Influence of Surface Seal Variables on Bitumen Bond Strength Properties

Le Riche Lombard

Thesis presented in fulfilment of the requirements for the degree Master of Science in Engineering in the Faculty of Engineering at Stellenbosch University

Supervisor: Prof K.J. Jenkins
Department of Civil Engineering

December 2014

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ABSTRACT

Surface seals are widely used in South Africa. There are a number of reasons which include affordability, versatility and durability. There are, however, in some cases problems with stone loss that can lead to a shortened lifespan of the pavement. The loss of aggregate chippings in surface seals poses a major problem in the seal pavement industry. This study aims to identify the influencing factors that lead to these adhesive failures as well as to find optimum combinations of binders and aggregates at various conditions.

Various binders commonly used in South African surface seal construction will be tested using the Bitumen Bond Strength (BBS) test method. The binders used in the study include 80/100 penetration grade bitumen, elastomer modified bitumen, bitumen rubber, elastomer modified emulsion and cationic rapid setting emulsion. Aggregates used in the study include dolerite, granite and quartzite. The test samples were cured and tested at two temperatures, 15 °C and 35 °C. The samples were also cured for 2, 6 and 24 hours respectively.

The study tackles a wide range of variables in order to obtain a good understanding of adhesion properties of surface seals used in South Africa. Tests were repeated at least once to ensure repeatability and in some cases up to four repeats were performed. The loading rate at which the tests were performed had a significant influence on the BBS results. This rate varied which complicated the process of comparing the results. It was therefore decided to unify the loading rates.

The BBS results exposed the difference between hot applied binders and emulsions. The former having significant stronger adhesion properties. It was also confirmed by the results that temperature plays a key role in the BBS results due to the visco-elastic properties of bitumen. These influences will be discussed along with others such as aggregate types and curing times. The type of failure is also discussed. Failure can either be adhesive or cohesive, the former being a failure between the aggregate and the binder while the later refers to a failure in the binder itself.

The results of other students will also be discussed and compared to the results of this study. These include results of predecessors that tested emulsions as well as results from tests done on fractured aggregate surfaces and precoated aggregates. This study showed very similar results as these from other students, except for tests done with emulsions. It was discovered

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that the method of curing of the emulsions must be adapted to ensure proper curing of the emulsions.

It was found that aggregates did not influence the BBS properties to the same extent as temperature and binder application type. The BBS results of hot applied binders also did not significantly increase as the curing time increased, but the results of emulsions showed some increase. However, the emulsions needed more time to cure properly.

OPSOMMING

Oppervlak seëls word algemeen gebruik in Suid-Afrika. Daar is verskeie redes hiervoor waaronder bekostigbaarheid,veelsydigheid en duursaamheid. Daar is egter in sommige gevalle probleme met klipverlies wat kan lei tot n verkorte leeftyd. Hierdie klipverlies ontstaan as gevolg van verskeie redes of kombinasies daarvan. Die studie beoog om hierdie faktore wat die adhesie eienskappe beïnvloed te identifiseer sowel as om optimum kobinasies van bindmiddels en klipsoorte te bewerkstellig by verkeie kondisies.

‘n Verskeidenheid van bindmiddels wat algemeen in Suid-Afrika gebruik word, word in die studie getoets met die Bitumen Bond Sterkte (BBS) toets metode. Die bindmiddels wat in die studie gebruik word sluit 80/100 penetrasie graad bitumen, elastomeer gemodifiseerde bitumen, bitumen rubber, elastomeer gemodifiseerde emulsie en kationiese snel settende emulsie. Die klipsoorte wat vir die studie gebruikword is doleriet, graniet en kwartsiet. Hierdie gesteentes word algemeen in die praktyk gebruik. Die toets monsters word ook by twee temperature gekuur en getoets. Hierdie temperature is 15 °C en 35 °C. Die toets monsters word ook onderskeidelik vir 2, 6 en 24 uur gekuur.

Die studie ondersoek ’n wye verskeidenheid van veranderlikes om sodoende ’n goeie begrip van adhesie eienskappe van die oppervlak seëls wat in Suid-Afrika gebruik word te verkry. Elke toets was ten minste een maal herhaal om herhaalbaarheid te verseker. Sommige toetse was tot 4 keer herhaal. Die belasting tempo van die toetse het ‘n beduidende uitwerking op die BBS resultate as gevolg van die visko-elastiese eienskappe van bitumen. Hierdie tempo het gewissel en dit moeilik gemaak om die resultate te vergelyk. Daarom was daar besluit om die tempo van die toetse te verander na ‘n gelykvormige tempo.

Daar was ‘n duidelike verskil in BBS resultate van die warm toegepaste bindmiddels en die emulsies. Die warm bindmiddels het baie hoër BBS resultate gelwer. Dit was ook bevestig in die resultate dat temperatuur ‘n beduidende rol speel in die BBS. Hierdie invloede sal bespreek word tesame met ander, soos klipsoorte en kuring tye. Die tipe versaking word ook bespreek. Versaking kan plaasvind as gevolg van adhesie of cohesie, waar adhesie versaking ’n versaking is tussen die klip en die bindmiddel terwyl cohesie versaking verwys na ’n versaking in die bindmiddel self.

Die uitslae van die ander studente sal ook bespreek word en vergelyking word met die resultate van hierdie studie. Dit sluit die resultate van voorgangers in wat emulsies getoets het sowel as die resultate van toetse wat gedoen is op gebreekte klipoppervlaktes en bitumen behandelde

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klippe. Hierdie studie het baie soortgelyke resultate getoon as dié van ander studente, behalwe vir die toetse wat gedoen was met emulsies. Daar is vasgestel dat die metode van kuring van die emulsies moet aangepas word om behoorlike kuring van die emulsies te verseker.

Daar is ook gevind dat klipsoorte nie die BBS eienskappe in dieselfde mate as temperatuur en bindmiddel toepassingstipe beïnvloed het nie. Die BBS resultate van warm aangewende bindmiddels het ook nie aansienlik verhoog soos die kuringstyd toegeneem het nie, maar die resultate van emulsies het wel ’n toename getoon. Die emulsies het wel meer tyd nodig gehad om behoorlik te kuur.

ACKNOWLEDGEMENTS

Above all, I would like to thank our Lord and saviour Jesus Christ for His love, grace and for blessing me with abilities and opportunities.

I would also like to express my sincere gratitude to the following persons and organisations:

- Professor Kim Jenkins, for his guidance, encouragement and support.
- Professor Martin van de Ven, for his input and guidance.
- André Greyling for sharing his knowledge and findings of his research.
- Johan Gerber, colleague and friend for his advice and good insights.
- Colin Isaacs and Gavin Williams for their willingness and assistance in the laboratory.
- Riaan Stander and Shafee Abrahams for assisting with the testing and for sharing the results of their studies.
- Professor Daan Nel, from the Centre for Statistical Consultation of Stellenbosch University for his assistance with ANOVA.
- My parents, Wentzel and Elanie Lombard, for their continued love and support.
- My grandparents, Louwrence and Delene Lombard, as well as my entire family for their encouragement and support.
- Louzel Lombard, for assisting with translations and grammar.
- Theodi Albrecht, for her prayers and moral support.
- Murray & Roberts Infrastructure, especially the Brookes Nek management team, for allowing me to complete this study while working.

To each and every one who was a part of this and who assisted in any way over the last four years. Thank you!

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TABLE OF CONTENTS

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LIST OF FIGURES

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LIST OF TABLES

ABBREVIATIONS

°C	Degrees Celsius
BBS	Bitumen Bond Strength
CRS 60	Cationic Rapid Setting emulsion with 60% bitumen content
CSIR	Council for Scientific and Industrial Research
EVA	Ethylene-Vinyl-Acetate
h	Hours
HAB	Hot Applied Binders
HMA	Hot Mix Asphalt
k	Kilo
Pa	Pascal
PATTI	Pneumatic Adhesion Tensile Testing Instrument
PQG	PATTI Quantum Gold
s	Seconds
SABITA	Southern African Bitumen Association
SABS	South African Bureau of Standards
SBR	Styrene-Butadiene-Rubber
SBS	Styrene-Butadiene-Styrene
SC-E1	Elastomer Modified Bitumen Emulsion
S-E1	Elastomer Modified Bitumen
S-R1	Bitumen Rubber
TG	Technical Guideline
TMH	Technical Methods for Highways

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TRH	Technical Recommendations for Highways

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1. INTRODUCTION

1.1 BACKGROUND INFORMATION

Seal roads are widely used in South Africa, not only because it is more cost effective than asphalt roads, but construction thereof is also less complicated. It is however very important that strong measures be taken to ensure the seal is constructed correctly.

One of the many advantages of surface seals is the fact that it provides very good skid resistance, which leads to better road safety. Aggregate loss or raveling will directly influence the skid resistance as well as other benefits; therefore it is very important to prevent this.

Aggregate loss occurs when the bond between the binder and the aggregate breaks and the individual stones become loose. This bonding failure is due to various causes which include moisture content of the aggregate, dust particles, temperature related causes and curing times.

It is also known that some binders bond better with different types of aggregates. Therefore if the bitumen bond strength or BBS properties are known for various binder types and aggregates in different conditions, an informed decision can be made when selecting materials for a surface seal.

1.2 PROBLEM STATEMENT

Aggregate loss poses a major problem in surface seals. The aggregates in a surface seal provide skid resistance on the road. Losing this property the road becomes unsafe to use as breaking or slowing down becomes more difficult. Loose stones on the surface lead to more raveling and can also lead to windscreens being cracked. This worsening raveling leads to bare patches on the surface which becomes damaged easily and leads to the least desired outcome, leaving the base layer underneath the seal unprotected. This in turn leads to potholes and premature failure of the road.

During the construction phase of a seal, weather conditions especially temperature and moisture, play a significant role. High moisture conditions, low overnight temperatures as well as early exposure to traffic are main causes of raveling in the initial stages after construction.

The increase in traffic volumes demands for minimal closing times of traffic lanes on the road, which decreases the curing time of the binder. If the seal is exposed to traffic too soon after

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construction, the bond between aggregates and the binder is not yet strong enough, and raveling may occur.

1.3 PURPOSE OF STUDY

Loss of aggregate on surface sealed roads can be minimized by using the correct binder-aggregate combination for the specific locality. Aggregate loss and bitumen bond strength (BBS) have a reciprocal relationship. When the bond strength between the aggregate and the binder is strong, aggregate loss will be minimal.

The purpose of the study is to find optimal combinations of aggregates and binders in various conditions, in order to provide reliable and optimal seal performance. Temperature and curing time plays a significant role regarding the bond strength between these materials and will be variable factors during the study.

The results of this study are intended to be used to validate the adhesive and cohesive failure that is being developed in the Finite Element Method Seal Model at Stellenbosch University.

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1.4 RESEARCH OBJECTIVES

- Determining and comparing the bitumen bond strength of various combinations of aggregates and binders
- Determine whether the failure occurs in adhesion or cohesion
- Determining and discussing the influences that affect the BBS results as well as the type of failure
- Engaging work of other students to compare with results in this study

1.5 THESIS STATEMENT

Aggregate type and binder type are the two main influences that affect Bitumen Bond Strength properties of a surface seal.

1.6 DELINEATIONS AND LIMITATIONS

Tests done for the purpose of this study was done only on smooth, non-pre-coated aggregates, but work of other students which include fractured aggregate surfaces and precoated aggregates will be compared and discussed.

Three types of aggregate were selected for testing namely; granite, quartzite and dolerite. There were significant visual differences in both the granite and quartzite groups. Therefore it was decided to divide the granite and quartzite further into two groups namely: white granite and grey granite, and red quartzite and pink quartzite.

The binders used for testing include straight bitumen pen 80/100, polymer modified binder (S-E1), bitumen rubber (S-R1), polymer modified emulsion (SC-E1) and cationic rapid spray grade emulsion 60% (CRS 60).

Loading rate plays a significant role in the strength of the binder, because of the visco-elastic properties of the bituminous binders. This however was difficult to control precisely. Although the loading rate differs from test to test, the target was 700 kPa and the actual rate ranged predominantly in the range of 500 - 900 kPa/s.

1.7 ASSUMPTIONS

Smooth aggregate surfaces are considered worst case scenario, because a rough surface expands the surface area of the binder and aggregate interface.

Emulsions to be used in this study are all rapid setting and would therefore break within 1 hour.

The temperature of the laboratory where testing took place did not play a significant role during tests as test samples were not exposed to laboratory conditions for periods longer than 1 minute.

1.8 SIGNIFICANCE

At the commencement of this study, BBS testing were previously conducted only on emulsions at Stellenbosch University. This was part of a combined study with University of Wisconsin-Madison, which focussed solely on the evaluation of emulsions for seal tack coats. These studies confirmed that BBS testing is a viable and necessary test to determine the adhesion properties between emulsions and aggregates. Previous research conducted also included limited local aggregates.

This study will include BBS testing on hot applied binders, and will give insight to the adhesion properties of frequently used emulsions as well as hot applied binders in South African seal construction. The study will also expand knowledge of BBS properties by using local aggregates that are widely used in seals.

1.9 OVERVIEW OF CHAPTERS

This dissertation consists of a literature review, a research methodology, results, synopsis as well as a conclusion with recommendations.

The purpose of the literature review is to provide a theory base for the results of this dissertation. Chapter 2 will describe surface seals in South Africa as well as the two major components thereof. These components include binders and aggregates. The types and properties of binders will be explained. Aggregates and the influences they have on adhesion will be discussed, while emphasis will be placed on aggregates used in this study. The mechanisms of surface seal failure will be discussed especially the factors relating to adhesive failures. Types of adhesion failure between bitumen and aggregate will be discussed along with the influencing elements. An overview of the various tests that measure adhesive behaviour will be included. The BBS test, its development and influencing factors will also be discussed.

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The Chapter 3 shows what procedures were followed to arrive at the results. This method chapter includes the research design and discusses the strengths and weaknesses thereof. It focuses on the instruments used to complete the study as well as the materials on which the tests were carried out. The chapter also describes the test procedures and conditions. The data obtained by performing the tests will be discussed, as well as the analysis thereof. The limitations of the study will also be focused on.

The BBS tests results will be discussed in Chapter 4. The chapter includes comparisons between various influences. The type of failures of the tests will also be analysed and discussed.

In chapter 5 the works of others students will be discussed and compared to the results of this study. It includes similar studies on emulsions, influence of precoated aggregates as well as fractured aggregate faces.

Chapter 6 follows with conclusions and recommendations for future research.

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2. LITERATURE REVIEW

2.1 INTRODUCTION

This chapter aims to give insight on surface seals used in South Africa (S.A.). Background is given on the components and functions of seals, the types generally used in S.A., factors influencing the performance of seals as well as the methods and reasons for failure occurring in a seal.

Binders commonly used in surface seals will be discussed. The origin, manufacturing process and properties of the various binders will also be discussed. These properties include the visco-elastic behaviour of bitumen and other rheological behaviour of the binders used. Modified binders are described in terms of the modifiers used, the classification of the binders and the influence of the modification on rheological properties. The manufacturing process of emulsions and the different types will be discussed as well as the breaking process of emulsions.

Aggregates will be defined and the different types of aggregates used in road construction will be discussed. Emphasis will be placed on the specific aggregates used for this study. The role of surface charge will be discussed along with other factors such as physico-mechanical absorption.

Adhesion and cohesion will be distinguished from one another and discussed individually. Factors affecting adhesion between aggregates and binders will be discussed along with various failure mechanisms. Methods of improving adhesion in surface seals will also be included.

Various test methods for determining adhesion properties in surface seals will be discussed. The need for a performance related adhesion test for surface seals will be evident; therefore the significance of the Bitumen Bond Strength test is of major importance. The development of this BBS test will be discussed as well as the procedure and factors influencing results.

2.2 SURFACE SEALS

A surface seal, also referred to as a Chip and Spray seal, is a thin bituminous binder sprayed onto the base pavement surface and then immediately covered by an aggregate layer. Rolling follows this process to ensure close contact in order to promote good adhesion between the aggregate and the binder film. Rolling also initiates the process to orientate the aggregates into a mosaic pattern and working the bituminous binder into the voids between aggregate particles.

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The process is completed by the action of traffic, consequently producing a dense and relatively impermeable pavement layer (SANRAL, 2007).

2.2.1 FUNCTION OF A SURFACE SEAL

According to the Technical Recommendations for Highways 3 (TRH 3) the main functions of surface seals are:

- To provide a waterproof cover for the underlying pavement.
- To provide a safe all-weather, dust-free riding surface for traffic with adequate skid resistance.
- To protect the underlying layer from the abrasive and destructive forces of traffic and the environment.

