AN INVESTIGATION OF CEMENT COATING FOR AGGREGATES IN BITUMINOUS MATERIAL

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BEng (Hons.)

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My son, if you accept my words and store up my commands within you,
Turning your ear to wisdom and applying your heart to understanding
and if you call out for insight and cry aloud for understanding, and if you look for it as for silver and search for it as hidden treasure,
then you will understand the fear of the Lord and find the knowledge of God.
For the Lord gives wisdom, and from his mouth come knowledge and understanding.

Proverbs chapter 2 v 1-6, the Bible

ABSTRACT

This research was designed to investigate the properties of aggregate with a new cement coating applied, and to test the effect of including this aggregate in a bituminous road mixture. The investigation was divided into three main areas of study. They were, chemical and physical testing of the aggregate, and testing of a bituminous road mixture containing the modified aggregate, namely porous asphalt wearing course.

Chemical testing involved a regime to show the affinity between coated and uncoated aggregates, and bitumen, in terms of adsorption, and desorption in the presence of water.

Physical testing included all the common tests for demonstrating the advantageous properties of an aggregate. These tests included, the shear box test, the polished stone value test, the aggregate crushing value test and tests for surface roughness.

Porous asphalt was chosen as a suitable road material for testing the effects of the modified aggregate on a bituminous material, as it is a stone matrix dependant mixture and is currently enjoying increased acceptance Europe wide as a driver friendly, high quality surfacing material. Tests applied included the repeat load axial, and the repeat load indirect tensile tests.

In order to undertake large parts of the testing program, much of the equipment was constructed by the researcher at Liverpool John Moores University (LJMU). This included the shear box apparatus and the repeat load axial test apparatus. These were both designed to the relevant British standards and verified as being so.

Observations made during the testing programme showed the coated aggregates displayed a useful improvement in their chemical and physical properties over uncoated aggregates in almost all the areas tested. Future recommendations include

mass production prototyping so that the coated aggregate mixtures can be placed in road trial sections.

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ABBREVIATIONS / ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AAV	Aggregate Abrasion Value
ACV	Aggregate Crushing Value
ADC	Analogue to Digital Converter (or Conversion)
AIV	Aggregate Impact Value
BS	British Standard
DBM	Dense Bituminous Macadam
HAC	High Alumina Cement
HMA	Hot Mix Asphalt
HRA	Hot Rolled Asphalt
LAAT	Los Angeles Abrasion Test
LHPC	Low Heat Portland Cement
LJMU	Liverpool John Moores University
MRL	Materials Reference Library
NAT	Nottingham Asphalt Tester
NI	National Instruments
OD	Oven Dried
OPC	Ordinary Portland Cement
PA	Porous Asphalt
PSD	Position Sensitive Detector
PSV	Polished Stone Value
SCXI	Signal Conditioning eXtensions for Instrumentation
SHRP	Strategic Highways Research Program
SRPC	Sulphate Resisting Portland Cement
SSD	Saturated Surface Dried
RHPC	Rapid Hardening Portland Cement
RLAT	Repeat Load Axial Test
RLITT	Repeat Load Indirect Tensile Test
TFV	Ten Per cent Fines Value
TRRL	Transport and Roads Research Laboratory

UK	United Kingdom of Great Britain and Northern Ireland
USA	United States of America
UUJ	University of Ulster Jordanstown
VMA	Voids in Mixed Aggregate

GLOSSARY OF SYMBOLS

UNITS

m	Metres
hrs	Hours
mins	Minutes
s/secs	Seconds
Pa	Pascals
N	Newtons
g	grammes
l	Litres
V	Volts
psi	Pounds per Square Inch
pcf	Pounds per Cubic Foot
rpm	Revolutions per Minute
pen	Penetration grade
%	Percentage
°	Degrees (Angular)
°C	Degrees Centigrade, or Degrees Celsius
°F	Degrees Fahrenheit

MULTIPLIER PREFIXES

G	Giga	$x10^{9}$
M	Mega	$x10^{6}$
k	Kilo	$x10^{3}$
c	Centi	$x10^{-2}$
m	Milli	$x10^{-3}$
μ	Micro	$x10^{-6}$
n	Nano	$x10^{-9}$

CHAPTER 1

Introduction

1.1 Introduction

Throughout the transportation industry there is an ongoing need to improve the quality of the materials provided for the construction of flexible pavements. Flexible bituminous pavements constitute a very large part of the transportation network facility, therefore the performance and durability of bituminous material needs constantly upgrading to meet the socio-economic and environmental demands of the transportation network user.

In many countries there are insufficient supplies of crushed rock aggregates suitable for high stability, low deformation bituminous road surfacings. Often these countries need to import expensive aggregates to meet their construction needs. It follows then, that road construction and maintenance can become a burden on local and national economies. Poorer quality bituminous surfacings made from uncrushed gravel or reclaimed waste material are no longer acceptable, for they can fail under the stresses applied by modern vehicles. The use of these materials could therefore be costly in repair bills, and in the resulting traffic delays. Guidelines, specifications and regulations rule out the use of these materials in all but the least severe applications, in many countries.

It can be seen therefore that there is a need to improve the performance of gravels and recycled materials so they can be used in a wider range of applications. This will allow the imbalance of quarried (crushed) aggregate, versus gravels and recycled material to be redressed. Economic and environmental benefits may also ensue. As an example of this imbalance, shown in figure 1.1 are the British Aggregate Construction Materials Industries (BACMI) figures for (1994), figure 1.1, (1).

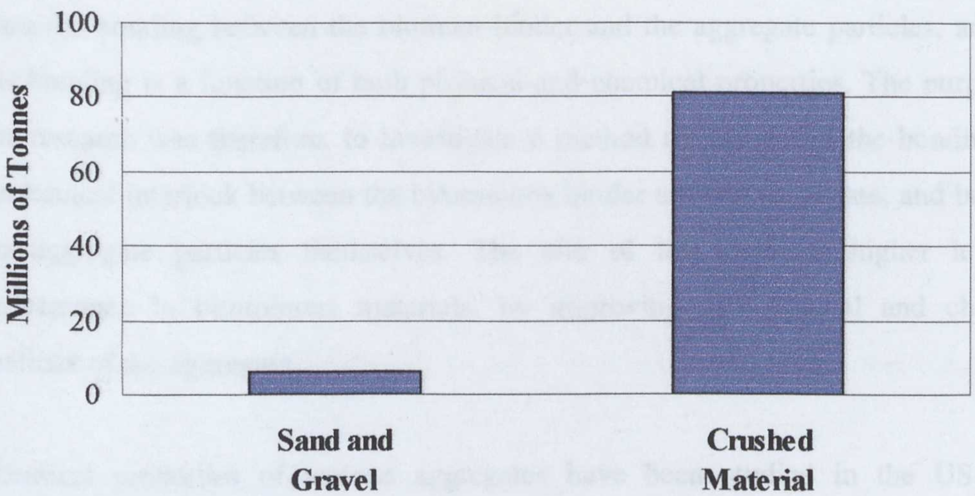


Figure 1.1 Roadstone Production 1993 (ref. 1)

This research seeks to redress the imbalance in some small way, by testing a cement coating to improve the properties of an aggregate to which it is applied.

1.2 Project Background

The research stems from previous and on going work at Liverpool John Moores University (LJMU), in collaboration with Elkem Chemicals Limited UK, Tarmac Topmix Limited UK, and the European Asphalt Pavement Association. The work concentrated mainly on new techniques for improving the roughness and porosity of natural, smooth surfaced aggregates using cement and chemical additives. The work was for application in the fields of, high quality flexible pavement mixtures, concrete pavement mixtures and for other more general construction uses. An interest generated by the factors mentioned in the introduction, together with a general interest in materials-science born out of undergraduate study further encouraged this research. Undergraduate study was composed of an investigation of concrete microstructure, especially the bonding between cement paste and aggregate particles, references (2, 3). The aim was to understand and improve the bonding at a chemical and microstructure level to increase the overall mechanical strength of concrete specimens. Methods of testing and observation, and skills acquired in that study, were very useful for this research work.

Preliminary studies showed that the performance of bituminous pavement depends upon the bonding between the bitumen binder and the aggregate particles, and that this bonding is a function of both physical and chemical properties. The purpose of this research was therefore, to investigate a method of improving the bonding and mechanical interlock between the bituminous binder and the aggregate, and between the aggregate particles themselves. The aim of this being a higher level of performance in bituminous materials, by improving the physical and chemical qualities of the aggregate.

Chemical properties of various aggregates have been studied in the USA, (4) especially in respect of the adsorption and desorption of bitumen on the aggregate surface. These tests were used to determine aggregate-bitumen pairings that were likely to produce a high performance bituminous pavement material. These studies gave substance to the hypothesis that bitumens share an affinity with calcareous, lime-rich, high surface area microtexture aggregates. They also indicated methods of improving the surface characteristics of poor quality aggregates, namely cement coating, cement being lime-rich and having a crystalline, high surface area microtexture.

1.3 Statement of Objectives

The following aims and objectives seek to define the scope of the research, and have provided the framework for the experimental programme and subsequent analysis.

(i) Reveal by literature review, those aggregate properties considered necessary for good bonding with bitumen and compare those properties with the properties of cement paste.

(ii) Design a basic cement paste coating suitable for this investigation.

(iii) Compare the affinity between the cement paste and bitumen, with the affinity between aggregates and bitumen, and compare the affinity between cement-coated and uncoated aggregates and bitumen.

(iv) Measure the physical properties of cement coated aggregates, and compare them with the properties of model uncoated aggregates.

(v) Quantify the effect of including coated aggregates in a bituminous road pavement mixture and compare this performance with mixtures made from model uncoated aggregates.

(vi) To make recommendations for further development of the cement coating.

1.4 Organisation of the Thesis

This thesis is arranged in a manner reflecting the order of investigation and experimentation.

Chapter 2 seeks to show the properties required of an aggregate to make it acceptable as a road material ingredient, and explain with theory why a cement coating demonstrates these properties.

Chapter 3 explains the choice of aggregates for this research program and the design of the cement coating.

Chapter 4 details the experimental method, results and conclusions of the chemical testing of the coated aggregate.

Chapter 5 explains the role and development of the Labview® graphical programming, in the subsequent experimentation.

Chapter 6 explains the methods, results and conclusions of testing of the physical properties of the coated aggregate.

Chapter 7 explains the choice of mixture type, and details the design of the porous asphalt mixtures used for repeat load axial and repeat load indirect tensile tests.

Chapter 8 details the testing of the porous asphalt mixtures using the repeat load indirect tensile test, and presents the results and conclusions drawn.

Chapter 9 details the testing of the porous asphalt mixtures using the repeat load axial test, and presents the results and conclusions drawn.

Chapter 10 is reserved for summarising the thesis, general conclusions, and recommendations for further research and application.

CHAPTER 2

Literature Review

2.1 The History of the Use of Cement and Cement Coating in Bituminous Material

2.1.1 General Use of Cement

The concept and practice of using cement in bituminous mixtures is not new. In general, the process is employed in an effort to ensure durable adhesion in the bitumen-aggregate system. Loose Ordinary Portland Cement (OPC) has been used primarily as filler in hot-mixed bituminous materials to increase the binder stiffness and prevent stripping of the binder from previously dried aggregate; it has also been used to enhance the coating of damp or wet aggregate with bitumen or tar.

Schmidt et al. (5) studied the effect of adding 1.3 per cent and 3 per cent OPC, by weight of the aggregate, in an attempt to improve the slow evolution of strength of bituminous emulsion mixtures. The cement was mixed with the aggregate at the time the bitumen emulsion was added during mixing. It was concluded that mixtures treated this way cured faster, developing a higher elastic modulus, and retained a higher resilient modulus following cyclic saturation. The tests also showed however, that fatigue resistance remained the same or in some cases reduced with the addition of cement.

Terrel et al. (6) have shown also, that the rate of development of modulus of elasticity in bitumen emulsion mixtures, is greatly increased by the addition of cement.

Head (7) has reported the results of research on cement-modified bituminous cold mixtures. He found that the addition of cement had a very significant effect on mixture stability. He showed that the addition of 1 per cent cement, by weight of the aggregate, resulted in an increase in stability of 200 - 300 per cent over that of untreated specimens. He also performed immersion tests and demonstrated that specimens without cement, immersed in water after Marshall stability tests, disintegrated after 24 hours. Conversely cement treated specimens displayed no deterioration. The tests also showed that the addition of 1 per cent cement had the side effect of doubling the Marshall flow. However with the inclusion of 2 per cent cement, this effect was negated. Results of the immersion-compression investigation indicated that the moisture found in the emulsion is not necessarily satisfactory for hydrating the cement, and that prewetting of the aggregate is usually necessary.

Schmidt et al. (8) have shown that dramatic water resistance, and with some aggregates, a large increase in the dry modulus of elasticity, are imparted by adding the cement and lime as a slurry to the aggregate 24 hours before the hot mixture was made.

2.1.2 Cement Coating of Aggregates

During the 1970's there was rapid development of the Kuwaiti road network. Unfortunately this rapid development allowed little opportunity to adequately monitor and collect feedback data on actual pavement performance. The lack of such information made it impossible to identify accurately at an early stage those forms of distress that later became prevalent in the hot and dry climate of the region. In later years, forms of distress such as surface corrugations, excessive permanent deformation in the wheel paths and fatting up significantly increased, and there was no remedial cure. The situation called for a long term solution to the problem. Initial diagnosis stressed the weakening effect of the very high temperatures in the asphalt pavement layers during the long summer season. It was obvious these temperatures caused large reductions in stability, which permitted plastic flow and reduced stiffness, which meant lower load spreadability. An obvious need had therefore arisen for the development of improved bituminous mixtures with reduced susceptibility to temperature.

Experimentation using Portland cement coated, local aggregates, for the production of high-quality mixtures began in 1977. Initial experiments were intended to improve the general mixture by enhancing the frictional component of stability and the aggregate-binder affinity and adhesion, the main aim being to reduce fatting up and excessive rutting in the long hot summer season. The aggregate was treated with about 4 per cent by weight of Portland cement with sufficient water to satisfy the requirements of aggregate absorption and cement hydration. The treated aggregate was allowed to cure for two days to form a coating of hydrated cement before it was used conventionally in the aggregate plant. Encouraging results led to the construction and monitoring of a 500m trial section on a major road. The performance of this trial section was judged to be very satisfactory, and the technique was subsequently introduced into the construction specification of the major road network.

A Kuwaiti paper, "Specification for Road Work" (9), published at the time, compared, in the laboratory, the performance of cement coated aggregates, with the corresponding performance of two conventional mixtures, of the same gradation and type of parent aggregate. Results showed that, on the whole, cement coating of the parent aggregate had the effect of increasing the Marshall stability, the optimum binder content and the void content of the mixture. These are all desirable qualities in the production of modern mixtures, especially stone mastic and porous asphalt type mixtures. Compactibility tests, (i.e. Marshall results at 50 and 75 blows) also showed that cement treated mixtures contained 37% more voids after 75 blows than ordinary mixtures at 50 blows. This indicated that cement coated mixtures are capable of reducing permanent deformation, supported by references (10, 11, 12, 13, 14).

Another advantage of cement coating highlighted in this paper, is the ability of treated mixtures to resist the deleterious effects of water on the pavement performance.

The Immersion-compression test (AASHTO T165) was conducted (9). The alternative procedure in which the immersed specimens are kept in water for 24h at

60°C ± 1°C was adopted. The results can be summarised with the following statements.

(i) Untreated specimens lost about half their compressive strength after immersion, specimens that had 1 per cent hydrated lime and those treated with cement appeared completely resistant to water.

(ii) The large drop in compressive strength of untreated specimens occured in spite of their high fines content of 8 to 10 per cent (mostly limestone dust), which should have improved the mechanical component of adhesion and thus the resistance to stripping by increasing the viscosity of the original binder in the mixture. This was thought to be because, unlike active fillers such as hydrated lime, limestone dust is inert and insoluble in water and does not therefore change the physicochemical mechanism at the aggregate-bitumen interface, which is known to influence greatly the adhesion and stripping of bitumen films.

(iii) The change of filler content from 8 to 10 per cent appeared to cause no significant change in the index of retained strength in almost all cases.

(iv) The compressive strength, in the case of both dry and immersed specimens was seen to increase by an average of 20 per cent for specimens with hydrated lime treatment and 13 per cent for specimens with heavy cement treatment. Specimens that had light cement treatment yielded the greatest improvement in compressive strength, the improvement being 52 and 34 per cent for the dry and the immersed conditions respectively.

The above statements provide evidence to support the hypothesis that cement coating in the correct proportions can significantly increase the performance of a road material, in both wet and dry environments.

Work by Daoud (15, 16) at the Road Research Centre in Kuwait, indicated that the optimum coating, (in terms of uniformity of distribution of the added cement paste among different size fractions of the treated aggregate), was usually achieved at 11-

15 per cent of cement, by weight of the aggregate. This depended on a number of material and processing variables, (including aggregate type and gradation, water/cement ratio, etc.).

Later Guirguis et al. (17) studied the findings of Daoud (15, 16), but considered a range of 11-15 per cent was not economically feasible for many applications. They therefore considered it necessary to determine the effect on bituminous mixture properties, of using aggregates with lower percentages of cement. Three levels of cement coating were therefore selected and the resulting coatings were identified as; light (5%), medium (6.5%) and heavy (8%). They found that, in summary, the inclusion of cement as a coating had the effect of, increasing the stability, lowering the potential for binder bleeding, and increasing the resistance to the effects of water. Also the mixtures tended to remain stiff at higher temperatures and resist excessive embrittlement at very low temperatures.

Presented below are some of the results of Guirguis et al.

Table 2.1 Marshall Stability Results (ref. 17)

	Aggregate Proportions (%)					Properties of Compacted Mixture			
	Aggregate Nominal size (mm)		Sand		Limestone Dust	Optimum Binder (%)	Marshall Stability Ratio (%)	Bulk Density (g/cm^3)	Void Content (%)
Type and Degree of Treatment	19	9.5	Crushed	Natural					
Untreated	28	20	30	14.5	7.5	4	100	2.37	3.1
Hydrated Lime, 1 per cent	28	20	30	14.5	7.5	4.25	109	2.36	3.1
Cement:									
Light	28	20	30	14.5	7.5	4.5	104	2.4	3.4
Medium	28	20	30	14.5	7.5	4.5	109	2.36	4.2
Heavy	28	20	30	14.5	7.5	4.5	124	2.35	4.9
Light	30	22.5	27	14	6.5	4.5	92	2.33	5
Medium	30	20	27.5	15	7.5	4.25	111	2.35	4.7
Heavy	28	20	30	14.5	7.5	4.5	124	2.35	4.9

It can be seen in Table 2.1 that the untreated mixture has the lowest stability in spite of its relatively high density (row 1). The addition of hydrated lime (row 2) did not change the void content or density significantly but it did increase the stability by 9 per cent. Guirguis et al. state; *"this is thought to be due to the fineness of the hydrated lime compared with the limestone dust (specific surfaces of 750 and 260 m^2/kg, respectively), which produce a binder of higher viscosity."*.

Rows 4, 5 and 6 of table 2.1 show that both voids and stability of the cement-treated mixtures increase with the degree of cement coating. Specimens made with increasing percentages of cement coating are respectively 10, 35 and 58 per cent higher in voids and 4, 9 and 24 per cent higher in stability than mixtures made with untreated aggregates. Guirguis et al. state; *"The higher void content obviously indicates a reduction in compactability of these mixes and is expected consequently to result in lower stabilities. However, it seems that the gain in mix stability due to enhancement of aggregate texture, (by precoating with cement), is more than the loss due to the lower density and higher voids of the resulting less-compactable mix."*.

The researcher concurs with these conclusions after examination of the results.

Table 2.2 Compactability Testing Results (ref. 17)

Type and Degree of Treatment	Optimum Binder (%)	Void Content (%)	Bulk Specific Gravity (g/cm^3)	Voids in Mineral Aggregate Value (VMA)	Voids Filled With Bitumen (%)
Untreated Mixture.					
50 blows	4.6	3.4	2.338	14.6	73
75 blows	4.8	3.2	2.351	14.0	79
Mixture with Hydrated Lime, 1%.					
50 blows	4.9	3.3	2.343	14.6	78
75 blows	4.9	3.0	2.358	14.0	81
Mixtures with Cement Coated Aggregate.					
Light Coat.					
50 blows	5.5	5.1	2.290	17.2	72.5
75 blows	5.0	4.6	2.306	16.2	70
Heavy Coat.					
50 blows	5.5	5.8	2.270	17.9	68
75 blows	5.5	4.6	2.300	16.9	73

The shaded area in table 2.2 shows the obvious benefits of cement coating. Increased optimum binder content indicates that cement coating would be of benefit in porous asphalt type mixtures because more binder could be incorporated before drainage takes place. VMA results indicate that the inclusion of cement produces an aggregate with more voids. Less voids filled with bitumen in the bituminous mixture would therefore indicate that the coating improves aggregate angularity, and possibly the aggregate's angle of internal shearing resistance, corroborated by references (17, 18, 19, 20). Increased aggregate angularity is well known to increase the resistance to permanent deformation in bituminous mixtures, this phenomenon is documented in references (10, 11, 12, 13, 14).

It can be seen therefore, that cement coating appears to have many advantages over untreated aggregates. However as yet, testing of the physical and chemical properties of such aggregates in contemporary bituminous mixtures, has not been performed.

Both chemical and physical properties of an aggregate contribute towards its performance in a bituminous mixture. Therefore these properties in coated aggregate, need full investigation to determine which properties contribute the most or least, and to give an indication of how best to improve the contribution of each property. Identification of the improvement in the properties of an aggregate, after cement coating, is also important for pin pointing which application of the coated aggregate will yield most benefit.

2.2 The Chemical Affinity Between Bitumen and Aggregate

2.2.1 Why Test for the Chemical Affinity Between Bitumen and Aggregate

Many researchers have recognised the need for research into the affinity between bitumen and aggregate, these include Mohamed (21), who states in the problem definition section of his thesis; *"Over the years, a great deal of basic and applied research has been conducted to study the nature of the stripping phenomenon. Stripping is recognised as the physical separation of asphalt cement and aggregate produced by adhesion failure. All stripping failures have been associated with presence of water. Virtually all investigators agree that stripping is caused by water displacing the asphalt from the aggregate surface."*. Many other researchers also concur with this line of thought (4, 21, 22, 23, 24, 25, 26). Resistance to stripping is of major importance in selecting bituminous mixture ingredients. Compatability of mixture ingredients to reduce stripping is essential also.

Curtis et al. (27) state; *"Asphalt-aggregate interactions are important to the adhesion of asphalt to aggregate because the initial first layers of asphalt must stick well for the adhesive binding action of asphalt to occur."*. To illustrate the importance of this bond, they provide a descriptive statement to help in visualising the complexities of the interactions between aggregate and binder. This statement can be summarised with the following points.

(i) The weight ratio of binder to aggregate in a mixture is typically five to six per cent binder and 94 to 95 per cent aggregate, so that the weight of the aggregate as well as its density is far greater than the binder.

(ii) Aggregate is present in a multiplicity of sizes from the large 20mm fraction to the fines that are in the <75μm range.

(iii) Aggregates used for road pavements are often obtained from local sources and vary widely in terms of composition, surface chemistry and morphology, including surface area, pore size distribution and friability.

(iv) When bitumen contacts aggregate, it interacts with a multiplicity of active and inactive sites for bonding. Some of the bitumen contacts extremely small particles that are so small that it is easier to visualise these particles as an extended portion of the bitumen rather than as aggregates themselves. The medium and larger particles are also coated, forming the strong skeleton of the mixture.

(v) The bitumen directly contacting the aggregate is important because that bitumen must adhere and remain adhered under different environmental conditions. Climatic and environmental conditions to which the pavement is exposed include; the heat and sunlight of the day, the cooling of the night, the rain, snow, ice and freeze thaw cycling of the seasons, the vibration and stress of traffic, the penetration of air, the seepage of environmentally contaminated water, and the leaching of organics from the bitumen by that water. These all effect the localised environment of the aggregate-bitumen bond.

With a clearer picture of the role of the aggregate-bitumen bond it can be seen that this bond is of the utmost importance to the performance of the bituminous mixture.

It is therefore imperative that the affinity between coated aggregate and bitumen is investigated fully.

2.2.2 Types of Aggregate-bitumen Affinity tests

Current testing practices for assessing the potential of aggregate-bitumen bonding and the susceptibility of the pairing to water damage, use variations of the following basic methods.

The European community primarily uses variations of the Rolling Bottle Test (25). In this test a large (10-15mm) stone is coated with bitumen and placed in an Erlenmeyer (conical) flask. The sample is covered with water, a stirring rod is added to provide tumbling action, and the flask is rotated, usually for a period of 24 hours. The amount of bitumen remaining on the stone after the treatment is evaluated visually.

In the USA, three tests predominate. The first is the Boiling Water Test (28). In this test an aggregate-bitumen mixture approximating the formulation used in road paving is placed in boiling water, usually for about ten minutes. The mixture is then taken out of the water and allowed to dry. The amount of bitumen remaining on the aggregate is then evaluated visually.

The other two widely used methods in the USA, incorporate accelerated conditioning procedures into the test method prior to determining mixture properties such as tensile strength and resilient modulus, before and after the conditioning. The tensile strength and resilient modulus results are used to calculate an index of retained strength. The two methods are known as the Root-Tunnicliff and Lottman procedures (25). The primary difference in the two methods being the degree of water saturation applied before conditioning. Both of these methods generate a measurement of mixture properties, rather than requiring visual examination, but there is no general agreement as to the correlation of test results with pavement performance. Variations of these two tests are now being used in Europe also.

A new research programme in the USA, the Strategic Highways Research Program (SHRP), produced a principal report (4) entitled, Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Adsorption.

One of the products of this programme was to develop a rapid and reliable test for measuring the compatibility and water sensitivity of aggregate-bitumen pairs. This test is called the Net Adsorption Test and is composed of two steps. First, bitumen is adsorbed onto the aggregate from a toluene solution, then the amount of bitumen remaining in solution is measured, and the amount of bitumen adsorbed to the aggregate is determined. Second, water is introduced into the system, bitumen is desorbed from the aggregate surface, the bitumen present in the solution is measured, and the amount remaining on the aggregate is calculated. The amount of bitumen remaining on the surface after the desorption step is termed net adsorption. The Net Adsorption Test serves as a means of screening aggregate-bitumen pairs to determine their affinity for one another and their ability to resist the detrimental effects of water. The stripping behaviour of aggregates, as described by the practitioners from their areas of origin, was well represented by the results obtained from the Net Adsorption Test.

The Researcher considers the Net Adsorption Test and the results generated by this test, as the most efficient, rapid and reliable, for application in this study.

2.2.3 Properties of Aggregate Considered most Beneficial for Successful Chemical Affinity with Bitumen

The many causes, mechanisms and models of aggregate-bitumen affinity and resistance to stripping, can be grouped into three categories; (a) the surface energy concept, (b) the mechanical concept, and (c) the chemical reaction concept.

The surface energy concept (a) approaches adhesion of the aggregate-bitumen system through interfacial energy relationships. Curtis et al. (4) state that; "*surface tension values are expressions of surface energy. The existence of the asphalt bond is explained by the relative magnitudes of the surface tension and interfacial tension. Interfacial tension is a measure of the attraction of the two phases, or adhesivity. Surface tension is a measure of the solid or liquid to itself, or cohesivity. Thus , the optimum bond occurs when there exists low surface tensions on both components and a relatively high interfacial tension.*".

The mechanical theory (b) explains the aggregate-bitumen bond through surface texture and related physical properties. Curtis et al. (4) state; *"A rough surface presents more opportunity for a second bond because of greater surface area per unit volume of aggregate. After the binder penetrates the surface voids of the aggregate, cohesive attraction within the asphalt provides an interlocking network and, consequently, a firm bond.*

The chemical concept (c) arises from the presence of reactive components (both acidic and basic (alkalinic)) in the aggregate-bitumen system. Curtis et al. (4) state; *"These components are termed radicals and exist chiefly in the form of dipoles,* (Particles oppositely charged at two points, a magnet for example), *This concept holds that the asphalt-aggregate bond results from the reaction of these components with one another to form compounds. Stripping sometimes occurs when these compounds are water soluble.*

Based on these descriptions of the three phenomena, it is evident that in reality all three theories contribute to the composite bond strength of the aggregate-bitumen bond.

Table 2.3 shows some Net Adsorption Test results taken from the SHRP. The results are expressed in milligrams of bitumen adsorbed from solution onto each gram of aggregate. The results are the average adsorption of three widely varying types of bitumen, therefore demonstrating the effect of the aggregate in the system, rather than the effect of the bitumen.

The RC-Limestone and the RK-Basalt are clearly ranked the top performers, Their net adsorption values being roughly twice the quantity of the RH-Greywacke and the RL-Gravel, when testing with aged and unaged bitumens.

Table 2.3 Adsorption, Desorption and Net Adsorption Behaviour of Three Bitumens on USA Materials Reference Library (MRL) Aggregates (ref. 4)

Aggregate	Adsorption (mg/g)	Desorption (mg/g)	Net Adsorption (mg/g)
		Unaged	
RC-Limestone	5.427	1.486	3.941
RK-Basalt	5.037	1.232	3.805
RH-Greywacke	2.045	0.362	1.683
RL-Gravel	1.325	0.233	1.092
		Aged	
RC-Limestone	4.651	1.416	3.236
RK-Basalt	4.35	1.171	3.179
RH-Greywacke	2.249	0.392	1.857
RL-Gravel	2.594	0.891	1.703

Table 2.4 shows some of the compositional properties of the experimental aggregates. CaO (calcium oxide or quicklime, although not present in that exact form), content, is a good measure of the basic (alkalinic) nature of an aggregate. SiO_2 (silicone dioxide) content gives a good measure of the siliceous (acidic) nature of an aggregate. Many researchers (15, 23, 29, 30, 31) support the theory that a large surface area and basic nature are very beneficial for a successful aggregate-bitumen bond, and that a siliceous nature is not always conducive to a successful bond. The shaded area of table 2.4 demonstrates this, by ranking the aggregates anticipated performance, by means of a relative affinity score, in a similar manner to the actual performance found by experimentation, shown in table 2.3. The top two performers, by a factor of greater than two, in both tables, are the RC-Limestone and the RK-Basalt. Both of these aggregates display a high surface area and / or a basic (alkalinic) nature.

Table 2.4 MRL Aggregate Properties (ref. 4)

Aggregate Type	Surface Area of Aggregate (m^2/g)	CaO Content (%)	SiO_2 Content (%)	Relative Affinity Score (Area x CaO / SiO_2)
RC-Limestone	1.78	48.9	6.49	13.41
RK-Basalt	17.4	10.3	50.1	3.58
RH-Greywacke	3.12	2.35	66	0.11
RL-Gravel	0.93	14.5	63.1	0.21

2.2.4 Why Cement Paste Exhibits Properties Considered Beneficial for Chemical Affinity with Aggregate

Monteiro et al. (32), provide a table of chemical properties of a typical OPC. This table, table 2.5, shows that cement has compositional chemical properties considered ideal by many researchers (16, 23, 29, 30, 31), as detailed earlier. The table also shows, in the calculated compound composition section, that all the compounds found in OPC paste are compounds of calcium which will further enhance the affinity of cement paste with bitumen.

Plates 2.1 and 2.2 show examples of hardened cement paste surface microstructure. It can be seen that various forms of the compounds detailed in table 2.5 grow to form crystalline structures during the hydration process. The two principal compounds are usually Calcium hydroxide and Ettringite, described by reference (33). These structures are also known to continue growing with time, further increasing the microsurface area. Other researchers concur with these finding, see references (32, 33, 34, 35, 36).

The crystalline microstructure serves to provide a very large surface area for the bitumen to adhere to. This is beneficial for adhesion as described by the mechanical theory, Curtis et al. (4), described in section 2.2.3 of this thesis.

Table 2.5 Typical Chemical Properties of Cement and Cement Paste. (ref. 32)

Chemical Analysis of Cement	
Compound	Percentage Present
Silicon dioxide, SiO_2	21
Aluminium oxide, Al_2O_3	4.6
Ferric oxide, Fe_2O_3	3
Calcium oxide, CaO	64.1
Magnesium oxide, MgO	2.4
Sulphur trioxide, SO_3	2.7
Sodium oxide, Na_2O	0.4
Potassium oxide, K_2O	0.2
Ignition loss	1.5
Calculated Compound Composition of Cement Paste	
Compound	Percentage Present
Tricalcium Silicate, C_3S	58.46
Dicalcium Silicate, C_2S	16.11
Tricalcium Aluminate, C_3A	7.11
Tetracalcium Aluminoferrite, C_4AF	9.13
Calcium Sulphate, $CaSO_4$	4.59

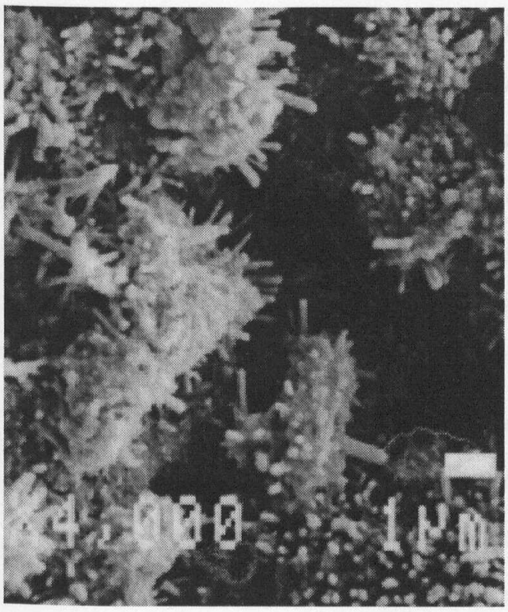


Plate 2.1 Ettringite Strands at 28 Days of Age

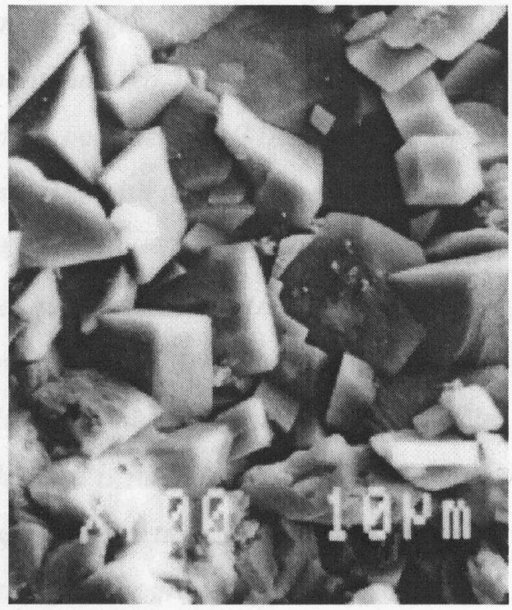


Plate 2.2 Calcium Hydroxide Crystals at 28 Days of Age

2.3 The Mechanical Properties of Aggregate and their Contribution to the Strength of Bituminous Materials

2.3.1 Properties of Established Aggregates

Wedding et al. (37) state; *"It has long been realised that angular coarse aggregates tend to produce more stable bituminous mixtures than mineralogically similar rounded course aggregates. A common provision in many state highway specifications is the requirement that gravel, when used as a coarse aggregate in an asphaltic concrete, must be crushed. One hundred per cent crushed particles in the coarse fraction is not an unusual requirement."*.

