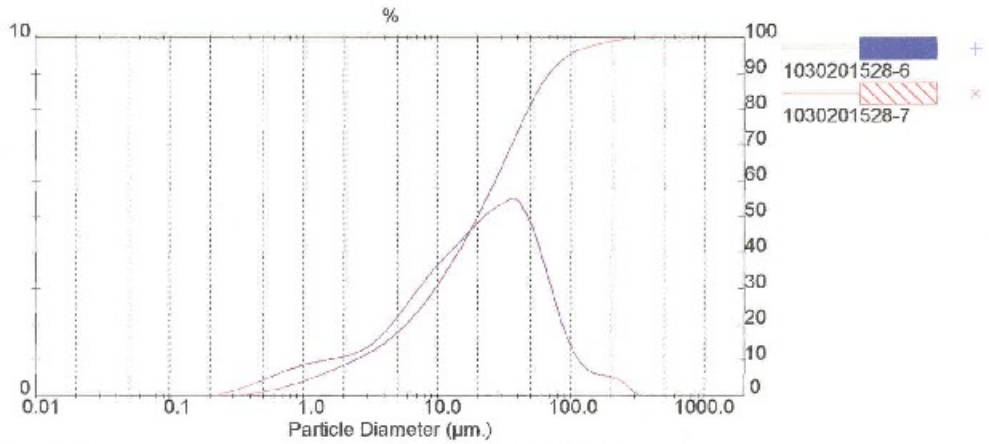
Distribution Type: Volume
Mean Diameters:
D [4, 3] = 31.70 um

Concentration = 0.0161 %Vol
D (v, 0.1) = 2.46 um
D [3, 2] = 5.77 um

Density = 1.000 g / cub. cm
D (v, 0.5) = 20.33 um
Span = 3.324E+00

Specific S.A. = 1.0405 sq. m / g
D (v, 0.9) = 70.02 um
Uniformity = 1.140E+00

Size_Low (um)	In %	Size_High (um)	Under%	Size_Low (um)	In %	Size_High (um)	Under%
0.05	0.00	0.06	0.00	5.63	2.93	7.72	24.77
0.06	0.00	0.07	0.00	7.72	3.24	9.00	28.02
0.07	0.00	0.08	0.00	9.00	3.54	10.48	31.56
0.08	0.00	0.09	0.00	10.48	3.81	12.21	35.37
0.09	0.00	0.11	0.00	12.21	4.08	14.22	39.45
0.11	0.00	0.13	0.00	14.22	4.34	16.57	43.79
0.13	0.00	0.15	0.00	16.57	4.60	19.31	48.39
0.15	0.00	0.17	0.00	19.31	4.85	22.49	53.24
0.17	0.00	0.20	0.00	22.49	5.08	26.20	58.33
0.20	0.00	0.23	0.00	26.20	5.27	30.53	63.60
0.23	0.06	0.27	0.06	30.53	5.41	35.56	69.01
0.27	0.12	0.31	0.18	35.56	5.51	41.43	74.52
0.31	0.20	0.36	0.38	41.43	5.25	48.27	79.77
0.36	0.28	0.42	0.66	48.27	4.74	56.23	84.50
0.42	0.36	0.49	1.04	56.23	4.01	65.51	88.51
0.49	0.46	0.58	1.51	65.51	3.17	76.32	91.68
0.58	0.56	0.67	2.08	76.32	2.34	88.91	94.02
0.67	0.66	0.78	2.77	88.91	1.63	103.58	95.65
0.78	0.76	0.91	3.53	103.58	1.11	120.67	96.76
0.91	0.84	1.06	4.37	120.67	0.79	140.56	97.55
1.06	0.91	1.24	5.28	140.56	0.64	163.77	98.20
1.24	0.96	1.44	6.24	163.77	0.59	190.80	98.78
1.44	1.00	1.68	7.24	190.80	0.53	222.28	99.31
1.68	1.05	1.95	8.29	222.28	0.42	258.95	99.73
1.95	1.11	2.28	9.40	258.95	0.23	301.68	99.96
2.28	1.19	2.65	10.58	301.68	0.04	351.46	100.00
2.65	1.30	3.09	11.89	351.46	0.00	409.40	100.00
3.09	1.46	3.60	13.35	409.40	0.00	477.01	100.00
3.60	1.66	4.19	15.03	477.01	0.00	555.71	100.00
4.19	1.95	4.88	16.98	555.71	0.00	647.41	100.00
4.88	2.27	5.69	19.25	647.41	0.00	754.23	100.00
5.69	2.60	6.63	21.85	754.23	0.00	878.67	100.00