Generally surface seals are relatively thin and have no load distribution properties. However, the seal itself should have enough strength to accommodate the horizontal and vertical stresses induced by traffic (SANRAL, 2007).

2.2.2 SURFACE SEALS IN SOUTH AFRICA

South Africa has a road network of approximately 750 000 km. It is estimated that 20%, or 150 000km, of the entire network is surfaced and that surface seals contribute to 80%, or 120 000 km, of the surfaced roads (SANRAL, 2007).

Surface seals are commonly used for new construction and for the resealing of existing pavements. The key reasons for this popularity are relative inexpensive costs, simplicity of construction and the fact that they have proved to be successful on highways, rural roads and urban streets, under light and heavy traffic conditions (Greyling, 2012).

2.2.3 TYPES OF SURFACE SEALS

In South Africa there are a number of seals commonly in use. They include single seals, double seals, Cape seals, slurry seals and sand seals. Figure 2-1 illustrates these. There are also less used seals such as inverted double seals, geotextile seals, split seals, graded aggregate seals and choked seals (SANRAL, 2007).

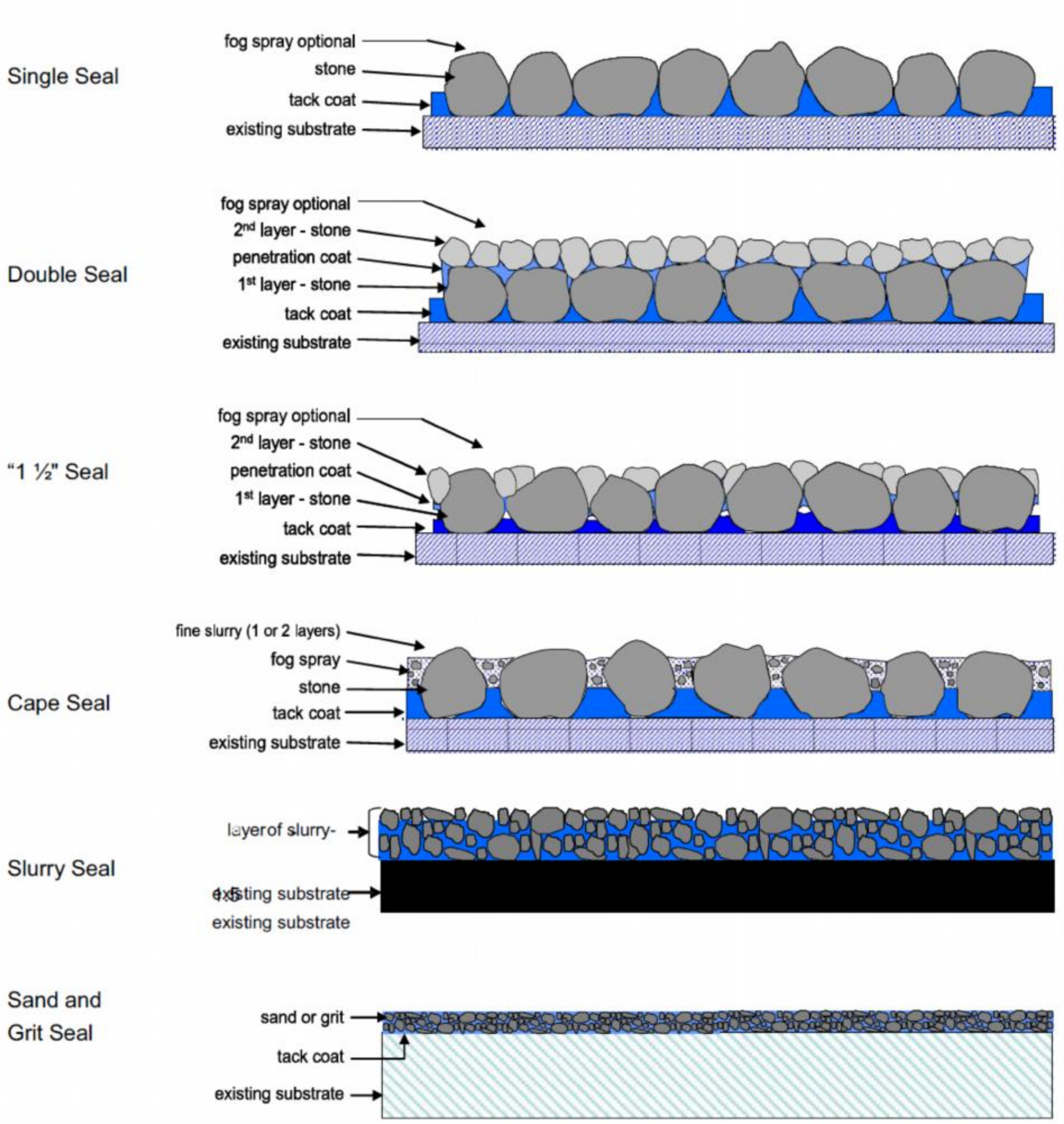

Figure 2-1: Surface Seals Commonly Used in South Africa (SANRAL, 2007)

2.2.4 PERFORMANCE INFLUENCING FACTORS

The performance of a surface seal is influenced by several factors and combinations thereof and is related to both the effective service life and the degree to which the functions of the seal are fulfilled (SANRAL, 2007).

Below are the factors that influence the performance of surface seals (SANRAL, 2007):

- Pavement structure and condition
- Existing substrate
- Traffic
- Road geometry
- Design
- Materials – Aggregates and binders used
- Preparation, pre-treatment and repairs before construction
- Construction and supervision
- Maintenance
- Physical and social environment

For the purpose of this study only material influences will be discussed.

2.2.5 FAILURE OF SURFACE SEALS

Terms such as “failure criteria”, “failed condition” or “the road has failed” are commonly used in practise and literature without clear definitions of their meaning. If it has been identified that a road has failed it generally suggest that some distress is evident on the road but it does not necessarily indicate the degree or seriousness of the distress (CSIR, 1985).

It is not easy to quantify the failure of surface seals, because it relates to speed, comfort and safety. Therefore functional features that can be measured have been identified and a standard could be set to ensure desired levels of speed, comfort and safety. According to the TRH 6 of 1985, for surfaced roads these are generally the skid resistance, riding quality and surface drainage of the road. If a pavement cannot provide these requirements the pavement is said to be in distress (Greyling, 2012).

Bitumen is a vital component of the seal and the composition thereof plays a critical role in the performance of the seal. Bitumen comprises of an internal multi-molecular matrix of polar molecules dispersed in a less polar to non-polar phase. The network formed by these polar molecules gives the bitumen its elastic properties, while the ability of the network to flow under prolonged stress gives bitumen its viscous behaviour. The relative viscous and elastic character varies with composition of the bitumen (Milne, 2004). Therefore the performance of the binder used in a seal plays a major role in the performance of the seal. Failure of the binder may lead to deformation, thermal and fatigue cracking as well as adhesion failure. Binders used in pavement construction will be discussed in the following sub-chapter.

Distress is the visual display at the road pavement surface of the deterioration of the condition of the pavement with respect to either the serviceability or the structural capacity. (Greyling, 2012). There are various modes of distress and they are summarised in Table 2-1 below:

Table 2-1: Various Types of Distress Associated With Each Mode of Distress (CSIR, 1985)

Mode of Distress	Type of Distress
Deformation	Depressions Mounds Ruts Ridges Displacements Corrugations Undulations
Cracking	Transverse cracks Longitudinal cracks Block cracks Map cracks Crocodile cracks Parabolic cracks Star cracks Meandering cracks Multiple cracks
Disintegration of surfacing	Ravelling Potholes Edge breaks Patches
Smoothing of surface texture	Bleeding Polishing

Table 2-1 is applicable to both hot mix asphalt and seals, but most of the types of distresses identified above applies to hot mix asphalt. Milne (2004) described the performance criteria applicable to surface seals as follows:

- Permanent deformation
    - Reduction in voids due to rotation of aggregate chippings in binders with higher viscosity.
    - Punching that leads to loss of surface texture.
    - Bleeding or flushing caused by lateral flow of binder under loads.
- Fatigue cracking
- Low temperature cracking and brittleness
- Moisture damage
- Adhesion failure
    - Raveling under dynamic loading, including loss of aggregates at low temperatures.

Raveling, sometimes referred to as stripping, is most relevant to this study and happens when the aggregate chip separates from the seal structure. This is a result of the bond failure of the bitumen/aggregate system. The type of failure achieved can be either adhesive or cohesive.

The adhesion of bitumen to aggregate is determined at molecular and inter molecular level. Polarity, or separation of charge of the molecules, promotes attraction between the bitumen and the polar surface of the aggregate. Interaction of the polar molecules of the bitumen and the aggregate leads to adhesion. Bitumen also has the ability to absorb water due to its polar nature, causing softer bitumen. The result in the performance of the bitumen is reduced strength leading to greater susceptibility to deformation and rutting (Milne, 2004). Adhesion and cohesion properties will both be discussed later in this chapter.

2.3 BINDERS

"Binders" is the term used to describe the various types of binding agents used in asphalt and surface seals. Predominantly bitumen, or modifications thereof, is used as binders in road construction. The various binders used in this research will be discussed below.

2.3.1 PENETRATION GRADE BITUMEN

Bitumen is a dark brown to black coloured viscous liquid or solid, consisting mainly of hydrocarbon material. At ambient temperatures bitumen has a solid or semi-solid consistency and softens gradually when heated. Bitumen is manufactured by refining petroleum crude oil, although it is also found as a naturally occurring deposit.

As a binder, bitumen is especially valuable to the engineer because it is a strong, readily adhesive, highly waterproof and durable material. Bitumen is a valuable and versatile road building material used in a broad range of applications, mainly in the construction of road and airport pavements. It also provides some flexibility to mixtures of mineral aggregates with which it is usually combined (SABITA, 2012).

Penetration grade bitumen can be manufactured by straight run distillation or by blending two base components (one hard such as 35/50 and the other soft as 150/200 pen). It is either used as a primary binder by itself or used as base binder for manufacturing modified bitumen, bitumen emulsions, or cutback bitumen (SABITA , 2011).

The physical and chemical properties of bitumen are dependent on the crude oil source from which it is derived. Refineries generally use consistent crude oil sources which results in consistent bitumen properties. However, the need remains to evaluate the bitumen through laboratory tests in order to assess its performance characteristics (SABITA, 2012).

2.3.1.1 Bitumen Production

In South Africa most bitumen used in road construction is processed at refineries in Sasolburg, Durban and Cape Town. Crude oils are refined to produce petrol, diesel fuel and other petroleum based products at these refineries. Bitumen only represents about 2.5% of the total percentage coming from a barrel of crude oil (SABITA, 2012).

Crude oil is heated and delivered into an atmospheric distillation column, where the lighter fractions are vaporised and drawn off, leaving a residue of heavy oil. This residue is processed, by further distillation under vacuum, to produce “vacuum bottoms”. Treatment under vacuum enables oil fractions to be drawn off in vapour form under relatively low temperatures. These “vacuum bottoms” are used to produce straight run bitumen. Sometimes it is further treated by air blowing to produce harder bitumen such as 40/50 penetration grade bitumen (SABITA, 2012).

2.3.1.2 Rheology of Bitumen

Rheology is the science that deals with the flow and deformation of material and constitutes a fundamental engineering property of bitumen. The rheological characteristics of bitumen at a particular temperature are determined by both the chemical composition and structure or physical arrangement of the molecules in the material. Therefore to understand the rheology of bitumen, it is essential to understand how the constitution and structure of bitumen interact to influence the rheology (Read & Whiteoak, 2003).

Temperature influence

Bitumen is a thermoplastic hydrocarbon material which softens when heated and turns to a glassy solid state when cooled. According to the SABITA Manual 2, the following phases generally describe the consistency of bitumen at various temperatures:

- At low road temperatures - a brittle solid
- At room temperatures - a sticky semi-solid
- At high service temperatures - a viscoelastic substance
- At elevated temperatures - a viscous liquid

Composition of Bitumen

Bitumen is a complex combination of hydrocarbons with small quantities of nitrogen, oxygen and sulphur. It also contains trace quantities of metals such as nickel, vanadium, magnesium and calcium. Most bitumen manufactured from a range of crude oil contains:

Carbon	82 - 88%
Hydrogen	8 – 11%
Sulphur	0 - 6%
Oxygen	0 – 1.5%
Nitrogen	0 – 1%

The precise composition of the bitumen depends on the crude oil source, the manufacturing process used by the particular refinery and ageing during in-service (Read & Whiteoak, 2003).

The chemistry of bitumen is rather complex and a complete chemical analysis of bitumen would be impractical. Bitumen can be separated into two broad chemical groups, namely asphaltenes and maltenes. Maltenes can further be divided into saturates, aromatics and resins and is shown in Figure 2-2 (SABITA, 2012).

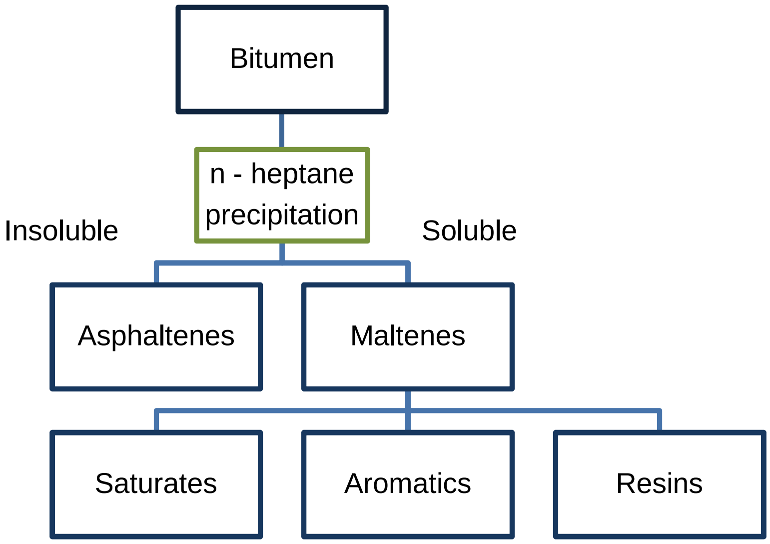

Figure 2-2: Broad Chemical Composition of Bitumen (from SABITA, 2012)

While it is known that the chemical composition of a type of bitumen will determine its physical properties and performance characteristics, the complex and variable molecular structure makes it extremely difficult to measure and define chemical composition for required performance.

It is also known that bitumen from different crude sources (which implies different chemical composition) can have very similar physical properties. It therefore makes no sense to describe or to specify bitumen in terms of its chemical component concentrations, nor define the concentrations of individual components. Consequently, general practice recommends using performance related physical properties for specifying and selecting bituminous binders (SABITA, 2012).

Structure of Bitumen

Bitumen is traditionally regarded as a colloidal system consisting of high molecular weight asphaltenes micelles dispersed or dissolved in a lower molecular weight oily medium called maltenes. The micelles are considered to be asphaltenes together with an absorbed sheath of high molecular weight aromatic resins which act as a stabilising solvating layer. Away from the centre of the micelle, there is a gradual transition to less polar aromatic resins, these layers extending outwards to the less aromatic oily dispersion medium (Read & Whiteoak, 2003).

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In the presence of sufficient quantities of resins and aromatics of adequate power, the asphaltenes are fully peptised and the resulting micelles have good mobility within the bitumen. These are known as “SOL” type bitumens and are illustrated in Figure 2-3.