Herrin et al. (11) state; *"Since the early days of modern bituminous paving, highway engineers have noted that the shape of the mineral aggregate affects the strength of bituminous-aggregate mixtures in which it is used. It was noted that sharply angular and roughly textured aggregates generally produced bituminous mixes with more stability than round smooth faced materials."*.

Kandhal et al. (13) state; *Fractured face count of aggregate when natural gravel is used as coarse aggregate and the use of manufactured fine sand are considered important to minimise rutting in hot mix asphalt pavements (HMA). Many highway agencies specify a minimum percentage of particles with two or more crushed faces when using gravel coarse aggregate in HMA mixtures. This percentage generally varies from 40 to 100 per cent. There is a need to correlate the fractured face count with the index of particle shape and texture of the coarse aggregate. It is also necessary to determine if there is an upper limit on the percentage of the particles with two or more faces crushed, above which there is no significant increase in the particle shape and texture index of coarse aggregate fraction. The latter is needed to achieve economy as the cost of increased crushing of the gravel can be high.*

Woodside (38) states; *"Resistance to deformation at "long term" loading conditions is dependant on both interparticle and binder friction. Interparticle friction is dependant on the roughness of the surfaces of the particles and the intergranular contact pressure; it is lowered if too much binder is present and the particles are kept apart."*.

The above statements underline the importance of particle shape and texture to aggregate-bitumen mixture stability. Tests such as the Particle Shape and Texture Index (13) and the Flakiness Index, BS 812: Section 105.1 (39), become important because of their ability to describe the angularity of an aggregate.

Herrin et al. (11) used the triaxial-compression test method to provide a very fundamental analysis of the factors that contribute to the stability of aggregate-bitumen mixtures. The data resulting from the tests were analysed in terms of basic properties of the cohesive granular mixture according to Mohr's theory of strength. Basically Mohr's theory of failure recognises two contributing factors to the resistance of aggregate-bitumen mixtures to compressive loads. These are termed internal friction (ϕ) and cohesion (c). The former is made up of frictional resistance to sliding due to interlocking of the mineral aggregate. The cohesion, though, is resistance to shear contributed by the binding material. These two factors are evaluated as the slope and vertical axis intercept, respectively, of a linear Mohr's rupture envelope. This envelope usually is obtained graphically by drawing a line tangent to different Mohr's circles of rupture which use the triaxial-compression data, (maximum compression strength and corresponding confining pressure).

The fraction of fine aggregate used when testing was kept very small, (just 5%), so that only the change in behaviour caused by the various coarse aggregate blends would be displayed. The Binder content was also kept constant for all mixtures. The experiment was very well designed and clearly shows an improvement in the aggregate's angle of internal friction with an increase in the proportion of crushed particles in the blend.

Table 2.6 Partial Results of Herrin et al. (ref. 11)

Proportion of Crushed Gravel, Remainder Manufactured Smooth Gravel	Average Density	Average Compressive Strength		Angle of Internal friction	Cohesion
		Confining Pressure 15 psi	Confining Pressure 30 psi		
	(pcf)	(psi)	(psi)	(degrees)	(psi)
0% Crushed	113.6	39.1	74.3	23.7	1.3
55% Crushed	110.5	49.3	90.5	27.8	2.4
70% Crushed	110.6	51.3	97.2	30.5	1.5
100% Crushed	110.1	58.7	108.7	32.6	2.4

Various other mechanical properties of aggregate are tested. These tests are usually performed in order to match the various aggregates with the most suitable application. The most common tests are usually variations of the following; (a) the aggregate impact value test, (b) the aggregate crushing value test, and (c) the polished stone value test.

The aggregate impact value (AIV) test (a) gives a relative measure of the resistance of an aggregate to sudden shock or impact, reference (40).

The aggregate crushing value (ACV) test (b) provides a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load, which in some aggregates differs from its resistance to a shock or impact load, reference (41).

The polished stone value test (PSV) (c) gives a measure of the the resistance of roadstone to the polishing action of a pneumatic tyre under conditions similar to those occuring on the surface of a road. Where the surface of a road consists largely of roadstone, (i.e. in a surfacing without additional rolled in chippings), the state of polish of the sample will be one of the major factors affecting the resistance of the surface to skidding, reference (42).

These three tests can be used to place an aggregate in the most suitable layer of a flexible pavement, for example; an aggregate with a good ACV, but with poor AIV and PSV, would not be suitable as a surface dressing or wearing course, but could be successfully used as a road base or regulating course.

2.3.2 Evidence of Improvement in Mechanical Properties When Cement Coating is Applied to Aggregates

The only substantial evidence for supporting the theory that cement coating may improve aggregate shape and macro-surface texture, is that provided by Guirguis et al. (17) in table 2.1 and 2.2 of this thesis.

The tables show that both voids and stability of the cement-treated mixtures increase with the degree of cement coating. Specimens made with increasing percentages of cement coating are respectively 10, 35 and 58 per cent higher in voids and 4, 9 and 24 per cent higher in stability than mixtures made with untreated aggregates, VMA Values also increase with the amount of coating. Guirguis et al. state; *"The higher void content obviously indicates a reduction in compactability of these mixes and is expected consequently to result in lower stabilities. However, it seems that the gain in mix stability due to enhancement of aggregate texture, (by precoating with* *cement), is more than the loss due to the lower density and higher voids of the resulting less-compactable mix."*.

After a very comprehensive search, no documentation of ACV, AIV, or PSV results for cement coated aggregates was found. The Kuwaiti experience with coated aggregate was limited to asphaltic concrete type mixtures where the binder and filler rather than the larger aggregates support the mixture. The Kuwaiti engineers pleased with the end result therefore, must not have appreciated the need to test these individual aggregate properties.

CHAPTER 3

Selection of Aggregate and Design of Cement Coating for Experimentation

3.1 Selection of Aggregates

Aggregates were selected on the basis that they would be model examples of what are considered to be very poor and very good performers for bituminous mixtures. This is based on the foundational chemical and mechanical principles detailed in sections 2.2.3 and 2.3.1 of this thesis.

Aggregates were chosen from the wide range of products available from Tarmac Quarry Products Ltd.

The model poor aggregate chosen was Croxden Gravel. This aggregate is a highly rounded, polished material taken from an ancient river bed environment. Most of the polished particles are of a quartz type material, the remainder being from a similar igneous or metamorphic origin. The mechanical surface characteristics and chemical analysis of Croxden Gravel are both considered poor for bituminous mixtures. Croxden Gravel usually finds application in the UK for concrete, especially for exposed aggregate finish concrete because of its pleasing appearance. The Chemical analysis and measured mechanical properties are detailed in tables 3.1 and 3.2 respectively.

The model good performer chosen was Arcow. Arcow is an aggregate currently used successfully as a high quality road aggregate. Arcow is quarried from a mountain in Yorkshire and is composed of dark grey relatively fine grained mudstone. It is hard and angular and does not have an unduly high siliceous material content. The

Chemical analysis and measured mechanical properties are detailed in tables 3.1 and 3.2 respectively.

Table 3.1 Chemical Analysis of Croxden and Arcow Aggregates

Determinand	Symbol	Aggregate Type	
		Croxden	Arcow
Silica	(SiO_2)	95.2	61.5
Titania	(TiO_2)	0.16	0.63
Alumina	(Al_2O_3)	2.27	12.5
Ferric oxide	(Fe_2O_3)	0.63	5
Lime	(CaO)	0.04	4.81
Magnesia	(MgO)	0.09	3.53
Potash	(K_2O)	0.98	2.65
Soda	(Na_2O)	<0.03	1.26
Phosphorus pentoxide	(P_2O_5)	0.02	0.14
Zirconia	(ZrO_2)	0.03	0
Barium oxide	(BaO)	0.02	0
Manganese oxide	(MnO)	0	0.07
Loss on Ignition at 1025°C		0.52	6.9
Total		99.96	98.99

It can be seen in table 3.1 that Croxden Gravel is composed almost entirely, (95.2%), of siliceous material. This indicates that chemically it is very unlikely to bond with bitumen. Its appearance, plate 3.1, displays a smooth polished surface with very few quality bonding sites available for bitumen, except where some of the particles are fractured.

Table 3.1 shows that Arcow is composed of significantly less siliceous materials, (61.5%), than Croxden Gravel, showing its chemical affinity with bitumen would be significant. Its appearance, plate 3.2, displays a rough angular surface composed entirely of high surface area sites suitable for bonding with bitumen.

Table 3.2 Mechanical Properties of Croxden and Arcow Aggregates

	Aggregate Type	
	Croxden	Arcow
Property Tested	Result	
Particle Density (OD)	2.63	2.72
Particle Density (SSD)	2.61	2.73
Water Adsorption (% by weight)	0.9	0.6
Aggregate Crushing Value (ACV)	11	10
Aggregate Impact Value (AIV) dry	15	10
Aggregate Impact Value (AIV) soaked	-	12
10% Fines Value (TFV) dry	380	390
10% Fines Value (TFV) soaked	-	330
Polished Stone Value (PSV)	-	63
Aggregate Abrasion Value (AAV)	1.2	6.1
Water Soluble Chloride (% Cl)	0	<0.01
Water Soluble Sulphate (g/l SO_3)	0.01	<0.1
Acid Soluble Sulphate (% SO_3)	0.01	0.04
Magnesium Sulphate Soundness Value	98	100

Croxden and Arcow although very different in their surface characteristics and ability to form successful bituminous mixtures, share very similar mechanical characteristics (table 3.2). This is another important reason for choosing these two aggregates in this study. When they are tested with the addition of a cement coating, the effect of the cement coating on the surface characteristics and the ability of the coating to produce a successful bituminous road material, alone is tested. The aggregate's other mechanical properties should not affect the result. Table 3.2 shows the most commonly measured mechanical properties of aggregate, however the values of AIV soaked, TFV soaked and PSV for the Croxden are not shown. This is because these properties are not normally obtained for aggregates such as Croxden used solely in concrete.

Plate 3.1 Croxden

Plate 3.2 Arcow

3.2 Design of Cement Coating

3.2.1 Choice of Cement Coating Type and Amount

There is a wide range of cement types available. These include Ordinary Portland Cement (OPC), Rapid Hardening Portland Cement (RHPC), Low Heat Portland Cement (LHPC), Sulphate Resisting Portland Cement (SRPC), and High Alumina Cement (HAC). There are also various proprietary cement blends suitable for high temperature applications usually known as boiler or furnace cements.

OPC, RHPC and LHPC are all of the same composition, the difference in performance is achieved by the relative fineness of grinding of each cement, the finer the grinding the faster the cement sets. LHPC sets the slowest because of its course grinding, and because the chemical reaction of setting is slow, the amount of heat produced in the chemical reaction, termed heat of hydration, is correspondingly low. RHPC has the finest grinding and sets the fastest of the three cements. OPC falls somewhere in the middle.

SRPC and HAC are cements with altered compositions. SRPC is designed to resist the detrimental effects of the ingress of ground water with dissolved sulphates into the body of concrete. HAC is designed to produce concrete with a very high early age strength, i.e. 95% of the ultimate strength at one day as opposed to 28 days for Portland cement concretes.

Boiler or furnace cements are generally a blend of Portland cement with a proportion of fine aggregate and additives to combat the effects of expansion and contraction associated with high temperature applications. Generally these are only available in small batches at a high price, and are definitely not economically feasible for the large quantities required for road use, unless formulations were made available. This type of cement does appear though, to be ideal for coating aggregates for bituminous mixtures made at high temperatures, i.e. not emulsion mixtures. Recommendations for further research into this material will be made in chapter ten.

SRPC will exhibit slower strength gain than most of the other Portland cements and is also more expensive, therefore it will not be considered for this study.

HAC suffers from a phenomenon often referred to as "concrete cancer". In this condition certain strong compounds are converted into weaker structures in warm moist conditions. HAC concrete is usually only used for dry indoor applications, and would not be at all suitable for road use.

OPC appears to be the most suitable cement type for the coating application because it is relatively cheap, available in large quality controlled batches, and because of its previous use in bituminous mixtures, will be in some way predictable in its behaviour.

The amount of cement coating required was determined by applying various percentages of cement paste, by weight of aggregate, to the aggregate until full coverage was adjudged visually. An arbitrary Water/Cement (W/C) ratio of 0.4 for the cement paste was chosen for this. Iterative procedures to reassess the amount of coating after determination of optimum W/C ratio were anticipated. However after tests to determine optimum W/C ratio detailed later, the optimum ratio was found to be 0.4 and therefore the iteration process was unnecessary. Table 3.3 below shows the findings. Results were obtained by manually measuring the surface area covered by cement paste for Croxden and Arcow aggregates. The measurements were not exact, and therefore the coverage was approximately equal for the two aggregates tested.

Table 3.3 Determination of Optimum Amount of Cement Paste

Cement Paste by weight of aggregate (%)	Coverage (%)
4	30
6	55
8	80
10	100

Following this test, 10 per cent by weight of the aggregate cement coating was used for all applications.

3.2.2 Determination of Optimum W/C Ratio for the Cement Coating

Optimum W/C ratio was adjudged to be "that water cement ratio producing the strongest bond between the aggregate and the cement coating". There are three main types of test for measuring this bond strength. They are;

(i) Tests where the bond is evaluated qualitatively using such methods as X-ray Diffraction, Scanning Electron Microscopy or Electrical Conductivity.

(ii) Tests involving splitting of cement paste from a large piece of cut aggregate.

(iii) Destructive compression or tensile tests using concrete made from the sampled aggregate and cement paste.

The first kind of tests (i) such as those found in previous studies (33, 34, 35, 36, 43) do not give an actual physical value for the strength of the bond between the cement paste and the aggregate. However, based on the evidence of crystalline growth with cement hydration at the cement paste/aggregate interface, the quality of the bond is assessed. These tests are usually used to demonstrate why an unexplained increase in measured physical strength has occurred. These tests are not considered acceptable for determining optimum W/C ratio because tests yielding enumerated physical results are much more desirable.

Type (ii) tests, the splitting tests detailed in references (44, 45), involve splitting a portion of cement paste from a cut piece of aggregate to which it is cast, by driving a calibrated wedge into a starter notch at the interface between the two materials (see figure 3.1). The result is expressed as the tensile force required to debond the cement paste and the aggregate to form a massive crack, resulting in the total separation of the two materials, i.e. failure. This test is probably the most fundamental and accurate for measuring the cement paste/aggregate bond. However, because the aggregate sample is cut and dressed, a measurement of bond strength between a modified aggregate surface and the cement paste is recorded, not the bond strength between a typical piece of aggregate and its cement coating. Also this test cannot be conducted on gravels because samples large enough to cut and dress are not available. These tests are therefore only suitable for quarried aggregates.

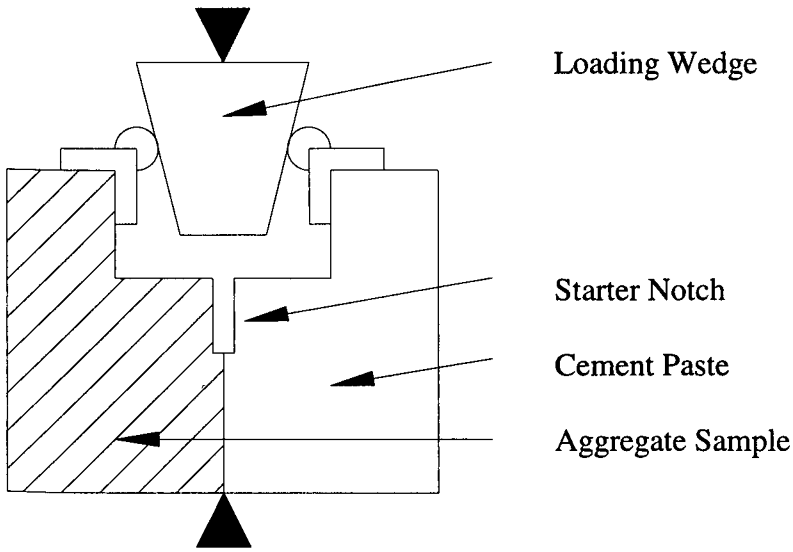


Figure 3.1 Typical Splitting Arrangement

Type (iii) tests use compressive or tensile force (more usually compressive) to test a concrete sample made from the aggregates and the cement pastes being studied. The results produced by this test give a strength for the composite tested and not the strength of the cement paste/aggregate bond. However, the strength of the composite, and the strength of the cement paste/aggregate bond within the composite, are directly related (32). Therefore, although a measure of bond strength is not obtained from these tests, for comparative testing to differentiate between the bond strengths formed by cement pastes of different W/C ratios, these tests are ideal. This type of test is the easiest test to conduct because standard concrete sample moulds can be utilised for making the test specimens, and standard compression machines can be used for testing them.

A compression test of type (iii) was considered as the most suitable for determining the optimum W/C ratio for the cement paste.

Because this research is not concerned with cement paste/aggregate bond within a normal concrete, but is concerned with a thin shell coating, it was considered incorrect to design a normal concrete cube that included fine aggregate as this would then include the effects of the fine aggregate chosen. This could give misleading results. It was also thought that designing a concrete cube with coarse aggregate only, but with sufficient cement paste to fill all the voids, was also misguided. This was because this would produce results dependent on the strength of the mass cement paste, which can be stronger than the aggregate itself. This type of cube would not demonstrate the strength of the cement paste/aggregate bond itself.

It was considered therefore that the most representative cubes could be made by producing no-fines, or porous concrete with course aggregate and cement paste only. The cement paste being of the same quantity as used for the final coating, namely 10 per cent by weight of the aggregate.

The sample cubes were made accordingly in standard 100mm x 100mm x 100mm moulds.

The cubes were manufactured to BS 1881: Part 113: 1983, Method for making and curing no-fines test cubes) (46).

The Aggregate grading used was the BS4987: Part 1: 1993 (47) grading for porous asphalt, using those fractions retained on a 3.35mm sieve and above. This was to match the gradings used in the testing of porous asphalt samples detailed later in chapter seven. The ingredient design and final ingredient proportions for the cubes are shown in appendix A.

The concrete samples were cured in water tanks at a temperature of 20°C for 28 days before being removed for compression testing.

The results of the compression tests are shown in figures 3.2 and 3.3 for Croxden Gravel and Arcow respectively. Six specimens were tested to give each average shown on the figures. The figures also show the standard deviation for each shown on the figures. The figures also show the standard deviation for each specimen group average. This is depicted as the vertical line with upper and lower limits shown as small horizontal bars.

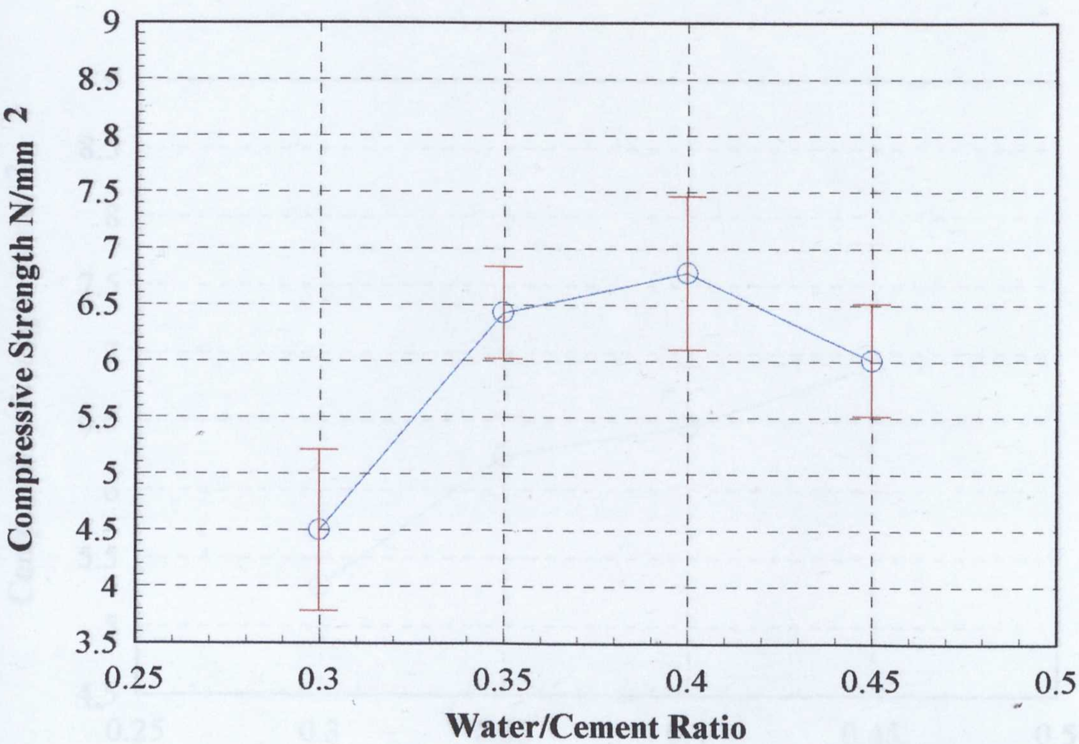


Figure 3.2 Croxden Gravel Porous Concrete for Determination of Cement Paste W/C Ratio.

Results for the Croxden gravel (figure 3.2) clearly show that the optimum W/C ratio is 0.4. The coating at 0.4 W/C ratio was also ranked highest on visual inspection, being the most homogeneous, and uniform in cover thickness. 0.4 W/C ratio coating was therefore chosen for all Croxden coating.

Results for Arcow (figure 3.3) show that in terms of average value for each set, a W/C ratio of 0.45 is the strongest. However the standard deviation for the 0.45 W/C ratio is very large. A statistical student T test shows that the average results for the W/C ratios of 0.4 and 0.45 are not significantly different. On visual inspection of the coated aggregates the 0.45 W/C ratio coating appeared non uniform, being very thin or missing on the upper surfaces of the aggregates and very thick at the bottom surfaces due to the high water content. This may explain the anomalous standard deviation of the 0.45 result. The 0.4 W/C ratio coating appeared the most uniform in thickness and most homogeneous of the four W/C ratios tested. Therefore a W/C ratio 0.4 was used for all coating of Arcow aggregate.

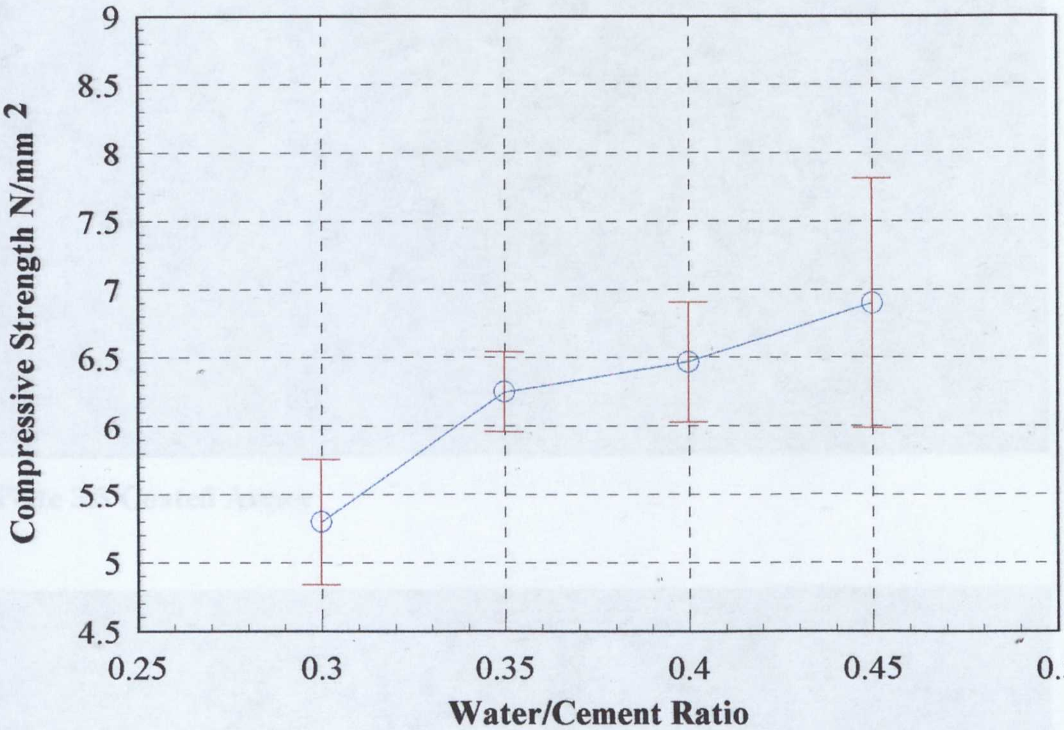


Figure 3.3 Arcow Porous Concrete for Determination of Cement Paste W/C Ratio.

Photographs of coated Croxden and coated Arcow can be seen on the following page.

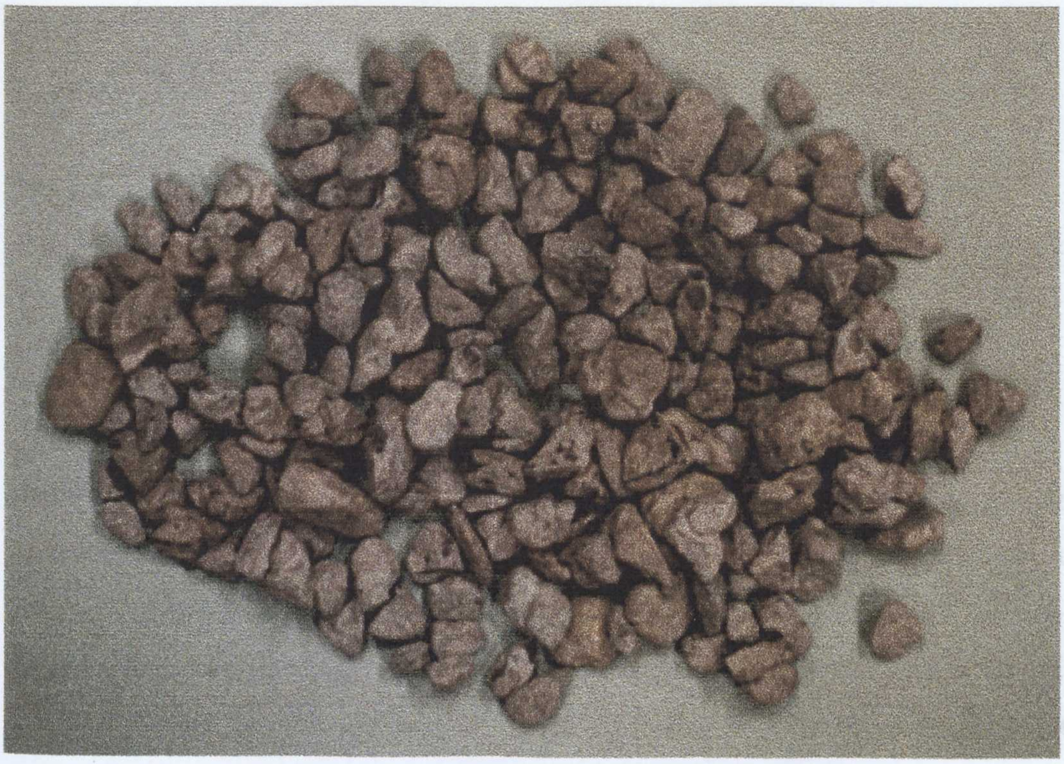


Plate 3.3 Coated Arcow

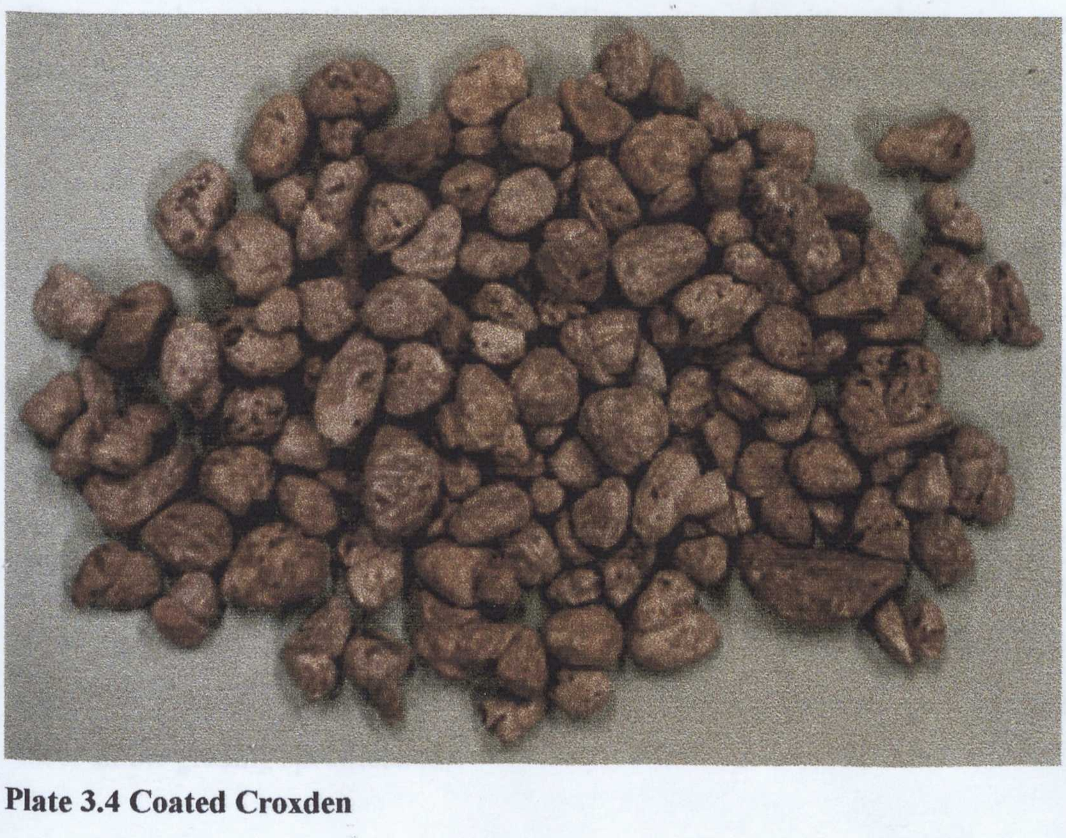


Plate 3.4 Coated Croxden

CHAPTER 4

Chemical Testing of Coated Aggregates

4.1 Introduction

Uncoated aggregates were compared with coated aggregates and the coating material to determine whether or not the coating could provide an improved affinity with bitumen. The test used was the Net Adsorption test detailed in chapter 2, section 2.2 developed in the USA for the SHRP. The test method adopted was a simplified procedure used by the University of Ulster for testing in references (48, 49). Details of this method are found in section 4.4 of this thesis.

The research work at the University of Ulster showed, with various size graded materials, that particle size affects the magnitude of the net adsorption observed. Net adsorption tests are therefore performed on two distinct aggregate sample types. The first type (A) is a graded sample shown in table 4.1. This is the same as the graded sample used at the University of Ulster. Results obtained from this graded material fell around the mean value obtained for individual size fractions ranging from 5.00 - 2.36mm to <75μm, obtained in an investigation by Woodside et al. (48, 49). The graded aggregate sample was expected to produce results largely representative of the finer material making up a bituminous road material. Samples of Croxden, Arcow and crushed cement paste coating material made with 0.4 W/C ratio, were produced. The cement paste sample was made by crushing solid cement paste cubes, at 28 days of age, to produce sufficient fines for the sample. Crushed cement paste was used because aggregate could not be coated in size fractions small enough to meet all the grading specifications.

The second sample type tested, type (B), was composed of a single size fraction, (5.00 - 2.36mm). Croxden and Arcow were sieved as before. However, coated

Croxden and coated Arcow were used in place of the crushed cement paste. The size fraction 5.00 - 2.36mm is the smallest size fraction that can be coated, and the largest size fraction considered safe for use in the rotating flasks. Larger sizes could damage the glassware during high speed agitation. The 5.00 - 2.36mm size fraction was therefore chosen to represent the larger aggregate particles in a bituminous road material, i.e. 20 - 2.36mm, during testing for the affinity between aggregate and bitumen

Table 4.1 Grading for Type A Sample

Sieve Size (mm)	% Retained	Mass of Aggregate (g)
5.00 - 2.36	8.3	4.15
2.36 - 1.18	25	12.5
1.18 - 0.60	16.7	8.35
0.60 - 0.30	23.9	11.95
0.30 - 0.15	13.3	6.65
0.15 - 0.075	6.1	3.05
<0.075	6.7	3.35
Total	100	50

4.2 Testing Apparatus

The testing apparatus consisted of the following items:

(i) Rotating table apparatus - capable of holding six Erlenmeyer flasks.

(ii) Spectrophotometer - Hewlett Packard 8452A, Diode Array Spectrophotometer capable of providing a continuous wavelength range from 300 - 500nm with an accuracy of ±2nm and precision of not more than 0.5nm. The photometric precision should not be more than 0.2%. The apparatus should be capable of receiving standard 10mm path-length cuvettes and be capable of measuring adsorbance between 0.000 and 1.999.

(iii) Spectrophotometer cuvettes - these should have a capacity of 4.5ml with a 10mm pathlength and suitable optical characteristics for measurement of wavelengths from 375 - 410nm, (quartz cuvettes were used, as plastic ones dissolve).

(iv) Six Erlenmeyer flasks per test - 500ml capacity, wide mouthed with neoprene rubber stoppers.

(v) Erlenmeyer or volumetric flask - 1000ml capacity.

(vi) Six volumetric flasks per test - 25ml capacity, Class A.

(vii) Funnel - 75mm diameter with ring stand and clamps.

(viii) Filter paper - Whatman No.42, 125mm diameter.

(ix) Graduated glass cylinder - 250ml capacity.

(x) Pipettes - 1-10ml capacity.

(xi) Magnetic stirrer and stir ball - of sufficient size to stir the binder in toluene solution.

(xii) Analytical balance - Sensitivity of ±0.001g.

(xiii) Oven for drying Aggregates - capable of maintaining 135°C.

All of the above apparatus met the specifications and was supplied by the School of Pharmacy and Chemistry, LJMU.

4.3 Test Reagents and Aggregate Preparation

4.3.1 Reagents

(i) Bitumen - Lanfina 100 penetration grade, refined from Mexican crude oil.

(ii) Water - distilled or deionised water.

(iii) Toluene - Spectrophotometry, (HPLC) grade.

4.3.2 Aggregate Preparation

(i) Obtain a 50g sample of aggregate of the desired grading.

(ii) Dry uncovered in a 135°C, (275°F) oven overnight.

(iii) Remove aggregate from oven 15 minutes prior to testing.