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Mastersizer S long bed Ver. 2.19
Serial Number: 32418-12

02 Sep 03 10:5

NPC CEM III (32.5)

PROCESS SERVICES

Particle Size Analysis

PPC

Result: Analysis Report

Sample Details

Sample ID: 1021200820
Sample File: 21200820
Sample Path: C:\SIZERS\DATA\
Sample Notes: LIMS Sample No 1021200820
NPC /CEM IIIA-S
26/11/2002

Run Number: 4
Record Number: 3

Measurement Date: 27.2.2003 11:08PM
Analysis Date: 27.2.2003 11:08PM
Result Source: Analysed

System Details

Range Lens: 300Mi- mm
Presentation: 3$6D
Analysis Model: Polydisperse
Modifications: None

Beam Length: 2.40 mm
Fraunhofer

Sampler: MS17

Obscuration: 17.0 %
Residual: 0.857 %

Result Statistics

Distribution Type: Volume
Mean Diameters:
D [4, 3] = 19.84 um

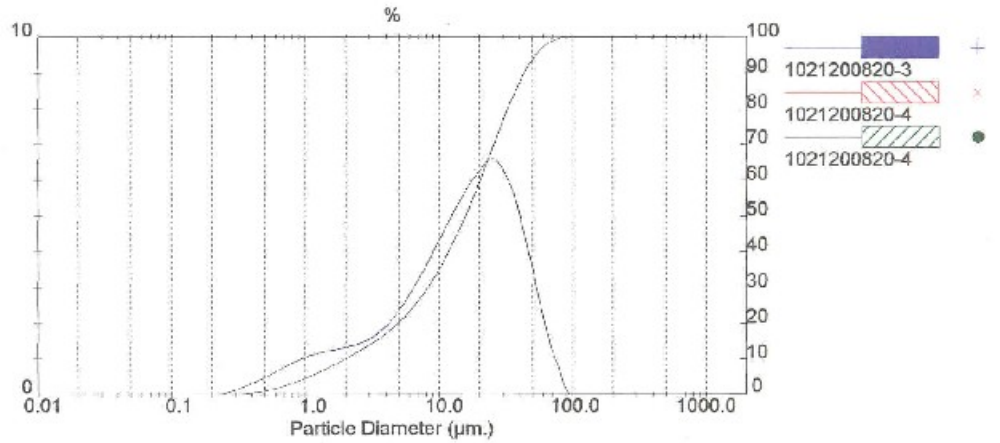
Concentration = 0.0130 %Vol
D (v, 0.1) = 1.58 um
D [3, 2] = 5.02 um