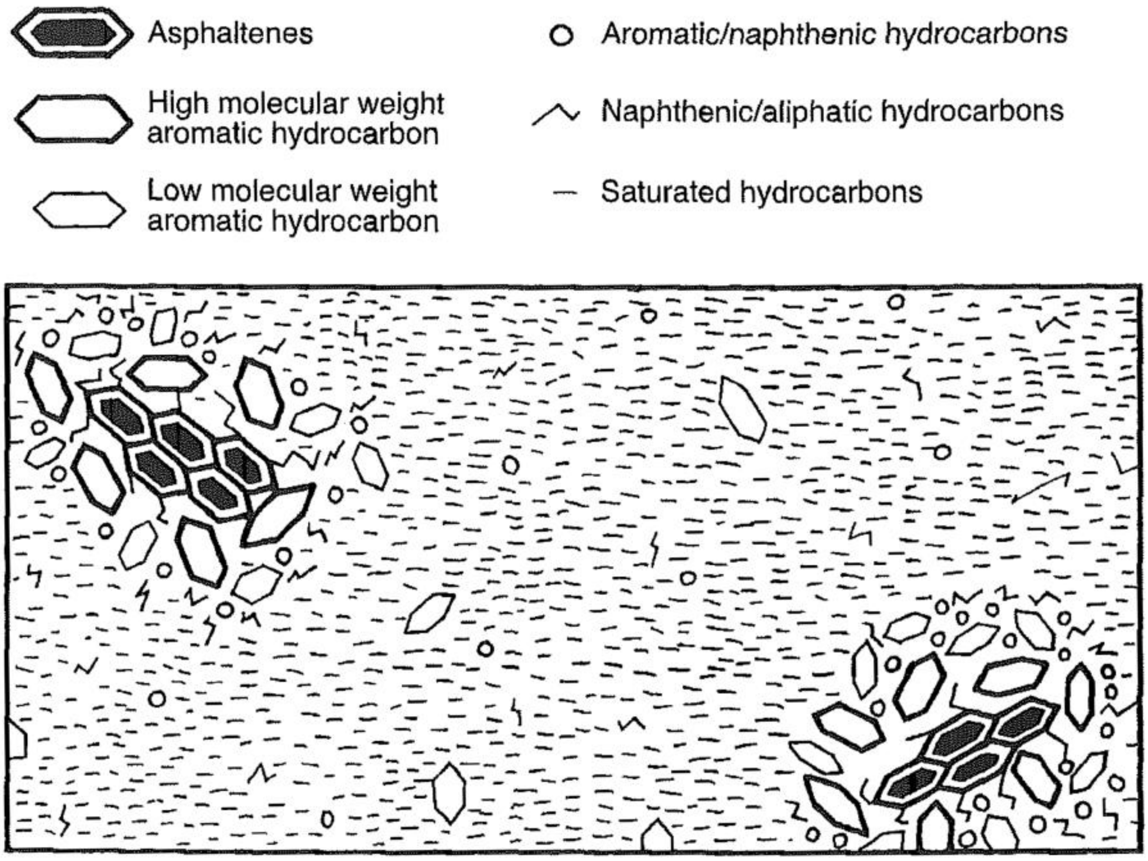

Figure 2-3: Schematic Representation of a SOL type Bitumen (Read & Whiteoak, 2003)

If the aromatic/resin fraction is not present in sufficient quantities to peptise the micelles, or has insufficient power, the asphaltenes can associate together further. This can lead to an irregular open packed structure of linked micelles in which internal voids are filled with an intermicellar fluid of mixed constitution. These bitumens are known as “GEL” types, as depicted in Figure 2-4 (Read & Whiteoak, 2003).

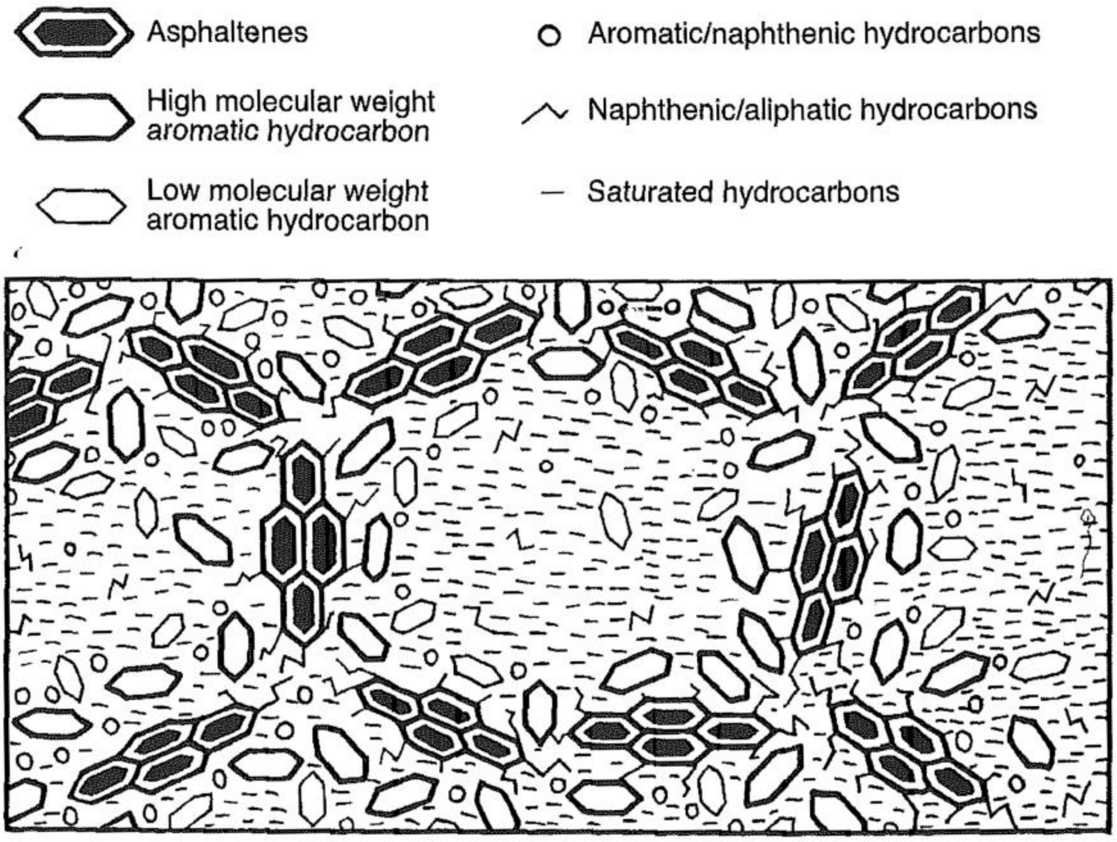

Figure 2-4: Schematic Representation of a GEL Type Bitumen (Read & Whiteoak, 2003)

In practice, most bitumen types are of intermediate character. The colloidal behaviour of the asphaltenes in bitumen results from aggregation and solvation. The degree to which they are peptised will have a considerable influence on the resultant viscosity of the material. Such effects decrease with increasing temperatures and the GEL character of certain bitumens may be lost when they are heated to high temperatures (Read & Whiteoak, 2003).

It is important to note that there is no formula for the ideal proportions of saturates, resins, aromatics and asphaltenes; rather it is the interaction between these fractions that will characterise the rheology of bitumen (SABITA, 2012).

2.3.1.3 Viscoelastic Properties of Bitumen

Bitumen demonstrates both elastic and viscous behaviour depending largely on temperature and loading rate. This viscoelastic nature of bitumen results in its varied reaction under different temperatures and loading rate conditions (Jenkins, 2013).

Elastic Behaviour

At low temperature and short duration loads

- Bitumen tents to act as an elastic solid, returning to its original position after removing the load.
- Excessively low temperatures in conjunction with rapid loading may cause brittle failure and cracking.
- Prolonged low temperatures may cause internal stress build-up that could result in cracking.

Viscous Behaviour

Viscosity measurement:

Dynamic viscosity measures the resistance to flow of a fluid and is expressed as the ratio:

$$\frac{Applied\ Shear\ Stress}{Rate\ of\ Shear}$$

The SI unit of Dynamic viscosity is Pascal-second (Pa.s).

Kinematic viscosity is expressed as the ratio:

$$\frac{Dynamic\ viscosity}{Density\ of\ the\ fluid}$$

The SI unit of kinematic is mm^2/s or Centistoke (cSt).

At elevated temperatures and long duration loads:

- Bitumen acts as a viscous fluid and undergoes plastic deformation that is not recovered.
- Flow takes place as adjacent molecules flow past each other.
- The force resisting the flow is related to the relative velocity of the sliding.
- Fluids like water and penetration grade bitumen above 60 – 100 °C show a linear relationship:

$$\frac{Resistive\ force}{Relative\ velocity\ of\ sliding}$$

Viscosity is therefore constant irrespective of the magnitude of applied shear. Materials that display this behaviour are known as Newtonian fluids.

To illustrate how viscoelastic materials respond to applied loads it is common practice to represent material behaviour by a system of springs to simulate the elastic components, and dashpots to simulate the viscous behaviour as follows:

- Spring:
  - Elastic deformation;
  - Not time dependent;
  - No permanent deformation.

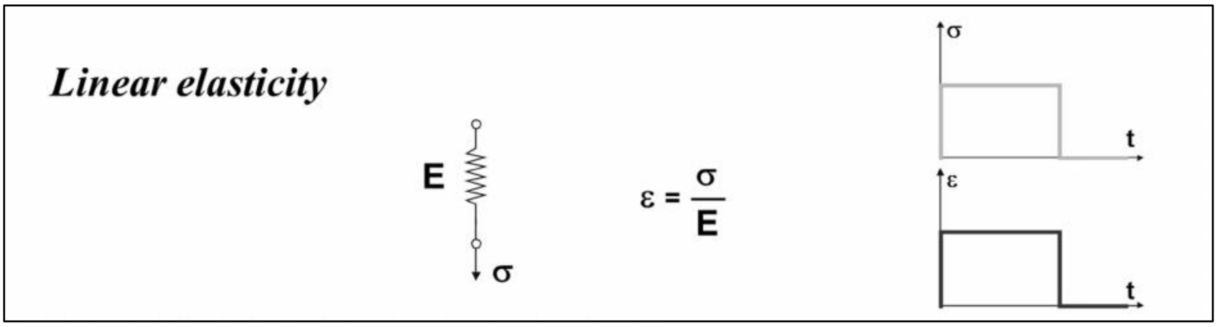

Figure 2-5: A Spring illustrating Linear Elasticity (Jenkins, 2013)

- Dashpot:
  - Viscous deformation;
  - Time dependent;
  - Some permanent deformation.

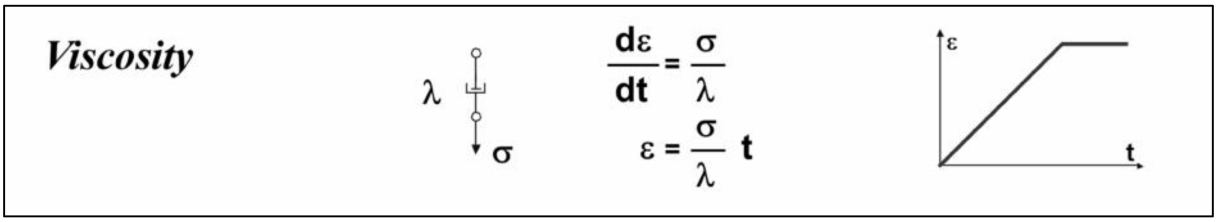

Figure 2-6: A Dashpot illustration Viscosity (Jenkins, 2013)

- Spring-dashpot in parallel:
  - Delayed elastic deformation;
  - Time dependent;
  - No permanent deformation.

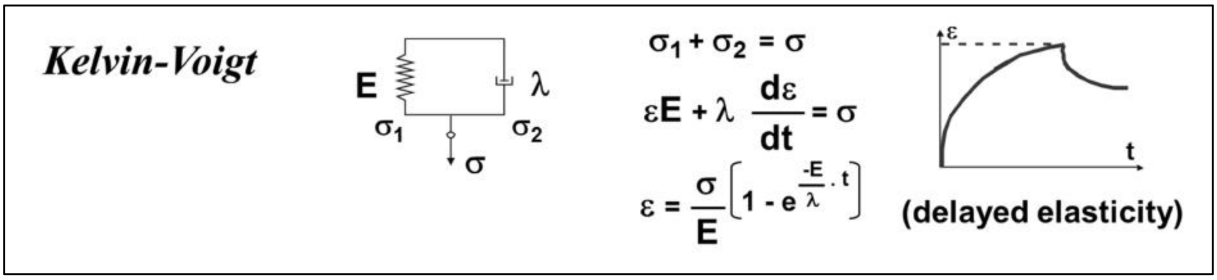

Figure 2-7: A Spring-Dashpot in Parallel (Jenkins, 2013)

Burger's model is often used to characterise the response of bitumen to imposed stresses. The model is shown in Figure 2-8, and the components are described in Table 2-2.

Burger's model:

- A spring and dashpot in series (Maxwell model);
- Spring and dashpot in parallel (Kelvin-Voigt model).

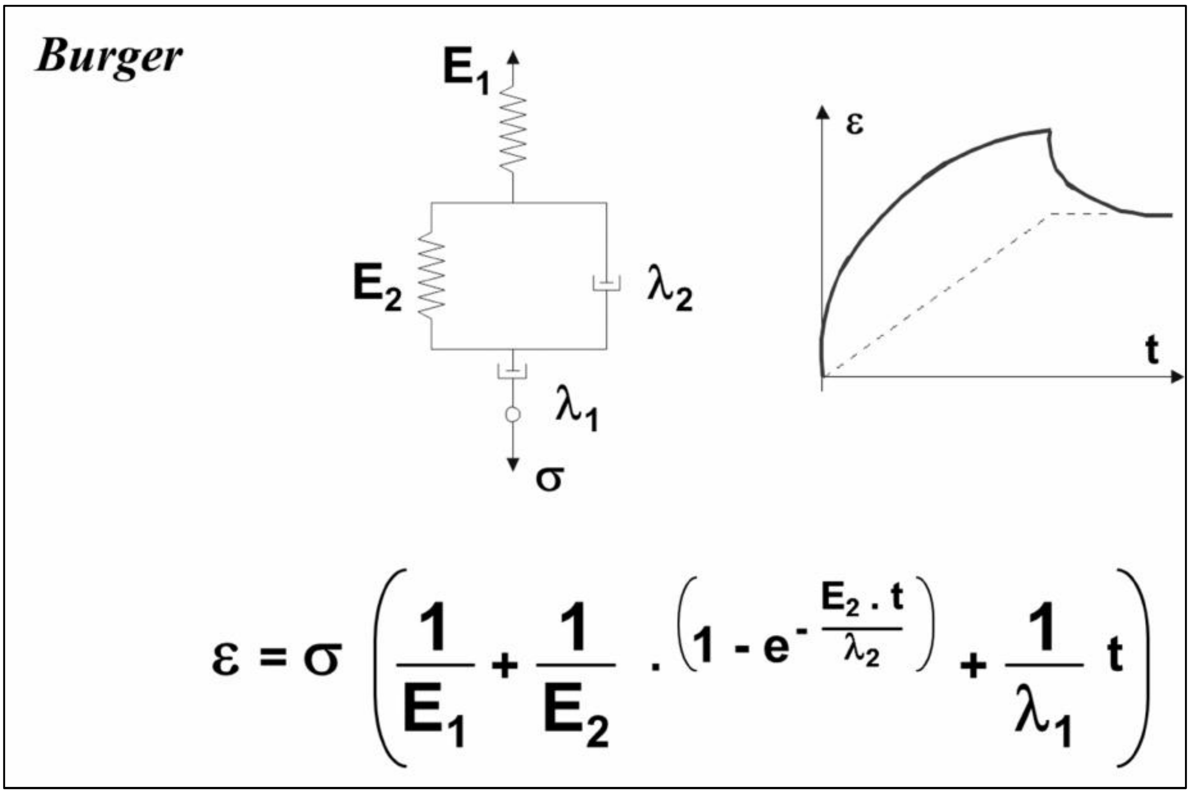

Figure 2-8: Burger's Model illustrating Viscoelastic Behaviour (Jenkins, 2013)

Table 2-2: Components of Burger's Model (from Jenkins, 2013)

Model component		**Type of deformation due to constant load**
Spring	Maxwell	Elastic deformation – not time dependent, no permanent deformation
Dashpot		Viscous deformation – time dependent, permanent deformation
Spring – dashpot in parallel	Kelvin-Voigt	Delayed elastic deformation – time dependent, no permanent deformation

The Dynamic Shear Rheometer (DSR) is a test used to determine the rheological properties of bitumen. This test is capable of measuring both elastic and viscous properties of bituminous binders at in-service temperatures (SABITA, 2012).

The DSR measures the bitumen sample's Complex Shear Modulus (G*) as well as the Phase Angle (δ). Figure 2-9 and Figure 2-10 illustrates these rheological properties.