(iv) **Extreme caution** should be used to avoid adding warm aggregate to the stock solution as toluene has a low flash point.

4.4 Summary of the Test Method for the Net Adsorption Test.

(i) Prepare a stock solution by adding 1g of bitumen (to the nearest 0.001g) to 1000ml of toluene, using a magnetic stirrer to ensure total mixing.

(ii) Take 4ml of stock solution using a pipette and transfer to a 25ml graduated or volumetric flask. Dilute to 25ml with fresh toluene. After passing through a clean filter paper, place a suitable amount in a non plastic cuvette and determine the adsorbence of light at a wavelength of 410nm using the spectrophotometer. This is recorded as value A1, (the reading for the calculation of initial concentration of bitumen in toluene).

(iii) Add 140ml of stock solution into each of six 500ml Erlenmeyer flasks.

(iv) Add 50g of aggregate sample to five of the flasks. The sixth flask has no aggregate and is used as a control.

(v) Ensure that the lids of the flasks are secure and are of a type not affected by the toluene.

(vi) Anchor each flask on the rotating apparatus.

(vii) Rotate the table at 200rpm for 6.5 hours.

(viii) At the end of this time remove 4ml of solution from each flask and dilute to 25ml in a graduated or volumetric flask, filter each sample to remove any suspended material and transfer to cuvettes.

(ix) Determine adsorbence. This reading should be recorded as A2, (the reading used for determining the concentration of bitumen in toluene after the initial adsorption of bitumen onto the aggregate).

(x) Add 2ml of water to each flask and resume rotation. After 18 hours remove 4ml of solution, dilute to 25ml, filter and determine adsorbance. This reading should be recorded as A3, (the reading used for determining the concentration of bitumen in toluene after the desorption of bitumen from the aggregate).

4.5 Expression of Results

Results can be expressed by two main methods, the original SHRP method and the University of Ulster Jordanstown, (UUJ) method.

In simple terms the original SHRP method expresses the initial adsorption as the amount of bitumen adsorbed from solution to the aggregate. The desorption is expressed as the amount of bitumen desorbed from the aggregate to solution. The net adsorption is taken as the amount of bitumen remaining on the aggregate after the desorption stage, and is expressed as a percentage of the initial adsorption. This method of expressing results can be very misleading because by this method, aggregates that display a high net adsorption could actually have less retained bitumen than other aggregates described as having low net adsorption. This method, when used without considerable experience, can be very misleading when attempting to rank aggregate performance. Woodside et al. (49) state, *"the SHRP method does not relate the values obtained to the optimum value that could be attained. Rather it merely relates the initial and net adsorption values to each other."*.

The UUJ method expresses initial adsorption, desorption and net adsorption as a percentage of a theoretical maximum adsorbence, i.e. when all the bitumen has been adsorbed from solution onto the aggregate. Using the UUJ method aggregates can be easily ranked. The UUJ method of expression will be used for all results shown in this study.

4.6 Calculation Methods

Some of the SHRP calculations are necessary before the final expression of results by the UUJ method. The SHRP calculations are therefore shown with the UUJ ones. The SHRP calculations also serve to highlight the difference between the original SHRP and UUJ methods of expressing the results.

Initial Adsorption (AiSHRP) - The amount of bitumen initially adsorbed onto the aggregate surface.

$$AiSHRP = VC\,(A1 - A2)\,/\,WA1 = Ai$$

Net Adsorption (AnSHRP) - The amount of bitumen remaining on the aggregate after water has been added.

$$AnSHRP = VrC\,(A1 - A3)\,/\,WA1 = An$$

% Net Adsorption (%AnSHRP) - The percentage of bitumen remaining on the aggregate after the test. This is the method the SHRP uses to rank aggregate/bitumen affinities.

$$\%AnSHRP = (An / Ai) \times 100$$

Maximum Adsorbance (Amax) - theoretical adsorbence reading when all bitumen in solution has been adsorbed by the aggregate.

$$Amax = VC (A1 - 0) / WA1$$

% Initial Adsorption UUJ (%AiUUJ) - re-evaluation of SHRP data to determine the percentage of bitumen initially adsorbed onto the aggregate surface.

$$\%AiUUJ = (Ai / Amax) \times 100$$

% Net Adsorption UUJ (%AnUUJ) - re-evaluation of SHRP data to determine the percentage of bitumen remaining on the aggregate after the desorption stage at the end of the test.

$$\%AnUUJ = (An / Amax) \times 100$$

Where:

	Ai =	Initial Adsorption (mg/g),
	V =	Volume of solution in the flask at the time A1 is obtained (normally 140ml),
	W =	Aggregate mass (g),
	C =	Initial concentration of bitumen in solution (g/l),
	A1 =	Initial light absorbence reading,
	A2 =	Light absorbence reading after six hours,
	A3 =	Light absorbence reading after desorption stage,
	An =	Net Adsorption (mg/g),
	Vr =	Volume of solution in the flask at the time A3 is obtained (normally 136ml).

Vr = Volume of solution in the flask at the time A3 is obtained (normally 136ml).

4.7 Results

The results for the Type A graded and Type B aggregate samples are shown in Tables 4.1 and 4.2 respectively. The Histogram columns show the average result for each set of five or six samples tested. The deviation from the mean of each set's individual results was very small. Student "T" tests verified that the mean of each set of results shown as a column was statistically "significantly different" from the means shown in the other columns. Percentage improvements in performance when comparing one sample to another are therefore considered reliable.

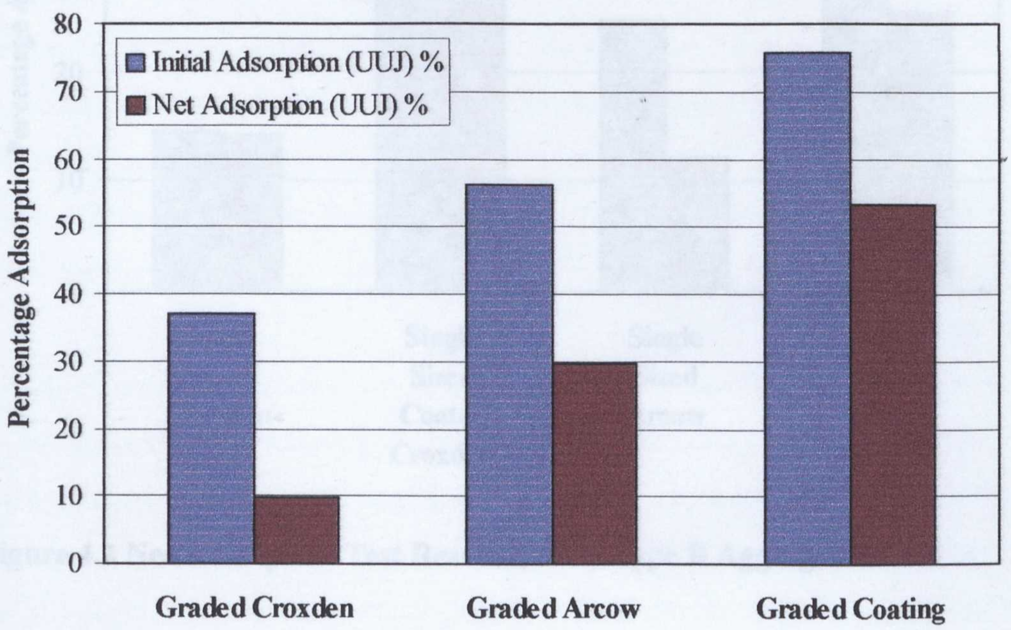


Figure 4.1 Net Adsorption Test Results (UUJ) Type A Graded Aggregates.

Figure 4.1 shows that for a graded sample representing the fine material in a bituminous mixture, Arcow demonstrates a 52 per cent improvement in initial adsorption over Croxden, and Coating material displays a 104 per cent increase in initial adsorption over Croxden and a 35 per cent improvement in initial adsorption over Arcow. In net adsorption, Arcow demonstrates a 200 per cent improvement over Croxden and the coating material shows a 439 per cent improvement over Croxden and a 79 per cent improvement over Arcow.

Figure 4.2 shows that in initial adsorption, coated Croxden demonstrates a 150 per cent improvement over uncoated Croxden whilst coated Arcow is observed to exhibit a 71 per cent improvement over uncoated Arcow. In net adsorption, coated Croxden exhibits a 116 per cent improvement over uncoated Croxden whereas coated Arcow demonstrates a 108 per cent improvement over uncoated Arcow.

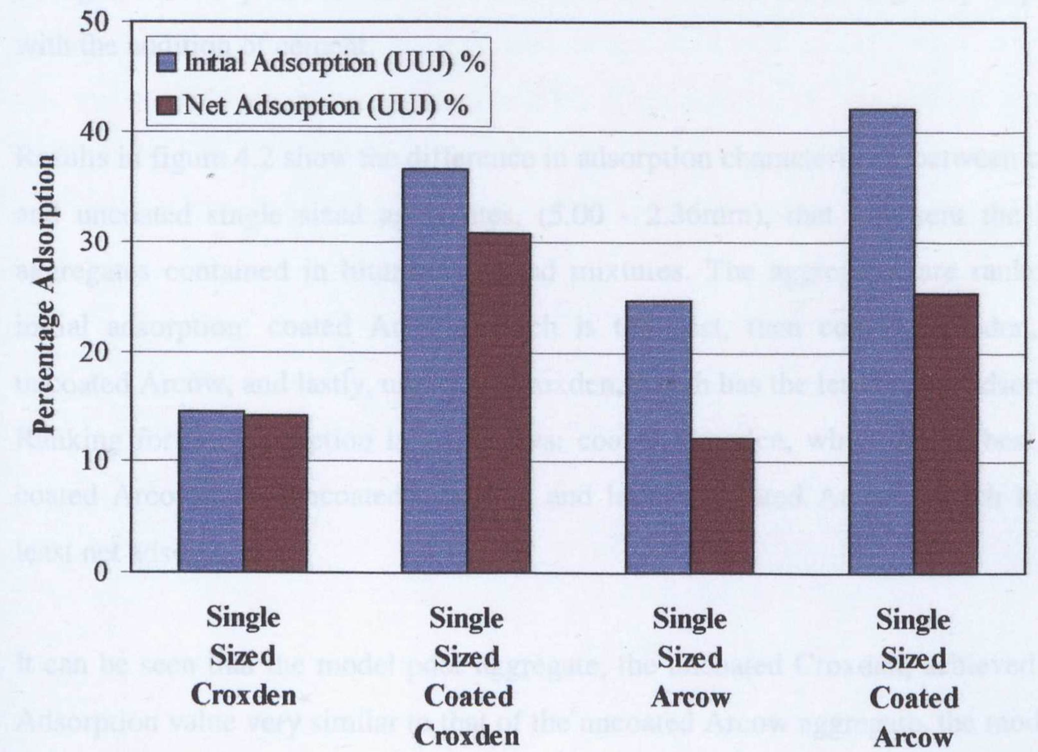


Figure 4.2 Net Adsorption Test Results (UUJ) Type B Aggregates.

4.8 Discussion of Results and Conclusions

Figure 4.1 is used to rank the adsorptive properties of the Croxden, Arcow and the Coating Material. The three aggregates are ranked as follows. Coating material, which was the best, followed by Arcow, with Croxden displaying the least initial and net adsorption values. Croxden gravel was expected to perform the least well, as it was selected as a model poor quality road aggregate. Arcow also behaved as expected, in that it was much more adsorbent than the Croxden, proving itself as an of its surface qualities. Details of these qualities, known to be favourable for binder affinity, are detailed in the literature review, chapter two. Testing revealed, however, that much more than just a small improvement in adsorption was evidenced, i.e. 35 per cent and 79 per cent improvement in initial and net adsorption respectively was achieved. This result demonstrates that cement paste does possess those surface qualities necessary for a very effective affinity with bitumen. This result also appears to demonstrate quite clearly the mechanism by which cementitious materials in bituminous mixtures can improve the initial and long term aggregate/binder bond strength, i.e. the quantities of initial and retained bitumen are both greatly improved with the addition of cement.

Results in figure 4.2 show the difference in adsorption characteristics between coated and uncoated single sized aggregates, (5.00 - 2.36mm), that represent the larger aggregates contained in bituminous road mixtures. The aggregates are ranked for initial adsorption: coated Arcow, which is the best, then coated Croxden, next uncoated Arcow, and lastly, uncoated Croxden, which has the least initial adsorption. Ranking for net adsorption is as follows: coated Croxden, which is the best, then coated Arcow, next uncoated Croxden, and lastly uncoated Arcow, which has the least net adsorption.

It can be seen that the model poor aggregate, the uncoated Croxden, achieved a net Adsorption value very similar to that of the uncoated Arcow aggregate, the model for conventional reputable road aggregates. On initial inspection this seemed to be quite unexpected. After closer examination, however, the Croxden gravel falling in the 5.00 - 2.36mm size fraction, displayed a high fractured face count, unlike the rounded particle, larger size fractions, (20 - 5mm). The smallest size fraction appeared to be a product of the breaking up of the larger particles of Croxden. These textured fractured faces appear to account for the higher than expected adsorption result, that was not expected of the smooth 20 - 5mm particle size fractions. The adsorptivity values for uncoated Arcow were not expected to vary much between the 20 - 5mm particle size fractions, and the 5.00 - 2.36mm fraction tested, as the microsurface areas and the surface textures do not significantly change.

When comparing uncoated and coated Croxden, it is observed that after coating the Croxden displays a greatly improved adsorptivity, i.e. an improvement of 116 per cent, that is more than twice as much net adsorption. The coated Croxden also demonstrates a 154 per cent improvement in net adsorption over the uncoated Arcow. This great improvement demonstrates the effectiveness of the coating to convert a model poor aggregate into a material superior to reputable aggregates in terms of their ability to bond with bitumen and resist the effects of water. The improvement appears to be only attributable to the presence of the cement coating.

Comparing the initial and net adsorption of uncoated and coated Arcow, it is seen that the coating more than doubles the affinity between the Arcow and the bitumen, (108 per cent improvement in adsorption). It can therefore be postulated that coating can also enhance the performance of reputable aggregates further.

CHAPTER 5

National Instruments Hardware and LabVIEW® Graphical Programming

5.1 Introduction to the Hardware

National Instruments, (NI), hardware and LabVIEW® graphical programming were used to enable the acquisition of data and provide feedback responses, to enable shearbox testing of aggregates and repeat load axial testing of porous asphalt.

The NI hardware consisted of an SCXI-1000 chassis unit. SCXI is an abbreviation for Signal Conditioning eXtensions for Instrumentation (bus). The chassis contained two SCXI-1121 four channel isolated universal transducer modules for signal conditioning, each fitted with SCXI-1321 terminal blocks. The analogue data received by the SCXI-1121 units was converted by an SCXI-1200 Analogue to Digital Converter (ADC) unit, also housed in the chassis unit. The digital data output from the SCXI-1200 was received by a laptop computer connected via a parallel port data cable. A Computer with a Pentium® type central processor unit was required, along with a minimum of 16 megabytes of random access memory, to operate the software that controls this system.

The SCXI 1121 units are capable of receiving inputs from displacement transducers, loadcells, direct current (DC) voltage inputs up to ±5 volts DC, and thermocouples, via the SCXI-1321 connector blocks. The SCXI-1321 units are also capable of supplying various voltages for the transducers and loadcells requiring excitation. The SCXI-1200 ADC unit is also capable of directly receiving imputs and providing output voltages. The output voltage facility was used only for the repeat load axial test, (RLAT). The output voltage was used as part of a feedback unit, powering a relay to switch a heater on and off in the temperature controlled enclosure.

The SCXI-1200 ADC samples at 12 bits; that is the full scale of ±5 volts is split into 2^{12} divisions and any reading is sampled to the nearest 2^{12th} division. The SCXI-1200 also has a variable gain setting. i.e. if a gain of ten was selected, the full scale would be reduced to ±0.5 volts, however the division between the individual readings would be ten times smaller, increasing the accuracy ten fold. Thermocouples, loadcells and displacement transducers output very small changes in voltage. Displacement transducers for example, on average, output 25mv for their full range of travel - all transducers used in this study had a range of 50mm. The SCXI-1200 has gain settings of up to 2000, therefore even these small voltage output devices could be recorded very accurately.

Pictures of the hardware used can be seen in plates 5.1 - 5.3.

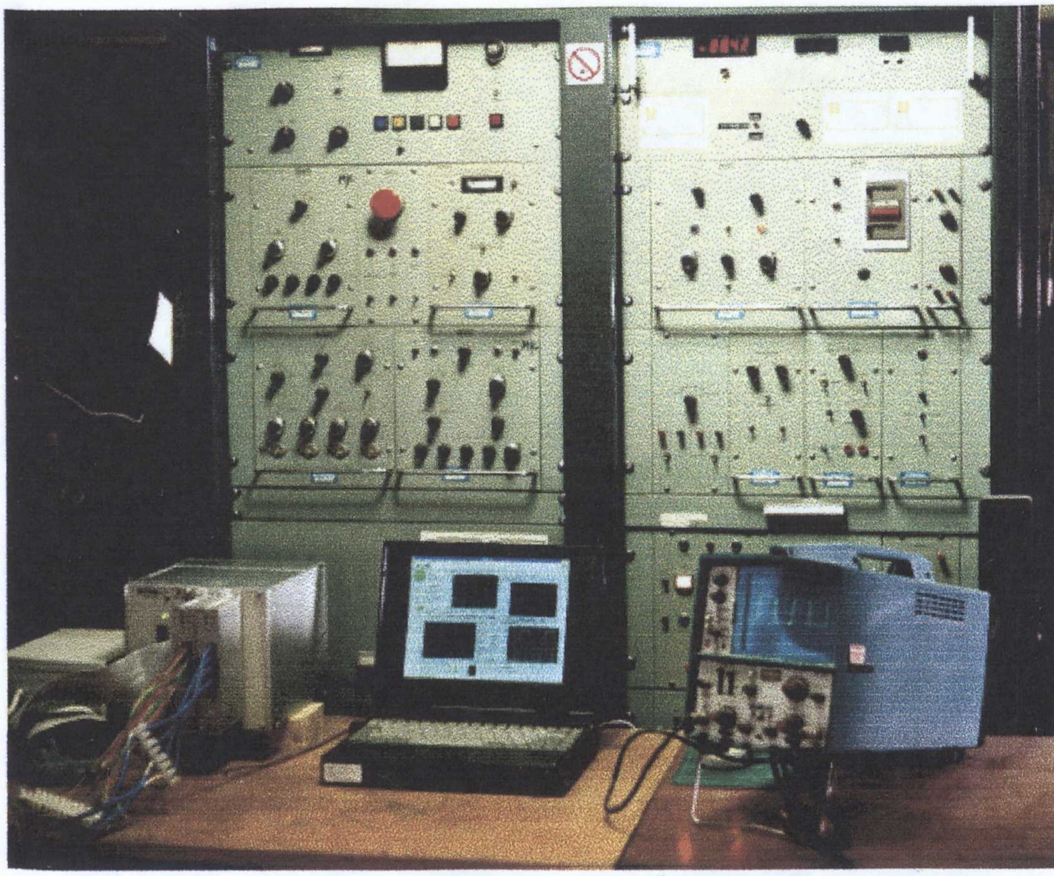


Plate 5.1 The Mayes universal tester control unit (background), with left to right, SCXI data acquisition unit, laptop computer and multichannel oscilloscope.

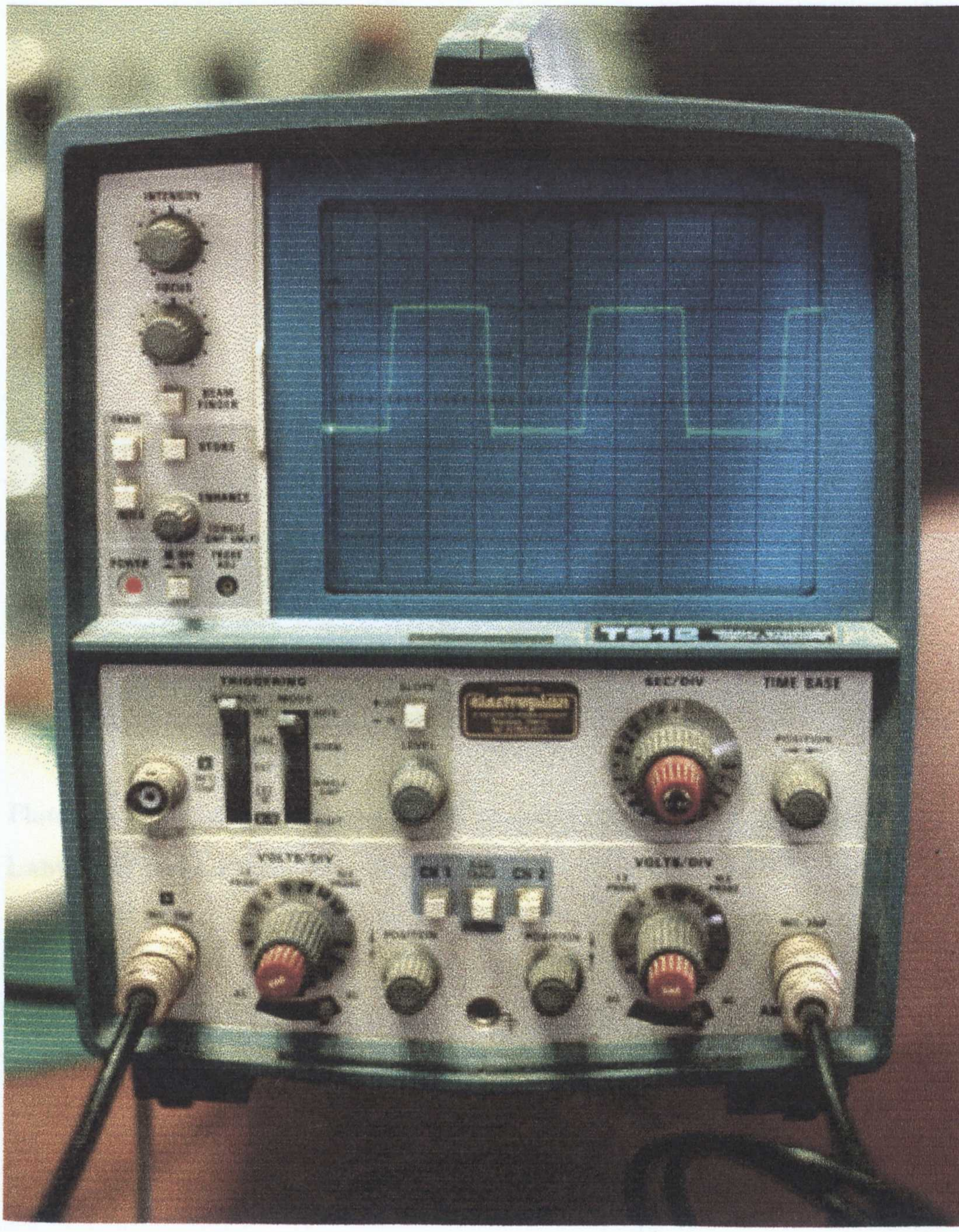


Plate 5.2 Twin channel oscilloscope for verification of high speed data acquisition.

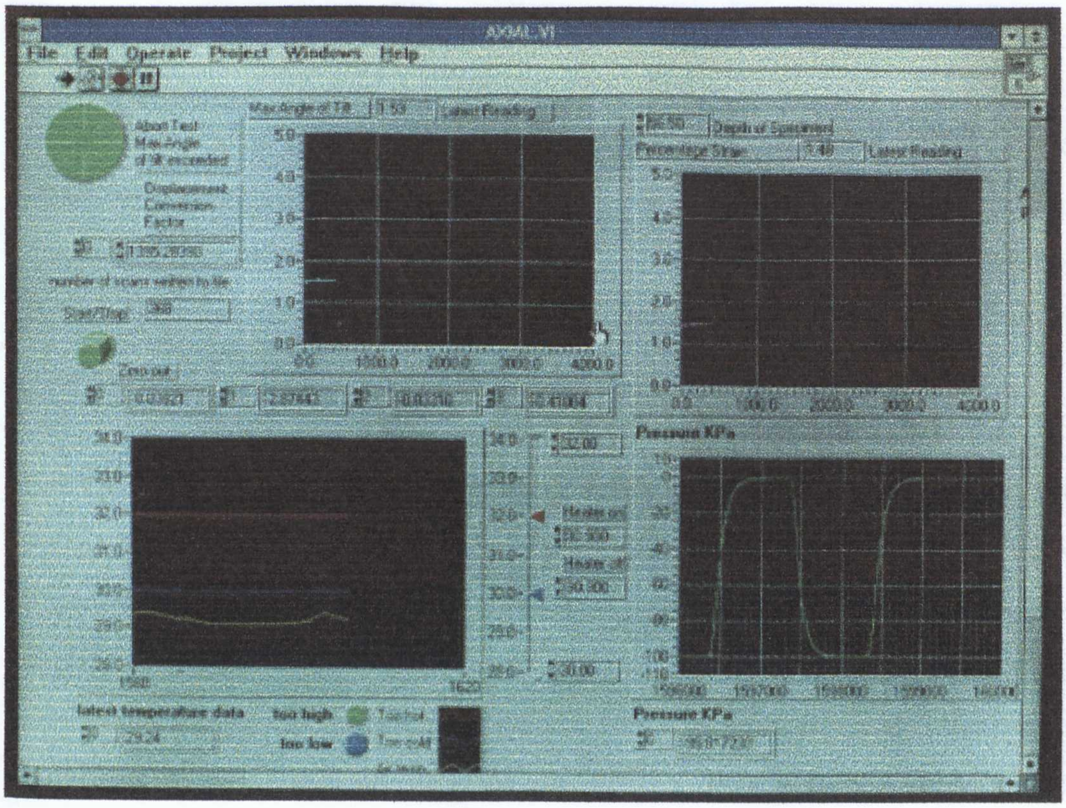


Plate 5.3 The laptop computer screen showing the Repeat Load Axial Test Labview® virtual instument interface.

5.2 Introduction to the Software

LabVIEW® is a program development application, much like C or BASIC. However, LabVIEW® is different from those applications in one important respect. Other programming systems use *text-based* languages to create lines of code, while LabVIEW® uses a *graphical* programming language, to create programs in block diagram form.

LabVIEW®, like C or BASIC, is a general-purpose programming system with extensive libraries of functions for any programming task. LabVIEW® includes libraries for data acquisition, general purpose interface board and serial instrument control, data analysis, data presentation, and data storage. LabVIEW® also includes conventional program development tools, so one can animate the execution to trace how data passes through the program, and single-step through the program to make debugging and program development easier.

LabVIEW® programs are called *virtual-instruments* (VIs) because their appearance and operation can imitate actual instruments. However, VIs are similar to the functions of conventional language programs.

A VI consists of (i) an interactive user interface, (ii) a dataflow (block) diagram, that serves as the source code, and (iii) icon connections that allow the VI to be called from higher level VIs:

(i) The interactive user interface of the VI is called the *front panel.* The front panel window of a VI simulates the panel of a physical instrument. The front panel can contain knobs, push buttons, graphs, digital read outs, and other controls and indicators. Controls simulate instrument input devices and supply data to the block diagram of the VI. Indicators simulate instrument output devices that display data acquired or generated by the block diagram of the VI.

(ii) The diagram window holds the *block diagram* of the VI, which is the graphical source code of a LabVIEW® VI. The block diagram is constructed by *wiring* together objects that send or receive data, perform specific functions, and control flow of execution. When a control or indicator is placed on the front panel, LabVIEW® places a corresponding terminal on the block diagram. The terminal that belongs to a control or indicator cannot be deleted. The terminal disappears only when its control or indicator is deleted. Terminals can be thought of as entry and exit ports. For example, data that is entered into a control on the front panel *exits* the front panel via the control's terminal on the back panel. Conversely, data produced by a function on the back panel *exits* the function by its exit terminal and *enters* the front panel, through the indicator's entry terminal, where the data is displayed. All data is said to exit from a *source terminal* and enter a destination or *sink terminal.*

Nodes are program execution elements. They are analogous to statements, operators, functions and subroutines in conventional programming languages. For example add and subtract functions are one type of node. LabVIEW® has an extensive library of functions for mathematics, comparison, conversion, input/output (I/O), and more. Another type of node is a *structure.* Structures are graphical representations of the loops and case statements of traditional programming languages; repeating blocks of code or executing them conditionally. LabVIEW® also has special nodes for linking to external text-based code, and for evaluating text-based formulae. Wires are the data paths between source and sink (destination) terminals. You cannot wire a source terminal to another source, nor can you wire a sink terminal to another sink. However, you can wire one source to many sinks. Wires are assigned different colours and thicknesses depending on the type of data being carried.

The principle that governs LabVIEW® program execution is called *data flow*. Stated simply, a node executes only when all necessary data inputs have arrived; the node supplies data to all of its output terminals when it finishes executing; and the data passes immediately from source to sink (or destination) terminals. Data flow contrasts with the control flow method of executing a conventional program, in which instructions are executed in the sequence in which they are written. Control flow execution is instruction driven. Dataflow execution is *data driven* or *data dependent.*

(iii) Icon and connector; When an icon of a VI is placed on the diagram of another VI, it becomes a subVI, the LabVIEW® version of a subroutine. The controls and indicators of a subVI receive data from, and return the data to, the calling VI's diagram.

The connector is a set of terminals that correspond to the subVI's controls and indicators. The icon is either a pictorial representation of the purpose of the VI, or a textual description of the VI or its terminals.

The connector is much like the parameter list of a function call; the connector terminals act like parameters. Each terminal corresponds to a particular control or indicator on the front panel of the subVI. A connector receives data at its input terminals and passes the data to the subVI code via the subVI controls, and receives the results at its output terminals from the subVI indicators.

Every VI has a default icon, which is displayed in an icon pane, in the upper right corner of the front panel and block diagram windows.

Every VI also has a connector, which is accessed by choosing "show connector" from the icon pane pop-up menu on the front panel. When the connector is viewed for the first time, LabVIEW® suggests a connector pattern. This pattern may be accepted, or an alternative one chosen. The connector generally has one terminal for each control or indicator on the front panel. Up to 28 terminals can be assigned. If future changes are anticipated, extra terminals can be left unconnected for future use. With the extra terminals, any new inputs or outputs will not affect other VIs that use the VI being programmed as a subVI.

With these three foundational features, LabVIEW® promotes and adheres to the concept of *modular programming.* An application is divided into a series of tasks, which can be divided again, until a complicated application becomes a series of simple subtasks. A VI is built to accomplish each subtask, and then these VIs are combined on another block diagram to accomplish the larger task. Finally, a top-level VI will contain a collection of subVIs that represent application functions.

Because each VI can be executed by itself, apart from the rest of the application, debugging is made much easier. Furthermore, many low-level subVIs can be written to perform tasks common to several applications. Therefore, a specialised set of subVIs can be developed, each well suited to applications likely to be constructed in the future.

5.3 The Shearbox VI

The purpose of the shearbox VI was to display on screen, real-time, and record in spreadsheet format, the horizontal force, and vertical displacement generated by the shearbox apparatus whilst in operation. Input values were received by the SCXI unit from a single 50mm range displacement transducer, and a 50kN loadcell. The shearbox VI was responsible for converting the voltage readings acquired into standard force and displacement values, namely Newtons and millimetres respectively. The values were then displayed on screen and saved to file, for viewing later in a spreadsheet package. The readings were taken at a rate of 1000 per second and after averaging for accuracy, one value per second was plotted on the screen graph and recorded simultaneously to file.

The front panel and block diagrams for the shearbox VI can be viewed in appendix F

More details of the shearbox test and the interpretation of the results can be found in chapter six of this thesis.

5.4 The RLAT VI

The RLAT VI was a much larger VI than the shearbox VI and contained three smaller subVIs written specially for this study. They were, the temperature VI, the displacement calculations VI, and the Mayes universal test machine loadcell output voltage VI. These subVIs contained large portions of code, that would, if placed straight on the top-level VI, confuse the programmer and render debugging and comprehension of the application almost impossible.

The temperature subVI was responsible for displaying the temperature of the RLAT controlled temperature cabinet, and provided switching for the heater therein. The temperature VI also allowed monitoring of the temperature of a dummy specimen in the RLAT cabinet, and monitoring of the temperature in an environmental chamber where specimens for subsequent testing were stored. The switching was enabled by providing a voltage from the SCXI-1200 that powered a relay. This provision of a voltage was known as *writing a voltage.* If the relay required five volts to switch the heater on, then five volts were *written* to the channel on the SCXI-1200 where the relay was connected, latching the relay in the "on" position. The heater was turned off by *writing* zero volts to the same channel on the SCXI-1200. Upper and lower limits were set on the top-level RLAT VI, which acted as operators to *write* zero or five volts to maintain the required temperature specifications.

The displacement calculation subVI provided a monitor for the average displacement, and angle of differential movement in the specimen being tested. The displacement VI converted raw data into standard units, displayed the results graphically on screen and recorded them into a spreadsheet file.

The Loadcell subVI converted voltage readings from the Mayes universal testing machine and displayed the corresponding load values graphically on screen. These loading values were shown on a virtual oscilloscope display. The loadcell readings were not required to be stored in a spreadsheet file. The virtual oscilloscope was used only as a monitor to set the required loadings, and to check the loading magnitude and the loading application cycle remained within the standard specification.

The front panel and block diagrams for the RLAT VI and its subVIs can be viewed in appendix F

More details of the RLAT test and the interpretation of the results can be found in chapter nine of this thesis.

CHAPTER 6

Investigating the Physical Properties of Coated Aggregate

6.1 Introduction

Chapter six is divided into four main areas of study subheaded; measurement of the angle of internal shearing resistance, measurement of surface roughness, measurement of polished stone value and measurement of aggregate crushing value. Each subheading area studied contains a method, results and conclusions section. The experiments chosen for each subheading section have been designed to provide a measure of the performance of the coated and uncoated aggregates, in the properties considered essential for producing high quality road pavement mixtures.

6.2 Measurement of the Angle of Internal Shearing Resistance of Coated and Uncoated Aggregates

6.2.1 Introduction

Shearing resistance can be described as the ability of a homogenous body to resist a shearing force applied through a given plane of the body. The magnitude of the shear resistance depends on; the size of the plane through which the external shear force is applied, the inherent resistance to shearing, (coefficient of internal friction) of the material composing the body being sheared, and the amount of surcharge load being applied normal to the plane of shearing. Bituminous materials resist shearing or any differential movement by two mechanisms, they are; internal friction and cohesion, as described in section 2.3.1 of this thesis. In a Bituminous road material the binder is responsible for the cohesional component, whilst the aggregate is responsible for the frictional component, Herrin et al. (11). When the internal friction coefficient of a road aggregate is measured, an indication of that aggregate's contribution to the strength of a bituminous mixture is obtained. This section of the thesis examines the improvement in the contribution of the aggregate, to the coefficient of internal shearing resistance of a bituminous material, when cement coating is added.