Density = 1.000 g / cub. cm
D (v, 0.5) = 15.76 um
Span = 2.633E+00

Specific S.A. = 1.194 sq. m / g
D (v, 0.9) = 40.50 um
Uniformity = 8.169E-01

Size_Low (um)	In %	Size_High (um)	Under%
0.05	0.00	0.06	0.00
0.06	0.00	0.07	0.00
0.07	0.00	0.08	0.00
0.08	0.00	0.09	0.00
0.09	0.00	0.11	0.00
0.11	0.00	0.13	0.00
0.13	0.00	0.15	0.00
0.15	0.00	0.17	0.00
0.17	0.00	0.20	0.00
0.20	0.00	0.23	0.00
0.23	0.04	0.27	0.04
0.27	0.11	0.31	0.15
0.31	0.20	0.36	0.36
0.36	0.31	0.42	0.66
0.42	0.42	0.49	1.08
0.49	0.54	0.58	1.63
0.58	0.67	0.67	2.30
0.67	0.80	0.76	3.10
0.76	0.92	0.91	4.02
0.91	1.03	1.06	5.05
1.06	1.12	1.24	6.17
1.24	1.19	1.44	7.36
1.44	1.24	1.68	8.60
1.68	1.30	1.95	9.90
1.95	1.36	2.26	11.26
2.26	1.43	2.65	12.69
2.65	1.53	3.09	14.21
3.09	1.67	3.60	15.88
3.60	1.67	4.19	17.75
4.19	2.13	4.88	19.89
4.88	2.46	5.69	22.35
5.69	2.84	6.63	25.20

Size_Low (um)	In %	Size_High (um)	Under%
6.63	3.26	7.72	28.46
7.72	3.72	9.00	32.18
9.00	4.20	10.48	36.38
10.48	4.60	12.21	41.07
12.21	5.17	14.22	46.24
14.22	5.61	16.57	51.86
16.57	6.00	19.31	57.86
19.31	6.32	22.49	64.17
22.49	6.59	26.20	70.76
26.20	6.44	30.53	77.20
30.53	6.01	35.56	83.21
35.56	5.29	41.43	88.50
41.43	4.33	48.27	92.83
48.27	3.24	56.23	96.07
56.23	2.16	65.51	98.23
65.51	1.22	76.32	99.45
76.32	0.55	88.91	100.00
88.91	0.00	103.58	100.00
103.58	0.00	120.67	100.00
120.67	0.00	140.58	100.00
140.58	0.00	163.77	100.00
163.77	0.00	190.80	100.00
190.80	0.00	222.28	100.00
222.28	0.00	258.95	100.00
258.95	0.00	301.68	100.00
301.68	0.00	351.46	100.00
351.46	0.00	409.45	100.00
409.45	0.00	477.01	100.00
477.01	0.00	555.71	100.00
555.71	0.00	647.41	100.00
647.41	0.00	754.23	100.00
754.23	0.00	878.67	100.00