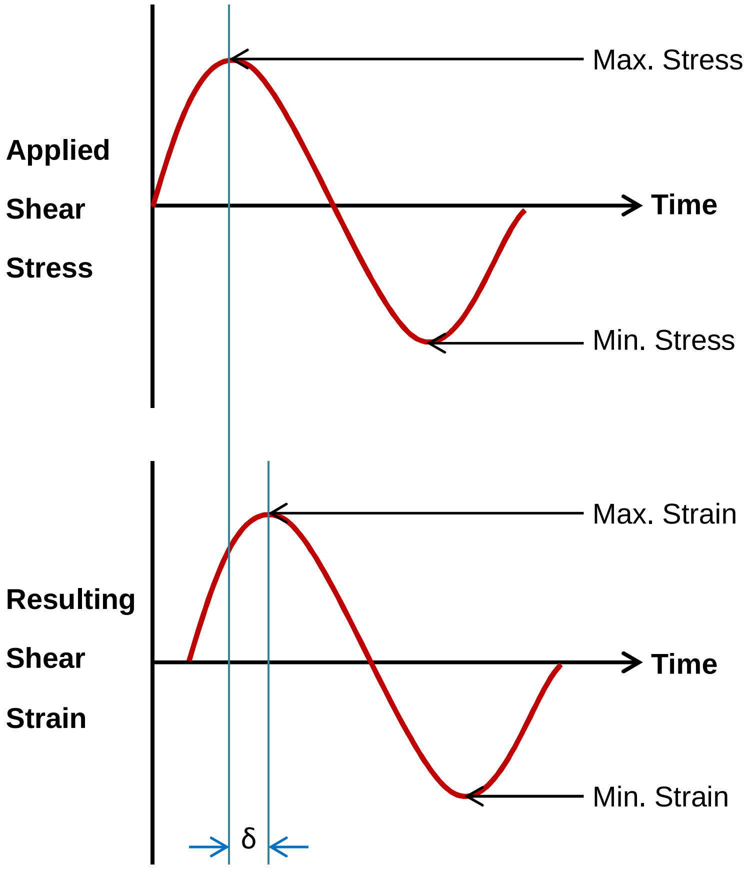

Figure 2-9: Measurements of Dynamic Shear Rheometer Test (from SABITA, 2012)

The complex shear modulus (G*) comprises the specimen's total resistance to deformation if repeatedly sheared and is expressed by the equation below:

$$G^* = \frac{Max\,Stress - Min\,Stress}{Max\,Strain - Min\,Strain}$$

The phase angle represents the lag between the applied shear stress and resulting shear strain. The limiting values of the phase angle are:

- For completely elastic material: δ = 0° ;
- For completely viscous Material: δ = 90°.

The phase angle of unmodified bitumen varies between 88° - 89°, while certain modified binders can exhibit a phase angle close to 60° (SABITA, 2012).

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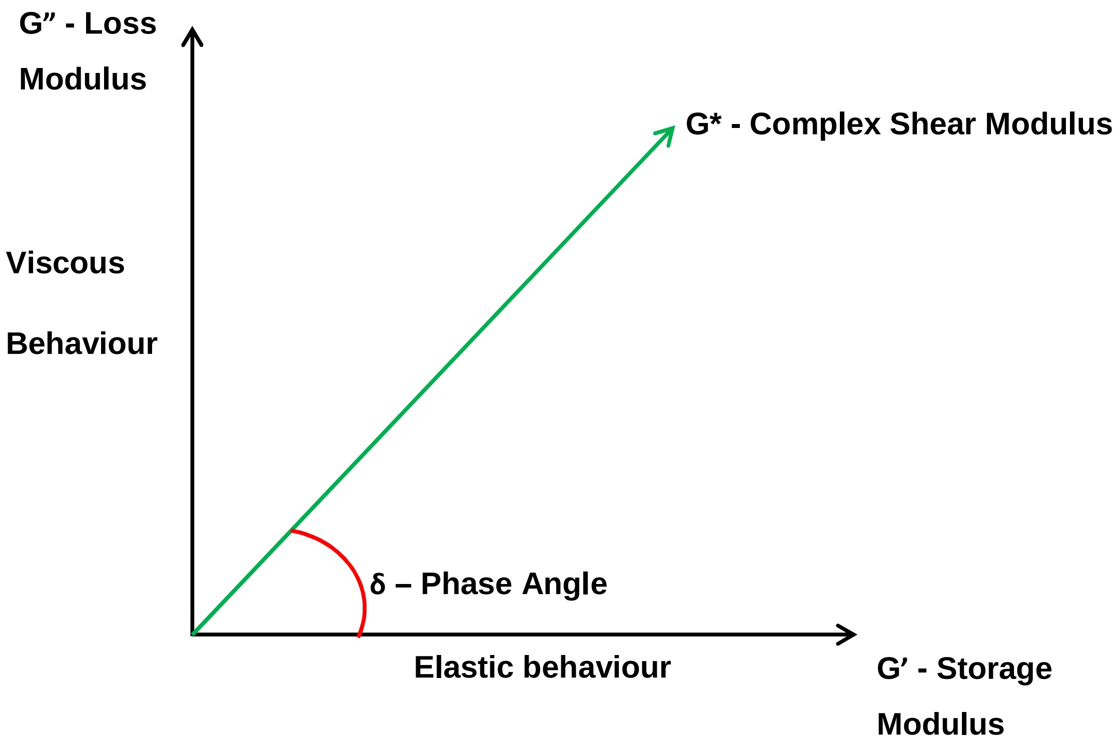

Figure 2-10: Viscous and Elastic Behaviour of Bitumen (from SABITA, 2012)

The phase angle (δ) reduces as temperature decreases, making the binder more elastic and less viscous (Jenkins, 2013).

2.3.1.4 Types of Binders

Figure 2-11 below depicts the bituminous binders available in South Africa.

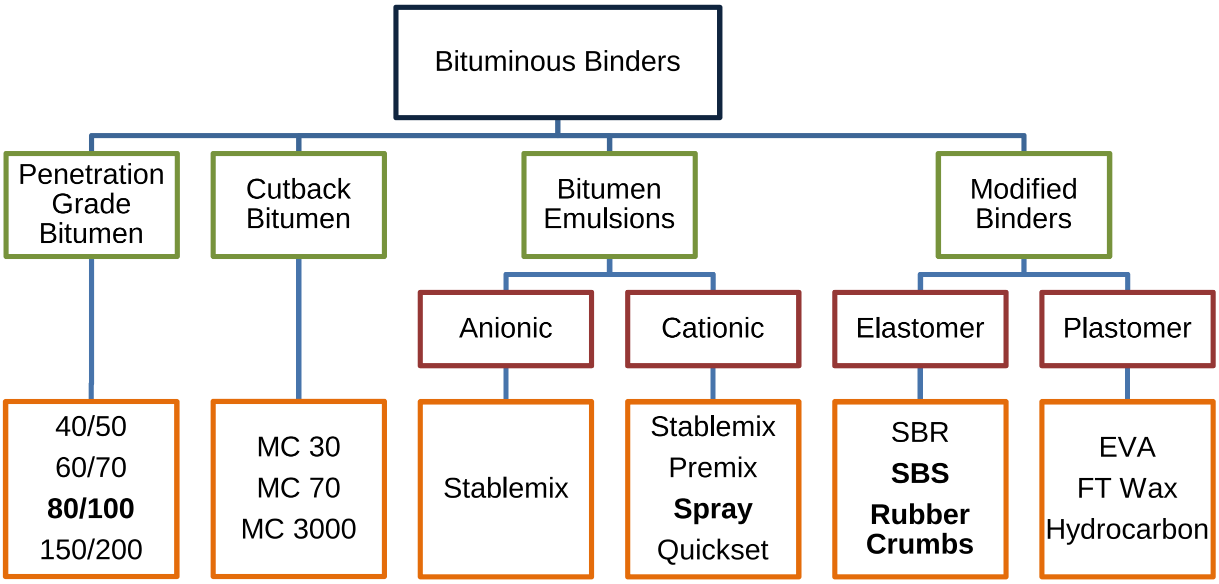

Figure 2-11: Binders Available in South Africa (from SABITA, 2013)

2.3.2 CUTBACK BITUMEN

Cutback bitumen is a blend of penetration grade bitumen and petroleum solvents. The choice of solvent determines the rate at which the bitumen will cure when exposed to air. A rapid-curing (RC) solvent will evaporate more quickly than a medium-curing (MC) solvent. The viscosity of the cut back bitumen is determined by the proportion of solvent added - the higher the proportion of solvent, the lower is the viscosity of the cutback. The solvent used in cutback bitumen is sometimes also referred to as the "cutter" or "flux".

When the solvent has evaporated, the binder reverts to the original penetration grade. The advantage of cutback bitumen is that it can be applied at lower temperatures than penetration grades because of its lower viscosity. A disadvantage is that cutback bitumen consumes non-renewable energy resources which are ultimately lost through evaporation (SABITA, 2012).

2.3.3 MODIFIED BITUMEN

Penetration grade bitumen is often not able to meet all the requirements when a surface seal is exposed to severe conditions. Extreme road surface temperatures, high traffic loading or heavily trafficked intersections and steep road gradients are some of the challenges that binders must address (Greyling, 2012).

Modified binders have the ability to offer improved performance over conventional binders. They are less sensitive to bleeding under high traffic volumes than unmodified binders and have better elastic properties, enabling them to accommodate high deflections at low temperatures (Van Zyl, et al., 2012).

Improved consistency, reduced temperature vulnerability, improved stiffness and cohesion, resilience and toughness, enhanced flexibility, improved resistance to in service ageing and better binder and aggregate adhesion are several of the benefits that can be derived from modification (Greyling, 2012).

2.3.3.1 Modification

Modified bitumen is produced by adding a polymer to penetration grade bitumen. The type of modified binder depends on the polymer used. The polymers can be a plastomer or elastomer. Plastomers improve the viscosity of the bitumen, while elastomers increase the strength and elastic properties of a binder. Table 2-2 shows the different types and varieties of modifiers used.

Table 2-3: Types and Varieties of Modifiers (from SABITA, 2012)

Modifier Type		Varieties
Polymer	Elastomer	Styrene-Butadiene-Rubber (SBR) latex
		Styrene-Butadiene-Styrene (SBS)
		Bitumen Rubber
	Plastomer	Ethylene-Vinyl-Acetate (EVA)
Hydrocarbon substances	Aliphatic synthetic wax	Fisher-Tropsch (F-T) wax
	Naturally occurring hydrocarbons	Gilsonite
		Durasphalt

2.3.3.2 Classification of Modified Bitumen

The Asphalt Academy's Technical Guideline (TG1) is currently the primary principles used in South Africa regarding the modified binders used in road construction. The document classifies modified binders according to four groups that include type of application, type of binder system, type of modifier used and the level of modification. It can be summarised as follows:

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Type of application

S – Seal

A – Asphalt

C – Crack sealant

Type of binder system

The letter “C” would follow directly after the letter that indicates the application type to indicate that the binder is an emulsion.

For hot applied binder no letter follows the application type.

Predominant type of modifier used

E – Elastomer

P – Plastomer

R – Rubber Crumb

H - Hydrocarbon

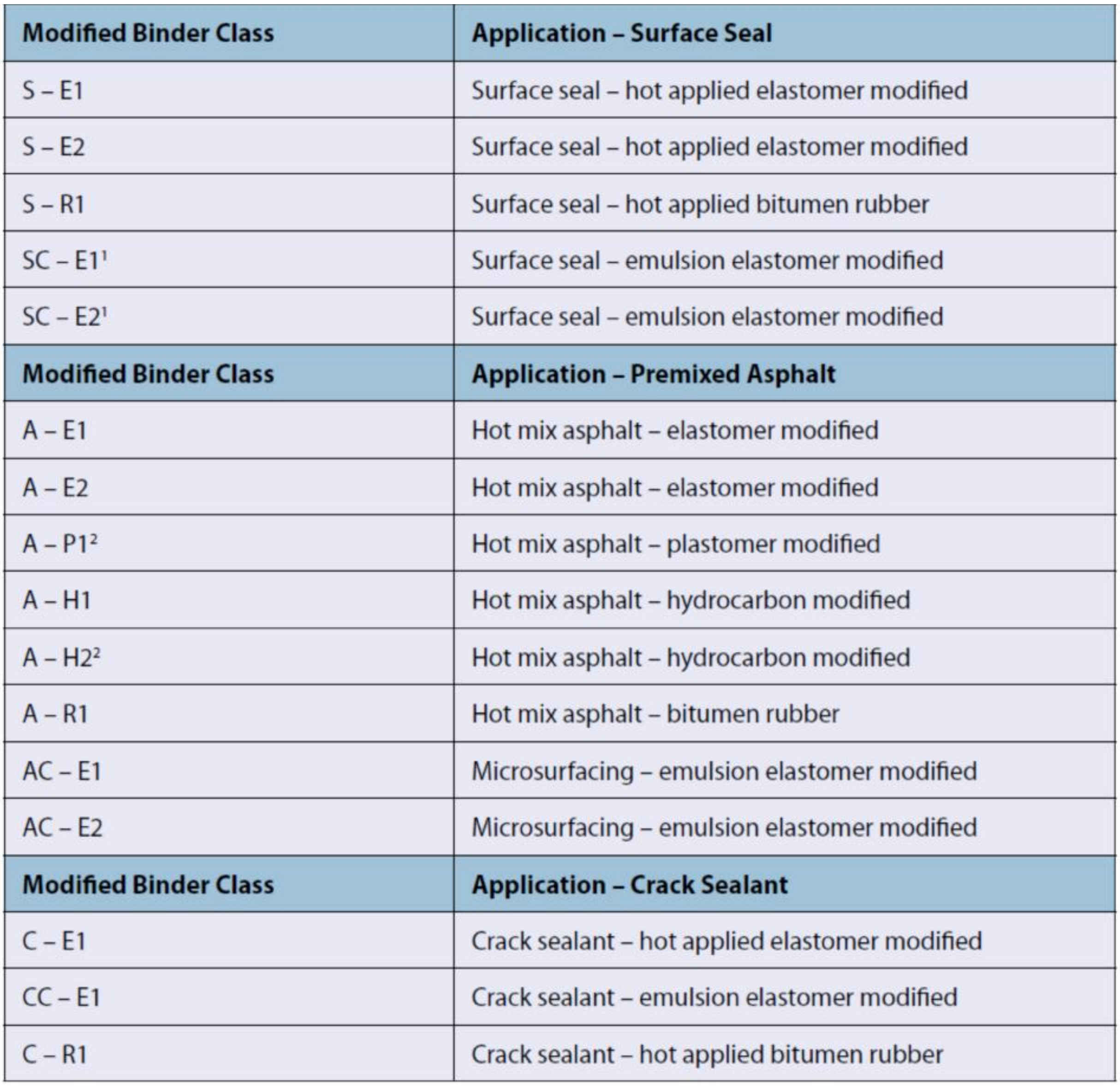
Level of modification

A numerical number is used to indicate increasing softening point values.

If the binder application does not permit the use of flux or cutter the letter “t” should be shown in brackets after the classification (Asphalt Academy, 2007).

Table 2-4 shows a summary of the typical binder classes specified in the TG1 (Asphalt Academy, 2007).

Table 2-4: Classification System of Modified Binders (Asphalt Academy, 2007)



Modified Binder Class	Application – Surface Seal
S – E1	Surface seal – hot applied elastomer modified
S – E2	Surface seal – hot applied elastomer modified
S – R1	Surface seal – hot applied bitumen rubber
SC – E1[1]	Surface seal – emulsion elastomer modified
SC – E2[1]	Surface seal – emulsion elastomer modified
Modified Binder Class	**Application – Premixed Asphalt**
A – E1	Hot mix asphalt – elastomer modified
A – E2	Hot mix asphalt – elastomer modified
A – P1[2]	Hot mix asphalt – plastomer modified
A – H1	Hot mix asphalt – hydrocarbon modified
A – H2[2]	Hot mix asphalt – hydrocarbon modified
A – R1	Hot mix asphalt – bitumen rubber
AC – E1	Microsurfacing – emulsion elastomer modified
AC – E2	Microsurfacing – emulsion elastomer modified
Modified Binder Class	**Application – Crack Sealant**
C – E1	Crack sealant – hot applied elastomer modified
CC – E1	Crack sealant – emulsion elastomer modified
C – R1	Crack sealant – hot applied bitumen rubber

2.3.3.3 Rheology of Modified Binders

The rheology of unmodified bitumen is relatively simple, and behaviour can be predicted through the use of simple tests such as Penetration, Softening Point and Viscosity at various temperatures. The rheology of modified binders on the other hand is highly complex, and, although the results from conventional tests may indicate a significant improvement in properties, the in-service performance of these binders is not easily categorised (Asphalt Academy, 2007).

Unlike conventional bitumen which displays Newtonian behaviour above its softening point temperature, modified binders tend to display shear thinning behaviour thus minimising the significance of dynamic shear viscosity measurements at normal shear rates.

In most instances, the addition of polymer results in the binder having lower moduli at lower temperatures, and is consequently more flexible. At high temperatures, however, the binder exhibits an improved stiffness and elasticity when compared to the unmodified bitumen. Figure 2-12 illustrates the effects that elastomers can have on the rheological profile of bitumen and it can be concluded that the modified binder would offer improved rheological performance in areas of high temperatures and tensile strains (SABITA, 2012).