6.2.2 The Shearbox Test

Unbound aggregate is a loose substance that cannot be sheared effectively without some kind of confinement. The shearbox was designed to allow effective shearing of a substance and provide the necessary degree of confinement for loose materials. The British Standards Institution allow two kinds of shearbox test, they are the small and the large shearbox tests. The small shearbox, (100mm x 100mm), is suitable for cohesive clays with a small percentage of larger particles, and for cohesionless fine sands without any large particles. The large shearbox, (305mm x 305mm) is again suitable for cohesive and cohesionless materials, however the cohesionless materials can be larger and up to 15 per cent of the particles can be as big as 20mm in diameter. Testing for this study was performed with large shearbox apparatus, so allowing coarse aggregate to be used. Although aggregate was coated in fractions from 3.35 - 20mm the smallest fraction (3.35 - 6.3mm) was deemed most suitable. The larger size fractions were considered to be very near or over the upper particle size limits of the large shearbox, and anomalous results from the larger fractions, were anticipated. The 3.35 - 6.3mm size fraction was therefore chosen, and samples were obtained for each of the aggregate types to be tested.

The BS large shearbox (50), consisted of a steel box divided horizontally into two halves, each half having inside dimensions of 305mm x 305mm square on plan x 75mm in height. The two halves sat one on top of the other, and slid one over the other, on ball bearings, on one axis confined by edge guides. The lower half of the box had a base plate, which was securely bolted to a long, upturned, steel channel section. The drive motor and gearing for horizontal motion were also bolted to this channel section. The upper half of the box had a lid which fitted inside the upper rim and it was used as the load spreading platen for the vertically applied confinement load.

Large Shearboxes are not kept as stock items of equipment at engineering suppliers, and are usually individually produced at the factory. The expense of purchasing a large shearbox was therefore prohibitive. Instead a shearbox was manufactured at LJMU in the School of the Built Environment workshops by the researcher. The shearbox, the base plate and the lid, were constructed from 15mm thick mild steel plate, in accordance with the relevant BS (50). The drive motor and gearing arrangement were borrowed from another custom made shearbox at LJMU.

The vertical confinement load and the horizontal shearing load were monitored throughout the test using 10kN maximum load and 50kN maximum load transducers respectively. The vertical load was applied using a mechanical lever loading system. The horizontal force was applied via a push rod arrangement on the end of the gearing system providing horizontal motion. The rate of horizontal motion was verified as being constant to within 10 per cent, the BS standard, using a displacement transducer. The shearbox apparatus can be seen in more detail in plate 6.1.

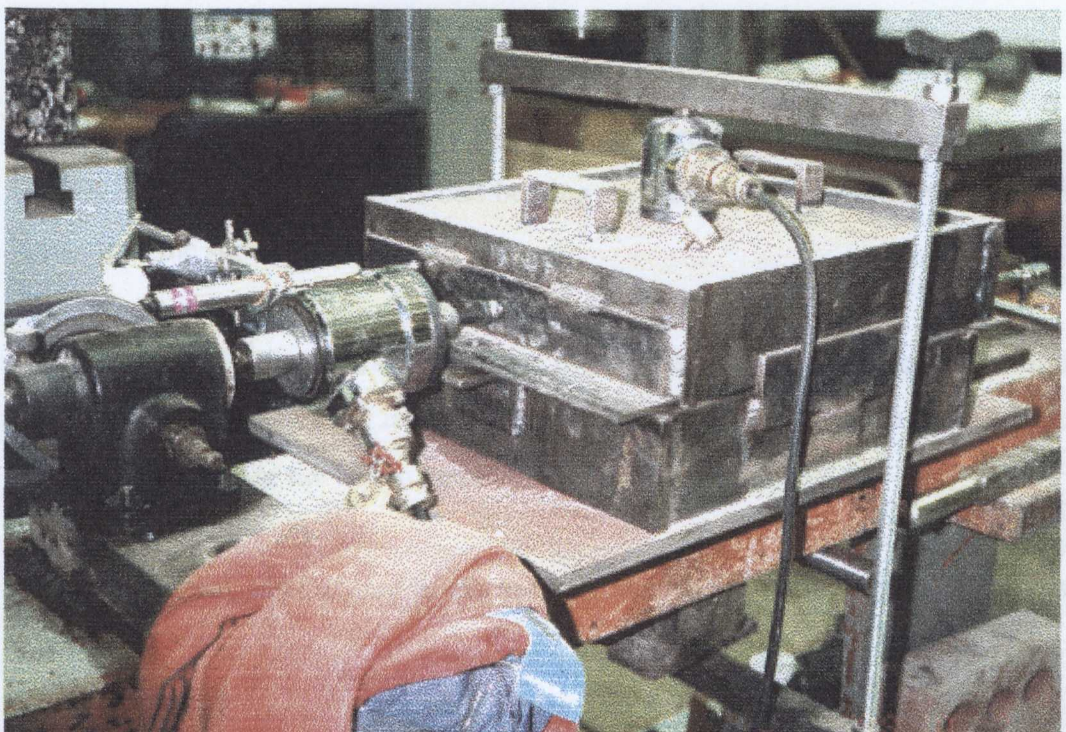


Plate 6.1 The Large Shearbox Apparatus

6.2.3 The Shearbox Test Method

(i) The two halves of the shearbox were firmly clamped together, then the aggregate sample was placed in the shearbox using the BS method for loose cohesionless materials BS1377: Part 7: 1990: Clause 5.4.7 (50).

(ii) The shearbox lid was carefully lowered into position without disturbing the gravel sample in the box. The loadcell for measuring the vertically applied force was then centred on the lid, and the loading yolk, supported on a ball bearing, was placed on top of the loadcell.

(iii) The cantilever arm was then attached to the loading yolk and the weights added to the hanger to apply the vertical load. The loadcell situated on the shearbox lid was used to record the load applied by the weights on the cantilever, the lever arm and the loading yolk. Therefore the hanger weights did not need to be calibrated as the loadcell recorded the total applied confinement load.

(iv) The Horizontal push rod assembly, which contained the horizontal loadcell, was then located, by means of a ball bearing and centre divot, against the face of the top half of the shearbox.

(v) The displacement transducer was then placed against the face of the top half of the shearbox in a smaller location divot. The two halves of the shearbox were then unclamped ready for the test to commence.

The arrangement and location of the parts detailed in instructions (i - v) can be seen in plate 6.1

(vi) The loadcell and displacement transducer, both requiring five volts DC excitation, were wired into the SCXI data acquisition unit, in the appropriate channels, and zeroed out before commencement of the test.

(vii) The LabVIEW® shearbox VI was started, with any incoming data being displayed on screen and logged to a spreadsheet file. The motor providing the horizontal motion was then started. The progress of the test was monitored on the computer screen.

(viii) When the horizontal force reached a maximum value and settled to retain a constant, the test was concluded. After the test was concluded the whole procedure, (i - vii), was repeated, but with a different confinement load. The test was repeated until four different confinement loads had been applied.

The 50kN loadcell was calibrated by applying calibrated Newton weights and measuring the change in voltage produced by the cells. The change in voltage was plotted against the change in force evidenced with each increment in weight. The slope of a best-fit line, passing through zero, of the plotted points, gave the multiplication factor to change volts into Newtons. The best-fit line was found mathematically using the linear regression tool found in Microsoft Excel®. After calibration, force could be recorded to the nearest ten Newtons when using the optimum SCXI-1200 gain setting. The 50kN loadcell, giving dynamic readings, was monitored using the SCXI unit. However the static, vertical confinement load, measured with the 10kN loadcell, was viewed using a conventional analogue loadcell reader which was accurate to the nearest Newton.

Displacement transducers were calibrated similarly, by plotting a graph of displacement against voltage. Results could be recorded to the nearest hundredth of a millimetre through the SCXI unit.

The displacement transducer output graph showed a constant rate of displacement of 1.6mm per minute. The slope of the line, (displacement versus time), never deviated by more than two per cent, which was well within the ten per cent limit specified by the BS. The 1.6mm per minute displacement rate was fixed by the gear ratios of the standard shearbox motor and gearbox equipment, and was therefore considered adequate for the test.

6.2.4 Shearbox Test Results

The maximum horizontal shear force measured, was divided by the area of the shear plane, (305 x 305mm), to give the shearing pressure. The vertical force was divided by the area over which it was applied, (305 x 305mm), to give the vertical pressure. Shearing pressure values were then plotted against each of the four corresponding vertical, confining pressure values. The best-fit line plotted from the four points formed an angle with the axis of vertical pressure, see figure 6.1 and table 6.1. This angle is known as the angle of internal shearing resistance. If loose aggregate was truly cohesionless the best-fit line would pass through the origin of the graph. However all materials possess some small amount of cohesion, and this is evidenced by the best-fit lines for all the materials, intersecting the shearing pressure axis, at values just greater than zero. The points plotted to produce figure 6.1, are the average values from three tests on each material. The slope of the line differed by a maximum of 2.25° (<4.5%) in any set of three tests used to give an average value. Student "T" tests showed that all the results were statistically significant by a large margin. (The minimum improvement with coating was 4.26°).

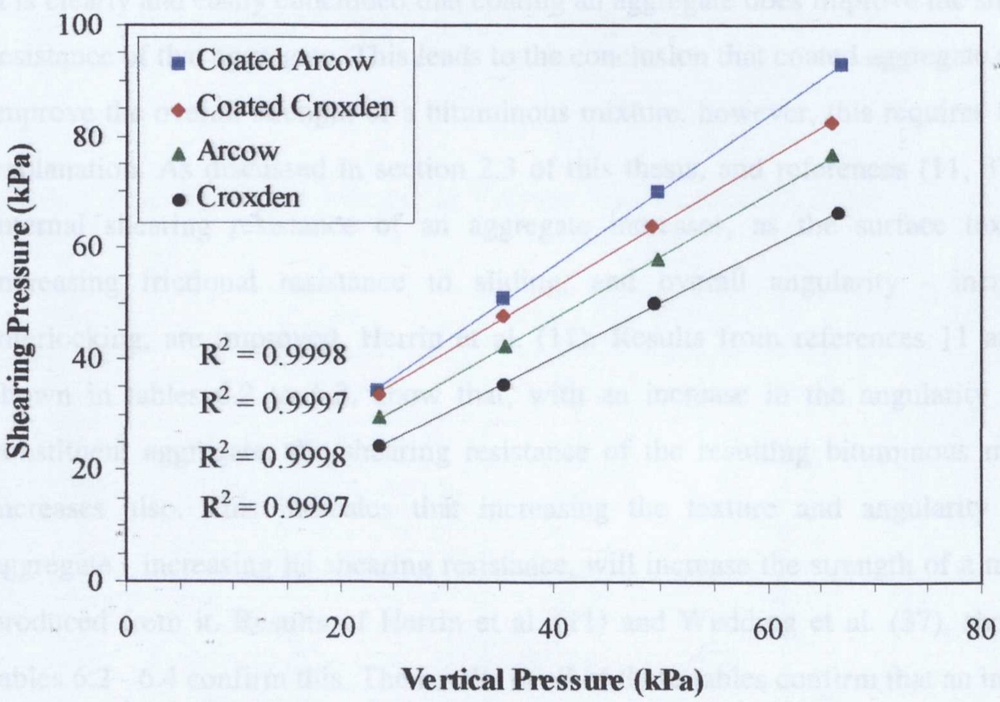


Figure 6.1 Angle of Internal Shearing Resistance of Coated and Uncoated Aggregates from the Large Shearbox Test.

Table 6.1 Angle of Internal Shearing Resistance of Coated and Uncoated Aggregates from the Large Shearbox Test.

Aggregate Type	Angle of Internal Friction (Degrees) (ϕ)
Coated Arcow	53.39
Coated Croxden	48.94
Uncoated Arcow	48.15
Uncoated Croxden	44.68

Table 6.1 shows that coating improves the angle of internal shearing resistance of Croxden by 9.53 per cent. Arcow exhibits a 10.88 per cent improvement in shearing resistance when coated. Coated Croxden can achieve an angle of internal shearing resistance 1.64 per cent better than uncoated Arcow.

6.2.5 Shearbox Test Conclusions

It is clearly and easily concluded that coating an aggregate does improve the shearing resistance of that aggregate. This leads to the conclusion that coated aggregate should improve the overall strength of a bituminous mixture, however, this requires further explanation. As discussed in section 2.3 of this thesis, and references (11, 37), the internal shearing resistance of an aggregate increases, as the surface texture - increasing frictional resistance to sliding, and overall angularity - increasing interlocking, are improved, Herrin et al. (11). Results from references 11 and 37, shown in tables 6.2 to 6.3, show that, with an increase in the angularity of the constituent aggregate, the shearing resistance of the resulting bituminous mixture increases also. This indicates that increasing the texture and angularity of an aggregate - increasing its shearing resistance, will increase the strength of a mixture produced from it. Results of Herrin et al. (11) and Wedding et al. (37), shown in tables 6.2 - 6.4 confirm this. The results in all of these tables confirm that an increase in aggregate angularity produces a steepening in the bituminous mixture's angle of internal friction. This in turn produces a mixture with an increased magnitude of compressive strength or Marshall stability.

Table 6.2 Results of Herrin et al. (11) for Gap Graded Mixtures

Fine Aggregate	Coarse Aggregate	Average Density (pcf)	Average Compressive Strength When Confining Pressure is 30psi (psi)	Angle of Internal Friction (degrees)
Natural Sand	0% Crushed Gravel	142.2	177.6	37.4
	55% Crushed Gravel	140.8	189.5	37.7
	70% Crushed Gravel	139.3	196.4	38.2
Crushed Stone	0% Crushed Gravel	145.2	247.3	31.9
	55% Crushed Gravel	145.4	261.6	32.5
	100% Crushed Gravel	145.7	265.3	32.5

Table 6.3 Results of Herrin et al. (11) for Single Sized Mixtures

Coarse Aggregate	Average Density (pcf)	Average Compressive Strength When Confining Pressure is 30psi (psi)	Angle of Internal Friction (degrees)
0% Crushed Gravel	113.6	74.3	23.7
55% Crushed Gravel	110.5	90.5	27.8
70% Crushed Gravel	110.6	97.2	30.5
100% Crushed Gravel	110.1	108.7	32.6

Table 6.4 Results of Wedding et al. (37) for Gap Graded Mixtures

Fine Aggregate	Coarse Aggregate	Average Density (pcf)	Marshall Stability (pounds)
Crushed Sand	0% Crushed Gravel	150.4	1430
	50% Crushed Gravel	150.2	1670
	75% Crushed Gravel	150.6	1790
	100% Crushed Gravel	150.5	1830
Natural Sand	0% Crushed Gravel	150.6	1340
	50% Crushed Gravel	150.8	1590
	75% Crushed Gravel	151.1	1670
	100% Crushed Gravel	150.7	1790

It is reasonable to conclude then, that coating an aggregate with cement paste, can improve the strength of a bituminous mixture made from it.

Chapter eight of this thesis seeks to confirm this conclusion by comparing the strengths of coated and uncoated aggregate bituminous mixtures.

6.3 Measurement of the Surface Roughness of Coated and Uncoated Aggregates

6.3.1 Introduction

The measurement of surface roughness is included in this study to supplement the findings from the shearbox testing. One of the mechanisms of improved internal shearing resistance of an aggregate as mentioned in section 6.2.5 of this thesis, is the surface texture of an aggregate. This surface texture is often measured by a fractured face surface count, as mentioned in references (10, 11, 12, 13, 17, 37, 51). However when aggregates have been produced from crushed quarried rock, or have been coated, the fractured face count is no longer suitable. A surface roughness test was therefore chosen to indicate the relative texture depths of coated and uncoated aggregates.

6.3.2 The Surface Roughness Measurement Apparatus

The measurement apparatus comprised a Uniscan Instruments® Optical Surface Profiling System, model OSP100, a high accuracy, non-contact topography mapping system. The system consisted of a precision 3 dimensional scanner, granite bed, optical sensor, control electronics and software.

The optical sensor operated on the triangulation principle, where a finely focused point of light was projected onto a surface and reflected from the surface onto a position sensitive detector (PSD) housed in the same unit. The PSD gave an analogue voltage output which was proportional to the distance between the sensor and the target. The OSP100 software allowed for the calibration of the displayed output signals in terms of height measurements in micro-metres.

As the sensor was scanned over the surface to be measured, its position in the horizontal axis was determined optically on each scan axis so that a highly accurate surface topography profile or map could be recorded.

The granite base was supplied with a certificated flatness of ±3μm. Texture depth could be measured to a tolerance of ±0.5μm

The data obtained from the optical sensor apparatus was viewed using a dedicated Microsoft Windows® based application. The data could then be stored in tabled form, or as a full colour, high resolution contour map, and could be exported in a variety of formats to other software applications.

6.3.3 Surface Roughness Measurement Method

Three pieces of aggregate were selected to represent each type being tested. The aggregate was obtained from the size fraction retained on a 20mm sieve. This larger size was used as this was easy to manipulate and hold in place in the scanning machine. The aggregate was positioned so that a flat face was presented to the scanning apparatus. The flat face was used so a map of the surface texture was produced without undue influence from the general curvature of the aggregate. The OSP100 always scans with an aspect ratio of three parts in width to four parts in length. The area chosen for this study was the area considered the largest possible without including the effects of aggregate curvature. The area chosen, therefore, was 7.5mm x 10mm. The OSP100 system was used at its maximum resolution setting of 512 divisions per horizontal axis. This produced very detailed contour maps of the aggregate surfaces. The contour maps are colour coded; deep blue in the lowest regions, to bright red in the highest areas. The colour scale represents the maximum range of texture depth shown in table 6.5 for each sample tested.

6.3.4 Surface Roughness Measurement Results.

Table 6.5 Texture Depth of Coated and Uncoated Aggregates.

Aggregate Type	Maximum Texture Depth (μm)	3 Sample Average Texture Depth (μm)
Croxden		
Sample 1	85.74	
Sample 2	82.74	85.95
Sample 3	89.38	
Coated Croxden		
Sample 1	124.75	
Sample 2	168.78	140.83
Sample 3	128.97	
Arcow		
Sample 1	112.11	
Sample 2	117.05	111.30
Sample 3	104.75	
Coated Arcow		
Sample 1	276.22	
Sample 2	340.27	336.02
Sample 3	391.56	

Table 6.5 shows, that with the addition of cement coating, Croxden achieves an increase in average surface texture depth of 63.85%. Coated Croxden also demonstrates an improvement, in texture depth, of 26.53% over uncoated Arcow. Arcow demonstrates an average texture depth increase of 201.9% with the addition of cement coating.

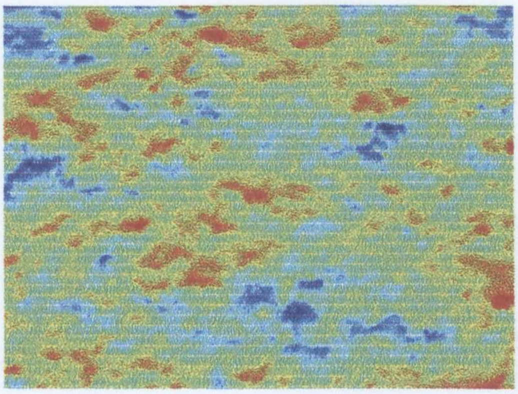


Plate 6.2 Croxden Sample No.1

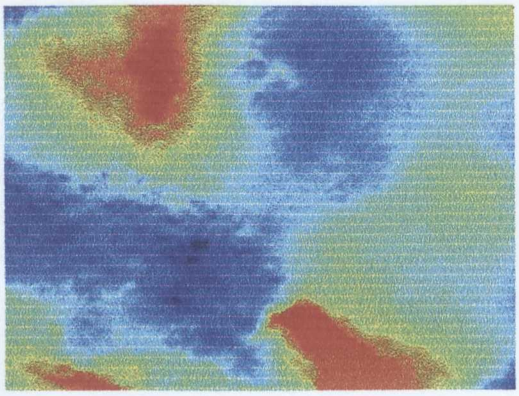


Plate 6.5 Coated Croxden Sample No.1

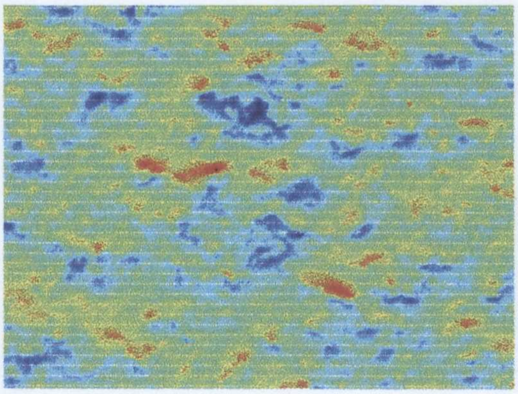


Plate 6.3 Croxden Sample No.2

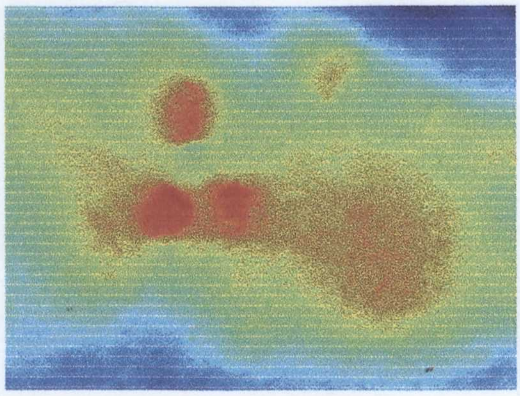


Plate 6.6 Coated Croxden Sample No.2

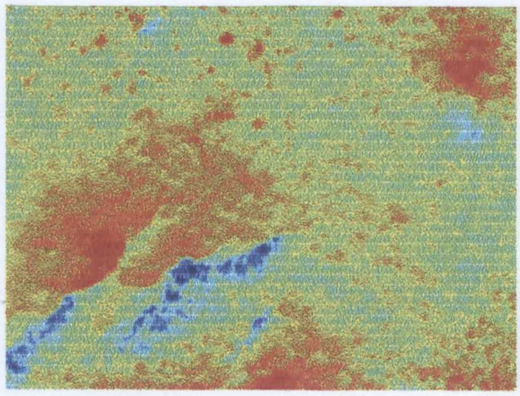


Plate 6.4 Croxden Sample No.3

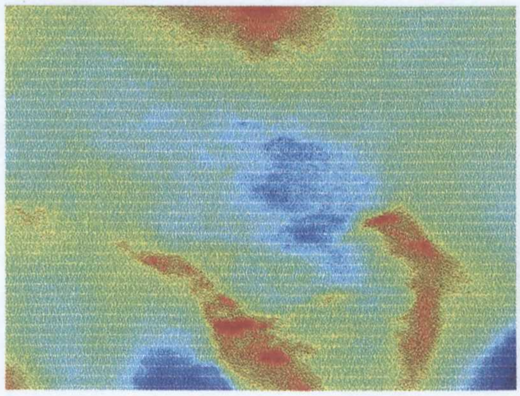


Plate 6.7 Coated Croxden Sample No.3

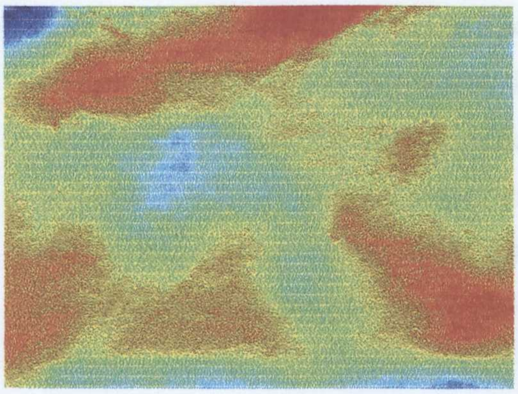


Plate 6.8 Arcow Sample No.1

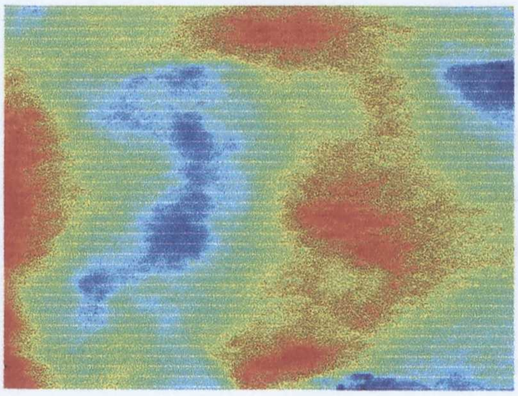


Plate 6.9 Arcow Sample No.2

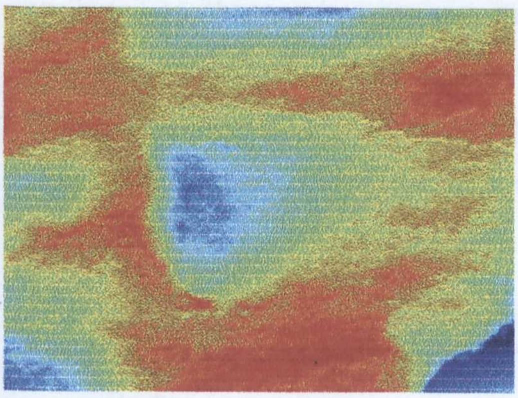


Plate 6.10 Arcow Sample No.3

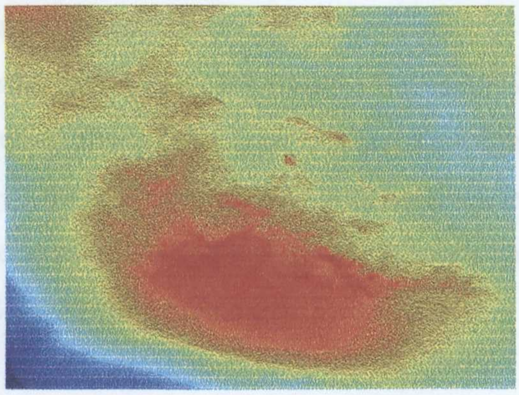


Plate 6.11 Coated Arcow Sample No.1

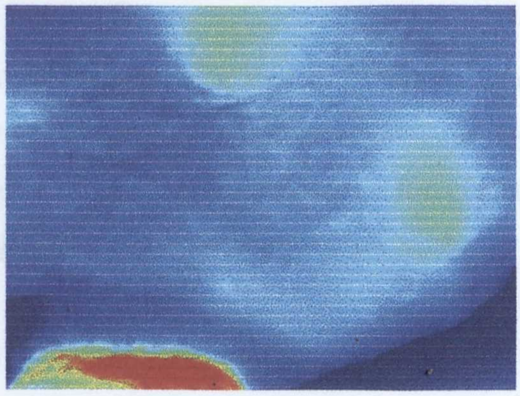


Plate 6.12 Coated Arcow Sample No.2

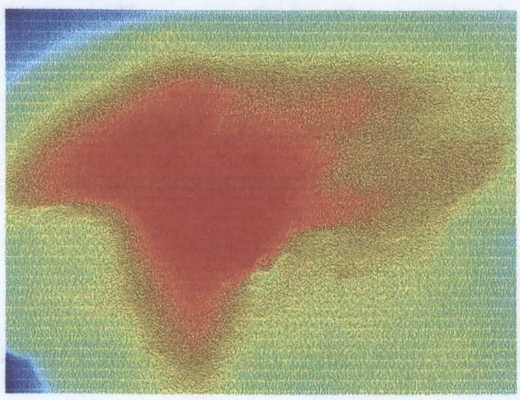


Plate 6.13 Coated Arcow Sample No.3

6.3.5 Conclusions of the Surface Roughness Measurement Test

Comparing plates 6.2 - 6.4 (uncoated Croxden) with 6.5 - 6.7 (coated Croxden), it can be seen that adding cement paste increases the texture size, not just in height (from table 6.5, showing an improvement of 63.85%) but also in horizontal scale. The Croxden, when coated, adopts a surface appearance and texture depth similar to that of uncoated Arcow; shown in plates 6.8 - 6.10 and in table 6.5.

From table 6.5, and when comparing plates 6.8 - 6.10 (uncoated Arcow) with 6.11 - 6.13 (coated Arcow), it can be seen, that with the addition of cement coating, the depth and horizontal scale of the texture is increased markedly (201.9%).

It can be simply concluded then, that coating an aggregate that has poor surface qualities, can enhance those surface properties to provide a surface texture quality similar to that provided by an aggregate known for its high performance. It can also be concluded that, coating a high quality aggregate can improve its texture further.

These conclusions are backed up by the findings of the shear box tests.

The surface studies are not of sufficient magnification to show the cement coating's microstructure. Therefore from these studies, no improvement in texture can be attributed to changes in aggregate microstructure. However, these changes in the microstructure are not likely to affect the mechanical properties of the aggregate. Changes in aggregate microstructure are only likely to affect the affinity with bitumen at a chemical level, which is discussed in depth in section 2.2.4 and chapter 4 of this thesis.

From the plates, the improvement in the surface texture appears to be attributed to two main factors;

(i) The inclusion of small dust-like particles from the parent aggregate in the cement paste. Evidence of this can be seen in plates 6.6 and 6.12.

(ii) The non-uniform thickness of the cement paste deposited on the aggregate. This can be seen in plates 6.5, 6.7, 6.11 and 6.13.

The effect of the increased surface texture on a bituminous mixture's performance, will be examined further in chapter eight.

6.4 Measurement of Polished Stone Value (PSV)

6.4.1 Introduction

In all bituminous surface layers, the aggregate at the top surface must be capable of withstanding the affects and forces directly applied by the riding vehicles. There are many tests available to model these forces, and test the aggregate's response. The most frequently used tests include the Aggregate Crushing Value (ACV), the Aggregate Impact Value (AIV), the Polished Stone Value test (PSV), the Aggregate Abrasion Value test (AAV), and the Los Angeles Abrasion Test (LAAV). These tests are described in more detail in references (40, 41, and 42), and section 2.3 of this thesis.

The frequently used tests can be divided into two types; those tests for examination of the resistance of the aggregate to imposed loads, and those tests for examination of the aggregate's resistance to erosion/polishing from tyre abrasion.

For this study, only the ACV and PSV tests were performed, however they fell one into each of the two types described above. Although a wider range of tests would be preferable, these tests should provide enough data.

6.4.2 The Polished Stone Value Test

The PSV gives a measure of the resistance of roadstone to the polishing action of the vehicle tyres under conditions similar to those occurring on the surface of a road. Where the surface of a road consists largely of roadstone the state of polish of a sample will be very representative of the resistance of the road surface to skidding. The actual relationship between PSV and skidding resistance is however much more complex than the ratio of the amount of roadstone in the sample, to the amount of roadstone at the road-mix surface. The driving conditions (wet versus dry and temperature), and the other ingredients in the road-mix all play their part.

The procedure for obtaining the PSV can be split into two simple parts;

(i) Samples of stone are subjected to a polishing action in an accelerated polishing machine.

(ii) The state of polish reached by each sample is measured by means of a friction test and is expressed as a laboratory determined PSV.

The apparatus, sample preparation method, test procedure, calculations and method for expression of results are described in detail in BS 812: Part 114: 1989 (42).

Apparatus used for the accelerated polishing of the samples and for the friction test are shown in plates 6.14 and 6.15.

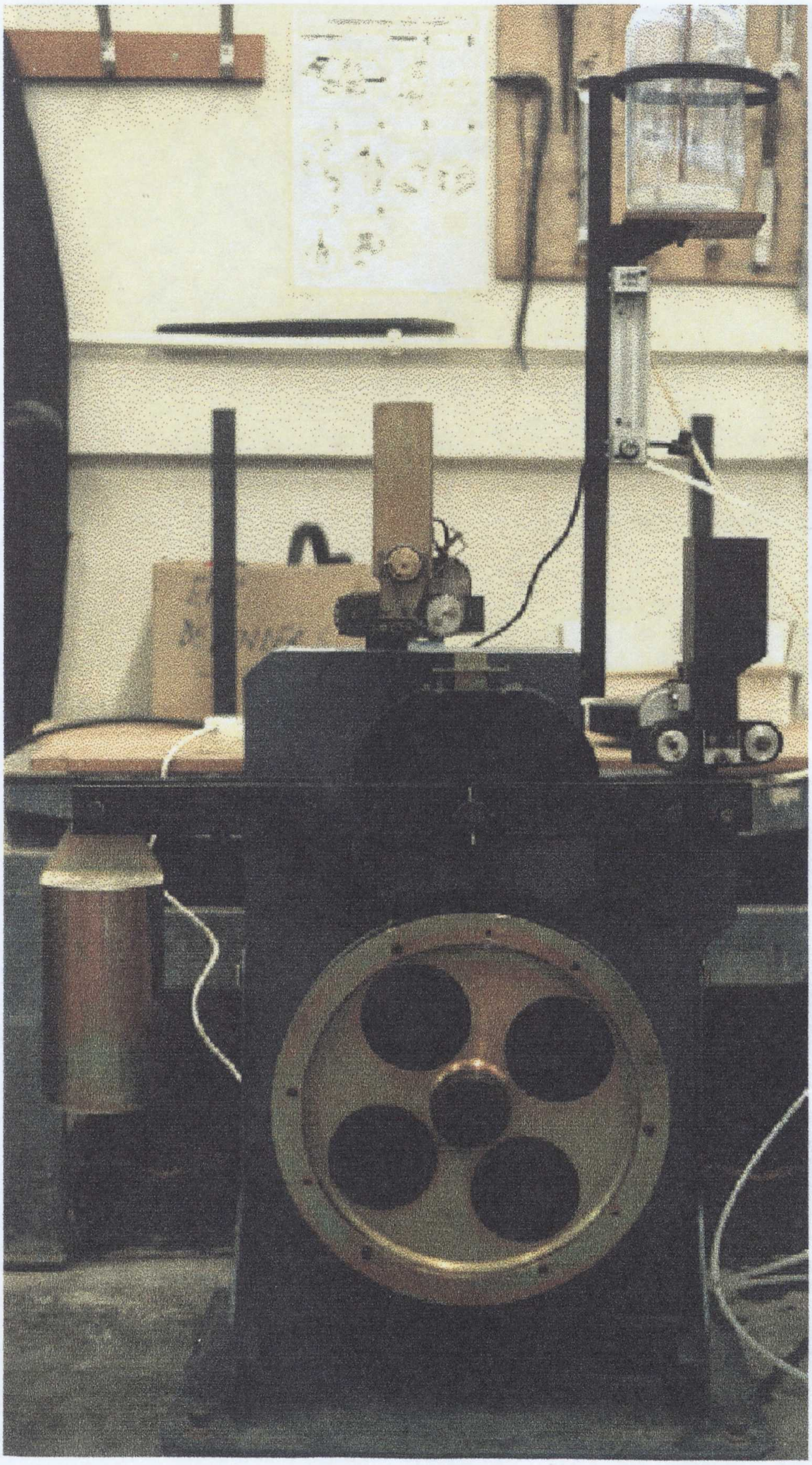


Plate 6.14 The Accelerated Polishing Machine

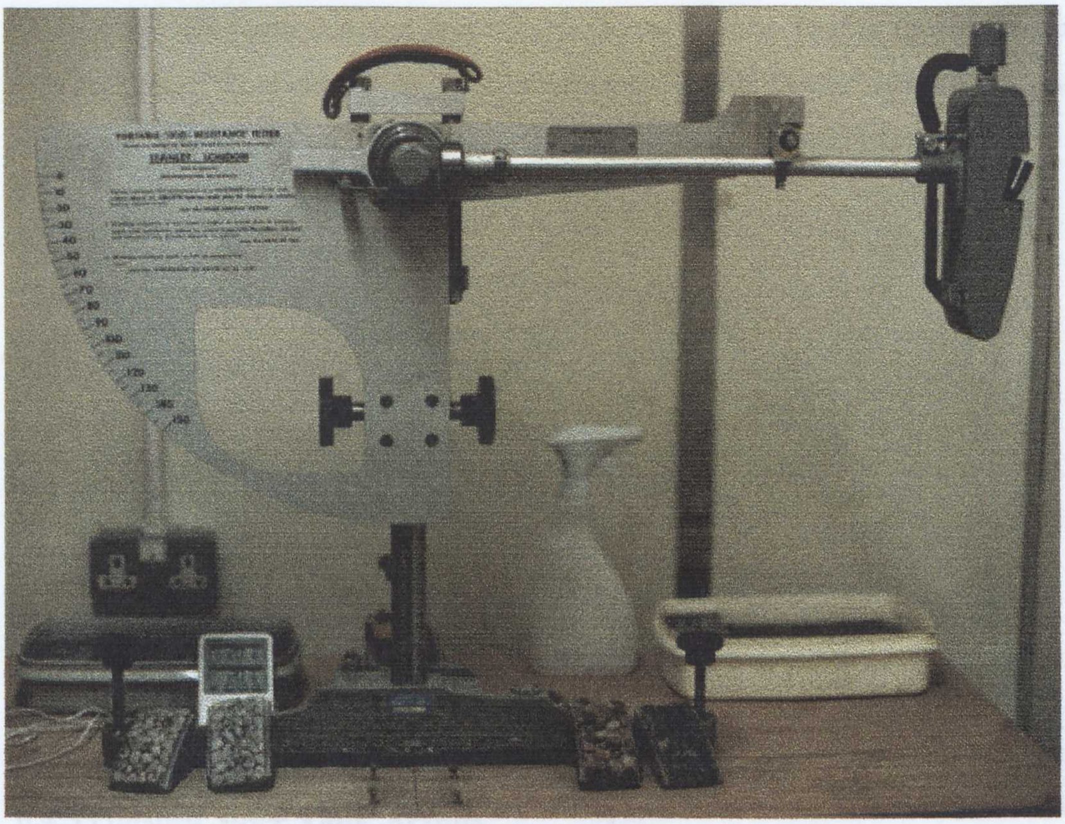


Plate 6.15 The Skid Resistance (Friction) Tester

All samples were polished and skid resistance tested at the Tarmac Quarry Products UK / Stanger laboratories, in Wolverhampton. The polishing method and skid resistance measurement were both in accordance with the British Standard (42).