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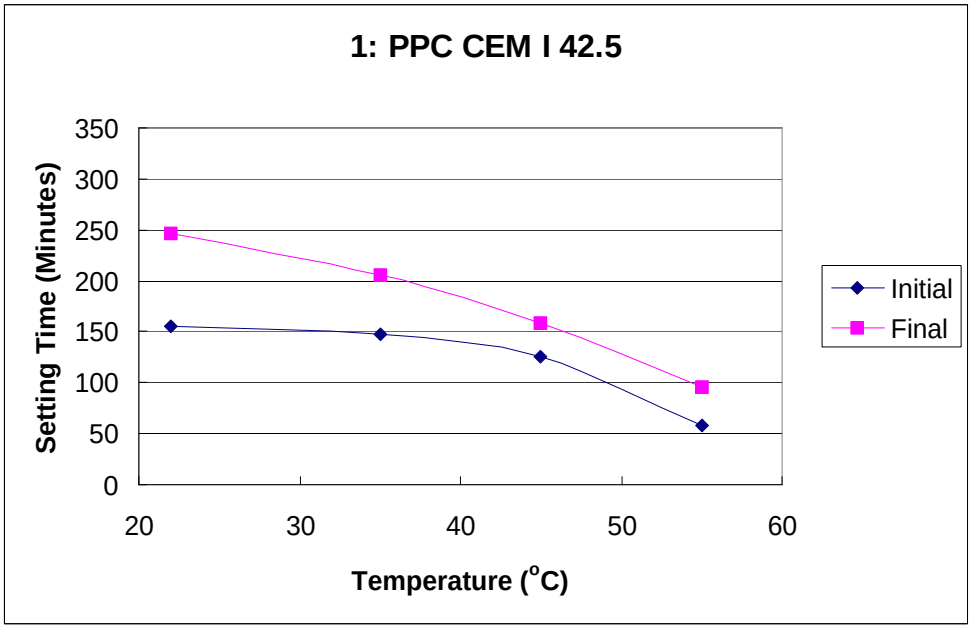
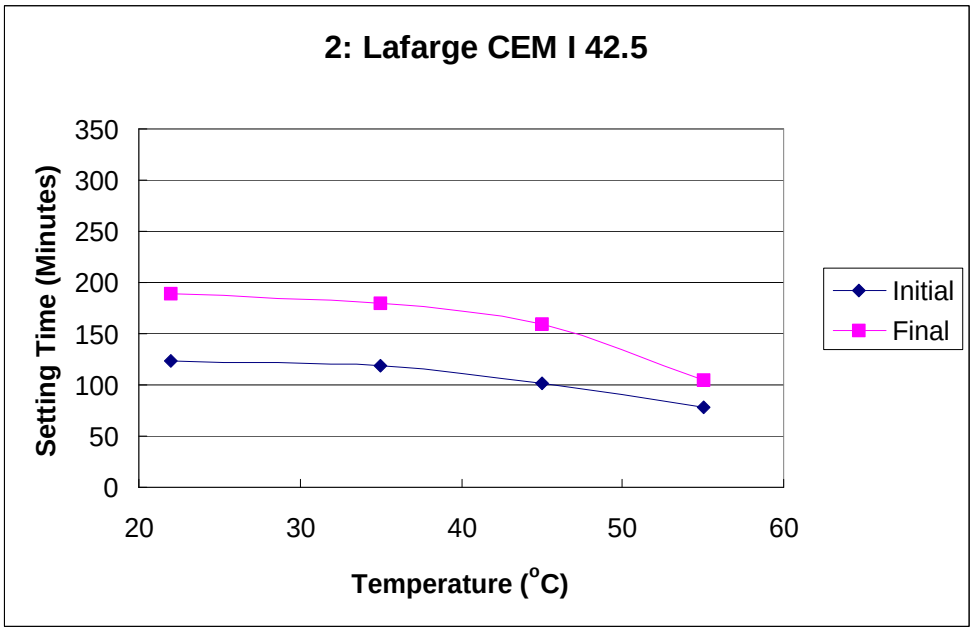
Mastersizer S long bed Ver. 2.19
Serial Number: 32418-12