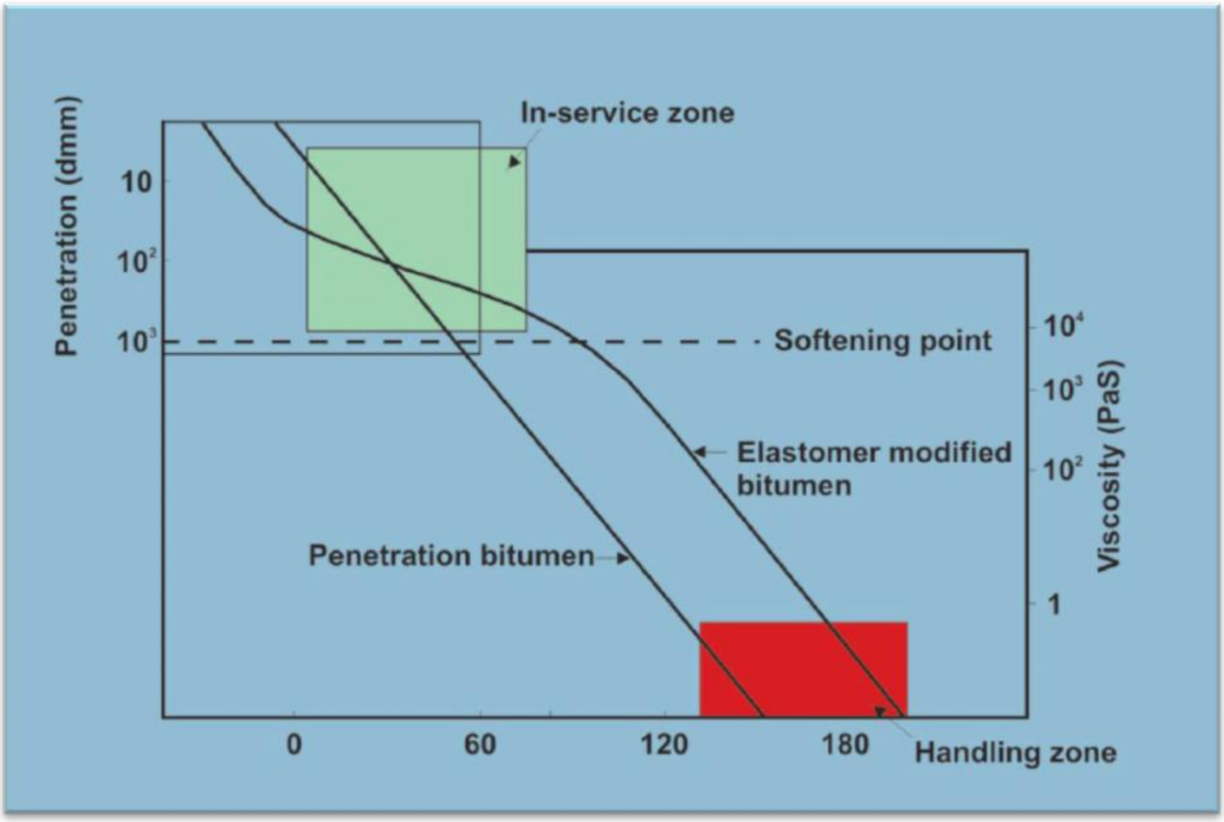


Figure 2-12: Rheological Effect of an Elastomer on Bitumen (SABITA, 2012)

2.3.4 EMULSIONS

An emulsion can be defined as a dispersion of small droplets of one liquid in another liquid. Bitumen emulsions belong to the oil-in-water types of emulsion, where bitumen is dispersed in water as depicted in Figure 2-13 (ScanRoad, 1983).

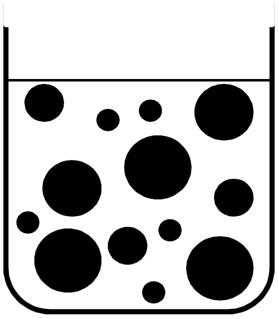


Figure 2-13: Oil-in-Water emulsion (from ScanRoad, 1983)

Emulsification of bitumen is a means of reducing the viscosity of a binder so that it behaves as a fluid during handling and application. The emulsifiers are added to assist in the formation of the emulsion, to render it stable, and to modify its properties (SABITA, 2012).

Bitumen emulsions are typically available in either anionic or cationic emulsions. The terms cationic and anionic is referring to the electrical charges of the dispersed bitumen particles. In anionic emulsions the bitumen particles are negatively charged, while in cationic emulsions positively. Cationic emulsions are more widely used due to superior adhesive properties to a range of mineral aggregates (Gransburg, et al., 2010).

2.3.4.1 Manufacturing of Emulsions

A bitumen emulsion plant can either be a batch type or continuous and both usually incorporates a colloid mill. In the manufacturing process, an emulsifier solution and bitumen are passed through the colloid mill, where the emulsification takes place as illustrated in Figure 2-14.

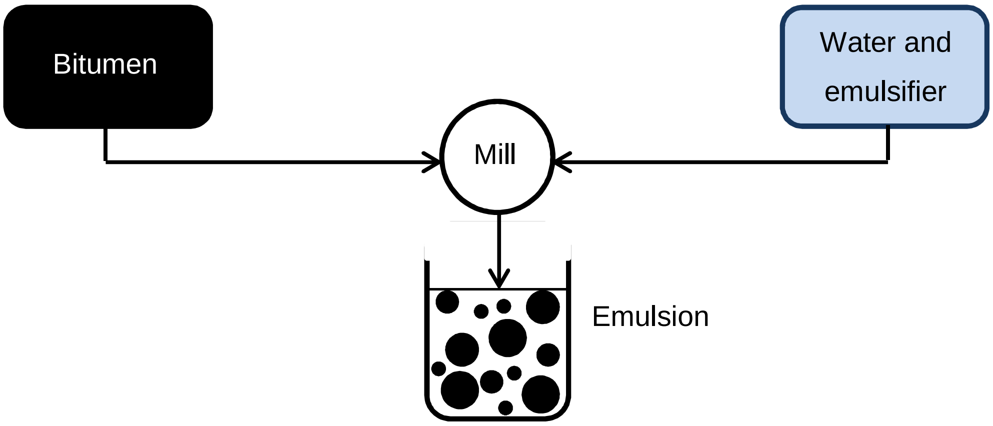


Figure 2-14: Bitumen Emulsion Manufacturing Process (from ScanRoad, 1983)

The emulsifier solution contains water, emulsifier, acid and if required a stabiliser, which are carefully mixed in such proportions that a uniform solution with the right pH is obtained. The bitumen is either pure or mixed with a solvent.

The temperature of the emulsion should be kept between 85 ˚C and 95 ˚C and must never reach 100 ˚C during manufacture. However, the bitumen phase must be sufficiently hot to be pumped.

2.3.4.2 Types of Emulsions

The polarity charge of the bitumen particles suspended in the emulsion and the rate of setting of the emulsion are the main factors by which emulsions are classified. Anionic emulsions contain negatively charged bitumen particles and cationic emulsions have positively charged droplets.

The SANS standards used in South Africa divide both anionic and cationic emulsions into three categories according to their application or use as defined below:

Spray grade emulsions are characterised by rapid breaking on application to the aggregate. Rapid-setting (RS) emulsions set quickly when in contact with clean aggregates of low surface area, typically used in surface seals.

Pre-mix type emulsions have sufficient stability to allow mixing with certain aggregate types before breaking of emulsion occur. Medium-setting (MS) emulsions set sufficiently slower so that they can be mixed with aggregates of low surface area, such as those used in open graded asphalt mixes.

Stable mix emulsions have sufficient mechanical and chemical stability for all purposes involving mixing with stone chips, natural gravels and soil. This includes aggregates containing large

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proportions of fines or chemically active materials such as cement of hydrated lime. Slow-setting (SS) emulsions take longer to set and will mix with reactive aggregates of high surface area (Greyling, 2012).

2.3.4.3 Breaking of Emulsions

The main purpose of bitumen emulsion is to transfer it to a fluid state at ambient temperature. The emulsion should be stable during transport and storage, but when applied to mineral aggregate or pavement surfaces, it should break at a predetermined rate. The rate of breaking is largely controlled by the type and dosage of emulsifier. However, other factors also have an influence; they include type of aggregate, temperature and other climatic conditions (ScanRoad, 1983).

Emulsified bitumen must revert to a continuous bitumen film in order to act as a binder in a seal. This involves flocculation and coalescence of the droplets and removal of the water in the emulsion. Evaporation and absorption of water by the aggregate may be the main breaking mechanism for very slow-setting emulsions, but in most cases chemical reactions between the aggregate and the emulsion contribute to the emulsion setting and it is not necessary for all the water to evaporate before curing takes place (James, 2006).

The emulsion contains emulsifier ions both in the water phase and on the surface of the bitumen particles. If the concentration of emulsifier ions is high the ions will form micelles. In a stable emulsion a state of equilibrium exists between the ions in the solution and the ions on the surface of the droplets. The equilibrium of a stable emulsion is disturbed by the removal of emulsifier ions from the solution, the balance will be restored by ions released from micelles if there are any available, or by ions released from the surface of the droplets. In the latter case, the stability of the emulsion will decrease which may lead to start the coalescence process and ultimately will lead to the breaking of the emulsion. This is what happens when an emulsion is applied to the surface of a mineral aggregate (ScanRoad, 1983).

During the coalescence process some of the water will be trapped inside the bitumen phase. The emulsion has inverted and is now bitumen like. The trapped water will slowly evaporate and once it is evaporated the bitumen regains its original properties. This may take from a couple of hours at ambient temperature to several days at extremely low temperatures. Climatic conditions apart from temperature such as relative humidity and wind velocity also affects the rate of breaking. Breaking can also be accelerated by mechanical forces like vibrations from a roller or even traffic (ScanRoad, 1983).

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Table 2-5: Results of Cationic and Anionic Emulsions with Two Types of Aggregates (from ScanRoad, 1983)

Emulsion	Aggregate	Results	
		Breaking Rate	Adhesion
Anionic	Acidic	Slow	Poor
Anionic	Basic	Medium	Good
Cationic	Acidic	Fast	Excellent
Cationic	Basic	Fast	Good

2.4 AGGREGATES

The term aggregates refers to the crushed rock that is used in surface seals and is a major component thereof as it bonds with the bituminous binder to form a strong, durable and waterproof surface.

The functions of aggregate in a surface seal are to provide resistance to the abrasion of moving wheel loads and to transfer the wheel loads to the underlying pavement structure, while providing a skid resistance surface. Aggregates should provide a structure to accommodate the elastic and impermeable bituminous binder that needs to have sufficient voids to prevent the binder flushing to the surface under loading. It should also protect the binder from the harmful ultra-violet rays of the sun.

Aggregate related factors affecting performance of a seal are:

- Shape, nominal size and grading
- Spread rate
- Adhesion characteristics, cleanliness and dust content
- Strength, durability and wearing characteristics
- Porosity/absorption (SANRAL, 2007)

2.4.1 AGGREGATE TYPE

Aggregates are formed by mining quarries and crushing rock boulders into various sizes. The type of aggregate depends on the type of rock that is mined at the quarry.

All rocks can categorised according to their mineral and chemical composition, by texture of the constituent particles and by the processes that formed them and be separated into three major categories: Igneous, sedimentary and metamorphic rocks.

Igneous rocks form by the crystallization of once molten material. This molten rock is called magma and then lava once it reaches the surface. These rocks are divided into two main categories: plutonic and volcanic rock. Plutonic rocks result when magma cools and crystalizes slowly within the earth’s crust (e.g. granite), while volcanic rocks result from magma reaching the surface either as lava or fragmental ejected rock (e.g. pumice and basalt).It is essentially a silicate melt and may contain, as well as silicon and oxygen, other elements, particularly aluminium, iron, calcium, sodium, potassium, and magnesium. These combine, as the magma or lava crystallizes, to form silicate minerals, which in combination make up igneous rocks (Pellant, 1992).

Sedimentary rocks are formed by deposition of clastic sediments, organic matter or chemical precipitates, followed by compaction of the particulate matter and cementation during diagenesis. Sedimentary rocks form at or near the earth’s surface (Pellant, 1992).

Metamorphic rocks are formed by subjecting any rock type, including previously formed metamorphic rock, to different temperature and pressure conditions than those in which the original rock was formed. These temperatures and pressures are always higher than those at the earth’s surface and must be sufficiently high so as to change the original minerals into other mineral types or else into other forms of the same minerals (Pellant, 1992).

Aggregates used for road building are classified as either acidic or basic. This is because aggregates differ in their affinity to bitumen. Aggregates with high silica content, e.g. granite and quartz (i.e. acidic rocks) are generally more difficult to coat with bitumen than basic rock such as dolerite and limestone (Read & Whiteoak, 2003).

Table 2-6: Characteristic Combinations of Rock Forming Materials in Rocks (from Weinert, 1980)

Major Rock Group	Sub Group	Characteristics Minerals	Typical Rock
Igneous	Acid	Quartz, Orthoclase, Mica or Amphibole	Granite
	Intermediate	Orthoclase, Amphibole	Syenite
		Orthoclase, Amphibole	Diorite
	Basic	Orthoclase, Amphibole	Norite, Dolerite
	Ultra-Basic	Pyroxene, Oliviae	Pyroxenite, Peridotite
Sedimentary	Clastic	Quartz	Sandstone
		Quartz, Orthoclase	Arkose
		Quartz and incidental others	Conglomerate
		Clay mineral, some quartz	Shale
		Quartz, clay mineral and incidental others	Tillite, Greywacke, volcanic ejecta
	Chemical Precipices	Calcite	Limestone
		Dolomite	Dolomite
		Opal and/or Chalcedony	Chert
		Various salts	Gypsum and other salt deposits
	Organic	No minerals	Coal, oil
Metamorphic	Subdivisions are complicated and of little relevance to the engineering properties of rock	Quartz, Orthoclase (Occasionally Mica)	Gneiss
		Quartz, Muscovite (Occasional Biotite)	Mica schist
		Amphibole	Amphibolite
		Quartz	Quartzite
		Calcite	Marble
		Amorphous silica or quartz and various others	Hornfels

Failure of the bitumen/aggregate bond is commonly referred to as aggregate loss, ravelling or “stripping”. One of the main factors is the type of aggregate. The majority of adhesion failures have been associated with siliceous aggregates such as granites, rhyolites, quartzites, cherts, etc. The fact that satisfactory performance is achieved with these same aggregates and that failures occur using aggregates that have good resistance to stripping, e.g. limestone, emphasizes the complexity of bitumen/aggregate adhesion and the possibility that some other factors may play a role in the failure (Read & Whiteoak, 2003).

2.4.2 *AGGREGATES USED IN THIS RESEARCH*

Granite

White granite is an igneous rock and has a coarse grain size. High silica content (over 65% total silica content and not less than 20% quartz) classifies white granite as an acid rock. K-feldspars (orthoclase and microcline) are dominant, and are white in colour. Usually, there is some albitic plagioclase. Dark biotite mica and hornblende give the rock a mottled appearance. Light, glittery muscovite is also common (Pellant, 1992).

Quartzite

Quartzite is a metamorphic rock that comprises almost entirely from quartz, giving it a pale almost sugary appearance. Quartz is one of the most common minerals. Its composition is almost entirely silica oxide. Quartzite is formed from quartz rich sandstone (Pellant, 1992).

Dolerite

An igneous rock of basic composition, with a total silica content of less than 55%; the quartz content is usually lower than 10%. Dolerite consists of calcium rich plagioclase feldspar, and pyroxene with some quartz, and sometimes magnetite and olivine. A medium grained rock which usually forms as dykes and sills in basaltic provinces (Pellant, 1992).

2.4.3 *SURFACE CHARGE*

The surface charge is also referred to as the residual valance. This refers to the polarity state of the aggregate surface where surface energy exists. The polarity can be influenced and satisfied by the coating layer. If the binder’s state of polarity is opposite of that of the aggregate an adhesion bond will form (Read & Whiteoak, 2003).

Two types of coating layers can form on aggregates namely water or bitumen layers. If water satisfies the surface energy better than the bitumen, the bond will be formed between the water and the aggregate. This bond is not strong and causes stripping. This illustrates the importance of choosing the correct binder for the specific aggregate and constructions conditions (Read & Whiteoak, 2003).

2.4.4 PHYSICO-MECHANICAL ABSORPTION

This refers to the absorption of bitumen by the aggregate. Physico-mechanical absorption of bitumen into the aggregate depends on several factors including the total volume of permeable pore space, size of pore openings, micro-cracks, the bitumen's viscosity and surface tension of the bitumen. This absorption decreases the thickness of the layer of the bitumen on the aggregate and leads to failure in the adhesion bond (Read & Whiteoak, 2003).

2.4.5 OTHER FACTORS

Surface texture, the presence of dust on the aggregate and, to a lesser extent, the pH of the water in contact with the interface is also factors affecting the initial adhesion and subsequent bond. It is believed that rougher aggregate surfaces have better adhesion characteristics. Smooth surfaces are however more easily wetted therefore a balance is required. It has been suggested that the good mechanical bond achieved on a rough aggregate can be even more important than the aggregate mineralogy in maintaining bitumen/aggregate adhesion (Read & Whiteoak, 2003).