The results are shown in table 6.6.

Table 6.6 Polished Stone Value Results

Aggregate Type	PSV
Arcow	63
Coated Arcow	59
Croxden	54.5
Coated Croxden	58.5

6.4.3 Polished Stone Value Results

The PSV value obtained for Arcow was 63. This was, as expected, the highest value of all of the aggregates tested, demonstrating Arcow to be the model for high quality aggregate.

The PSV for Croxden was 54.5. This was the lowest value recorded and was as expected for an aggregate with smooth rounded surface characteristics.

The coated Arcow and coated Croxden achieved polished stone values of 59 and 58.5 respectively.

Plates 6.16 and 6.17 show the PSV samples before and after accelerated polishing

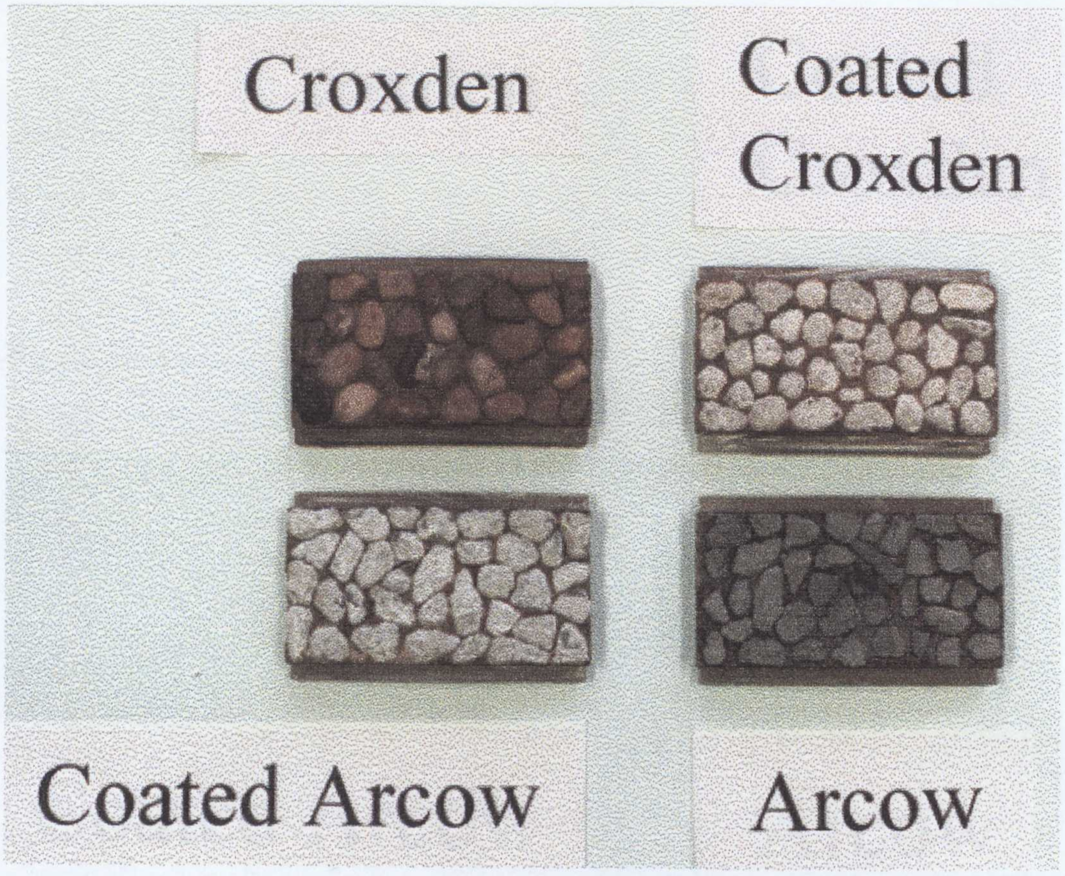


Plate 6.16 The Aggregates Prepared for the Accelerated Polishing

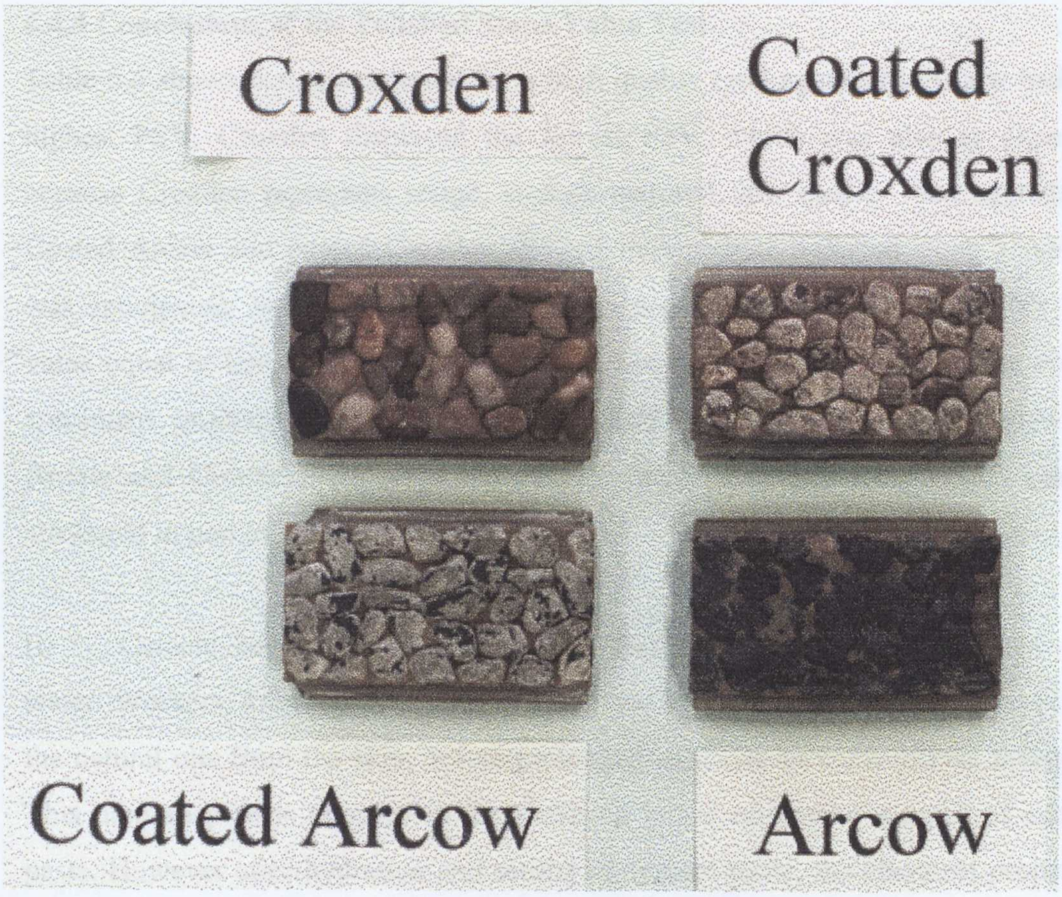


Plate 6.17 Aggregates after Accelerated Polishing

6.4.4 Conclusions of the Polished Stone Value Test

Table 6.6 shows that, as expected for a high quality road aggregate, Arcow had the highest PSV. Croxden displayed the lowest PSV, which was also as expected because Croxden represents round, smooth textured, low quality road aggregates. Coated Arcow and coated Croxden showed intermediate polished stone values. It was anticipated, before testing, that cement coating would increase the PSV to a value equal to that of the Arcow. However, the skid resistance test for the coated specimens produced values approximately half way between those obtained for Arcow and Croxden, see table 6.6. These, lower than expected, values can be attributed in part to two factors;

(i) Cement because of its composition forms a hard soap when mixed with water. Workers, knowing this, use barrier cream to prevent this hard soap stripping the natural oils from the skin, before prolonged exposure to cementitious materials. This hard soap feels slippery to the touch on initial mixing of a batch of cement paste. However after hydration and setting of cement paste, the chemical properties are changed and the slipperiness disappears to the discernible touch. Any remaining unhydrated cement particles, however, can still form hard soaps on exposure to water at a later stage. During the Accelerated polishing process, which uses both water and abrasives, newly exposed unhydrated particles may create fresh hard soaps which act as lubricants during the friction test lowering the measured PSV.

(ii) The cement coating, when applied to the aggregate forms a very intimate contact, filling all the natural cracks in the aggregate. After accelerated polishing the coating is markedly abraded away and polished in the raised areas of the aggregate, but remains in the cracks and the lower areas, being polished there also, see plate 6.17. The nett effect is that the aggregate surface is very smooth with no textured portions to provide a degree of friction. This is in contrast to the uncoated specimens which display lower sections with considerable texture as well as polished raised sections.

From these results, it appears reasonable to conclude that coated aggregates may not be suitable for application at the top surface of high speed wearing courses because of their lack of skid resistance. However for applications at lower speeds, or at locations away from junctions, the use of coated aggregates would seem appropriate.

6.5 The Aggregate Crushing Value Test

6.5.1 Introduction

The aggregate crushing value (ACV) test provides a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load, reference (41). This test is one of the many used to model the behaviour of the aggregate particles exposed directly to the loads applied by the riding vehicles, see sections 2.3.1 and 6.4.1 of this thesis.

6.5.2 The Principle of the Aggregate Crushing Value Test

A test specimen is compacted in a standardised manner into a steel cylinder fitted with a freely moving plunger. The specimen is then subjected to a standard loading regime through the plunger. The action crushes the aggregate to a degree which is dependent on the crushing resistance of the material. This degree is assessed by a sieving test on the crushed specimen and is taken as a measure of the ACV, reference (41).

6.5.3 Aggregate Crushing Value Test Method and Apparatus

A sample of aggregate passing a 14mm sieve and being retained on a 10mm sieve was crushed to the British standard regime. The fines, passing a 2.36mm sieve, resulting from the crushing regime were weighed and their mass was expressed as a percentage of the initial mass of the test specimen.

$$ACV = (M_2 / M_1) \times 100$$

where:

M_1 is the mass of the test specimen (in g).

M_2 is the mass of the material passing the 2.36mm test sieve (in g)

The mean value of only two results was expressed as the ACV, because neither of the two results differed by more than 0.07 times the mean result, in accordance with the British standard.

Detailed apparatus specifications and test methods are found in BS 812: Part 110: 1990, reference (41), to which all aggregate crushing value (ACV) testing for this thesis conforms.

6.5.4 Results of the Aggregate Crushing Value Test

Aggregate crushing values obtained for the uncoated and coated aggregates are shown in table 6.7. With the addition of cement coating the ACV increases from 11 to 16 for Croxden, an increase of 45.4 per cent. Arcow ACV increases from 10 to 13 with the addition of cement coating, an increase of 30 per cent.

Table 6.7 Aggregate Crushing Value Results

Aggregate Type	Aggregate Crushing Value
Arcow *	10
Coated Arcow	13
Croxden *	11
Coated Croxden	16

* Obtained from Quarry Tarmac Products Ltd. quarry specification certificates.

6.5.5 Conclusions of the Aggregate Crushing Value Test

Although increases in ACV of 30 and 45.4 per cent for Arcow and Croxden respectively appear large, the actual ACV's of 13 and 16 are actually quite respectable values. The values of 13 and 16 for the coated aggregates, although not quite as good as the values before coating, indicate the aggregates are quite acceptable for wearing course application.

The change in ACV appears to be directly related to the ability of the cement coating to bond to the aggregate. An examination of the fines passing the 2.36mm sieve revealed that the fines were comprised of a mixture of aggregate shards with cement paste still bonded, and flakes of disbonded cement paste. The Arcow fines had the larger proportion of aggregate shards with cement paste remaining, whilst the Croxden fines were made up of a larger proportion of disbonded cement paste flakes. This gives an indication that the bonding between Arcow and the coating is stronger than the bonding between the Croxden and the coating. This is substantiated by the test for surface roughness, described in section 6.3 of this thesis, which showed that uncoated Arcow has a deeper surface texture than uncoated Croxden, providing a better key for bonding. This is corroborated by researchers Zubelewicz et al. (52) and Perry et al. (53). Another possible reason for debonding of the cement paste, was the effect of differential expansion and contraction of the aggregate and the cement paste shell whilst preparing the aggregates for the ACV test. The differential expansion of the aggregate and cement paste shell would induce stresses on the bonding interface, leading to a breakdown of the aggregate/cement paste bond.

CHAPTER 7

Design of the Bituminous Mixture for Repeat load Axial and Repeat Load Indirect Tensile Testing

7.1 Introduction

This chapter explains the basis for choosing, and the design of the bituminous mixtures used for the repeat load axial test (RLAT) and the repeat load indirect tensile test (RLITT), detailed in chapters eight and nine of this thesis

7.2 Choice of Bituminous Mixture Type for Testing

With the overall aim of this study being to investigate the effect of the cement coating of aggregates on the performance of bituminous mixtures, it was considered essential to choose a bituminous mixture type that would display most clearly the benefits or disbenefits of the coating.

Bituminous mixtures can be divided loosely into two categories; The "Hot Rolled Asphalts" and the "Dense Bituminous Macadams".

Hot rolled asphalt (HRA) mixtures rely almost entirely on the bitumen and filler content of the mixture for their strength. Whiteoak (38) states *"Reliance of the material on the competence of the sand/bitumen fraction, where the mechanical properties are strongly influenced by the bitumen, means that under severe circumstances HRA wearing course may rut."* and *"Bitumen is responsible for the visco-elastic behaviour characteristic of asphalt and it is this which plays a large role in determining the resistance of HRA to rutting."*. It can be seen then, that HRA mixtures may demonstrate changes in bitumen properties very well, but would be useless for demonstrating the effect of differing aggregate properties.

Dense bituminous macadam (DBM) relies not on the filler and binder for its strength, but instead relies on the interlock of the aggregate particles as the major contributor. The authors of reference (54) state "*Coated macadam - a road material consisting of graded aggregate that has been coated with tar or bitumen (or a mixture of the two) and in which the intimate interlocking of the aggregate particles is a major factor in the strength of the compacted material.*". Evidence suggests then, that DBM may be the most suitable material for demonstrating the influence of changing the aggregate properties with cement coating, on the bituminous mixture.

For this study, only aggregate size fractions retained on a 3.35mm sieve or larger could be coated with reasonable success. Therefore to display the effect of the coated material, a mixture design that contained as much material as possible of 3.35mm or larger was required. Three wearing courses were examined to determine their suitability, they were; 14mm size open graded wearing course DBM, 14mm size close graded wearing course DBM and 20mm size porous asphalt PA. The proportion of each mixture whose size was greater than or equal to 3.35mm was compared. The retained mid-point value, of the British standard recipe, reference (47), for each mixture was used for the comparison, see table 7.1

Table 7.1 Comparison of DBM Size Fraction Proportions

Test Sieve Aperture Size	Percentage of Aggregate Retained on Each Sieve		
	Open Graded DBM (14mm)	Close Graded DBM (14mm)	Porous Asphalt (20mm)
20mm	0	0	2.5
14mm	5	2.5	32.5
10mm	30	17.5	-
6.3mm	30	25	40
3.35mm	15	17.5	15
1.18mm	-	15	-
75µm	15.5	17	5.5
<75µm	4.5	5.5	*4.5
Percentage of Material Greater Than 3.35mm	80	62.5	90

* this includes 2 per cent, by mass of the aggregate, hydrated lime

It can be seen in table 7.1 that porous asphalt, also referred to as pervious macadam which is more accurately descriptive, has the highest proportion of particles greater than 3.35mm in size. Therefore porous asphalt (PA) was chosen as the most appropriate material for the RLAT and RLITT, as it was deemed most likely to display conclusive results.

Porous asphalt (PA) like the other DBM's has a standard recipe binder content. However a more thorough way to design PA is to use a binder drainage test to establish the optimum binder content. This is necessary in practise because PA, being very porous in nature, allows oxidising agents such as air and water inside, where embrittlement of the binder causing cracking, quickly sets in, if insufficient binder is used. The binder drainage test ensures that the maximum amount of bitumen is applied to each type of aggregate, without the occurrence of binder drainage during transportation and laying. Target bitumen contents of the PA mixtures for this test programme were therefore designed using the binder drainage test.

7.3 The Binder Drainage Test

7.3.1 Introduction

This section describes the procedure followed to determine the target binder content for the four porous asphalt mixtures used in this study. The procedure followed was recommended in the Transport and Roads Research Laboratory (TRRL) research report No.323 entitled Trials of Porous Asphalt and Rolled Asphalt on the A38 at Burton, reference (55). This draft method was submitted for inclusion in the Department of Transport specification for Highway Works and as British standard DD232: 1996. The procedure is presented in detail in section 7.3.2 of this thesis.

7.3.2 Binder Drainage Test Method

7.3.2.1 Summary

The quantity of binder lost through drainage after three hours at the maximum mixing temperature was measured in duplicate for mixtures with the same aggregate contents, but with different binder contents. The target binder content was defined as the value 0.3 per cent less than that at which 0.3 per cent binder drainage occurs.

7.3.2.2 Apparatus

(i) Digital scales, 5kg Capacity, accurate to 0.1g.

(ii) Oven, vibration free with fan assisted circulation, fitted with a thermostatic control to maintain the temperature to ±1°C in the range 50°C to 200°C.

(ii) Hobart mechanical mixing unit with 10 l capacity, capable of combining the test aggregate and binder quickly and thoroughly without loss.

(iv) Drainage baskets, ten in number, constructed from perforated metal with 3mm diameter holes and with 40 per cent open area on sides and base to form 100mm cubes. Feet were fitted to the bottom corners, 3mm in diameter and 5mm in height.

(v) Disposable aluminium foil trays 150mm in diameter and 10mm deep, ten in number.

(vi) Metal boxes or trays to contain aggregates for heating, eleven in number.

(vii) Spatula, with a blade approximately 150mm long by 25mm wide.

7.3.2.3 Materials

Sufficient aggregates and binder to manufacture approximately 20kg of porous asphalt were required. The aggregates were dried and graded into the fractions appropriate to the specified grading. The aggregate grading for this study complied with the mid-point of the limits specified in table 37 of BS4987: Part 1: 1993: Coated Macadam for Roads and Other Paved Areas - Specification for Constituent Materials and for Mixtures, reference (47). This was with the exception of the 20mm fraction which was slightly amended, see section 7.4 of this thesis. The aggregate grading used can be seen in more detail in table 7.2. The binder used was Lanfina bitumen 100 penetration grade, refined from Mexican crude oil.

Table 7.2 Aggregate Grading used for Binder Drainage Test

Aggregate Size Fraction	Percentage Retained
20mm	0
14mm	35
6.3mm	40
3.35mm	15
75µm	5.5
<75µm	2.5
Hydrated Lime	2
Total	100

7.3.2.4 Procedure

(i) The test was conducted at the temperature specified in table 9/13 of reference (55), reproduced in table 7.3 below, which provided approximate temperatures at which various grades of binder have a viscosity of 0.5 Pa.s.

Table 7.3 Test Temperatures, (ref. 55)

Binder Grade	Test Temperature (°C)
200 pen bitumen	125±1
200 pen bitumen plus 5% natural rubber	150±1
100 pen bitumen	130±1
100 pen bitumen plus 5% natural rubber	160±1

(ii) Eleven batches of 1.1kg of aggregate were weighed in the proportions described in table 7.2. Each batch was then placed in a separate tin.

(iii) The oven was preheated to the maximum mixing temperature, 130°C (table 7.3), before adding the tins with the aggregates, the binder and the mixing implements, which were left to heat for at least two hours prior to use.

(iv) Each disposable aluminium tray was weighed to the nearest 0.1g (W_1).

(v) A 1.1kg batch of aggregate was transferred to the mixing bowl.

(vi) The heated binder was stirred in its container and the required amount of binder, to the nearest 0.5g, was weighed by difference into the mixing bowl to give 3.0 per cent by mass of aggregate.

(vii) The mixing bowl was fitted to the mixer which was run for 60 seconds. Using a spatula any material on the top and sides of the bowl, and the mixing blade was scraped into the mixture. The mixing was then started for another 60 seconds.

(viii) The first mixture was discarded and steps (v) - (vii) were repeated with fresh materials

(ix) The material was then transferred to a basket, ensuring that the mixer bowl and mixing blade were scraped thoroughly using the spatula. This operation was conducted as rapidly as possible to minimise the loss of heat.

(x) The basket was placed on the foil tray and then into the oven at 130°C, (see table 7.3), for between 3 hours and 3.25 hours.

(xi) The basket and tray was then removed from the oven, and the basket removed from the drainage tray. After the tray had cooled sufficiently it was weighed again to the nearest 0.1g (W_2).

(xii) After the first mixture was placed into the oven, the procedure in steps (viii) - - (xi) was repeated for a duplicate sample at the same binder content.

(xiii) The procedure in steps (viii) - (xii) was repeated four times, but increasing the binder content in step (vi) to 3.5, 4.0, 4.5, 5.0 and 5.5 per cent by mass of the aggregate, respectively.

7.3.2.5 Calculations

For each mixture the retained binder (in per cent), R, was calculated from;

$$R = 100 \times B \left[1 - D / (B + F) \right] / (1100 + B)$$

where; D was the mass of the binder and filler drained, [$W_2 - W_1$] (g)

B was the initial mass of the binder in the mixture (g)

F was the initial mass of the filler in the mixture (g)

If, for any pair of mixtures at the same binder content, the difference in retained binder per cent exceeded 0.5 per cent of binder, the procedure in section 7.3.2.4 was repeated for that pair of mixtures.

The mean retained binder content was calculated for each mixed binder content pair. The retained binder content was plotted against the initial mixed binder content, together with the line of equality where the retained binder content equalled the mixed binder content. A smooth curve was then drawn through the plotted values, see figure 7.1. The maximum mixed binder content and the maximum retained binder content were then recorded.

The "maximum mixed binder content" was the mixed binder content at which the retained binder reaches a maximum value. If the retained binder did not peak, it was recorded as being greater than the highest value of mixed binder plotted e.g. "greater than 5 per cent".

The "maximum retained binder content" was the peak value that occurs at the maximum mixed binder content.

The "binder drainage" was the difference in per cent, between the mixed binder content and the retained binder content, at any particular mixed binder content point.

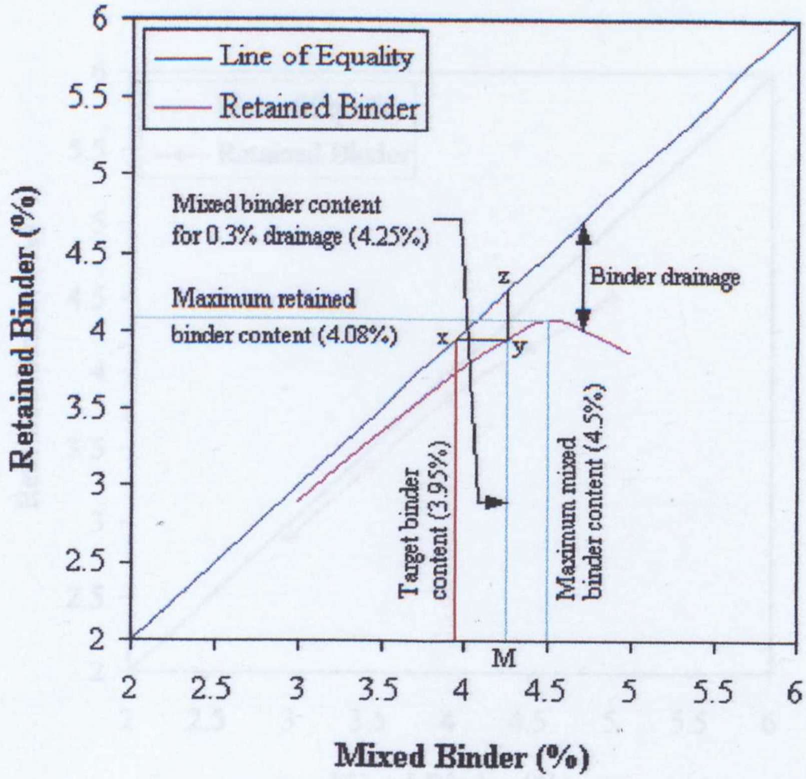


Figure 7.1 Diagram to Indicate Definitions used for Binder Drainage Test Calculations

7.3.2.6 Determination Of the Target Binder Content

From figure 7.1, the mixed binder content (M) was determined where the binder drainage is 0.3 per cent (yz).

The target binder content was (M - 0.3) per cent.

As a check, the abscissa, (xy), should also equal 0.3 per cent between the line of equality and the point on the drainage curve where the binder drainage is 0.3 per cent (yz).

7.3.3 Binder Drainage Test Results

Graphical plots, from which target binder contents were calculated, are shown in figures 7.2 to 7.5 Tabled results are found in table 7.3

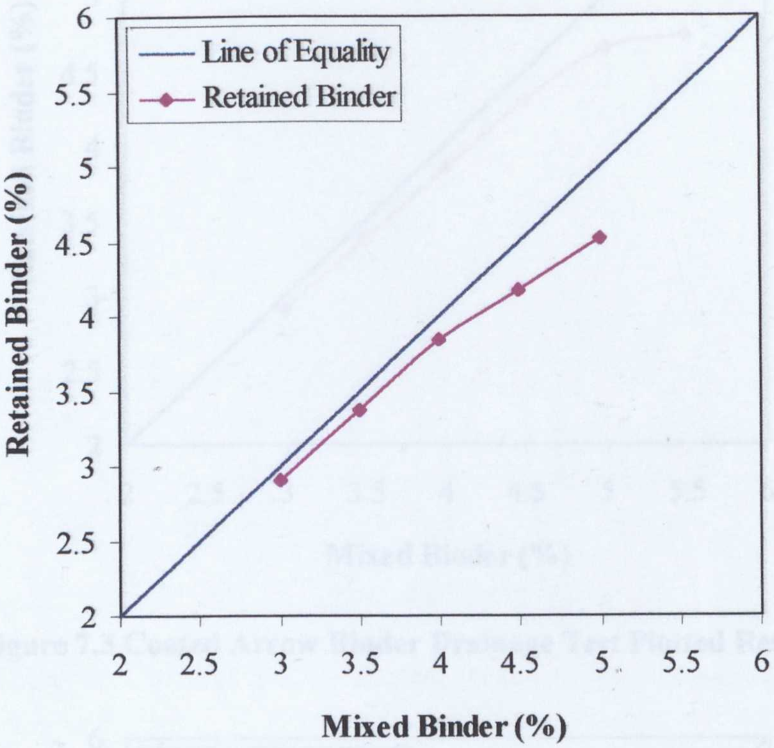


Figure 7.2 Arcow Binder Drainage Test Plotted Results

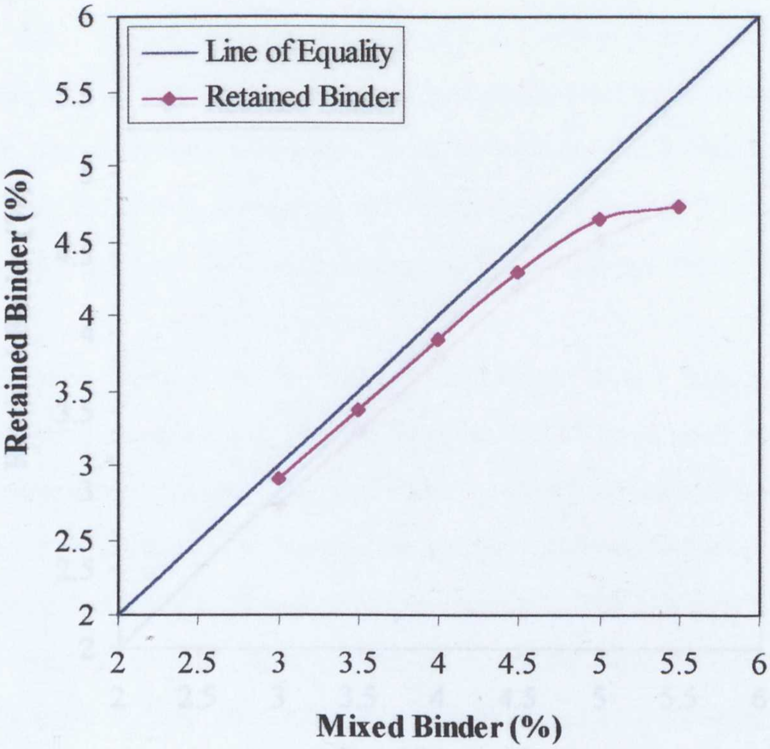


Figure 7.3 Coated Arcow Binder Drainage Test Plotted Results

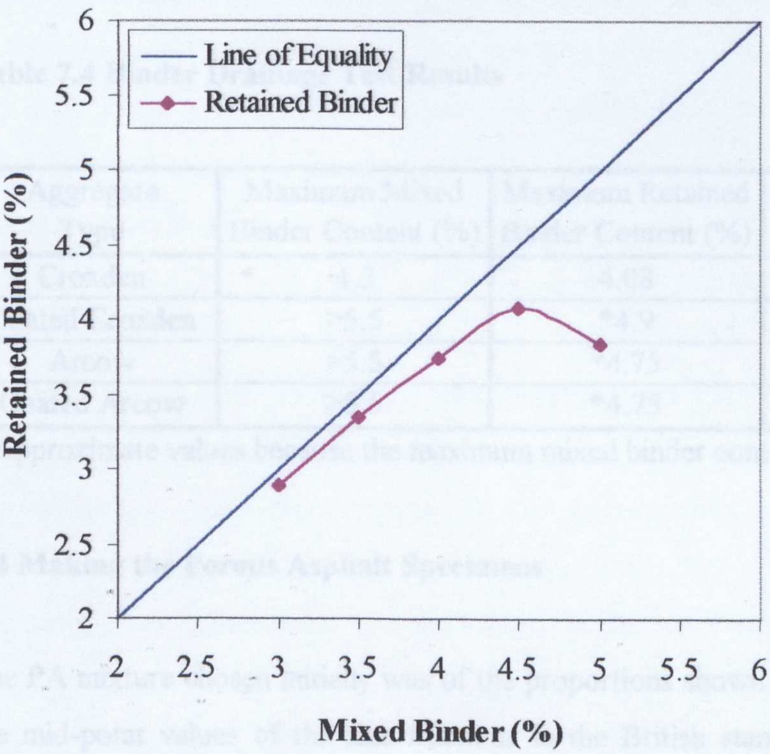


Figure 7.4 Croxden Binder Drainage Test Plotted Results

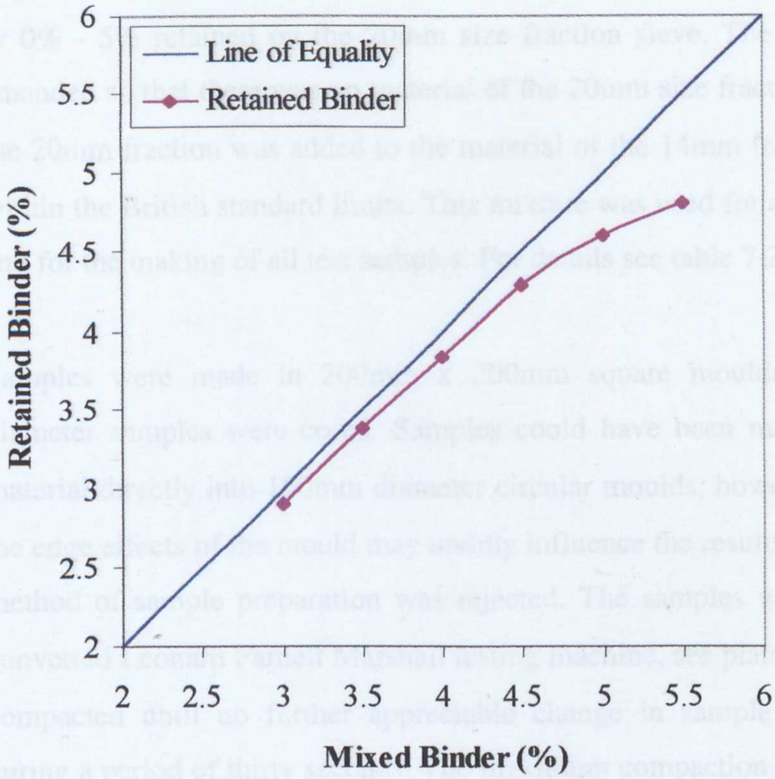


Figure 7.5 Coated Croxden Binder Drainage Test Plotted Results

Table 7.4 Binder Drainage Test Results

Aggregate Type	Maximum Mixed Binder Content (%)	Maximum Retained Binder Content (%)	Target Binder Content (%)
Croxden	4.5	4.08	3.95
Coated Croxden	>5.5	*4.9	4.45
Arcow	>5.5	*4.75	4.2
Coated Arcow	>5.5	*4.75	4.6

* Approximate values because the maximum mixed binder content is greater than 5.5.