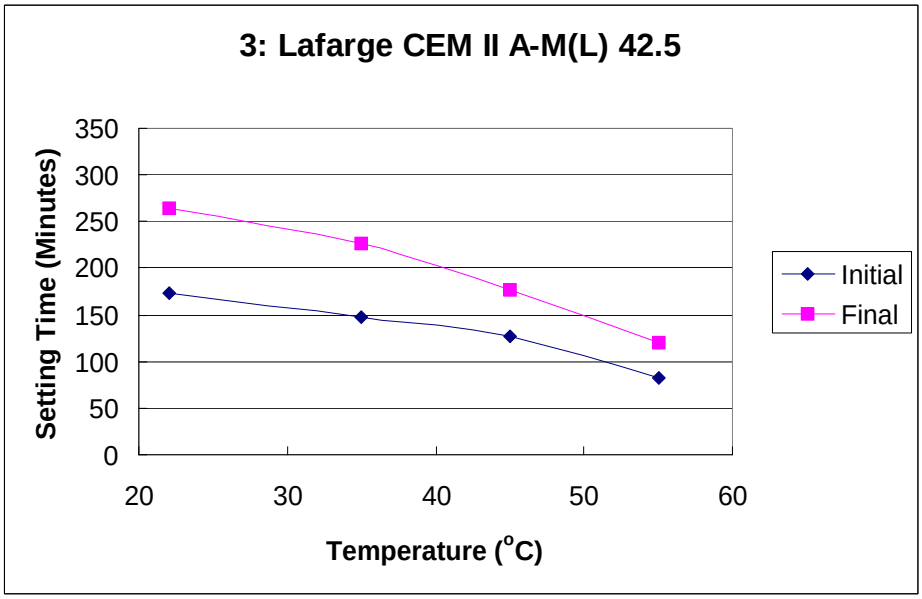
02 Sep 03 10:5

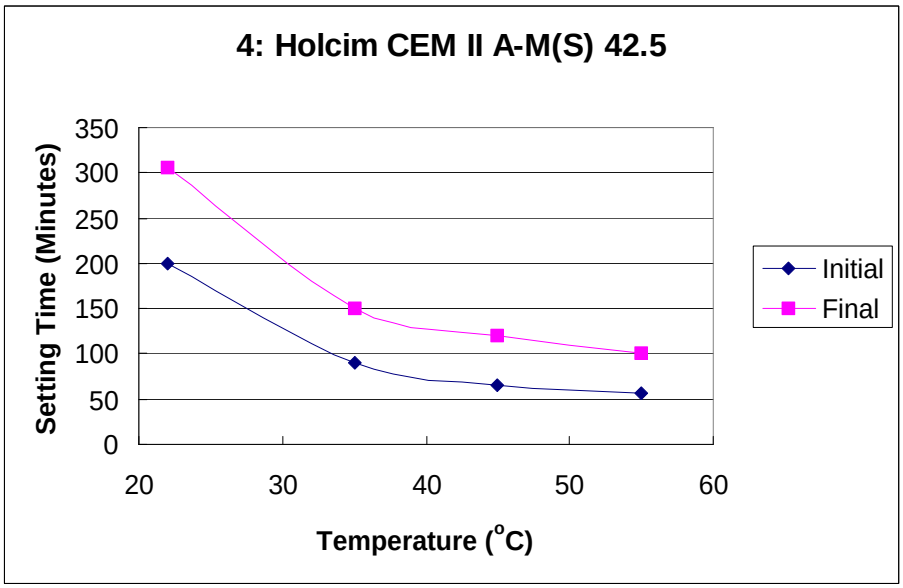
APPENDIX C
INITIAL AND FINAL SETTING TIMES AT DIFFERENT TEMPERATURES

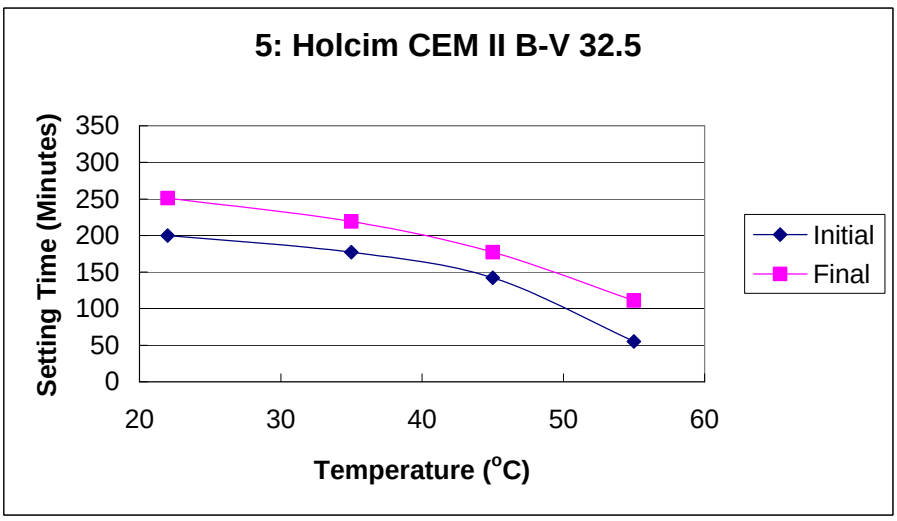
APPENDIX C: INITIAL AND FINAL SETTING TIMES AT DIFFERENT TEMPERATURES

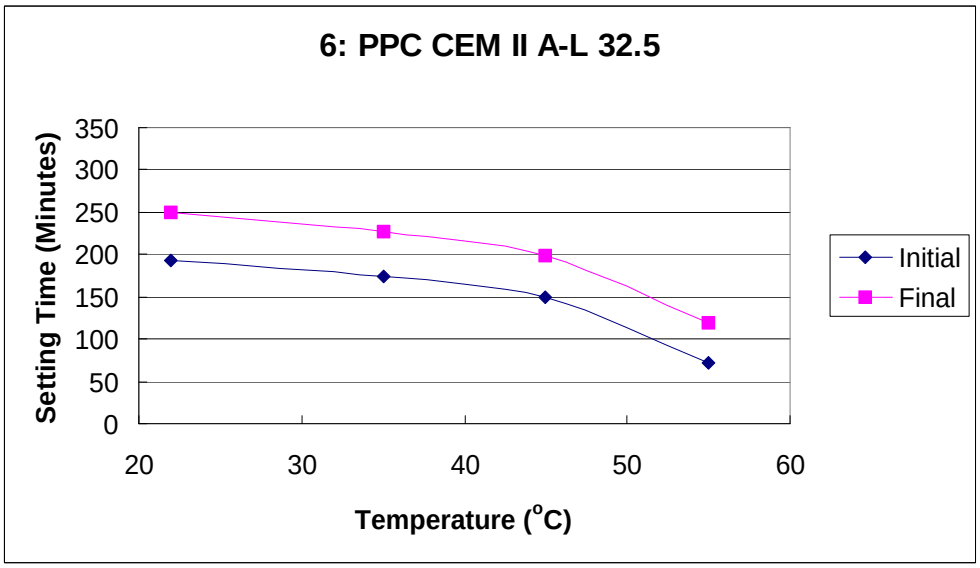


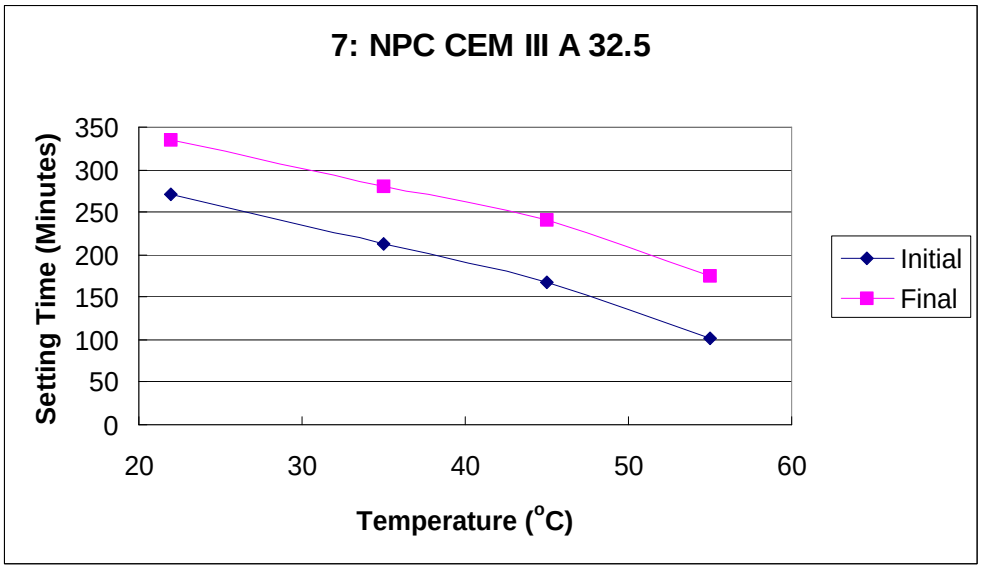



3: Lafarge CEM II A-M(L) 42.5
Setting Time (Minutes)
350
300
250
200
150
100
50
0
20
30
40
50
60
Temperature (°C)
Initial
Final


4: Holcim CEM II A-M(S) 42.5
Setting Time (Minutes)
350
300
250
200
150
100
50
0
20
30
40
50
60
Temperature (°C)
Initial
Final


5: Holcim CEM II B-V 32.5
Setting Time (Minutes)
350
300
250
200
150
100
50
0
20
30
40
50
60
Temperature (°C)
Initial
Final