Road surfacing aggregates are required to be hard wearing (abrasion resistant) and igneous rocks are generally preferred for this purpose (British Geological Survey, 2007).

2.5 COHESION

The Oxford Dictionary defines cohesion as: *"The tendency of similar particles or surfaces (or particles of the same substance) to cling to one another."*

Direct measurement of the cohesion of bitumen is very difficult. Cohesion in bituminous binders depends on many factors, the most important of which is temperature. Bitumen is a thermoplastic material: liquid at high temperatures, viscoelastic at usable temperatures, and solid at low temperatures (Stahl, 1972).

The inherent strength, tenacity, and toughness of the bituminous binders can be improved by modification with thermoplastic polymers and rubber crumbs. Hence, a greater force or tensile strength is required to break the molecular bonds of modified binders and cause failure compared with a lower tensile stress required to break the bonds of conventional binders.

A force-ductility test is used to measure the cohesive strength of a modified binder and involves the elongation of a sample with the force measured at very small elongation intervals. Figure 2-15 shows a graph of the typical profile of various binder types obtained during the test.

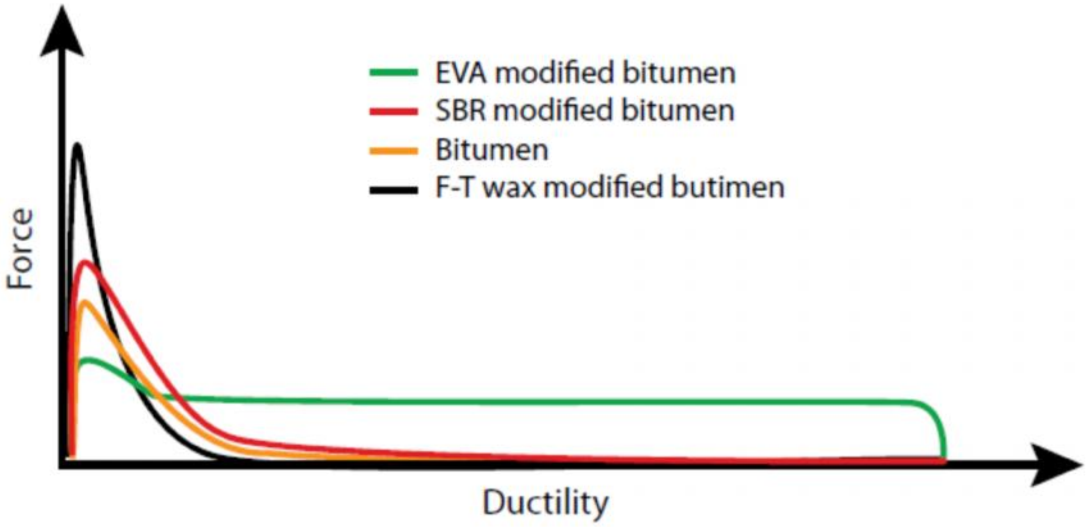

Figure 2-15: Typical Force-Ductility Curves for Various Modified Binders (Asphalt Academy, 2007)

As shown in Figure 2-15, the maximum force is reached early in the elongation process. The elastic phase is represented by the area before the initial peak and the total area under the curve can be used to calculate the toughness. This is a good indication of the energy required to extend the binder and therefore provides a good estimation of resistance to cracking.

The energy required to elongate elastomeric modified binders is generally significantly more than that for conventional binder. Plastomeric modified binders will impart stiffness to the bitumen but not necessarily improve its cohesive nature. Such modified binders may well perform in a brittle manner in tension. The cohesive properties of modified binders provides direction to design engineers on how soon after construction a seal could be opened to traffic as well as providing an assessment of ability of the binder to withstand shear stresses imparted by heavy traffic (Asphalt Academy, 2007).

If aggregate is clean and dry and the mixture is effectively impermeable, the mode of failure will be cohesive (Read & Whiteoak, 2003).

2.6 ADHESION

Adhesion refers to the tendency of different particles or surfaces to cling to one another.

The primary function of bitumen is to act as an adhesive. It is required either to bind aggregate particles together or to provide a bond between particles and the existing surface. Although the incidence of premature failure attributed to adhesion is relatively rare, failures when they occur

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may involve considerable expense. The need to ensure adhesion between the aggregate and bitumen is very important (Read & Whiteoak, 2003).

Hefer, et al. (2005) described the three types of interaction forces responsible for adhesion between the bitumen binder and aggregate. The first type corresponds to electrostatic interactions between ions and refers to forces between two separated charges, resulting from Coulomb's inverse-square law (i.e. Coulomb forces).

The second type corresponds to electrodynamic interactions through Van der Waals forces. In this case, the forces result in bonds that are weaker in comparison to ionic bonds and include different types of interactions depending on the molecular electric dipole conditions at the interface of the two materials (Caro, et al., 2008).

The third type corresponds to interactions through electron pair sharing (i.e. covalent bond). In this case, the bonds result from the union of two components when sharing an electron pair; the electron pair can be donated by the two components or by one of them. The electrostatic and electrodynamic interactions are regarded as physio-chemical bonds, and the interactions in the last group are regarded as chemical bonds (Caro, et al., 2008).

2.6.1 PRIMARY ADHESION FACTORS

Table 2-7 summarises the main influential factors of the bitumen-aggregate bond properties. It is considered that approximately 80% of these factors are controllable during production or construction (Read & Whiteoak, 2003).

Table 2-7: Material properties and external factors that can affect the bitumen/aggregate bond

Aggregate Properties	Bitumen Properties	Mixture Properties	External Factors
Mineralogy	Rheology	Void Content	Rainfall
Surface Texture	Electrical Polarity	Permeability	Humidity
Porosity	Constitution	Bitumen Content	Water pH
Dust		Bitumen Film Thickness	Presence of Salts
Durability		Filler Type	Temperature
Surface Area		Aggregate Grading	Temperature Cycling
Absorption		Type of Mixture	Traffic
Moisture Content			Design
Shape			Workmanship
Weathering			Drainage

(Read & Whiteoak, 2003)

It is visible from the table above that the properties of the aggregate play a dominant role in adhesion in seals.

2.6.2 *ADHESIVE BOND MECHANISMS*

Weak Boundary Layers

This theory states that the presence of an interface region of low cohesive strength may lead to adhesive failure. An example of a weak boundary layer in surface seals is the aggregate-binder bond that results when aggregates used are coated with dust (Caro, et al., 2008).

Electrostatic Forces

The electrostatic theory states that the Coulombic forces of attraction at the surface of two materials result in the adhesive strength between the materials. Interactions between liquid mediums containing dissolved ions, such as water, and solid surfaces are especially significant to explain moisture damage in bitumen-aggregate systems. Exposing a solid surface with an active charge to water, two charged layers are formed namely; a stern layer and a diffuse layer. The stern layer comprises of one or more layers of ions of opposite charge that bind to the surface in order to neutralise charges, while the diffuse layer develops from the thermal motion of the ions beyond the stern layer (Caro, et al., 2008).

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Chemical Bonding

In order to understand the moisture damage mechanisms in some aggregate-binder systems, research on adhesion due to chemical bonding is essential. The chemical bonding theory states that the adhesion bond between bitumen and aggregate results from a chemical reaction between the two materials. Although bonding of two materials due to electrostatic interactions or free surface energy is also based on the chemical nature of these materials, there is a significant distinction between these mechanisms and adhesion due to chemical bonding. The adhesion due to chemical bonding is caused by the formation of a new material due to the reaction between the active functional groups from the binder and the aggregate at their interface (Caro, et al., 2008).

The quality and the durability of the adhesive bond with the bituminous binder is determined by the chemical and mineral composition of the aggregate. Generally, basic aggregates are easier to coat with binder than acidic aggregates (high silica content) because siliceous aggregates contains high concentrations hydroxyl groups with greater affinity for carboxylic acid and water. The surface of these aggregates absorbs the carboxylic acid components that are present in the binder, creating a binder-aggregate bond. However, the bonds with the carboxylic acids are also prone to displacement in the presence of water (Caro, et al., 2008).

Mechanical Bonding

This theory suggests that a mechanical interlock is produced as the bituminous binder is forced into the irregularities of the aggregate surface. The characterisation of the physical properties of aggregates, as well as its role in mechanical adhesion and resistance to moisture damage contributes to this theory. It was found that aggregates with a high amount of surface pores and rough surface texture are also more resistant to moisture damage (Caro, et al., 2008).

Adhesion due to Surface Free Energy

Physio-chemical adhesion between two materials is a thermodynamic phenomenon that relies on the surface free energy of the materials. Surface free energy is defined as the amount of external work to be done on a material to create a new unit surface area in vacuum. The energy required to separate the materials from their interface to create a new unit of area of each material in a vacuum is the work of adhesion between two materials. The interaction of the acid component of the bituminous binder and the basic component from the aggregate contributes the most to the total bond strength at the binder-aggregate interface. A higher magnitude of work of adhesion indicates higher resistance of the interface to an adhesive failure (Caro, et al., 2008).

2.6.3 ADHESION FAILURE METHODS

Failure of bitumen in surface seals can either be cohesive or adhesive. Adhesion failure will almost always occur when water is present on the aggregate surface and will lead to stripping of the bitumen from the aggregate surface. Several adhesion disbonding mechanisms are possible and are discussed below.

Displacement

This theory relates to the thermodynamic equilibrium of the three-phase bitumen/aggregate/water system. If water is introduced to the aggregate/bitumen bond the bitumen will retract along the surface of the bitumen as showed in Figure 2-16.

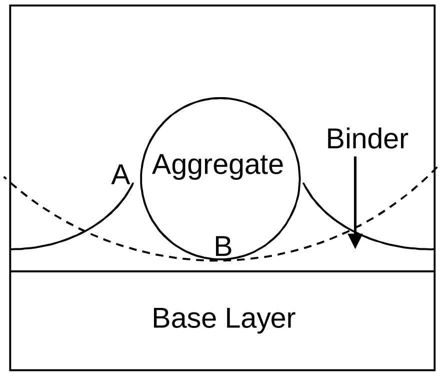

Figure 2-16: Disbonding (from Read & Whiteoak, 2003)

Point A illustrates the contact position of the bitumen when the aggregate is dry. In wet conditions the equilibrium point shifts or retracts over the surface to point B. This reduces the contact area of the bond and the possibility of failure is increased (Read & Whiteoak, 2003).

Detachment

Once a thin film of water or dust particles settle between the bitumen and the aggregate detachment occurs. This happens with no obvious break in the surface of the bitumen film being apparent. Although the bitumen film completely encapsulates the aggregate particle, no adhesive bond exists and the bitumen can easily be peeled from the aggregate surface (Read & Whiteoak, 2003).

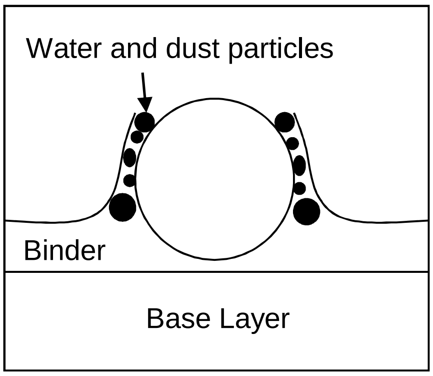

Figure 2-17: Detachment (from Read & Whiteoak, 2003)

Film Rupture

This phenomenon may occur despite the fact that the bitumen fully covers the aggregate. The bitumen coating is the thinnest on sharp edges or asperities of the aggregate and it is possible that water can penetrate through the bitumen film to reach the aggregate surface. The water settles between the aggregate and bitumen to produce a detached film of bitumen. Stresses imposed by traffic will rupture the bitumen film and leave the aggregate exposed (Read & Whiteoak, 2003).

Blistering and Pitting

Viscosity of bitumen reduces as temperature increases. When the temperature of the pavement rises after rain has fallen, blistering and pitting may occur. Bitumen creeps up the edges of the water droplets to form a blister. As the temperature further increases the blister expands, leaving a hollow pit which allows water to access the surface of the aggregate (Read & Whiteoak, 2003). Figure 2-18 and Figure 2-19 illustrates the process.

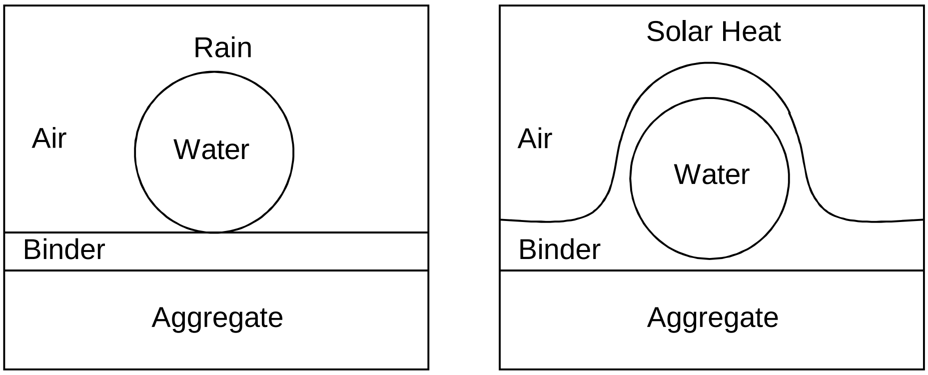

Figure 2-18: Blistering (from Read & Whiteoak, 2003)

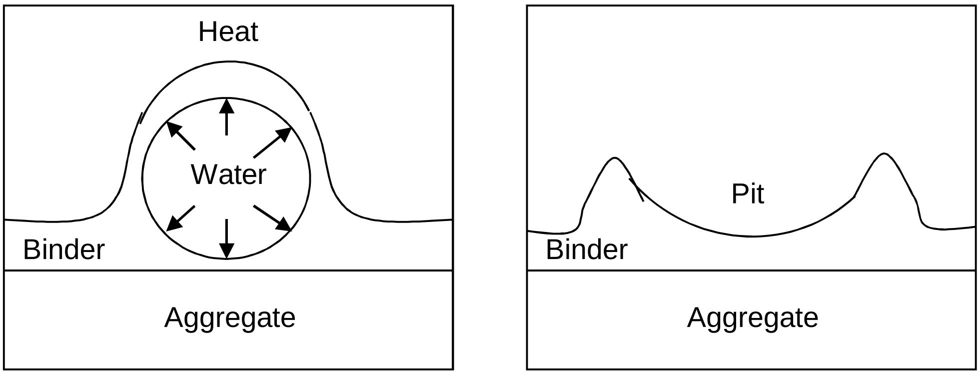

Figure 2-19: Pitting (from Read & Whiteoak, 2003)

Hydraulic Scouring

Hydraulic scouring happens when the surfaces of motor vehicle tires come into contact with saturated, or wet, pavement surfaces. The water on the surface of the pavement naturally rests in the creaks and voids of the road surface, and when the vehicle tire runs over it, water is sucked from the cracks. This action, also known as pumping, leads to the bitumen being detached from the aggregate (Read & Whiteoak, 2003).

Pore Pressure

Pore pressure refers a type of road surface failure where water, which becomes trapped inside the road surface, creates channels around the bitumen-aggregate interface. This is a result of poorly compacted mixes and predominately occurs in hot mix asphalt. The water originally rests in the cracks in the road surface, and is compacted within the road surface through consistent pressure from the tyres of motor vehicles. From there, where the water has nowhere to go, the failure is catalysed (Read & Whiteoak, 2003).

Chemical Disbonding

With chemical disbonding, the presence of excess water on the aggregate surface causes the aggregate to have a negative charge. Because the bitumen is also charged slightly negative, more and more water will be attracted to the aggregate surface, and disbonding/detachment of the bitumen will eventually occur (Read & Whiteoak, 2003).

2.6.4 ADHESION IMPROVEMENT

Under ideal circumstances, aggregates and bitumen binders adhere to the desired outcomes they were designed for. In the presence of external role-players, like water and varying temperatures for example, standard performance of the bitumen and aggregates are apprehended. Methods have been developed to prevent this malfunction. Traditional methods

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include using a binder with a higher viscosity, or using hydrated lime or other surface active agents to improve the bond between the bitumen and the aggregate (Read & Whiteoak, 2003). Bitumen can also be modified, as discussed previously, to improve adhesion properties.

2.6.5 ADHESION TESTS

Since premature failure of surface seals are so probable, there is an undoubted need for predictive laboratory tests in order to narrow the margin of error. Although many test have been developed to compare various combinations of water, binders and aggregates, these test lack efficiency because of the lack of information relating the prediction made in the laboratory to the performance in service and in practicality.