7.4 Making the Porous Asphalt Specimens

The PA mixture chosen initially was of the proportions shown in table 7.1, this being the mid-point values of the size fractions in the British standard recipe. However when mixing the ingredients for the binder drainage test, it became clear immediately that the 20mm size fraction was jamming between the mixing blade and the bowl, stalling the mixer. The British standard allowed for a range of 95% - 100% passing, stalling the mixer. The British standard allowed for a range of 95% - 100% passing, or 0% - 5% retained on the 20mm size fraction sieve. The mixture was therefore amended so that there was no material of the 20mm size fraction, and the 2.5% from the 20mm fraction was added to the material of the 14mm fraction, which remained within the British standard limits. This mixture was used for all binder drainage tests and for the making of all test samples. For details see table 7.2.

Samples were made in 200mm x 200mm square moulds from which 150mm diameter samples were cored. Samples could have been made by compacting the material directly into 150mm diameter circular moulds, however it was thought that the edge effects of the mould may unduly influence the results, and consequently this method of sample preparation was rejected. The samples were compacted using a converted Leonard Farnell Marshall testing machine, see plate 7.1. The samples were compacted until no further appreciable change in sample height was evidenced during a period of thirty seconds. The maximum compaction load applied was 40kN. Brennan et al. (56) found 40kN to be the maximum loading appliable before crushing of the aggregate became audible during compaction. Brennan et al. also found that a 40kN compaction load produced void contents of a range similar to those displayed by in-situ road samples. After cooling the sample mould base plates were removed and the moulds were clamped onto the coring machine base for coring. The coring apparatus consisted of a Minute Man® mobile drilling machine bolted to a mass concrete base fitted with holding down bolts for the sample moulds. The coring bit was a 150mm diameter diamond tipped model suitable for concrete, stone and bituminous products supplied by Hilti®. The cored specimens attained an actual diameter of 148mm. The coring apparatus is shown in plates 7.2 and 7.3. Mixture ingredients and the calculations for the mixture ingredient proportions are found in table 7.5 and appendix C of this thesis, respectively. The Actual bulk densities and volumes of voids attained by the test samples are shown in appendix D of this thesis.

Table 7.5 Ingredients for the Porous Asphalt Samples to fill moulds of size 200mm x 200mm

Ingredient	Percentage	Weight of Ingredient (kg)			
		Croxden	Coated Croxden	Arcow	Coated Arcow
20mm Aggregate	0	0	0	0	0
14mm Aggregate	35	1.422	1.317	1.398	1.273
6.3mm Aggregate	40	1.625	1.506	1.598	1.455
3.35mm Aggregate	15	0.609	0.565	0.599	0.546
75μm Aggregate	5.5				
<75μm Aggregate	2.5	0.325	0.301	0.32	0.291
Hydrated Lime	2	0.081	0.075	0.08	0.073
Total Aggregate	100	4.062	3.764	3.994	3.638
Croxden Bitumen	3.95	0.16			
Coated Croxden Bitumen	4.45		0.167		
Arcow Bitumen	4.2			0.168	
Coated Arcow Bitumen	4.6				0.167

The size fractions 75μm and <75μm were combined to reduce dust production during batching, the proportion of each fraction in the overall mixture remained unaltered. The masses of aggregate shown were to produce an aggregate depth of 50mm in the mould, allowing for each of the aggregate's respective bulk densities. Varying amounts of bitumen and relative compactability of the aggregates, resulted in the actual recorded sample depths varying from one aggregate type to another, this is discussed in more detail in section 7.5 of this thesis.

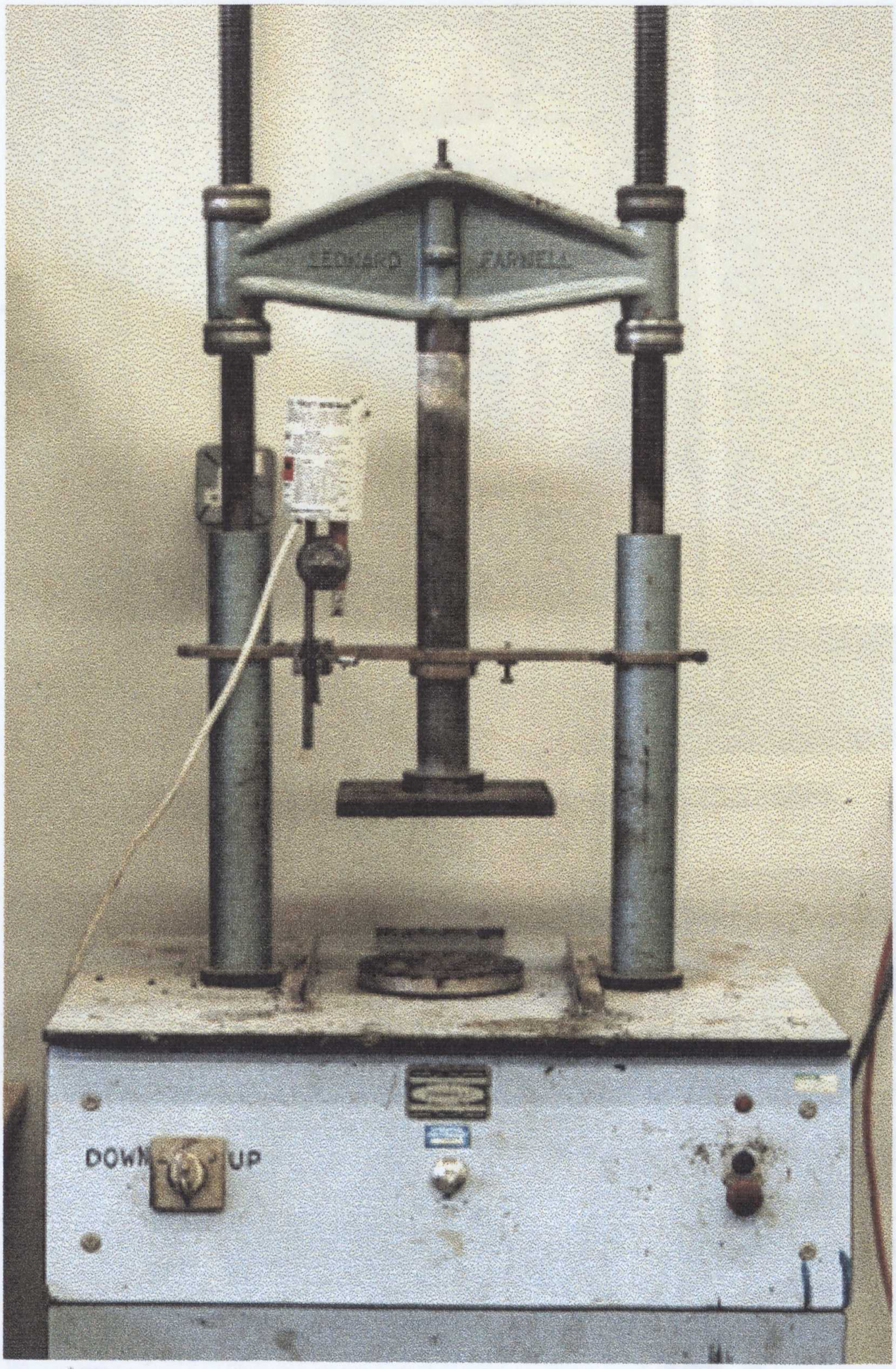


Plate 7.1 The modified Marshall machine compaction apparatus

Plate 7.2 The Coring Apparatus

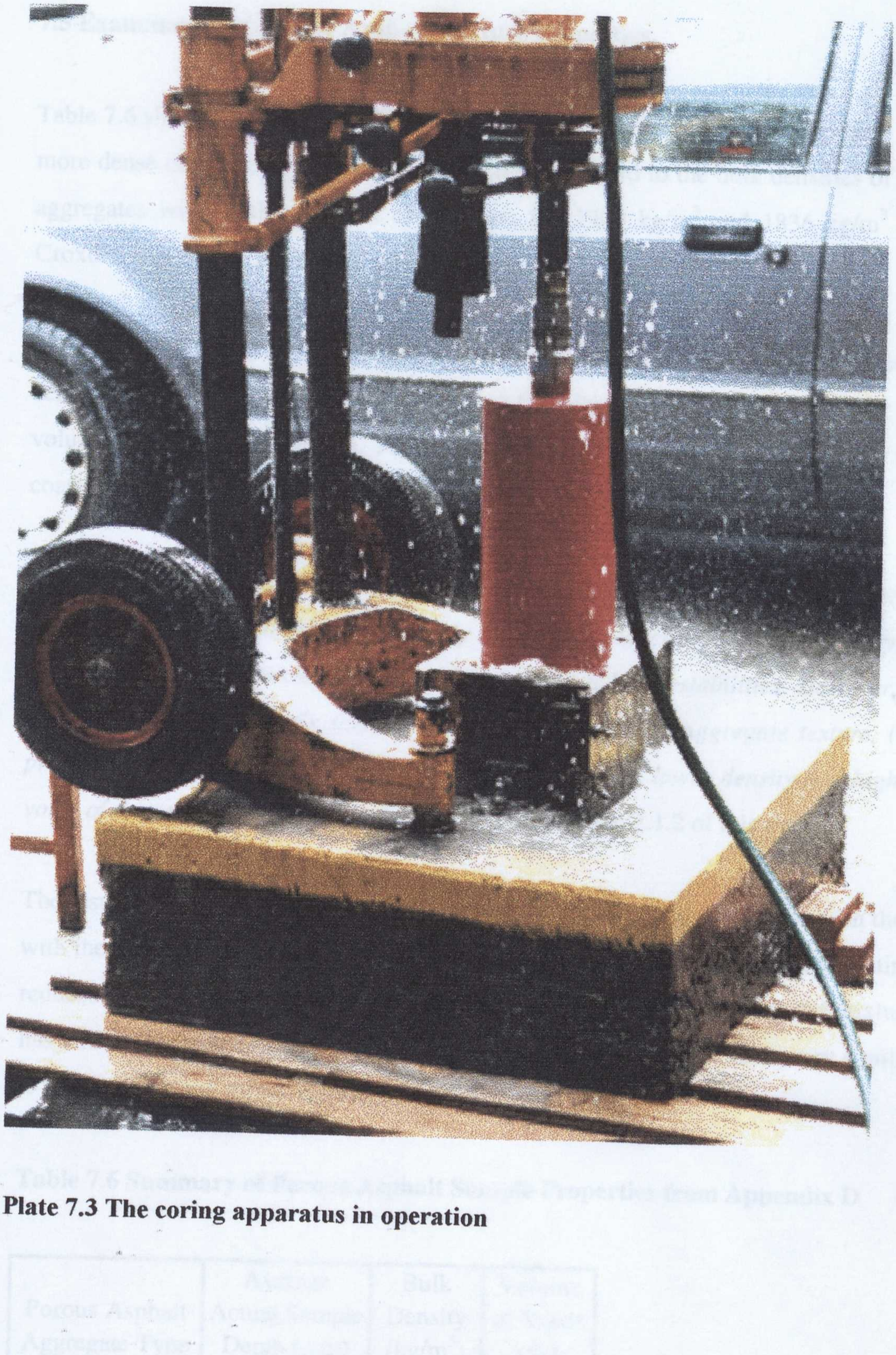


Plate 7.3 The coring apparatus in operation

7.5 Examination of Porous Asphalt Mixture Properties.

Table 7.6 shows that porous asphalt (PA) samples made from Croxden aggregate are more dense than Arcow mixtures. This is directly related to the bulk densities of the aggregates without the addition of bitumen, i.e. 1900 kg/m^3 and 1836 kg/m^3 for Croxden and Arcow respectively.

Table 7.6 also shows that the addition of the cement paste coating reduces the bulk density when it is applied to both Arcow and Croxden Aggregates, and increases the volume of voids in the mixture. This can be attributed to the increased angularity the coating gives the aggregate, impairing compaction, see section 6.2.5 of this thesis.

This very same phenomena was observed by Guirguis et al. reference (17), who states *"The higher void content obviously indicates a reduction in compactability of these mixes and is expected consequently to result in lower stabilities. However, it seems that the gain in mix stability due to enhancement of aggregate texture, (by precoating with cement), is more than the loss due to the lower density and higher voids of the resulting less-compactable mix."*, see section 2.1.2 of this thesis.

The results of Guirguis et al. are shown, in part, in table 7.7 where it can be seen that, with the exception of the untreated mixture, increasing the amount of cement coating reduces the bulk density and increases the percentage of voids. The untreated mixture has a lower bulk density because of its reduced bitumen content. This is very similar to the observations shown in table 7.6.

Table 7.6 Summary of Porous Asphalt Sample Properties from Appendix D

Porous Asphalt Aggregate Type	Average Actual Sample Depth (mm)	Bulk Density (kg/m^3)	Volume of Voids (%)
Arcow	60.3	1788.5	32.77
Croxden	57.6	1915.7	24.84
Coated Croxden	55.5	1834.6	27.29
Coated Arcow	56.6	1745.6	33.51

Table 7.7 Partial Results of Guirguis et al. (ref. 17)

Type and Degree of Cement Treatment	Properties of Compacted Mixture			
	Optimum Binder (mm)	Marshall Stability Ratio (%)	Bulk Density (g/cm^3)	Void Content (%)
Untreated	4	100	2.37	3.1
Light	4.5	104	2.4	3.4
Medium	4.5	109	2.36	4.2
Heavy	4.5	124	2.35	4.9

CHAPTER 8

Repeat Load Indirect Tensile Testing

8.1 Introduction

Determining the indirect tensile stiffness modulus of bituminous material following the British standard DD213: 1993 method (57), using a Nottingham Asphalt Tester (NAT) or its equivalent, is a non destructive method. Samples tested by this method can therefore, be retested using other non destructive or destructive tests and still provide valid results, Brown et al. (58). Repeat load indirect tensile tests (RLITT) were therefore performed on the porous asphalt specimens first, so the specimens could be retested later with the repeat load axial test (RLAT).

Past research has shown that there exists a strong relationship between mixture density and elastic stiffness. The general pattern is that the relationship is mainly linear, with an increase in mixture density yielding a corresponding increase in elastic stiffness, given similar aggregate types and bitumen contents.

Sample results shown in figure 8.1 and table 8.1 from studies by Brown et al. (59, 60), illustrate this relationship.

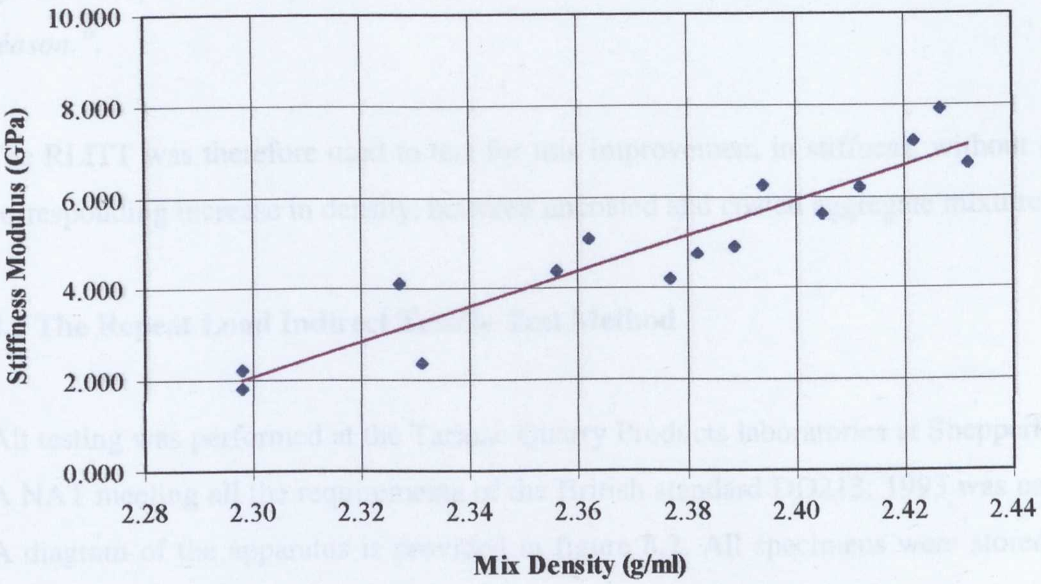


Figure 8.1 The effect of Mixture Density on the Elastic stiffness Modulus of Road Cores Taken from One Batch, (ref. 60)

Table 8.1 The Effects of Compaction and Mixture Density on the Elastic Stiffness Modulus of Dense Bituminous Macadam samples, (ref. 59)

Mass of Binder (%)	Compaction Level	Density (g/ml)	Volume of Voids (%)	Voids in the Mineral Aggregate (%)	Percentage of Refusal Density (%)	Elastic Stiffness (MPa)
5.1	1	2.516	2.1	14.7	100	4700
5.1	2	2.401	6.6	18.6	95.4	3100
5.1	3	2.395	6.8	18.8	95.2	2400

Past results from Guirguis et al. (17), discussed in section 2.1.2 of this thesis suggest however, that with the addition of a cement coating this trend may be reversed. Guirguis et al. state *"The higher void content obviously indicates a reduction in compactability of these mixes and is expected consequently to result in lower stabilities. However, it seems that the gain in mix stability due to enhancement of aggregate texture, (by precoating with cement), is more than the loss due to the lower density and higher voids of the resulting less-compactable mix."* and *"The use of cement-coated aggregates improved the temperature susceptibility of mix stiffness in the low frequency range of 1-4 Hz. This could be interpreted as having better* *dynamic response as a pavement layer under heavy and slow traffic during the hot season.".*

The RLITT was therefore used to test for this improvement in stiffness, without the corresponding increase in density, between uncoated and coated aggregate mixtures.

8.2 The Repeat Load Indirect Tensile Test Method

All testing was performed at the Tarmac Quarry Products laboratories at Shepperton. A NAT meeting all the requirements of the British standard DD213: 1993 was used. A diagram of the apparatus is provided in figure 8.2. All specimens were stored at <5°C until required for testing. The test temperature was 20°C in accordance with DD213: 1993. The NAT machine was calibrated each day before the commencement of testing using the standard system check method detailed in DD213: 1993.

The NAT computer software was used to acquire the stiffness readings, calculated from the applied loads and deformations recorded for each specimen. Five readings were taken for the pulsed loading in one axis. The mean of these five readings was recorded. A second axis was selected at an angle of 90 degrees to the first, and the test repeated. The mean value of stiffness modulus from this second test were compared with the results of the first test. If the mean result from the second test was within +10% of -20% of the mean value for the first test, the mean of the two results was calculated and recorded as the stiffness modulus for the specimen. If the difference between the two values was greater than that specified above, then the results were rejected. Figure 8.3 shows a specimen NAT computer program output.

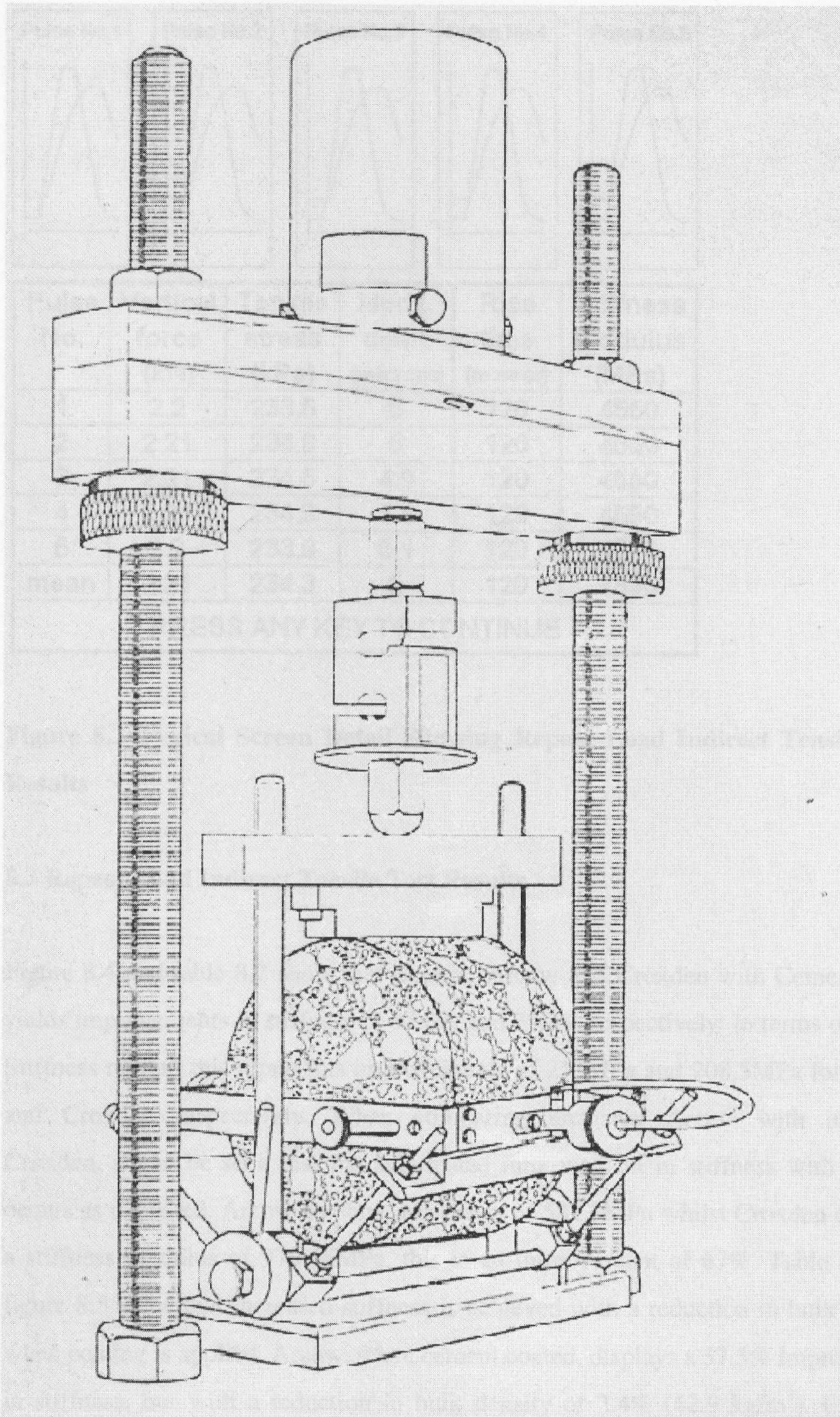
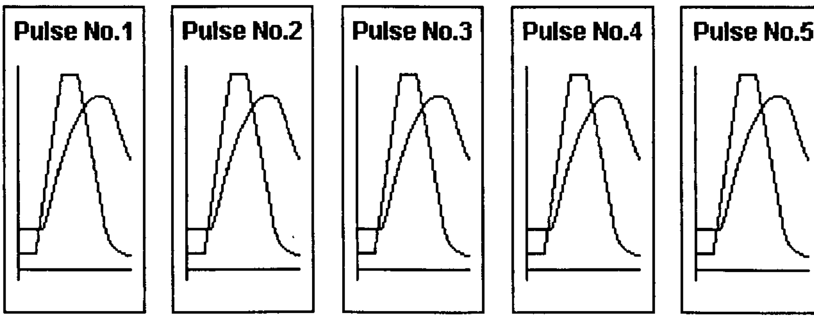


Figure 8.2 Repeat Load Indirect Tensile Test Apparatus



Pulse No.	Vertical force (kN)	Tensile stress (kPa)	Horiz. defm. (microns)	Rise time (m.secs)	Stiffness modulus (MPa)
1	2.2	233.5	5	120	4550
2	2.21	234.8	5	120	4550
3	2.21	234.5	4.9	120	4550
4	2.21	234.9	5.1	120	4550
5	2.2	233.9	5.1	120	4500
mean	2.21	234.3	5	120	4550
PRESS ANY KEY TO CONTINUE					

Figure 8.3 Typical Screen Detail Showing Repeat Load Indirect Tensile Test Results

8.3 Repeat Load Indirect Tensile Test Results

Figure 8.4 and table 8.2 show that Coating Arcow and Croxden with Cement paste yields improvements in stiffness of 37.5% and 21.5% respectively. In terms of actual Stiffness moduli this represents improvements of 218MPa and 208.5MPa for Arcow and Croxden respectively. When comparing uncoated Arcow with uncoated Croxden, it can be seen that the anticipated improvement in stiffness with density occurs as expected. Arcow displays a stiffness of 581.8MPa whilst Croxden displays a stiffness modulus of 970.65MPa, this is an improvement of 67%. Table 8.2 and figure 8.5 show that increased stiffness is achieved with a reduction in bulk density when coating is applied. Arcow, when cement coated, displays a 37.5% improvement in stiffness, but with a reduction in bulk density of 2.4% (42.9 kg/m^3). Croxden, when cement coated, displays a 21.5% improvement in stiffness, but with a reduction in bulk density of 4.2% (81.1 kg/m^3). All average results for each sample group were significance tested using the student "T" test. They were found to be significant to the highest degree of significance commonly found in the T tables.

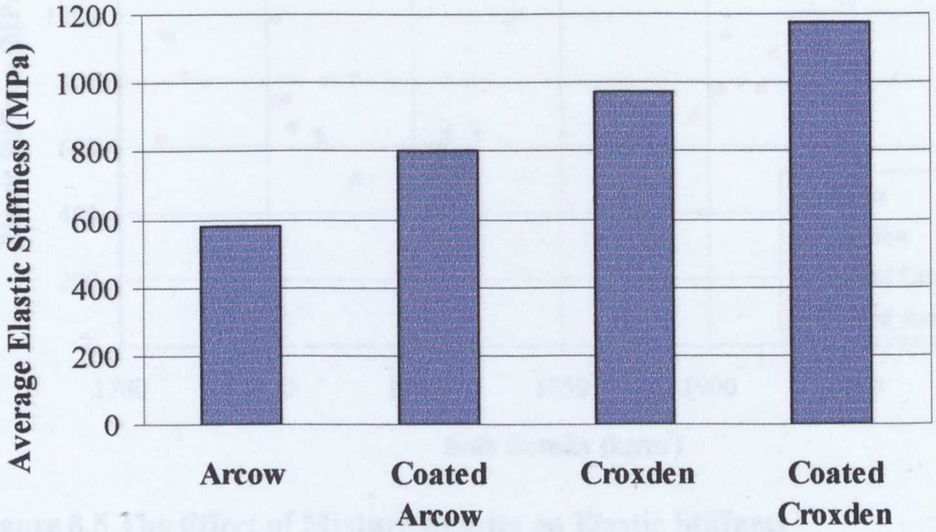


Figure 8.4 Results of the Repeat Load Indirect Tensile Test

Table 8.2 Results of the Repeat Load Indirect Tensile Test

Porous Asphalt Aggregate Type	Bulk Density (kg/m^3)	Average Elastic Stiffness (MPa)
Arcow	1788.5	581.80
Coated Arcow	1745.6	799.80
Croxden	1915.7	970.65
Coated Croxden	1834.6	1179.13

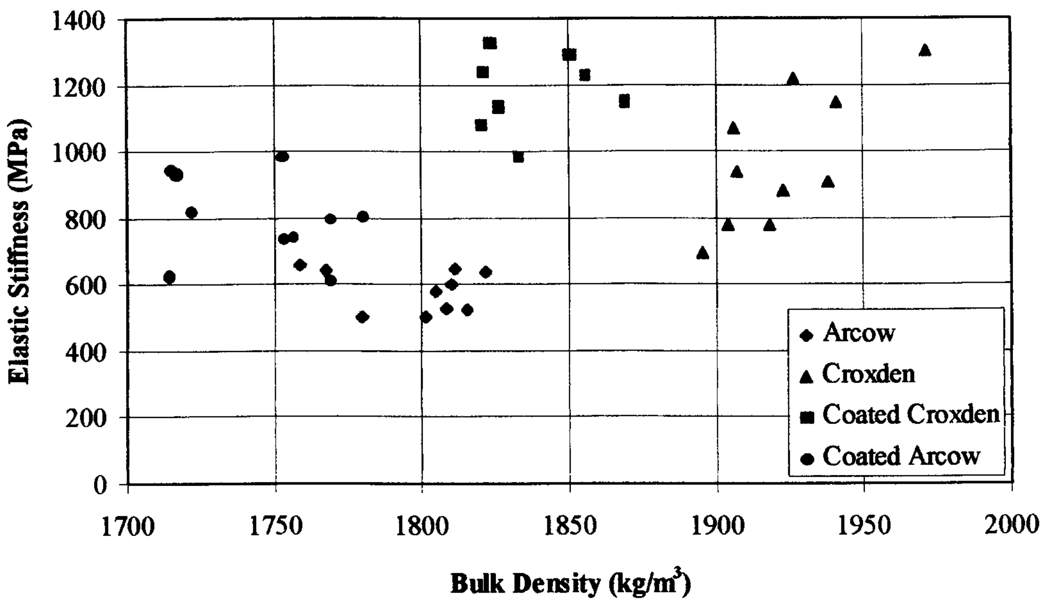


Figure 8.5 The Effect of Mixture Density on Elastic Stiffness

8.4 Discussion of the Repeat Load Indirect Tensile Test Results

Very little published data exists with values of elastic stiffness for porous asphalt. To put the values obtained in this study into perspective, the results of this study can only be compared with what little data exists. Scott Wilson Pavement Engineering Ltd. (SWPE), provided one study containing porous asphalt results, reference (61). The results of this study are shown in figure 8.3.

Table 8.3 Porous Asphalt Elastic Stiffness Results from Scott Wilson Pavement Engineering Ltd.

Core Reference	Bulk Density (kg/m^3)	Void Content (%)	Elastic Stiffness (MPa)		
			0°C	10°C	20°C
1	1712	31.3	3250	1160	400
2	1851	25.7	5110	1560	590
3	1781	28.5	3700	1250	500
4	1777	28.7	3490	1730	520
5	1803	27.6	3650	1210	490

The results in table 8.3 show porous asphalt with similar bulk densities and void contents to the porous asphalt produced for this thesis. The Elastic Stiffnesses for the samples tested at 20°C, shown in table 8.3 are, for approximately equal mixture densities to uncoated Arcow, of similar stiffness to uncoated Arcow. They are however more than 40% weaker than the average stiffness value of the specimens tested in this thesis.

Volume seven of the Design Manual for Roads and Bridges (62), states, *"The structural equivalence of a 50mm thickness of PA is considered to be 40% of that of a HRA wearing course, and one might reasonably deduce that the stiffness of the PA would be expected to be around 40% of that of HRA."*. SWPE's database provided typical stiffness values for hot rolled asphalt ranging from 1200-3000MPa. Taking the mid-point of this range, (2100MPa), 40% is 840MPa which suggests that the SWPE results for porous asphalt are on the low side. This conclusion was upheld by SWPE.

The average elastic stiffness results from this thesis fall around 880MPa which falls within the mid-range of the expected values stated by the Design Manual for Roads and Bridges, reference (62).

With the results set in perspective, the first and most important conclusion to be drawn is that the addition of cement coating does appear to increase the elastic stiffness of the porous asphalt mixtures. However the magnitude may not be quite as great as that initially indicated by the results. The mixtures were all produced with optimum target binder contents derived from the binder drainage test. As a result of this design method, the coated aggregates received a higher percentage of binder than the uncoated aggregates, (table 7.3 of this thesis). However the actual masses of binder used vary only slightly because of the bulk densities of the various aggregates, (table 7.4 of this thesis), and the binder film thickness looked very uniform when comparing all the different samples during testing. In a porous asphalt mixture where aggregate interlock plays such an important role in the overall strength, and the effect on the elastic stiffness of the cohesional component, provided by the binder, is considered marginal, this component should however, not be overlooked. The effect of the binder although marginal and not easily quantified does have an effect on the elastic stiffness of the mixtures. The cement coated samples therefore show an improvement whose magnitude is not solely due to the effect of the coating, but due in part, however small, to the increased binder content also.

It can also be concluded that in accordance with the findings of Guirguis et al. (17) the elastic stiffness of coated aggregate mixtures, increases without a corresponding increase in mixture density. This can be attributed mainly to the increased surface roughness and aggregate particle interlock as investigated in chapter six of this thesis, although the increased bitumen content does play a small part.

CHAPTER 9

Repeat Load Axial Testing

9.1 Introduction

Simple uniaxial creep tests have been used since the early 1970's. However they are now being superseded by repeated load tests. Repeated load tests are considered more representative of field conditions and are considered better able to distinguish between mixtures with different aggregate characteristics. The repeat load axial test's ability to rank mixtures is illustrated by figure 9.1, taken from reference (63).

Variable	Description	Reference Code
Bitumen Type	Boscan	B
	Valley	V
Binder Content	Optimum	0
	High	1
Aggregate Type	Texas Chert	T
	Watsonville Granite	W

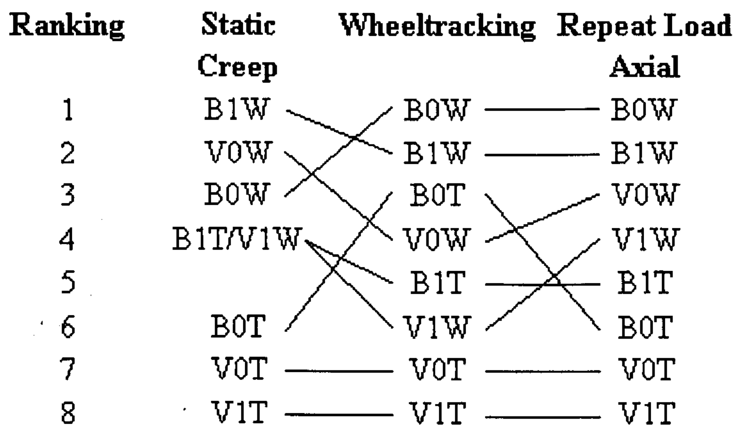


Figure 9.1 Ranking of Bituminous Mixtures (ref. 63)

The repeat load Axial Test (RLAT) has been used extensively to measure resistance to permanent deformation, both in mixture design, Gibb et al. (64), and for retrospective studies, Brown et al. (60). For bituminous mixtures such as porous asphalt where deformation resistance depends crucially on the aggregate interlock component, a degree of confinement is preferable to fully mobilise this component, Brown et al. (58). Other test apparatus such as the repeat load triaxial cell, and the wheeltracking apparatus provide the degree of confinement that would make them slightly more suitable for testing porous asphalt, however neither piece of apparatus was available, or buildable at LJMU.