6: PPC CEM II A-L 32.5
Setting Time (Minutes)
350
300
250
200
150
100
50
0
20
30
40
50
60
Temperature (°C)
Initial
Final


7: NPC CEM III A 32.5
Setting Time (Minutes)
350
300
250
200
150
100
50
0
20
30
40
50
60
Temperature (°C)
Initial
Final

APPENDIX D
SUMMARY OF STABILIZATION TEST RESULTS

APPENDIX D: SUMMARY OF STABILIZATION TEST RESULTS

Summary of density and UCS results for sample CCI 1

CCI 1 (DENSITY AND UCS)			7	4	5	6	1	2	3
			NPC CEM III A-S 32.5	**Holcim CEM II A-M 42.5**	**Holcim CEM II B-V 32.5**	**PPC CEM II A-L 32.5**	**PPC CEM I 42.5**	**Lafarge CEM I 42.5**	**Lafarge CEM II A-M 42.5**
Max. dry density (kg/m^3)			2116	2062	2132	2079	2062	2093	2085
Optimum moisture (%)			10.2	10.8	10.2	11.4	11.3	11.2	11.5
2 hours after hydration		**Avg. Density (kg/m^3)**	2119	2103	2124	2092	2118	2091	2131
	@ 10°C	**UCS (kPa)**	2060	2940	2440	2330	2770	3210	3430
		Avg. Density (kg/m^3)	2086	2063	2146	2053	2062	2072	2091
	@ 23°C	**UCS (kPa)**	1470	2640	2620	2660	2510	2870	2560
		Avg. Density (kg/m^3)	2067	2069	2087	2018	2015	2067	2085
	@ 40°C	**UCS (kPa)**	1060	1890	1621	1220	1820	2270	2470
4 hours after hydration		**Avg. Density (kg/m^3)**	2068	2073	2084	2053	2061	2102	2115
	@ 10°C	**UCS (kPa)**	1440	2760	2540	2730	2540	3050	2970
		Avg. Density (kg/m^3)	2065	2058	2152	2036	2077	2074	2096
	@ 23°C	**UCS (kPa)**	830	2110	2090	2260	1830	2485	2630
		Avg. Density (kg/m^3)	2046	2051	2041	1991	2014	2021	2065
	@ 40°C	**UCS (kPa)**	850	1790	960	1010	1480	1554	2194

Summary of density and ITS results for sample CCI 1

CCI 1 (DENSITY AND ITS)			7	4	5	6	1	2	3
			NPC CEM III A 32.5	**Holcim CEM II A-M(L) 42.5**	**Holcim CEM II B-V 32.5**	**PPC CEM II A-L 32.5**	**PPC CEM I 42.5**	**Lafardge CEM I 42.5**	**Lafarge CEM II A-M(L) 42.5**
Max. dry density (kg/m^3)			2116	2062	2132	2079	2062	2093	2085
Optimum moisture (%)			10.2	10.8	10.2	11.4	11.3	11.2	11.5
2 hours after hydration		**Avg. Density (kg/m^3)**	2106	2114	2120	2127	2119	2096	2111
	@ 10°C	**ITS (kPa)**	148	287.8	271.3	260.7	218.7	354.4	324.8
		Avg. Density (kg/m^3)	2092	2057	2146	2068	2068	2081	2114
	@ 23°C	**ITS (kPa)**	60.8	222	214.6	172.7	322.3	296	282.9
		Avg. Density (kg/m^3)	2061	2070	2076	2023	2010	2037	2062
	@ 40°C	**ITS (kPa)**	89.6	189.1	135.7	111.8	162.8	185	212.1
4 hours after hydration		**Avg. Density (kg/m^3)**	2100	2125	2097	2111	2057	2061	2133
	@ 10°C	**ITS (kPa)**	187.5	393	291.9	169.4	371.7	333.8	320.7
		Avg. Density (kg/m^3)	2080	2054	2145	2039	2109	2073	2098
	@ 23°C	**ITS (kPa)**	129.9	167.7	207.2	254.1	147.2	208	209.7
		Avg. Density (kg/m^3)	2057	2035	2051	1992	2020	2028	2068
	@ 40°C	**ITS (kPa)**	42.8	115.1	74.8	75.6	149.6	151	176