Under normal conditions, as described in *The Shell Bitumen Handbook,* aggregates should be coated with binder, immersed in water under controlled conditions, after which the effect of stripping will be determined after a certain period of time. Different methods of testing are used to achieve different outcomes; for example, the conditions under which the sample is immersed in water will affect the tests, and also the methods which are used to determine the degree of stripping can also influence the outcomes (Read & Whiteoak, 2003). Adhesion tests fall into a number of categories which will be discussed below.

Static Immersion Tests

Following *The Shell Bitumen Handbook's* stipulation by coating the aggregate with bitumen before immersing it in water, the degree of stripping will be determined visually after a specific, pre-determined period of time. This method is vulnerable in the sense that it is completely subjective because the outcome of the visual deterioration relies solely on the human operator. This method also has a slim chance of being repeated 100% similarly, which further problematizes it (Read & Whiteoak, 2003).

Dynamic Immersion Tests

These tests are fundamentally similar to Static Immersion Tests, discussed in the paragraph above. The singular difference is that agitation of the aggregate is done mechanically, either by kneading of mechanical shaking. However, these tests are limited in the same way as the Static Immersion Tests as they too are completely operator dependant, subjective and unrepeatable (Read & Whiteoak, 2003).

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Chemical Immersion Tests

Bitumen coated aggregates is boiled in solutions containing various concentrations of sodium carbonate. The strength of sodium carbonate solution in which stripping is first observed is used as a measure of adhesion (Read & Whiteoak, 2003). However the artificial condition of the test is highly unlikely to predict the performance on the surface seal road (Greyling, 2012).

Immersion Mechanical Tests

Immersion mechanical tests include the Retained Marshall Stability Tests, the Retained Stiffness Test and the Cantabro tests. These tests are essentially relevant to asphalt (pre-mix) testing.

Immersion Trafficking Tests

Unlike most adhesion tests, the Immersion Wheel Tracking Tests considers the effect of that traffic wheels have on stripping of the aggregates. This test is also more relevant on asphalt material.

Coating Tests

The purpose of this type of testing is to assess the adhesion between aggregate and bitumen in the presence of water. For example, in the case of the Immersion Tray Test, aggregate chippings are placed on a tray filled with bitumen that is covered with a thin layer of water. By careful examination of the aggregates, it may be possible to determine whether surface active agents increase adhesion under wet conditions (Read & Whiteoak, 2003).

Absorption Tests

The Net Absorption Test method is the result of the Strategic Highways Research Program (SHRP) done in the USA to investigate the effect of moisture damage (Read & Whiteoak, 2003). This test is an extremely complicated test and it requires a spectrophotometer, which is hard to come by, to perform measurement. It is not commonly used in South Africa (Greyling, 2012).

Impact Tests

There are two types of impact tests that utilises impact to measure the adhesion properties of bitumen and aggregate. They are the Vialit Pendulum Test and the Vialit Plate Test. Both methods are readily adaptable to predict a wide range of insitu conditions and are of great significance in situations where aggregates are in direct contact with traffic loads such as surface seals (Read & Whiteoak, 2003).

The Vialit Pendulum Test measures the degree of adhesion between aggregate and binder when subjected to a sudden impact. The method involves placing a thin binder film between two cubes and measuring the energy required to remove the upper block (Read & Whiteoak, 2003).

In the case of the Vialit Plate Test aggregates are placed onto a steel plate of bitumen. The plate is then turned upside down and a steel ball is dropped onto the reverse side. The impact of the ball may cause detachment of the aggregates depending on the test conditions. The number of released aggregate chips versus the number of impacts can be used as an performance indication. Visual assessment of the detached aggregates can usually determine the type of failure (Read & Whiteoak, 2003). In South Africa a modified version of the Vialit Plate Test is used as explained by Asphalt Academy TG1 Test Method MB-7 (Greyling, 2012).

Pull-off Tests

Instron Pull-off Test

This test used an Instron tensile apparatus to extract aggregate tests specimens from containers of bitumen under controlled laboratory conditions. Tests variables such as rock type, dust coating, temperature conditions, loading rate and type of bitumen have shown to influence the results (Read & Whiteoak, 2003).

Limpet Pull-off Test

The limpet pull-off test was developed to measure the bond strength between the aggregate of a surface seal and the base course. The test consists of a 50mm diameter steel plate that is fixed to the road surface and the maximum load to achieve pull off is measured (Read & Whiteoak, 2003).

Pull out Test Method for Surfacing Aggregate (Method MB-8)

This test method determines the pull out load required to dislodge a stone chip embedded in a surface seal to assess when the road can be opened to traffic (Asphalt Academy, 2007).

Pliers Test for Assessment of Adhesion Properties (Method MB-9)

The main and overriding criterion at the time of constructing a surface seal is to achieve adhesion between the aggregate and binder. This pliers test can be used as a quick check to determine effective wetting of the aggregate and adhesion characteristics of the binder at the prevailing conditions (Asphalt Academy, 2007).

Both test methods MB-8 and MB-9 are complicated and difficult to complete and the results are almost entirely operator dependent. The tests have low repeatability and are therefore seldom used in practice (Greyling, 2012).

2.7 BITUMEN BOND STRENGTH TEST

The need for determining performance related adhesion properties in surface seals could not be entirely satisfied by tests discussed previously. Therefore the University of Stellenbosch, University of Wisconsin – Madison and University of Ancona – Italy collaborated in developing a new test method to determine the adhesion between aggregates and binders, better known as the bitumen bond strength.

2.7.1 DEVELOPMENT OF THE BBS TEST

The Pneumatic Adhesion Tensile Testing Instrument (PATTI) device was originally developed for use in the painting industry to test the pull-off strength of a coating certain rigid substrates (Greyling, et al., 2010). This device was used by the pavement industry to measure the influence of moisture of the adhesive properties of the binder-aggregate system in the early 1990’s (Greyling, 2012). The BitVal Phase 1 Report published by the Forum of European National Highway Research Laboratories in 2004 suggested that this device be used as a possible adhesion tester for road surfacing.

Tests performed with earlier models of the PATTI identified various problems such as binder film thickness and loading rate. The latest version of the PATTI, called the PATTI Quantum Gold, reduces these effects while conforming to the surface seal industry requirements. It proved successful for determining the bond strength in the bitumen bond strength or BBS test (Greyling, et al., 2010).

The BBS test quantifies the tensile force needed to remove a pull-out stub from a bituminous binder cured on a rock substrate. The PATTI applies a pneumatic load to remove the stainless steel pull-out stub (Anon., 2009). The data resulting from the test can then be plotted as stress versus loading time and be compared to other samples.

2.7.2 INFLUENCING FACTORS

Various factors play a significant role in the bond strength between aggregates and binders. Substrate or aggregate type and surface roughness as well as the type of binder used are the material influences (Constable, 2009). These material related factors have been discussed in previous chapters and will therefore not be elaborated below. Testing conditions influencing the BBS result include temperature, moisture condition, curing time and loading rate.

Loading Rate

Miller, from the University of Wisconsin-Madison, did excellent work determining critical factors affecting the bitumen bond strength. He did tests over a very wide range of loading rates ranging from 0 kPa/s to 7000 kPa/s. His findings indicated that the loading rate plays a significant role in the test and that a power law models effectively describes the relationship between the loading rate and pull-off strength as seen in Figure 2-20. This is primarily due to the visco-elastic properties of bitumen (Greyling, 2012).

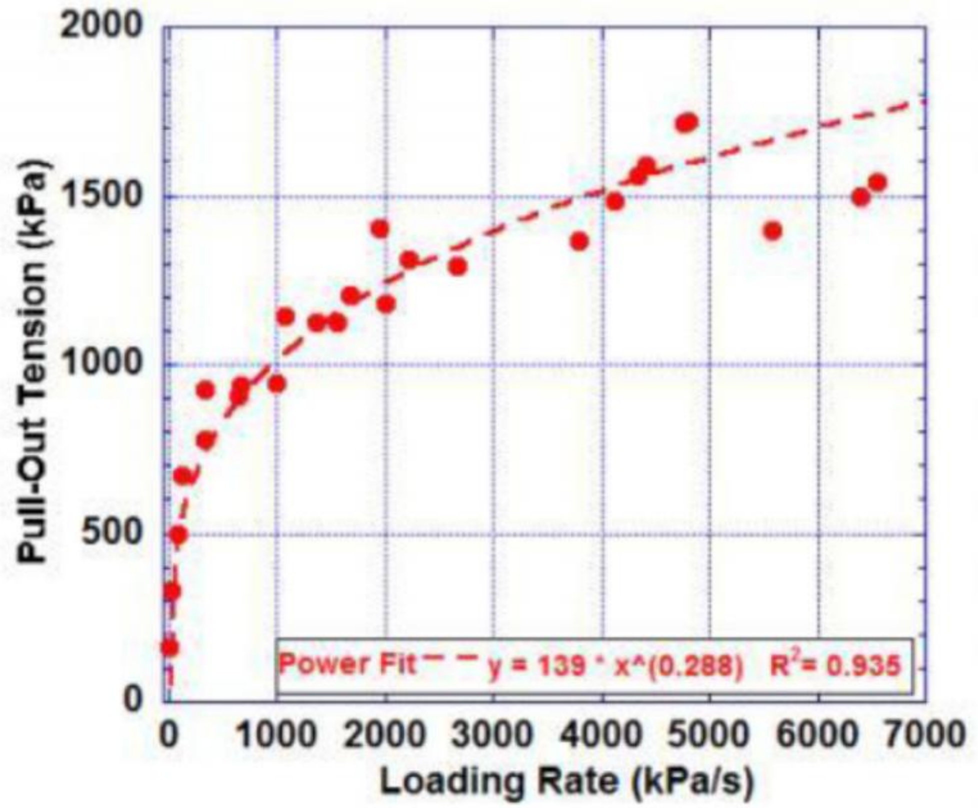

Figure 2-20: Loading Rate versus Pull-Out Tension (Greyling, et al., 2010)

Results from Millers testing shows that loading rates between 690 - 1030 kPa/s appear to exhibit a linear relationship. Loading rates exceeding 2700 kPa/s lead to increasing variability in both BBS and loading rate itself. Therefore, loading rates exceeding 2700 kPa/s should be avoided. It was clear that the BBS value increases as the loading rate increases (Greyling, et al., 2010).

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Temperature

BBS will increase as the temperature decreases. This is related to the rheological properties of bitumen and is discussed previously in this chapter.

Curing Time

A significant increase was seen in Millers results between the 2 hour curing and the 6 hour curing times, but samples only exhibited slight differences after 24 hours of curing (Greyling, 2012). It expected that curing time influences the BBS especially where emulsions are used. This is due to the water content present in the emulsions that needs to evaporate or escape as the emulsion breaks.

Moisture Condition

The moisture conditions of the aggregates tested in this study was kept constant at a dry condition. Although the moisture condition of the aggregates during the construction of a surface seal has a significant influence on the adhesion properties, it was not tested for the purpose of this study.

2.8 OVERVIEW OF LITERATURE REVIEW

The functionality of a surface seal was discussed along importance of surface seals used in South Africa. The different types of seals were also briefly explained. Factors that influence the performance of seals, especially the adhesion between binders and aggregates were identified and discussed along with the failure mechanisms of seals.

The main components of surface seals were discussed as well as the manner these interact under various conditions. Binders are one of these components and play a substantial role in the properties of a seal. Bitumen is the main ingredient, and often the only ingredient in a binder type. The properties and types of binders were thoroughly discussed. Modified binders and the various influences of modifications were also discussed.

The aggregate used in seals are the other main component used in seals and were discussed along with the various influences it has on surface seals.

Cohesion was explained and the methods of improving the cohesive properties of binders were described. Adhesion between aggregates and binders were discussed and the various factors affecting these bonds were also identified. The various test methods used to tests adhesion properties were also discussed. The BBS test method was elaborated.

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3. METHOD

3.1 INTRODUCTION

This chapter explains what means were used and how they were used to arrive at the conclusions. The chapter comprises of a research design, methodology and limitations of the study. The research design explains what type of approach was used to tests the thesis statement. In the methodology section, the instrumentation used is discussed along with the data and the analyses thereof. The limitations of the study are also commented.

3.2 RESEARCH DESIGN

Laboratory tests will be carried out to determine the BBS between various combinations of aggregates and binders frequently used in South African surface seals. These tests will be performed according to the Bitumen Bond Strength (BBS) Test Procedure (Anon., 2009), but deviates in the following ways:

The procedure states that the emulsion should be cured without the pull-off stub for the entire curing time in the relevant curing condition, then the pull-off stub should be positioned and be allowed to set for another 1.5 hours at 25 °C. This study chose to differ from this method by allowing the emulsion to cure without the pull-off stub for 1 hour and then be further cured with the stub for the remaining curing time. The reason for this being that a rapid setting emulsion is selected and should break well within 1 hour. In case of the hot applied bituminous binders the pull-off stub was immediately positioned firmly on top of the binder, because these binders do not need to cure. The tests will also be performed at two temperatures which represents the average pavement temperatures during summer and winter.

All samples will be left to cure for a particular curing time before testing to determine the effect of curing on the BBS. See Figure 3-1 below.

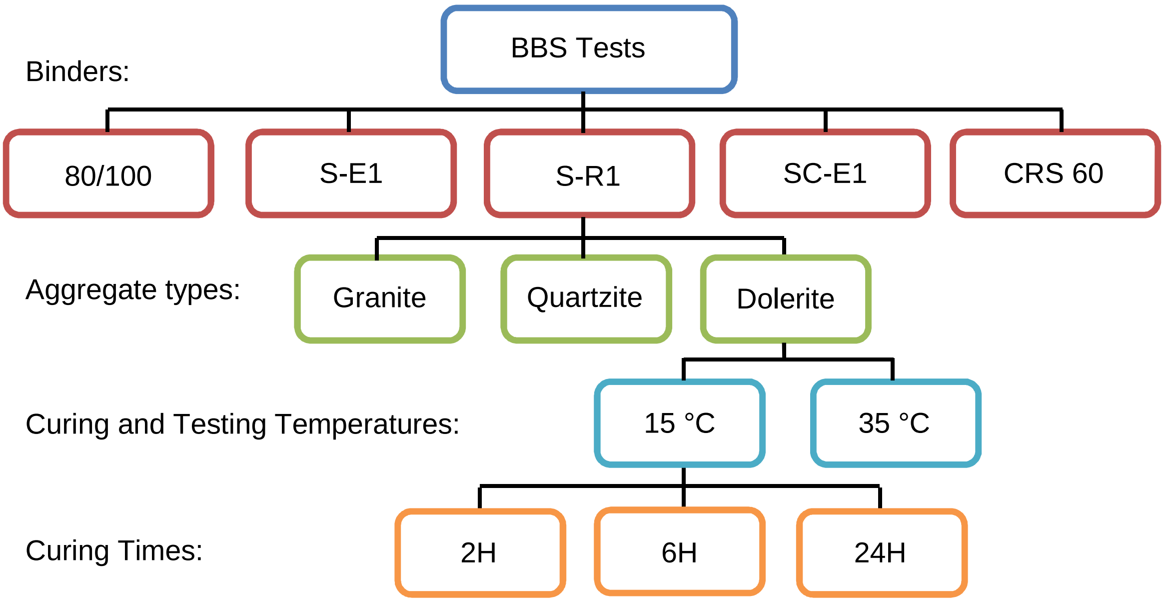


Figure 3-1: Experimental Design

3.2.1 Bitumen Bond Strength Tests

The bitumen bond strength between the various aggregates and binders in this study was determined using the Pneumatic Adhesive Tensile Testing Instrument (PATTI). This test is commonly referred to as the BBS test method. The aggregates and binders tested in the study are common materials that are widely used in surface seal applications throughout South Africa.

The results from the tests are given as the pull out strength (in kPa) versus the loading time. From these results we can determine the maximum pull off strength that is needed for bond failure as well as the time it takes to fail. It will also be visible if the bond failure was adhesive or cohesive.

Variables include five types of binders, three types of aggregates that was further divided into five groups, two temperature conditions and three curing intervals. Each test at the various conditions was repeated once. Tests that showed great variability under same conditions were repeated.

3.2.2 Strengths and Weaknesses of Research Method

Advantage of laboratory tests is a significant control of the environment in order to isolate the phenomenon to be studied. An experiment can therefore be more easily replicated than a field experiment. However, the results from laboratory tests are occasionally challenging to explain.

3.3 METHODOLOGY

This sub chapter describes how the research design was used to obtain the relevant data in order to come to a conclusion. It describes what instruments was used to carry out the tests, what data was recorded and how it was analysed.