For the purpose of this study it was considered more important to rank the porous aggregate samples and show the degree of change with cement paste coating, than to very accurately quantify the anticipated road performance of each of the sample group types. Therefore the RLAT test in accordance with DD226: 1996 (reference 65) was chosen for assessing the permanent deformation resistance of the porous asphalt mixtures with and without the addition of the cement paste coating.

9.2 The Repeat Load Axial Test Apparatus

RLAT apparatus was assembled at LJMU using the following parts:

(i) A Mayes® universal test machine with a hydraulic load actuator.

(ii) A 10 kN loadcell calibrated in accordance with BS1610: Part 1, to NAMAS grade 0.5.

(iii) Loading platens 200mm in diameter, lathed and polished to a flatness tolerance of not more than 0.03mm over the platen width. The Mayes® universal test machine applies the load from below, therefore the upper load platen was securely fixed to the loading frame, with the bottom platen allowed freedom of movement with a spherical seating. The Mayes® universal test machine supplied the constant stress of 2 kPa ± 10% usually applied by the mass of the top platen.

(iv) The Mayes® universal test machine's signal generator load application system capable of applying the required repeated load to produce a transient stress of 100 kPa ± < 2 kPa. The total duration of the axial load pulse being one second ± < 10 ms in accordance with the BS DD226: 1996 specifications. Typical values for the square wave load application produced by the Mayes® universal test machine are shown in figure 9.2 and plate 9.1.

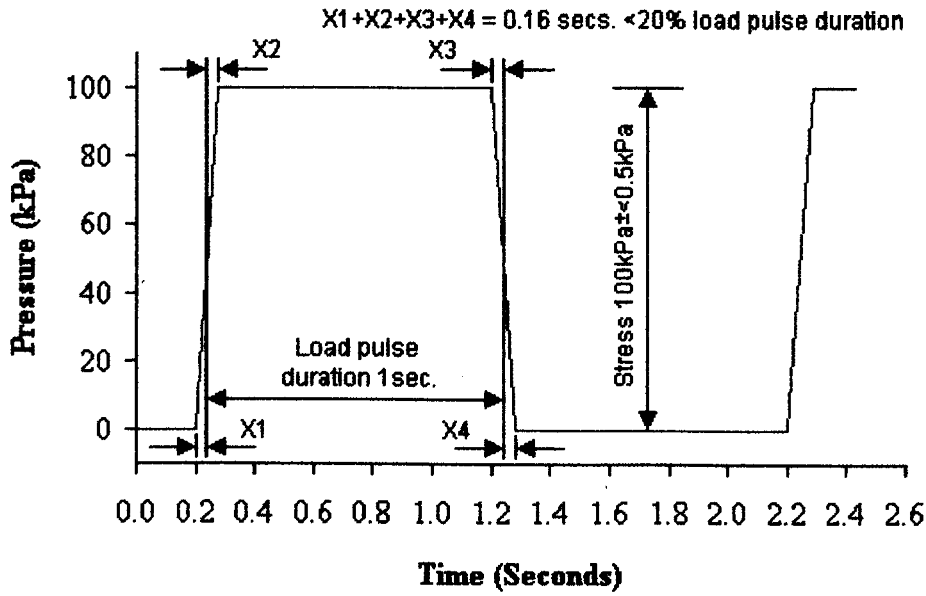


Figure 9.2 RLAT Square Wave Load Application

(v) Four electrical displacement transducers with a range of 50mm with an accuracy of greater than 0.05% over the range.

(vi) A 75mm thick polystyrene constant temperature enclosure cabinet with forced air circulation, enclosing the platens, transducer mounting frame and three to four spare specimens. See plate 9.2. An environmental chamber was used to store extra spare specimens at test temperature.

(vii) A LabVIEW® application was used to monitor and record permanent deformation, angle of tilt and load application, and control the temperature of the heated cabinet to the test temperature 30°C ± 0.25°C. For more details of the LabVIEW® software see chapter five of this thesis.

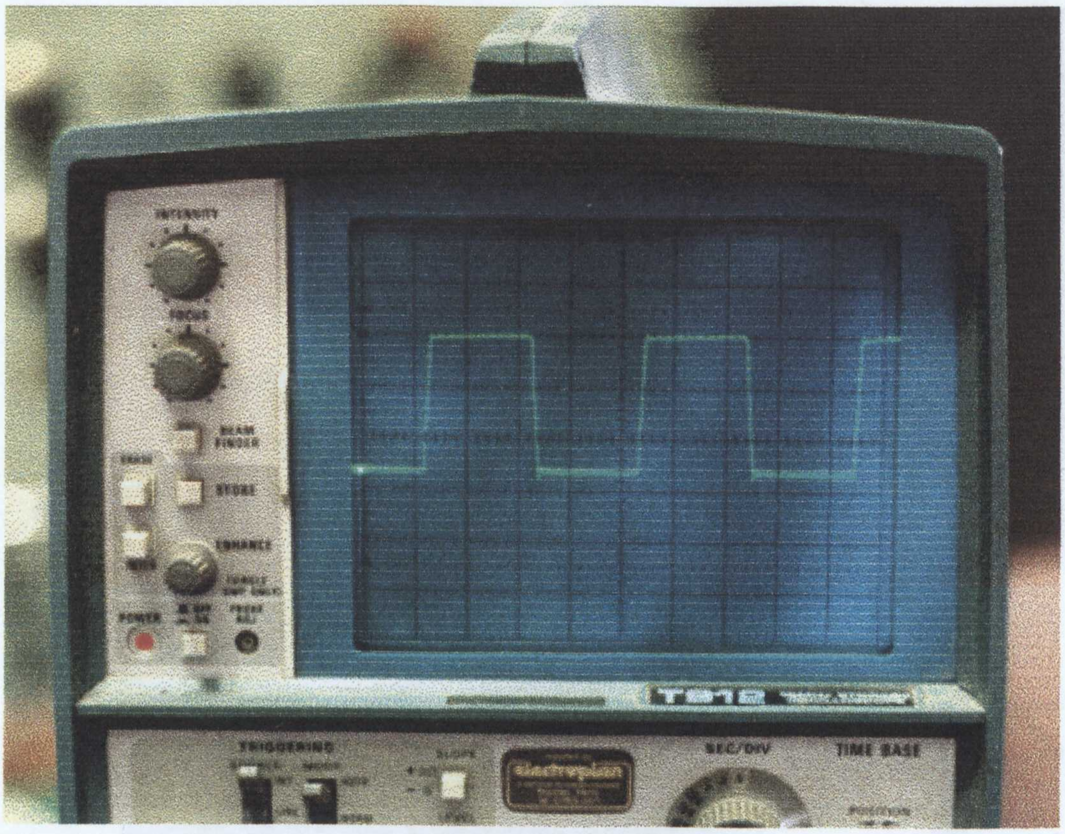


Plate 9.1 A Typical Square Wave Load Applied by the Mayes® Universal Test Machine

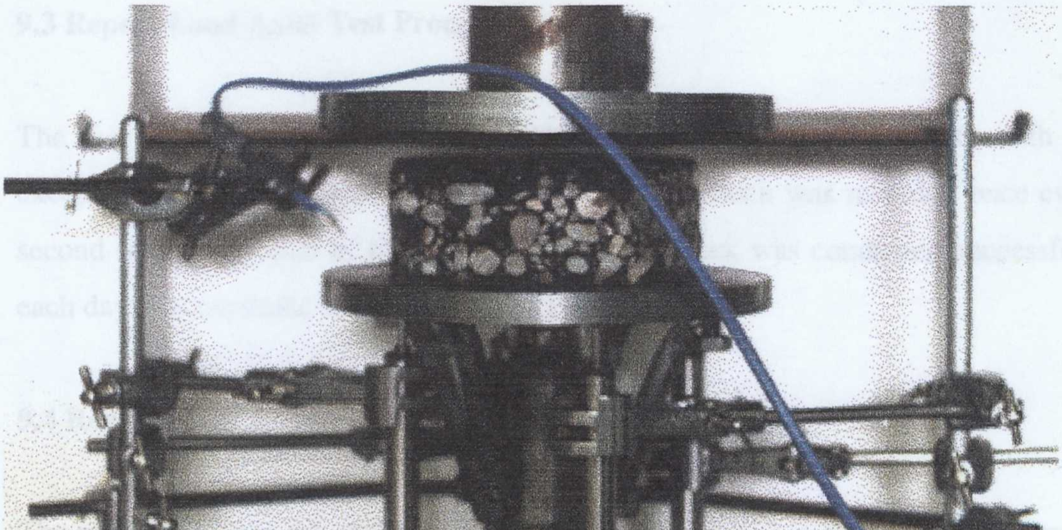


Plate 9.2 The Loading Platens, Transducers and Their Mounting frame, Loadcell and Heated Enclosure Cabinet (background)

9.3 Repeat Load Axial Test Procedure

The test procedure was wholly in accordance with BS DD226: 1996, with the exception of the measurement of axial deformation which was recorded once every second for the duration of the test. A calibration check was conducted successfully each day in accordance with BS DD226: 1996.

9.4 Repeat Load Axial Test Results

The mean displacement of the four transducers was placed in the following formula to give percentage axial deformation.

$$\text{Percentage axial deformation} = (\Delta h / h_0) \times 100$$

where: h_0 is the original thickness of the specimen (mm)
Δh is the axial deformation (mm)

The percentage axial deformation was calculated once each second and plotted against time to produce a graph, a specimen of which is shown in figure 9.3. The percentage axial deformation at 3600 seconds, the test duration, was recorded as the result for that particular specimen. Between twelve and fifteen specimens completed one sample type group. The average value of each group was tested for statistical significance using a student "T" test. It was found that all the groups averages displayed significant difference when compared one with another, with the exception of the two coated sample groups which when compared were significantly similar.

Group average results are shown in figure 9.4 and table 9.1.

The complete set of individual results are shown in appendix E

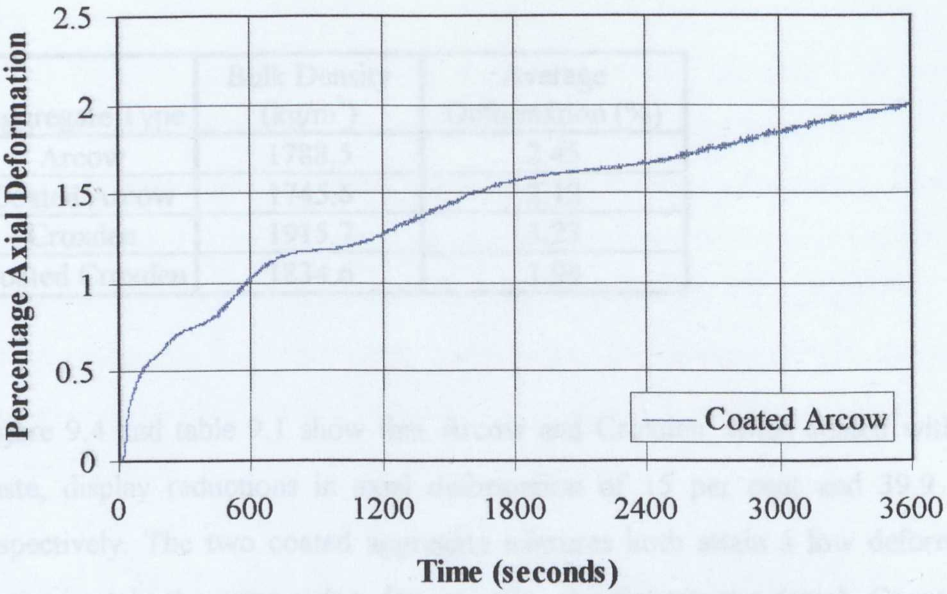


Figure 9.3 Typical Displacement Versus Time Graph Recorded Using the LabVIEW® Software

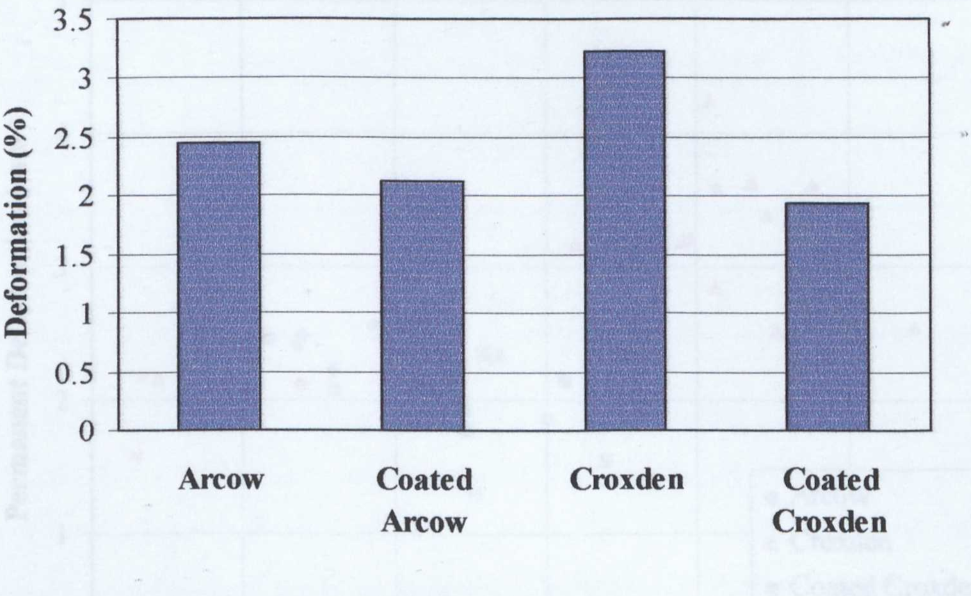


Figure 9.4 Results of the Repeat Load Axial Test

Table 9.1 Results of the Repeat Load Axial Test

Aggregate Type	Bulk Density (kg/m^3)	Average Deformation (%)
Arcow	1788.5	2.45
Coated Arcow	1745.6	2.12
Croxden	1915.7	3.23
Coated Croxden	1834.6	1.94

Figure 9.4 and table 9.1 show that Arcow and Croxden, when coated with cement paste, display reductions in axial deformation of 15 per cent and 39.9 per cent respectively. The two coated aggregate mixtures both attain a low deformation of approximately the same value, (statistically, significantly the same). Comparing the deformation results with the corresponding bulk densities, table 9.1 and figure 9.5, a reduction in bulk density between uncoated and coated materials yields a corresponding reduction in axial deformation.

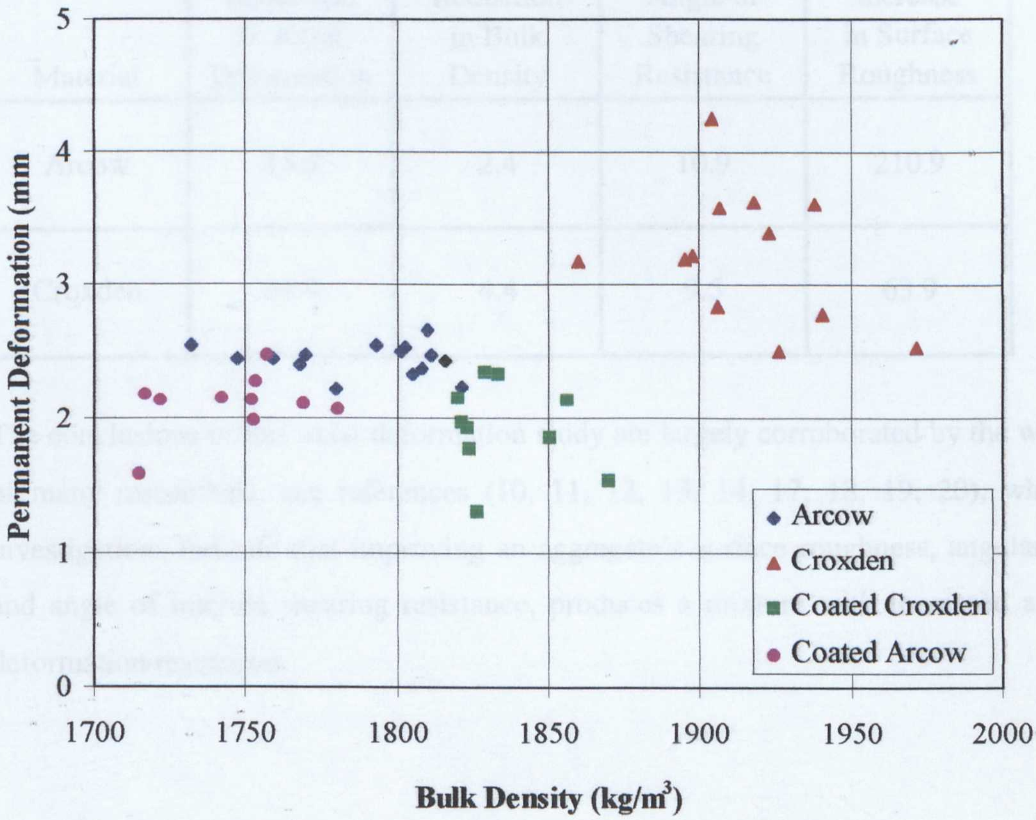


Figure 9.5 The Effect of Mixture Density on Axial Deformation

9.5 Conclusions of the Repeat Load Axial Test

It can be quite simply concluded that coating of the aggregate with cement paste decreases the amount of axial deformation, demonstrating that resistance to permanent deformation, (rutting) has increased. It appears that this is closely related to the reduction in bulk density of the coated mixtures, which is in turn related to the increased angularity and surface roughness investigated in chapter 6. Table 9.2 clearly illustrates this relationship by comparing the changes in bulk density, angle of shearing resistance, surface roughness and axial deformation with the addition of cement coating.

Table 9.2 The Change in Axial Deformation, Bulk Density, Angle of Shearing Resistance and Surface Roughness with the Application of Cement Coating

Percentage Change in Property with the Addition of Cement Coating				
Material	Reduction in Axial Deformation	Reduction in Bulk Density	Increase in Angle of Shearing Resistance	Increase in Surface Roughness
Arcow	15.6	2.4	10.9	210.9
Croxden	39.9	4.4	9.5	63.9

The conclusions of this axial deformation study are largely corroborated by the work of many researchers, see references (10, 11, 12, 13, 14, 17, 18, 19, 20), whose investigations indicate that improving an aggregate's surface roughness, angularity, and angle of internal shearing resistance, produces a mixture with increased axial deformation resistance.

CHAPTER 10

Conclusions and Recommendations

10.1 Introduction

The results and analysis of the background and experimental investigations presented in this thesis produced a number of new and important findings. The thesis clarifies the fundamental properties required of an aggregate to produce the mechanical properties required for a successful bituminous mixture. More importantly it demonstrates the properties of a cement coating, a coating that was found to improve the performance of bituminous materials.

The main objective of this thesis was to investigate the properties of a cement coating, designed as an aggregate enhancer for bituminous mixtures. This objective was met by adopting a research plan that tested the following phrases theoretically from literature, and by experimental method:

(i) What, by literature review, are the aggregate properties considered necessary for successful bituminous mixture production and how do these compare with the properties of aggregate coated with cement paste?

(ii) How does the chemical affinity between cement paste and bitumen,compare with the chemical affinity between aggregate and bitumen?

(iii) What are the beneficial physical properties of cement coated aggregates, and how do they compare with the properties of uncoated aggregates?

(iv) What is the magnitude of the effect of including coated aggregates in a bituminous road pavement mixture and how does its performance compare with the performance of mixtures made from uncoated aggregates?

The implementation of this thorough research plan has resulted in a number of important findings that are summarised in the following section.

10.2 Summary of Findings

In general the findings of this research were very conclusive. The cement coating behaved very well during chemical testing, proving itself to be very amenable to bonding with bitumen, and very resistant to the degrading effect of water ingress. Net adsorption, representing resistance to stripping, was improved by a factor of more than two, see table 10.1. This was in conformity with the results hypothesised from the background reading.

The physical properties of the aggregates tested were substantially improved with the addition of cement coating. The angle of internal shearing resistance and surface roughness of the aggregates were improved considerably - enhancing the strength of bituminous products made from them. This was in agreement with the literature review hypothesised outcome. The addition of cement coating, however, reduced the performance of the Arcow aggregate during polished stone value testing and the performance of Arcow and Croxden during aggregate crushing value testing. The effect of the addition of the coating on the resistance to polishing and crushing was not known at all before this investigation, and those results obtained have highlighted areas for future developmental work.

Using coated aggregate for the manufacture of porous asphalt yielded very pleasing results. Elastic stiffness and resistance to axial deformation were improved by quite significant factors with the addition of cement coating, see table 10.1 for a summary. The literature review revealed that some improvement would be evidenced, and this improvement was anticipated to be of only a small magnitude, however the improvements were much greater than anticipated.

Table 10.1 Summary of Research Findings

	Percentage Change in Property with the Addition of Cement Coating							
	Porous Asphalt Specimens							
Aggregate Type	Increase in Elastic Stiffness	Reduction in Axial Deformation	Reduction in Bulk Density	Increase in Angle of Shearing Resistance	Increase in Surface Roughness	Change in Polished Stone Value	Increase in Aggregate Crushing Value	Increase in Net Adsorption
Arcow	37.5	15.6	2.4	10.9	210.9	6.3 decrease	30	108
Croxden	21.5	39.9	4.4	9.5	63.9	7.3 increase	45.4	116

The specimen manufacture and testing apparatus developed by the researcher and built at LJMU proved to be accurate, yielding consistent, repeatable results, and was always within British standard specifications. The LabVIEW® software proved itself reliable, stable and bug free and, combined with the National Instruments hardware, provided an excellent means to acquire test data.

10.3 Identification of Testing Method Deficiencies

All of the tests used for this study had recognised British Standard, or British Standard Draught for Development status, and were therefore considered, largely, fundamentally correct.

Repeat load indirect tensile testing calculations require an approximation to the Poisson's ratio for the bituminous mixture being tested, the estimation being specified for a range of test temperatures by the British Standards Institution in BS DD213: 1993, reference (57). It can be suggested however, that mixture properties, such as bulk density, bitumen content and aggregate grading, as well as the test temperature, all affect the Poisson's ratio of the material being tested. The approximation to the Poisson's Ratio was seen as the cause of an enlarged result spread for each sample type tested.

For repeat load axial testing the results obtained were adequate. However a degree of confinement for the porous asphalt being tested would have been preferable. It became evident however, that no existing standardised equipment, and very little literature to aid with the development of a repeat load triaxial cell or similar, was available.

10.4 Recommendations for Future Work

10.4.1 Recommendations for Development of Testing Apparatus

For testing of porous asphalt specimens, and other bituminous mixtures that rely mainly on aggregate interlock for their resistance to permanent deformation, the development of a repeat load axial test with a degree of confinement would be of great benefit. This could take two possible forms:

(i) A repeat Load triaxial cell type arrangement through which various degrees of confining pressure could be applied to model the confinement usually supplied by the surrounding asphalt layer.

(ii) A Nottingham Asphalt Tester (NAT) type machine with specimens larger than the loading platens, the extra specimen material providing the confinement. Brown et al. (60, 64, 66, 67) have suggested this possibility in minor detail, but as yet no correlation between ratio of platen and specimen size and the effective degree of confinement has been investigated.

Another piece of test apparatus that would benefit from further refinement is the repeat load indirect load tensile test apparatus. For calculation of stiffness modulus an estimation of Poisson's ratio is assumed for all test conditions and material types. However as explained in section 10.3 of this thesis this cannot be so. The estimation to Poisson's ratio could be eliminated by providing a measurement system capable of monitoring the transient vertical deformation, as well as the transient horizontal diametral deformation of the specimen during the application of a load pulse. Poisson's ratio could then be simply calculated from the formula;

$$\text{Poisson's Ratio} = \Delta h / \Delta v$$

where; Δh is the maximum horizontal diametral deformation of the specimen during application of the load pulse.

Δv is the maximum vertical deformation of the specimen during application of the load pulse.

10.4.2 Recommendations for Further Refinement of Cement Coating

Although the addition of cement coating improves some of the qualities of aggregate, enabling better bonding to bitumen, stronger mixtures and greater durability, some of the aggregate properties, namely polishing resistance of the Arcow, and crushing resistance of both Arcow and Croxden are not improved. Without improvements, especially to the polishing resistance, the cement coated aggregate could only be used in a road for replacement of the current base or grading courses. If the aim was to road trial the cement coated aggregate material as a wearing course, the problems with polishing and crushing resistance would have to be rectified. In order to reach road trial stage it is therefore recommended that the following studies are performed;

(i) Aggregate crushing and impact value testing on aggregates with cement coatings made with bond enhancing additives.

(ii) Aggregate crushing and impact value testing on aggregates with high temperature boiler/furnace cement to combat the effects of the high oven temperatures during drying of the aggregates and mixing of the asphalts.

(iii) Polished stone value testing on aggregates with cement coating that includes varying proportions of angular fine aggregates. The addition of fine aggregate is known to improve the resistance of cement pastes to elastic stresses. These elastic forces are exerted by heating and cooling the aggregate during drying and mixing, therefore the effect of the fine aggregate on crushing and impact values should also be investigated.

Providing sufficient improvement in polished stone and aggregate crushing values are obtained, design and construction of full scale field trial sections could be implemented to test the performance of porous asphalt or other modern bituminous mixtures made from cement coated aggregates.

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APPENDIX A

Calculations of Porous Concrete Ingredient Proportions for Croxden Gravel and Arcow Aggregate mixes.

Densities determined in accordance with BS 812: Part 2: 1995 (reference 68)

Material	Mass (kg)	Average Mass (kg)	Mass of Mould (kg)	Mass of Aggregate (kg)	BS 812 (ref. 44) Bulk Density of Aggregate (kg/m^3)	BS 812 (ref. 44) Particle Density of Aggregate (kg/m^3)	Volume of Voids (%)
Arcow							
1	13.86						
2	13.82						
3	13.86	13.828	11.992	1.836	1836	2730	32.75
4	13.8						
5	13.8						
Croxden							
1	13.9						
2	13.9						
3	13.88	13.892	11.992	1.9	1900	2610	27.2
4	13.88						
5	13.9						

Bulk density is determined for aggregate meeting a standard gradation for Porous Asphalt.

The Exact grading is shown in tables 7.2 and 7.4

Bulk Density of Croxden Gravel at Porous Asphalt Grading = 1900kg/m^3
Determined empirically - BS 812 (ref. 68)

Calculations of Ingredient proportions for six Croxden Gravel Cubes Porous Cubes.

1 cube is 100mm x 100mm x 100mm this = 0.001m^3
6 cubes = 0.006m^3 in volume
0.006m^3 x 1900kg/m^3 = 11.4 kg of Croxden to fill 6 cubes

10% x 11.4kg = 1.140kg of cement paste for 6 cubes.

0.3 w/c	0.877kg of cement	0.263kg of water
0.35 w/c	0.844kg of cement	0.295kg of water
0.4 w/c	0.814kg of cement	0.326kg of water
0.45 w/c	0.786kg of cement	0.354kg of water

Bulk Density of Arcow at Porous Asphalt Grading = 1836kg/m^3
Determined empirically - BS 812 (ref. 68)

Calculations of Ingredient proportions for six Arcow Cubes Porous Cubes.

1 cube is 100mm x 100mm x 100mm this = 0.001m^3
6 cubes = 0.006m^3 in volume
0.006m^3 x 1836kg/m^3 = 11.02 kg of Croxden to fill 6 cubes

10% x 11.02kg = 1.102kg of cement paste for 6 cubes.

0.3 w/c	0.848kg of cement	0.254kg of water
0.35 w/c	0.816kg of cement	0.286kg of water
0.4 w/c	0.787kg of cement	0.315kg of water
0.45 w/c	0.760kg of cement	0.342kg of water

APPENDIX B

Net Adsorption Test Result Calculations - Final Expression using the UUJ method.

Net Adsorption Test Result Calculations for Type A graded Aggregate - Final Expression Using the UUJ Method

Aggregate type	A1	A2	A3	Max Adsorption (UUJ) mg/g	Initial Adsorption (SHRP) mg/g	Net Adsorption (SHRP) mg/g	Initial Adsorption (UUJ) %
Graded Arcow	0.5595	0.2797	0.3786	2.8000	1.400250	0.879442	50.008937
Graded Arcow	0.5595	0.2288	0.3944	2.8000	1.654978	0.802631	59.106345
Graded Arcow	0.5595	0.2308	0.3799	2.8000	1.644969	0.873122	58.748883
Graded Arcow	0.5595	0.2558	0.3876	2.8000	1.519857	0.835689	54.280608
Graded Arcow	0.5595	0.2292	0.4023	2.8000	1.652976	0.764225	59.034853
						Average	56.235925
Graded Croxden	0.524	0.348	0.4662	2.8000	0.940458	0.300031	33.587786
Graded Croxden	0.524	0.3142	0.4798	2.8000	1.121069	0.229435	40.038168
Graded Croxden	0.524	0.3526	0.4713	2.8000	0.915878	0.273557	32.709924
Graded Croxden	0.524	0.3374	0.4645	2.8000	0.997099	0.308855	35.610687
Graded Croxden	0.524	0.2968	0.4722	2.8000	1.214046	0.268885	43.358779
						Average	37.061069
Graded Coating	0.4937	0.1269	0.2358	2.8000	2.080292	1.420879	74.296131
Graded Coating	0.4937	0.1194	0.2142	2.8000	2.122828	1.539883	75.815272
Graded Coating	0.4937	0.1237	0.2219	2.8000	2.098440	1.497460	74.944298
Graded Coating	0.4937	0.113	0.2358	2.8000	2.159125	1.420879	77.111606
Graded Coating	0.4937	0.1177	0.2105	2.8000	2.132469	1.560267	76.159611
						Average	75.665384

Net Adsorption Test Result Calculations for Type B graded Aggregate - Final Expression Using the UUJ Method

Aggregate type	A1	A2	A3	Max Adsorption (UUJ) mg/g	Initial Adsorption (SHRP) mg/g	Net Adsorption (SHRP) mg/g	Initial Adsorption (UUJ) %	Net Adsorption (UUJ) %
Single Sized Arcow	0.4658	0.3305	0.3934	2.8000	0.813310	0.422774	29.046801	15.099062
Single Sized Arcow	0.4671	0.3297	0.3946	2.8000	0.823635	0.422179	29.415543	15.077836
Single Sized Arcow	0.4678	0.3636	0.4193	2.8000	0.623685	0.282001	22.274476	10.071459
Single Sized Arcow	0.4915	0.3638	0.4199	2.8000	0.727487	0.396240	25.981689	14.151431
Single Sized Arcow	0.4884	0.388	0.4415	2.8000	0.575594	0.261196	20.556921	9.328419
Single Sized Arcow	0.4882	0.3868	0.4408	2.8000	0.581565	0.264088	20.770176	9.431732
						Average	24.674268	12.193323
Single Sized Croxden	0.4809	0.4299	0.3951	2.8000	0.296943	0.485290	10.605115	17.331789
Single Sized Croxden	0.4811	0.4305	0.3947	2.8000	0.294492	0.488481	10.517564	17.445734
Single Sized Croxden	0.4815	0.3922	0.4059	2.8000	0.519294	0.427065	18.546210	15.252336
Single Sized Croxden	0.4663	0.3911	0.4065	2.8000	0.451555	0.348823	16.126957	12.457952
Single Sized Croxden	0.4673	0.3924	0.4107	2.8000	0.448791	0.329450	16.028247	11.766073
Single Sized Croxden	0.4668	0.3921	0.4107	2.8000	0.448072	0.326889	16.002571	11.674624
						Average	14.637777	14.321418
Single Sized Coated Arcow	0.4255	0.2453	0.3278	2.8000	1.185805	0.624545	42.350176	22.305187
Single Sized Coated Arcow	0.4265	0.2461	0.3279	2.8000	1.184338	0.628821	42.297773	22.457880
Single Sized Coated Arcow	0.4263	0.2658	0.3238	2.8000	1.054187	0.654000	37.649543	23.357126
Single Sized Coated Arcow	0.455	0.2656	0.3235	2.8000	1.165538	0.786110	41.626374	28.075353
Single Sized Coated Arcow	0.4551	0.2529	0.3243	2.8000	1.244034	0.781753	44.429796	27.919766
Single Sized Coated Arcow	0.4548	0.2524	0.324	2.8000	1.246086	0.782269	44.503078	27.938183
						Average	42.142790	25.342249
Single Sized Coated Croxden	0.4652	0.2969	0.3146	2.8000	1.012984	0.880550	36.177988	31.448225
Single Sized Coated Croxden	0.4652	0.2952	0.3149	2.8000	1.023216	0.878796	36.543422	31.385579
Single Sized Coated Croxden	0.4654	0.2874	0.3218	2.8000	1.070907	0.839261	38.246670	29.973602
Single Sized Coated Croxden	0.4674	0.287	0.3216	2.8000	1.080702	0.848472	38.596491	30.302586
Single Sized Coated Croxden	0.4673	0.3049	0.3177	2.8000	0.973079	0.870773	34.752835	31.099019
Single Sized Coated Croxden	0.4679	0.305	0.3172	2.8000	0.974824	0.876050	34.815131	31.287516
						Average	36.522090	30.916088

APPENDIX C

Calculations for Determination of Aggregate Content in Porous Asphalt Samples for Repeat Load Axial and Repeat Load Indirect Tensile Testing

Calculations For weight of aggregate to produce 200mm x 200mm x 50mm specimens at volume of voids equal to original volume of voids minus five percent.

Densities determined in accordance with BS 812: Part 2: 1995 (reference 68). Volume of mould used for initial weighing = $0.001 m^3$

Material	Mass (kg)	Average Mass (kg)	Mass of Mould (kg)	Mass of Aggregate (kg)	BS 812 (ref. 68) Bulk Density of Aggregate (kg/m^3)	BS 812 (ref. 68) Particle Density of Aggregate (kg/m^3)	Volume of Voids (%)	Target Volume of Voids After Compaction (%)	Recalculated Bulk Density After Compaction (kg/m^3)	Weight of Material To Fill Mould of Volume ($0.002m^3$)
Arcow										
1	13.86									
2	13.82									
3	13.86	13.828	11.992	1.836	1836	2730	32.75	27.75	1972	3.944
4	13.8									
5	13.8									
Coated Arcow										
1	12.6									
2	12.6									
3	12.6	12.604	10.92	1.684	1684	2700	37.63	32.63	1819	3.638
4	12.62									
5	12.6									
Croxden										
1	13.9									
2	13.9									
3	13.88	13.892	11.992	1.9	1900	2610	27.2	22.2	2031	4.062
4	13.88									
5	13.9									
Coated Croxden										
1	12.68									
2	12.68									
3	12.7	12.672	10.92	1.752	1752	2591	32.38	27.38	1882	3.764
4	12.66									
5	12.64									

APPENDIX D

General Properties of Porous Asphalt Samples for Repeat Load Axial and Repeat Load Indirect Tensile Testing and Calculations For Mixture Particle densities.