Summary of density and UCS results for sample CCI 2

CCI 2 (DENSITY AND UCS)			7	4	5	6	1	2	3
			NPC CEM III A-S 32.5	Holcim CEM II A-M (L) 42.5	Holcim CEM II B-V 32.5	PPC CEM II A-L 32.5	PPC CEM I 42.5	Lafarge CEM I 42.5	Lafarge CEM II A-M(S) 42.5
Max. dry density (kg/m^3)			2420	2390	2448	2451	2463	2456	2464
Optimum moisture (%)			8.6	9	7.2	7.5	7.7	8	8.2
2 hours after hydration		Avg. Density (kg/m^3)	2387	2394	2431	2431	2418	2421	2452
	@ 10°C	UCS (kPa)	3800	3450	3720	4720	4250	4430	4460
		Avg. Density (kg/m^3)	2445	2437	2421	2455	2463	2383	2420
	@ 23°C	UCS (kPa)	3370	3570	3100	3350	3500	3540	3480
		Avg. Density (kg/m^3)	2366	2387	2354	2310	2355	2307	2323
	@ 40°C	UCS (kPa)	2960	3320	2580	2620	2280	2310	2620
4 hours after hydration		Avg. Density (kg/m^3)	2423	2408	2416	2447	2424	2416	2412
	@ 10°C	UCS (kPa)	3480	3360	2710	3580	2650	3230	3420
		Avg. Density (kg/m^3)	2448	2400	2441	2427	2398	2344	2419
	@ 23°C	UCS (kPa)	3840	3450	2640	2740	3130	2350	3480
		Avg. Density (kg/m^3)	2391	2330	2325	2287	2329	2328	2336
	@ 40°C	UCS (kPa)	2800	2970	1680	1690	2180	2680	2280

Summary of density and ITS results for sample CCI 2

			7	4	5	6	1	2	3
CCI 2 (DENSITY AND ITS)			**NPC CEM III A-S 32.5**	**Holcim CEM II A-M (L) 42.5**	**Holcim CEM II B-V 32.5**	**PPC CEM II A-L 32.5**	**PPC CEM I 42.5**	**Lafarge CEM I 42.5**	**Lafarge CEM II A-M(S) 42.5**
Max. dry density (kg/m^3)			2420	2390	2448	2451	2463	2456	2464
Optimum moisture (%)			8.6	9	7.2	7.5	7.7	8	8.2
2 hours after hydration		**Avg. Density (kg/m^3)**	2397	2387	2425	2438	2418	2426	2461
	@ 10°C	**ITS (kPa)**	356	407.8	314.9	407	412.1	388.1	332.2
		Avg. Density (kg/m^3)	2454	2450	2425	2445	2451	2388	2418
	@ 23°C	**ITS (kPa)**	362.6	390.6	300	279.6	326.4	286.1	231.9
		Avg. Density (kg/m^3)	2366	2409	2357	2317	2357	2306	2330
	@ 40°C	**ITS (kPa)**	285.3	388.9	282	246.7	244.2	193.2	220
4 hours after hydration		**Avg. Density (kg/m^3)**	2424	2376	2425	2448	2412	2425	2411
	@ 10°C	**ITS (kPa)**	340.4	390.6	249.1	344.5	230.2	279.6	207.2
		Avg. Density (kg/m^3)	2442	2340	2395	2415	2407	2344	2413
	@ 23°C	**ITS (kPa)**	330.5	357.7	228.6	231.1	227.8	216.3	203.1
		Avg. Density (kg/m^3)	2381	2333	2319	2277	2317	2303	2319
	@ 40°C	**ITS (kPa)**	338.8	340.4	174.3	152.1	149.6	179.3	155.4

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