Sample No.	Sample Type and Description	Date Made	Date Cored	Dry Weight (g)	Average Height (mm)	Diameter (mm)	Bulk Density (kg/m^3)	Calculated Particle Density (kg/m^3)	Percentage of Voids	Average Voids
1	Arcow	21/4/98	23/4/98	1855.3	61	148	1767.95	2660.28	33.54	32.77
2	Arcow	21/4/98	23/4/98	1890.5	61	148	1801.50	2660.28	32.28	
3	Arcow	29/4/98	30/4/98	1901.2	61	148	1811.69	2660.28	31.90	
4	Arcow	29/4/98	30/4/98	1845.9	61	148	1758.99	2660.28	33.88	
5	Arcow	30/4/98	1/5/98	1894.3	61	148	1805.12	2660.28	32.15	
6	Arcow	30/4/98	1/5/98	1868.1	61	148	1780.15	2660.28	33.08	
7	Arcow	1/5/98	5/5/98	1874.2	60	148	1815.73	2660.28	31.75	
8	Arcow	1/5/98	5/5/98	1883.9	60.5	148	1810.04	2660.28	31.96	
9	Arcow	1/5/98	5/5/98	1866.9	60	148	1808.66	2660.28	32.01	
10	Arcow	6/5/98	7/5/98	1880.6	60	148	1821.93	2660.28	31.51	
11	Arcow	6/5/98	7/5/98	1842.3	60.5	148	1770.07	2660.28	33.46	
12	Arcow	6/5/98	7/5/98	1845.5	59.5	148	1802.95	2660.28	32.23	
13	Arcow	8/5/98	11/5/98	1851.3	60	148	1793.54	2660.28	32.58	
14	Arcow	8/5/98	11/5/98	1773.3	59	148	1747.09	2660.28	34.33	
15	Arcow	8/5/98	11/5/98	1758.2	59	148	1732.22	2660.28	34.89	
16	Croxden	11/5/98	12/5/98	1888.9	57	148	1926.28	2548.82	24.42	24.84
17	Croxden	11/5/98	12/5/98	1919.8	57.5	148	1940.77	2548.82	23.86	
18	Croxden	11/5/98	12/5/98	1933.1	57	148	1971.36	2548.82	22.66	
19	Croxden	13/5/98	14/5/98	1886.4	57.5	148	1907.01	2548.82	25.18	
20	Croxden	13/5/98	14/5/98	1914	58	148	1918.23	2548.82	24.74	
21	Croxden	13/5/98	14/5/98	1916.5	58.5	148	1904.32	2548.82	25.29	
22	Croxden	14/5/98	15/5/98	1885.5	57.5	148	1906.10	2548.82	25.22	
23	Croxden	14/5/98	15/5/98	1891.2	58	148	1895.38	2548.82	25.64	
24	Croxden	14/5/98	15/5/98	1902.1	57.5	148	1922.88	2548.82	24.56	
25	Croxden	1/6/98	2/6/98	1900.4	57	148	1938.01	2548.82	23.96	
26	Croxden	1/6/98	2/6/98	1893.9	58	148	1898.08	2548.82	25.53	
27	Croxden	1/6/98	2/6/98	1855.8	58	148	1859.90	2548.82	27.03	
28	Coated Croxden	2/6/98	3/6/98	1738.3	55.5	148	1820.61	2523.22	27.85	27.29
29	Coated Croxden	2/6/98	3/6/98	1754.7	56	148	1821.38	2523.22	27.82	
30	Coated Croxden	2/6/98	3/6/98	1753.4	54.5	148	1870.13	2523.22	25.88	
31	Coated Croxden	4/6/98	5/6/98	1765.3	56	148	1832.38	2523.22	27.38	
32	Coated Croxden	4/6/98	5/6/98	1750.7	55.5	148	1833.60	2523.22	27.33	
33	Coated Croxden	4/6/98	5/6/98	1760.2	56	148	1827.09	2523.22	27.59	
34	Coated Croxden	5/6/98	8/6/98	1756.6	55	148	1856.51	2523.22	26.42	
35	Coated Croxden	5/6/98	8/6/98	1759.7	56	148	1826.57	2523.22	27.61	
36	Coated Croxden	5/6/98	8/6/98	1725.7	55	148	1823.85	2523.22	27.72	
37	Coated Croxden	8/6/98	9/6/98	1719.1	54	148	1850.52	2523.22	26.66	
38	Coated Croxden	8/6/98	9/6/98	1772.3	56.5	148	1823.37	2523.22	27.74	
39	Coated Croxden	8/6.98	9/6/98	1762.5	56	148	1829.48	2523.22	27.49	
40	Coated Arcow	9/6/98	10/6/98	1693.1	56	148	1757.44	2625.2	33.05	33.51
41	Coated Arcow	9/6/98	10/6/98	1704.7	56	148	1769.48	2625.2	32.60	
42	Coated Arcow	9/6/98	10/6/98	1704.7	56	148	1769.48	2625.2	32.60	
43	Coated Arcow	10/6/98	11/6/98	1715.6	56	148	1780.80	2625.2	32.17	
44	Coated Arcow	10/6/98	11/6/98	1683.7	57	148	1717.02	2625.2	34.59	
45	Coated Arcow	10/6/98	11/6/98	1681.2	57	148	1714.47	2625.2	34.69	
46	Coated Arcow	11/6/98	12/6/98	1719.4	57	148	1753.43	2625.2	33.21	
47	Coated Arcow	11/6/98	12/6/98	1688.8	57	148	1722.22	2625.2	34.40	
48	Coated Arcow	11/6/98	12/6/98	1719.1	57	148	1753.12	2625.2	33.22	
49	Coated Arcow	12/6/98	17/6/98	1682.1	57	148	1715.39	2625.2	34.66	
50	Coated Arcow	12/6/98	17/6/98	1693.6	56.5	148	1742.40	2625.2	33.63	
51	Coated Arcow	12/6/98	17/6/98	1703.1	56.5	148	1752.18	2625.2	33.26	

Calculations for the Particle Density of Each Porous Asphalt Mixture

Particle density of bitumen =	1000 kg/m^3
Particle density of PA graded Arcow =	2730 kg/m^3
Particle density of PA graded Coated Arcow =	2700 kg/m^3
Particle density of PA graded Croxden =	2610 kg/m^3
Particle density of PA graded Coated Croxden =	2591 kg/m^3

When:
Arcow = 100%, bitumen = 4.2%
Coated Arcow = 100%, bitumen = 4.6%
Croxden = 100%, bitumen = 3.95%
Coated Croxden = 100%, bitumen = 4.45%

Therefore proportions in the mix are: Arcow = 95.97%, bitumen = 4.03%
Coated Arcow = 95.60%, bitumen = 4.40%
Croxden = 96.20%, bitumen = 3.80%
Coated Croxden = 95.74%, bitumen = 4.26%

Particle Density in any given mix is: (aggregate density x percentage of aggregate) + (bitumen density x percentage of bitumen) / 100

solving for Arcow:	(2730 x 95.97) + (1000 x 4.03) / 100 = 2660.28 kg/m^3
solving for Coated Arcow:	(2700 x 95.60) + (1000 x 4.40) / 100 = 2625.20 kg/m^3
solving for Croxden:	(2610 x 96.20) + (1000 x 3.80) / 100 = 2548.82 kg/m^3
solving for Coated Croxden:	(2591 x 95.74) + (1000 x 4.26) / 100 = 2523.22 kg/m^3

APPENDIX E

Repeat Load Axial and Repeat Load Indirect Tensile Test Results

Repeat Load Axial Test to DD226:1996					
Sample	Sample Type	Date	Time	Percentage Deformation	Notes
No.	and Description	Tested	Tested	at final Reading	
1	Arcow	15/7/98	12:00	2.42	* Result is null
2	Arcow	15/7/98	13:15	2.51	because the
3	Arcow	15/7/98	14:45	2.48	specimen was
4	Arcow	15/7/98	16:00	2.46	mechanically
5	Arcow	16/7/98	11:30	2.34	damaged before
6	Arcow	16/7/98	12:45	2.23	testing during
7	Arcow	16/7/98	14:30	2.45	transportaton
8	Arcow	16/7/98	15:45	2.67	
9	Arcow	17/7/98	12:00	2.38	
10	Arcow	17/7/98	13:00	2.25	
11	Arcow	17/7/98	14:15	2.49	
12	Arcow	17/7/98	15:30	2.54	
13	Arcow	20/7/98	11:15	2.56	
14	Arcow	20/7/98	12:30	2.46	Displacement
15	Arcow	20/7/98	13:45	2.56	Average = 2.45
16	Croxden	20/7/98	15:00	2.51	
17	Croxden	20/7/98	16:15	2.78	
18	Croxden	21/7/98	10:15	2.54	
19	Croxden	21/7/98	11:30	3.59	
20	Croxden	21/7/98	13:00	3.63	
21	Croxden	21/7/98	14:15	4.24	
22	Croxden	22/7/98	10:45	2.85	
23	Croxden	22/7/98	12:00	3.19	
24	Croxden	22/7/98	13:45	3.39	
25	Croxden	22/7/98	15:15	3.62	
26	Croxden	23/7/98	10:45	3.21	Displacement
27	Croxden	23/7/98	12:00	3.17	Average = 3.23
28	Coated Croxden	23/7/98	13:30	2.16	
29	Coated Croxden	23/7/98	14:45	1.97	
30	Coated Croxden	24/7/98	11:00	1.55	
31	Coated Croxden	24/7/98	12:15	1.95*	
32	Coated Croxden	24/7/98	13:45	2.35	
33	Coated Croxden	24/7/98	15:15	2.7*	
34	Coated Croxden	29/7/98	11:15	2.14	
35	Coated Croxden	29/7/98	12:15	1.31	
36	Coated Croxden	29/7/98	13:30	1.77	
37	Coated Croxden	29/7/98	14:45	1.86	
38	Coated Croxden	29/7/98	16:00	1.93	Displacement
39	Coated Croxden	30/7/98	11:15	2.36	Average = 1.94
40	Coated Arcow	30/7/98	12:30	2.48	
41	Coated Arcow	30/7/98	13:45	2.71*	
42	Coated Arcow	30/7/98	15:15	2.11	
43	Coated Arcow	31/7/98	10:45	2.07	
44	Coated Arcow	31/7/98	12:00	2.19	
45	Coated Arcow	31/7/98	13:15	2.75*	
46	Coated Arcow	31/7/98	14:30	2.29	
47	Coated Arcow	3/8/98	12:15	2.15	
48	Coated Arcow	3/8/98	13:45	1.99	
49	Coated Arcow	3/8/98	14:45	1.58	
50	Coated Arcow	5/8/98	13:00	2.16	Displacement
51	Coated Arcow	5/8/98	14:00	2.15	Average = 2.12

Repeat Load Indirect Tensile Test to DD213:1993					
Sample No.	Sample Type and Description	Date Tested	Time Tested	Elastic Stiffness (MPa)	Notes
1	Arcow	24/6/98	morning	640.5	* Result is null
2	Arcow	24/6/98	morning	502.5	because the
3	Arcow	24/6/98	morning	646.5	specimen was
4	Arcow	24/6/98	morning	659	mechanically
5	Arcow	24/6/98	morning	580.5	damaged before
6	Arcow	24/6/98	morning	500.5	testing during
7	Arcow	24/6/98	morning	522	transportaton
8	Arcow	24/6/98	morning	602.5	
9	Arcow	24/6/98	morning	528	Elastic Stiffness
10	Arcow	24/6/98	morning	636	Average = 581.8
16	Croxden	26/6/98	morning	1216	
17	Croxden	26/6/98	morning	1145.5	
18	Croxden	26/6/98	morning	1301	
19	Croxden	26/6/98	morning	936	
20	Croxden	26/6/98	morning	777	
21	Croxden	26/6/98	morning	777	
22	Croxden	26/6/98	morning	1070	
23	Croxden	26/6/98	morning	696	
24	Croxden	26/6/98	morning	880.5	Elastic Stiffness
25	Croxden	26/6/98	morning	907.5	Average = 970.65
28	Coated Croxden	26/6/98	afternoon	1076.5	
29	Coated Croxden	26/6/98	afternoon	1240.5	
30	Coated Croxden	26/6/98	afternoon	1150.5	
31	Coated Croxden	26/6/98	afternoon	867.5*	
32	Coated Croxden	26/6/98	afternoon	981	
33	Coated Croxden	26/6/98	afternoon	774.5*	
34	Coated Croxden	26/6/98	afternoon	1228.5	
35	Coated Croxden	26/6/98	afternoon	1138	
36	Coated Croxden	26/6/98	afternoon	1326	Elastic Stiffness
37	Coated Croxden	26/6/98	afternoon	1292	Average = 1179.13
40	Coated Arcow	26/6/98	afternoon	743.5	
41	Coated Arcow	26/6/98	afternoon	611.5	
42	Coated Arcow	26/6/98	afternoon	795.5	
43	Coated Arcow	26/6/98	afternoon	801.5	
44	Coated Arcow	26/6/98	afternoon	933	
45	Coated Arcow	26/6/98	afternoon	629.5	
46	Coated Arcow	26/6/98	afternoon	738.5	
47	Coated Arcow	26/6/98	afternoon	819.5	
48	Coated Arcow	26/6/98	afternoon	980.5	Elastic Stiffness
49	Coated Arcow	26/6/98	afternoon	945	Average = 799.8

APPENDIX F

Repeat Load Axial Test and Shearbox Test LabVIEW® Programming Front and Back Pages

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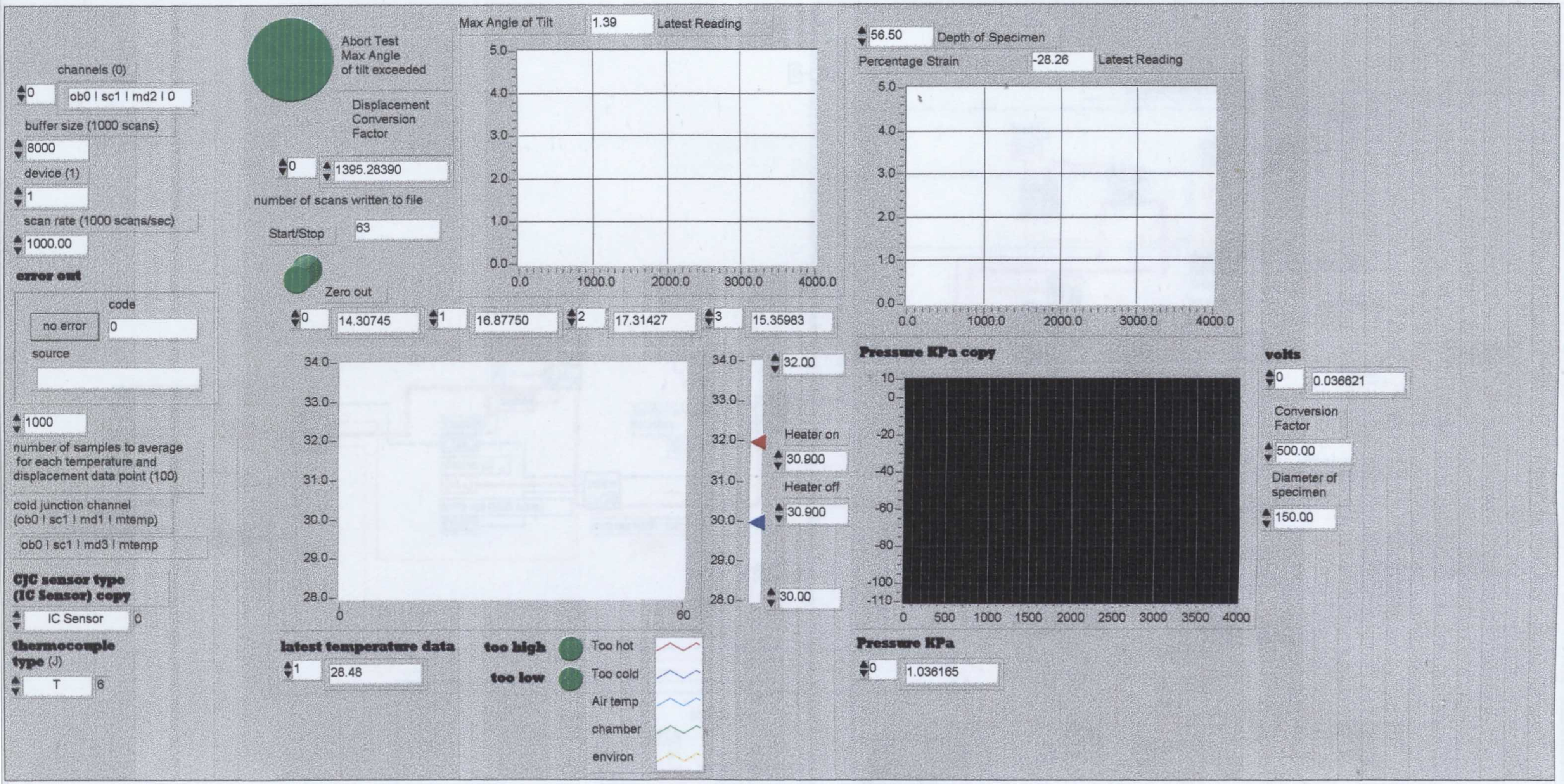
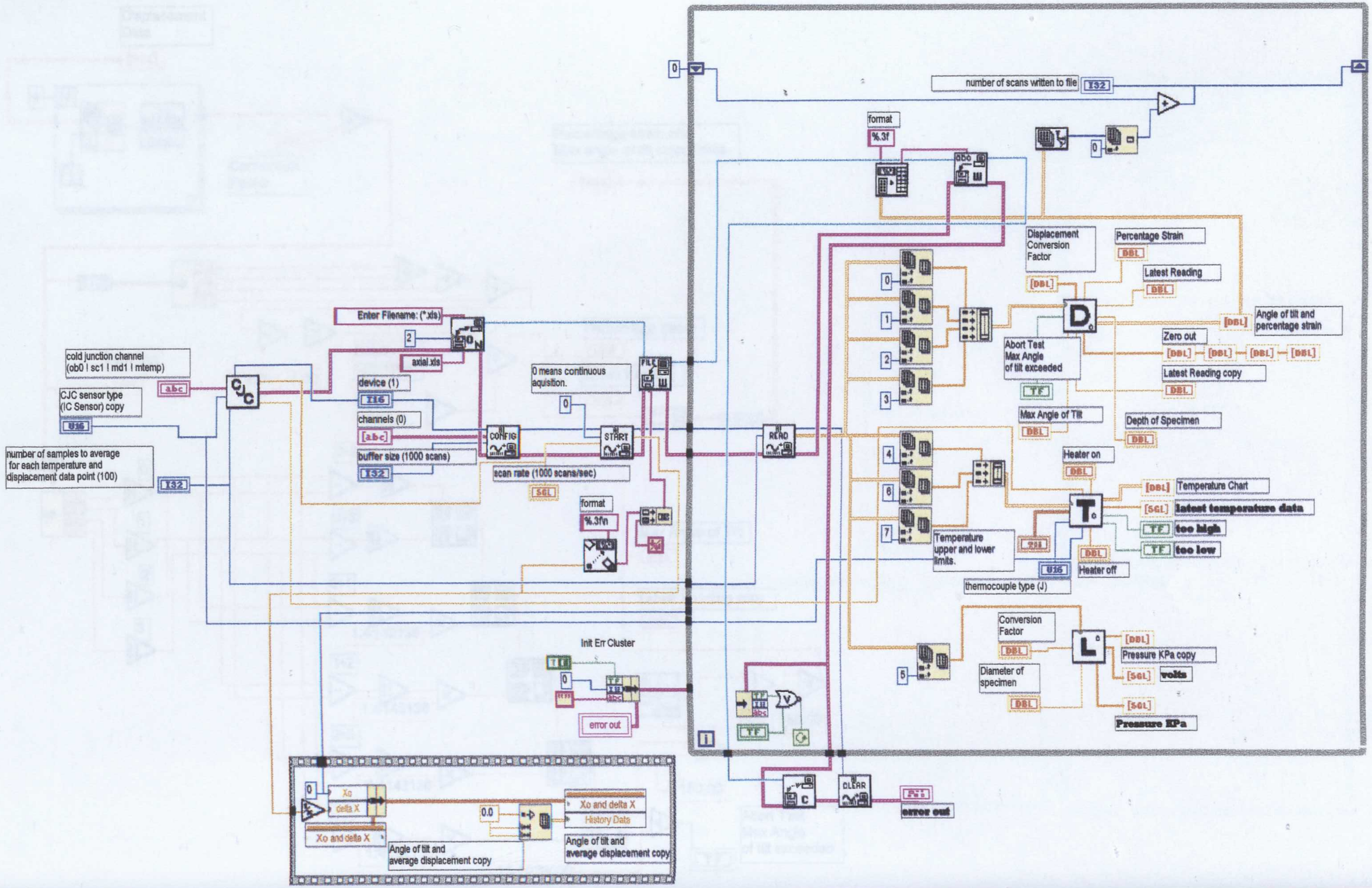
Printed on 27/07/99 at 11:39

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scan rate (1000 scans/sec)
0 means continuous aquisition.
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Init Err Cluster
error out
number of scans written to file
format
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Displacement Conversion Factor
Percentage Strain
Latest Reading
Angle of tilt and percentage strain
Zero out
Latest Reading copy
Abort Test Max Angle of tilt exceeded
Max Angle of Tilt
Depth of Specimen
Heater on
Temperature Chart
latest temperature data
too high
too low
Temperature upper and lower limits.
Heater off
thermocouple type (J)
Conversion Factor
Pressure KPa copy
volts
Diameter of specimen
Pressure KPa
Xo
delta X
Xo and delta X
Angle of tilt and average displacement copy
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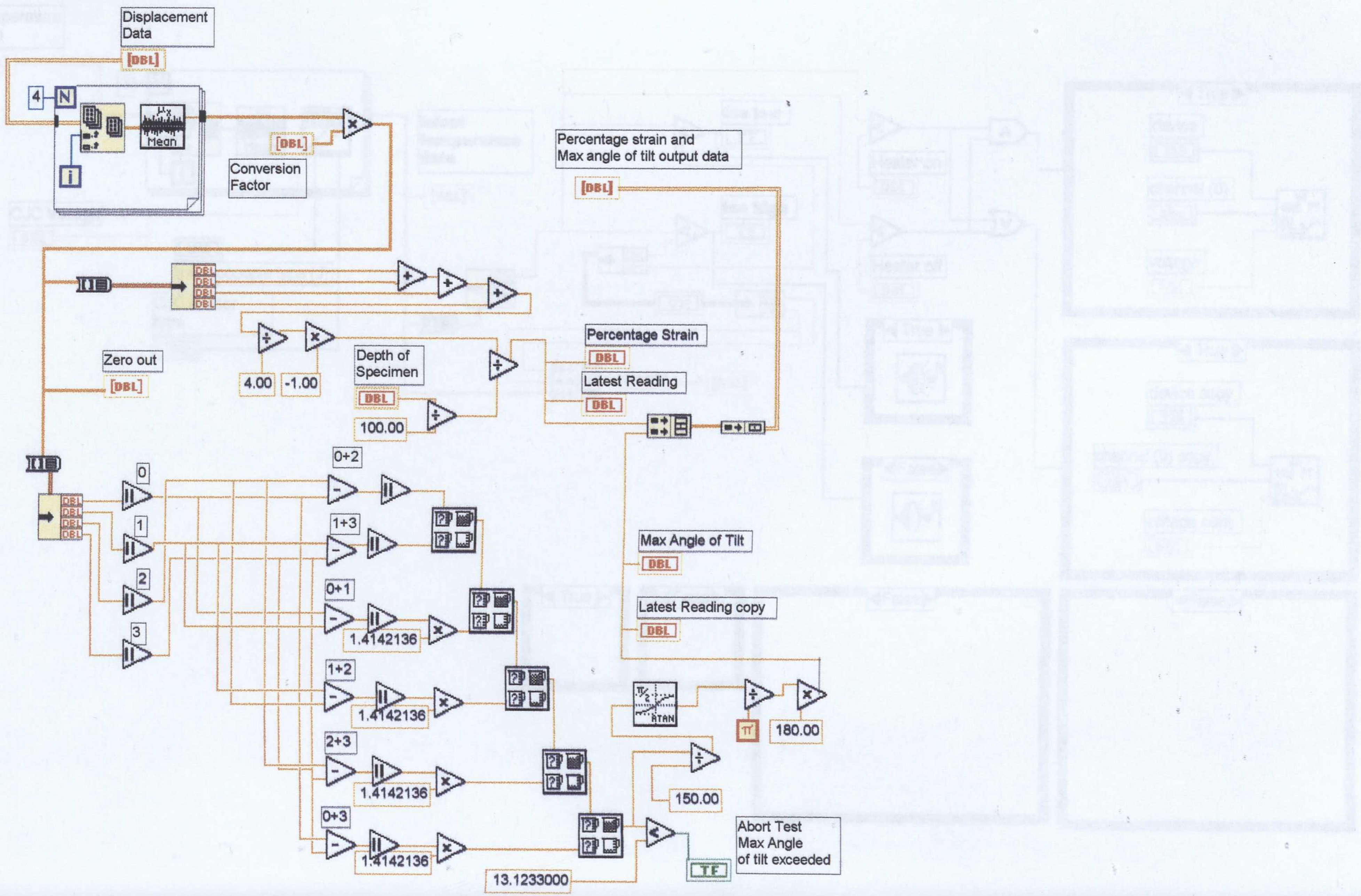

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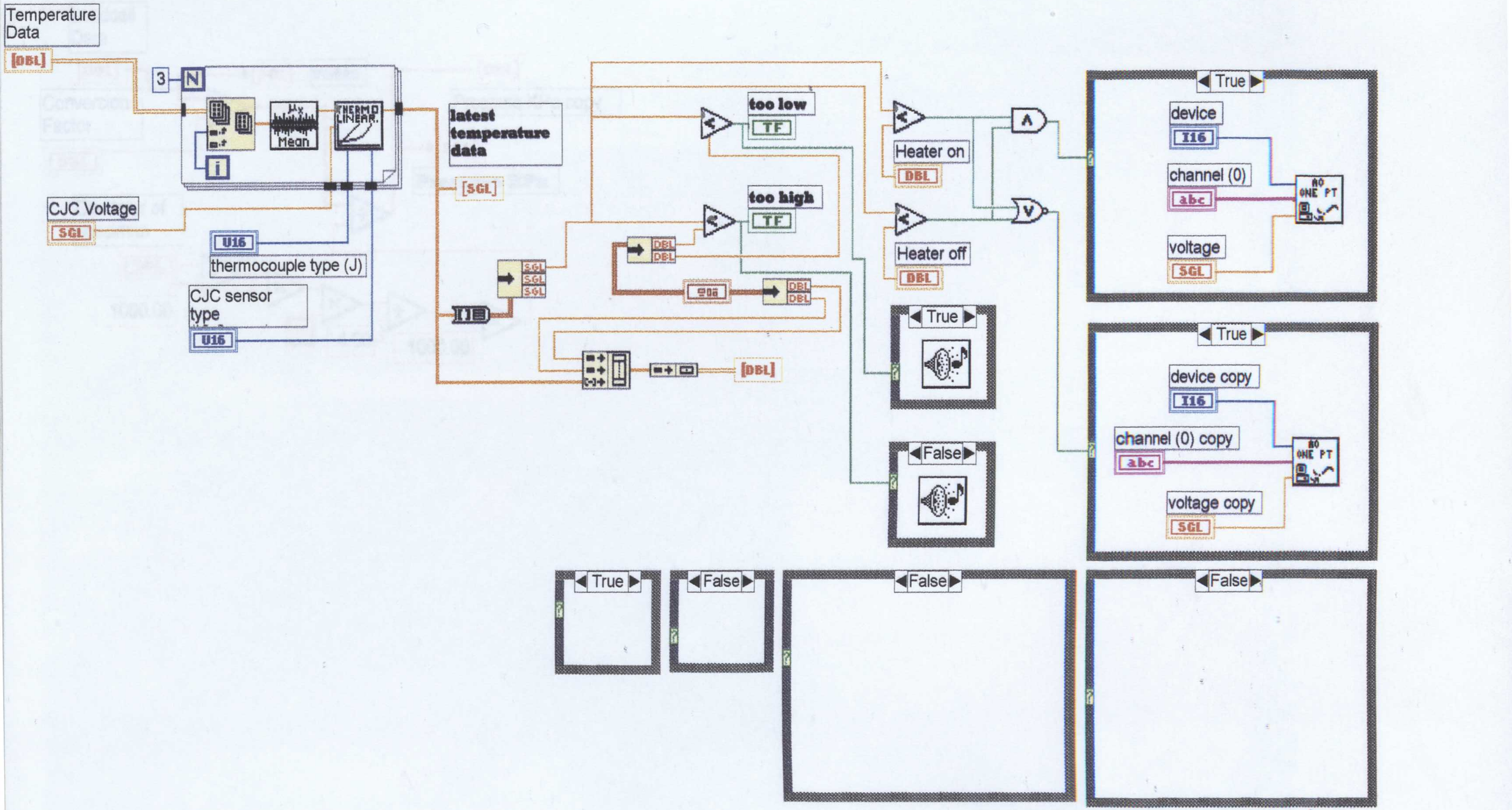

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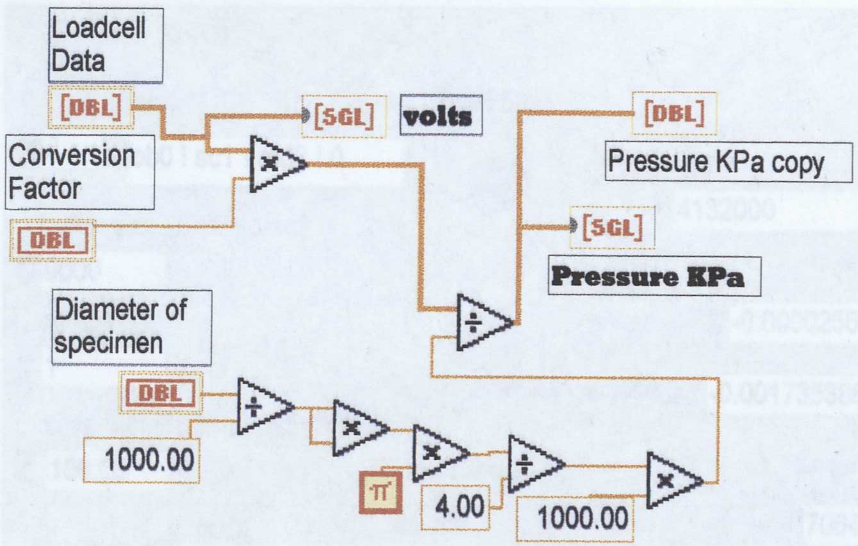

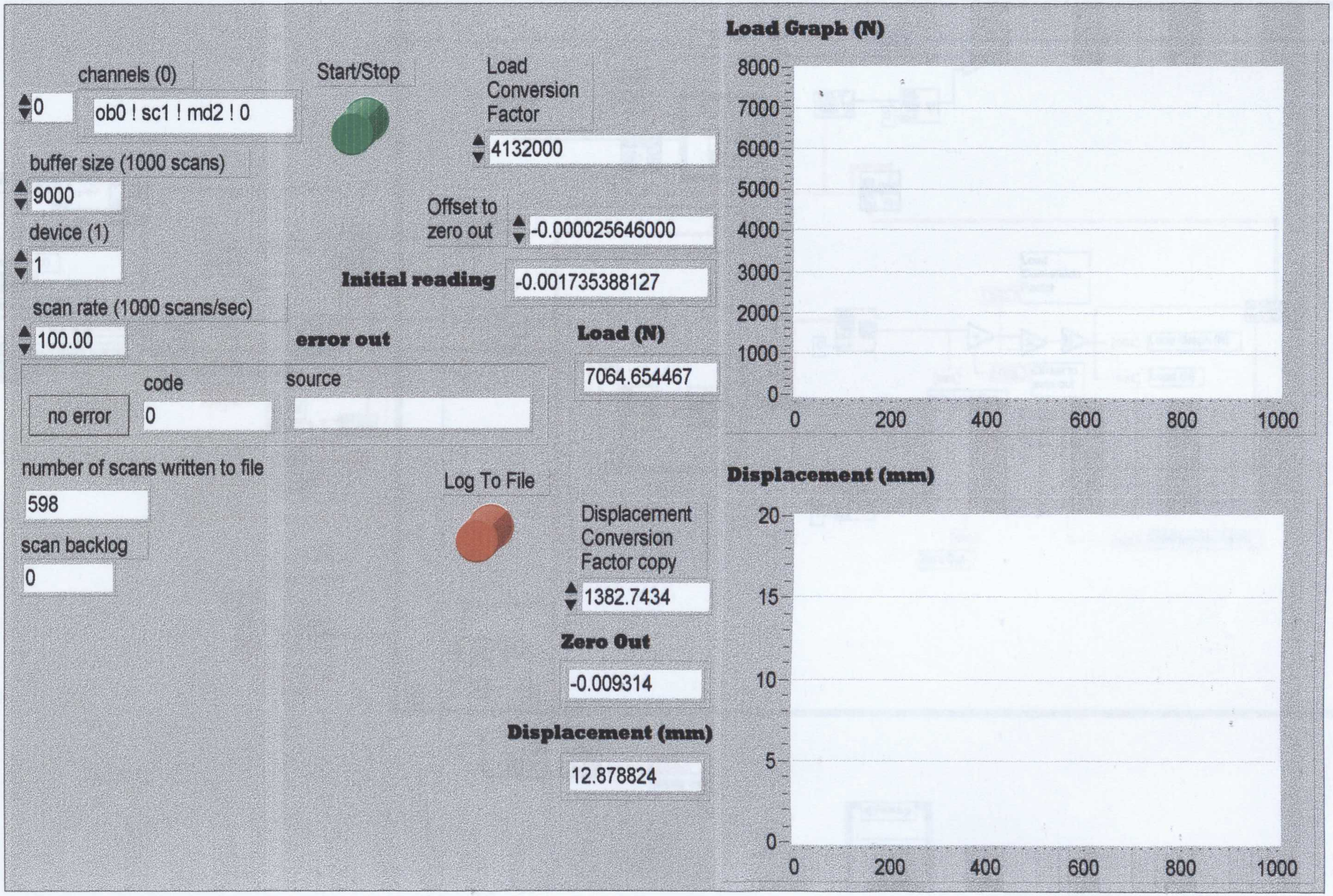
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Initial reading
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error out
Load (N)
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Displacement Conversion Factor copy
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Zero Out
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Displacement (mm)
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6000
5000
4000
3000
2000
1000
0
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400
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800
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Displacement (mm)
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SHEARBOX.VI
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