3.3.1 RESEARCH INSTRUMENTS

P.A.T.T.I. Quantum Gold

The PATTI Quantum Gold (PQG) device was used to perform the BBS tests. This setup consists of an adhesion tester, inlet and outlet pressure hoses, a piston, reaction plate and a pull-out stub as shown in Figure 3-2.

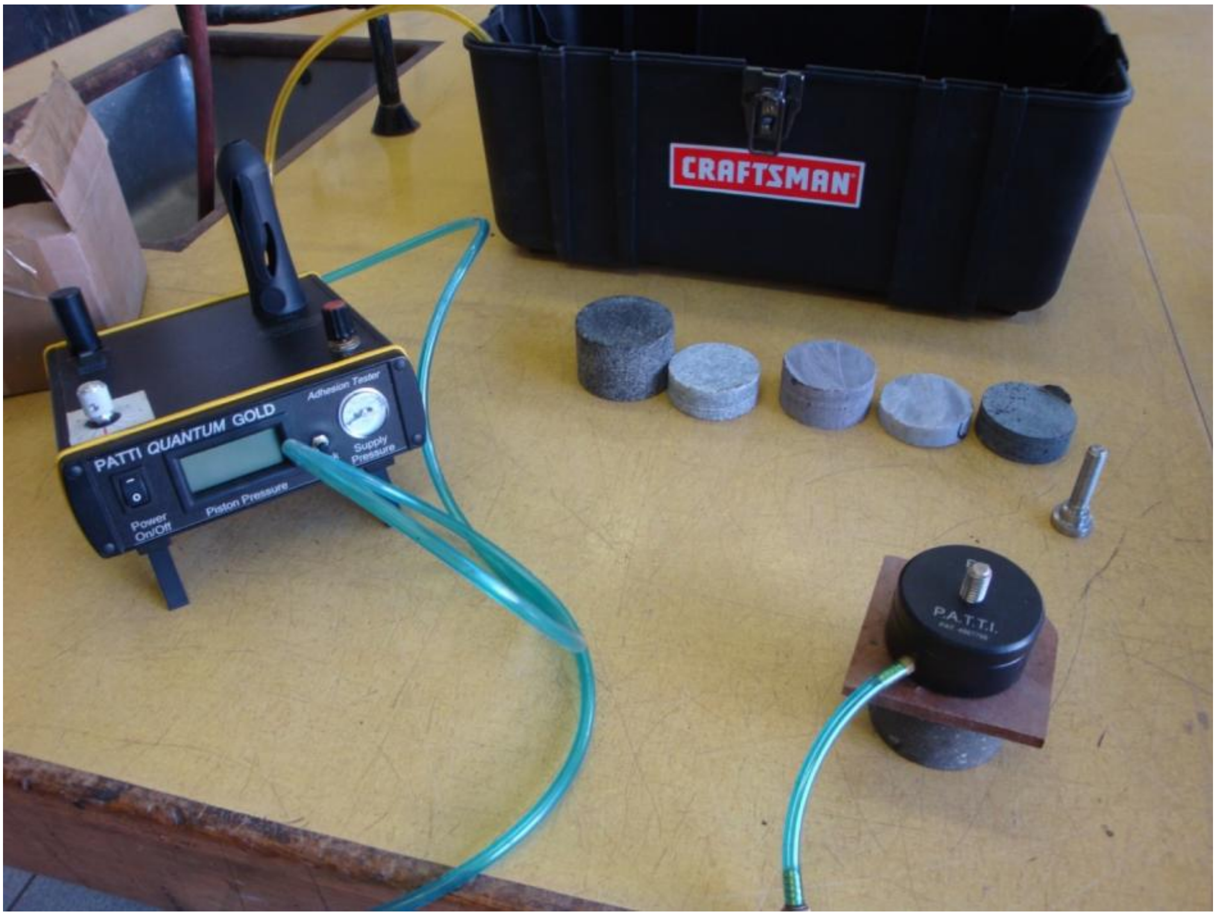


Figure 3-2: PATTI Quantum Gold Device and Piston Setup

The PQG comes equipped with LabView© software and effectively captures load over time, allowing for calculation of the loading rate.

Pressure can be provided either by an air compressor or a CO_2 cartridge. In this study an air compressor was utilised for all of the tests. Compressed air is sent to the PQG device via a yellow pressure hose. The device then controls the rate of pressure released resulting in the loading rate. The blue pressure hose introduces the compressed air from the device to the piston, resulting in an upward force on the pull-off stub and eventual failure of the binder. Figure 3-3 illustrates the piston setup.

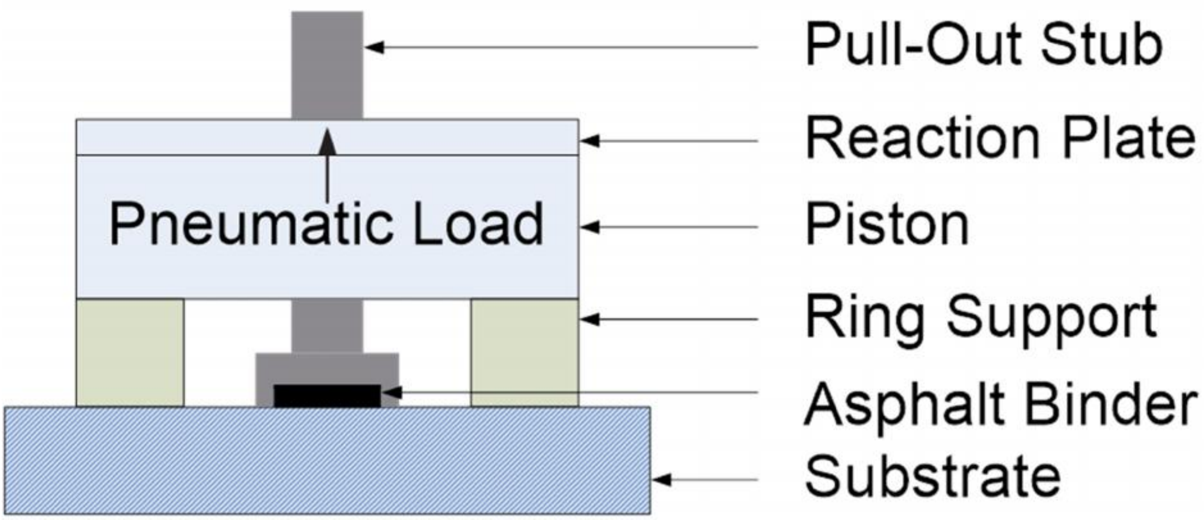
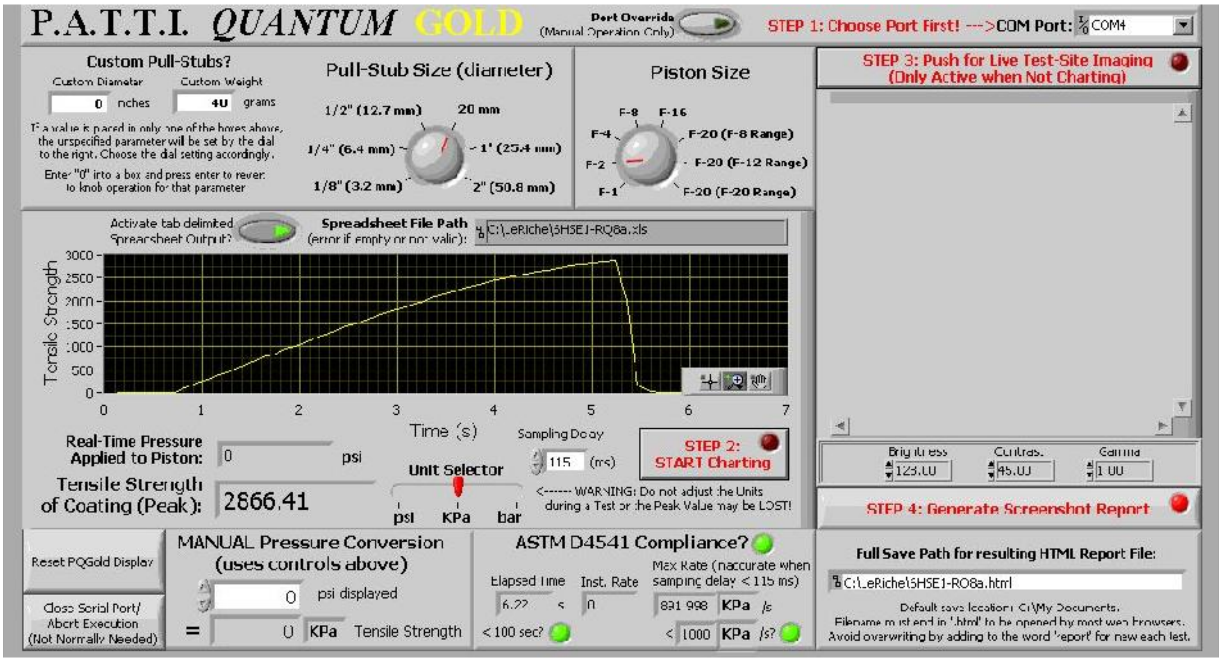


Figure 3-3: Test Setup of the Piston and Test Sample (Jenkins, et al., 2013)

The PQG device records the force (F) required to break the bond of the binder underneath the pull-off stub, with contact area (A), and calculates the stress (σ) accordingly.

$$\sigma = \frac{F}{A} \qquad [kPa]$$

The tensile strength (kPa) is then recorded against time (s) and the loading rate (kPa/s) is logged as shown in Figure 3-4 below. The bitumen bond strength (BBS) refers to the maximum pull-off tensile strength of the test.



Custom Diameter: 0 inches

Custom Weight: 40 grams

If a value is placed in only one of the boxes above, the unspecified parameter will be set by the dial to the right. Choose the dial setting accordingly.

Enter "0" into a box and press enter to revert to knob operation for that parameter

Spreadsheet File Path (error if empty or not valid): C:_eRiche\SHSE1-RO8a.xls

Real-Time Pressure Applied to Piston: 0 psi

Tensile Strength of Coating (Peak): 2866.41

Sampling Delay: 115 (ms)

<------ WARNING: Do not adjust the Units during a Test or the Peak Value may be LOST!

Brightness: 123.00

Contrast: 45.00

Gamma: 1.00

MANUAL Pressure Conversion (uses controls above): 0 psi displayed = 0 KPa Tensile Strength

Elapsed Time: 6.22 s

Inst. Rate: 0

Max Rate (accurate when sampling delay < 115 ms): 891 998 KPa /s

< 100 sec?

< 1000 KPa /s?

Full Save Path for resulting HTML Report File: C:_eRiche\SHSE1-RO8a.html

Default save location: C:\My Documents. Filename must end in '.html' to be opened by most web browsers. Avoid overwriting by adding to the word 'report' for new each test.

Figure 3-4: PATTI Quantum Gold User Interface

Bitumen's visco-elastic nature requires effective loading rate control for the consistent evaluation of the pull-off tensile strength. Research by the University of Wisconsin-Madison confirms that load control is critical for consistent pull-off tensile test results (Greyling, et al., 2010).

Early versions of PATTI were found to inadequately control loading rate so at the beginning of 2009, SEMicro launched the PATTI Quantum Gold© (PQG) test instrument that incorporated user feedback into the revised design, including improved loading rate control shown in Figure 3-5 and Figure 3-6. The ability to control the loading rate with a graduated rate control dial further improves consistency (Greyling, et al., 2010).

Figure 3-5: Loading Rate Dial on PQG (Constable, 2009)

Figure 3-6: Loading Rate Dial (Constable, 2009)

Variation in the bitumen film thickness will lead to variation in the adhesion strength. The film thickness of the binder during the BBS tests was also identified as a critical parameter and therefore extensive research was done to design the pull-out stubs used in the BBS tests (Greyling, et al., 2010).

The outcome of the work done to optimise the pull-out stub for a constant binder film thickness was the pull-out stub showed below in Figure 3-7 and Figure 3-8. The stub diameter is 22 mm and has circumferential support edges to limit the vertical position of the stub contact area, hence keeping the film thickness at 0.8 mm. Perimetrical channels on the edge of the stub allow excess binder to flow out beneath the contact surface. The diameter of the contact area is 20 mm.

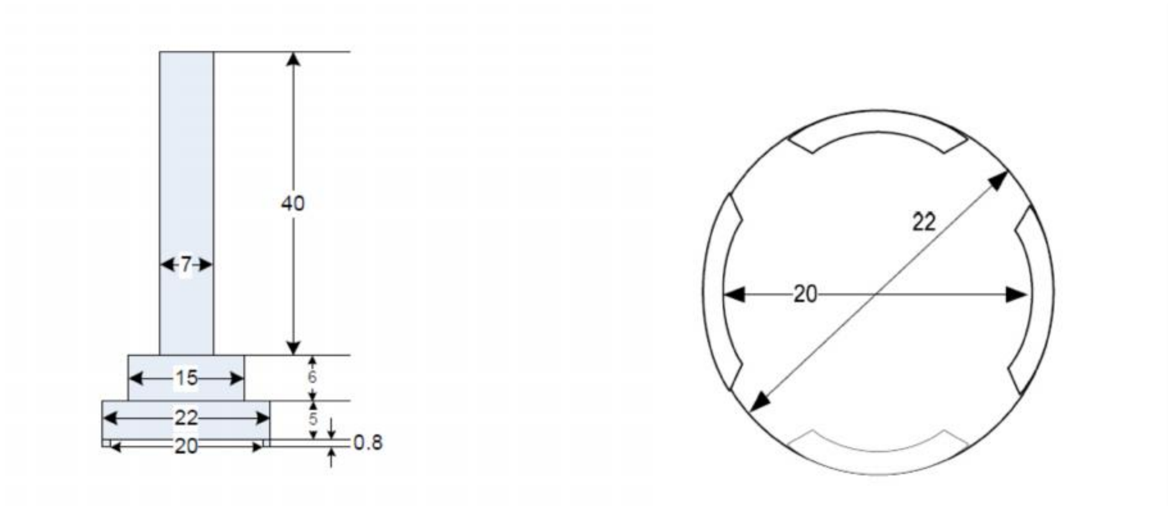


Figure 3-7: Pull-out Stub Dimensions (mm) for the BBS Test (Anon., 2009)

Figure 3-8: Pull-out Stubs used in BBS Tests

Limitations of device

Loading rate plays a key role in the determination of the BBS. Although the PATTI Quantum Gold device has a loading rate adjustment button, the loading rate is still difficult to control because the button does not indicate the loading rate. The button rather acts as an open/close valve to increase or decrease the loading rate. This button is also very sensitive and care must be taken when adjusting. A constant air supply is also compulsory to ensure an accurate loading rate.

3.3.2 MATERIALS

Binders

Five of the commonly used binders in South African seals were used in the study. The hot applied binders used in this study include 80/100 Pen Grade Bitumen, homogeneous polymer modified binder (S-E1) and non-homogenous polymer modified binder or bitumen rubber (S-R1). Emulsions chosen to be tested for this study include Cationic Rapid Spray 60% (CRS 60) and polymer modified emulsion SC-E1 (CRS 60/3).

All the binders were provided by Tosas and all the modified binders and the emulsions are made with 80/100 pen bitumen as base (initial binder). The straight bitumen utilized was an 80/100 pen bitumen that was refined at Natref. It was sampled from tanker no: FO9315 at 10H00 on the 17th of April 2011.

The cationic spray grade emulsion (CRS 60) was manufactured using 60% of 80/100 penetration grade bitumen as base. This emulsion was modified with 3% Styrene-Butadiene-Styrene (SBS) to create the polymer modified emulsion SC-E1 (CRS 60/3).

SBS was also used to modify the polymer modified binder (S-E1). The bitumen rubber (S-R1) was sampled from batch BR 76722 on the 20th of April 2011.

Aggregates

Aggregate cores were received from various quarry sites in South Africa. These cores included granite, dolerite and quartzite.

The dolerite was cored at Trichardt Crusher in Trichardt, Mpumalanga. These cores were visually similar. The granites came from the Jukskei quarry in Midrand, Gauteng. Both the grey granite and white granite came from this quarry, but there were visual differences. Quartzite was cored at the Ferro quarry in Pretoria, Gauteng. Both the red and pink quartzites were sampled at this quarry, but also differed visually.

The visual differences of the cores of granite as well quartzite, as depicted below, led to the initial decision of dividing these aggregate types acourding to colour. It was assumed that the aggregates were consisting of different compositions of minerals and would therefore react different with the binders during the BBS testing. Therefore, the aggregates would be evaluated in a phased approach. Firstly, it will be established if there are sigificant differences between the different forms of the mother rock, and then decide if they will be analysed separately or combined.

Figure 3-9: Grey Granite

Figure 3-10: White Granite

Figure 3-11: Red Quartzite

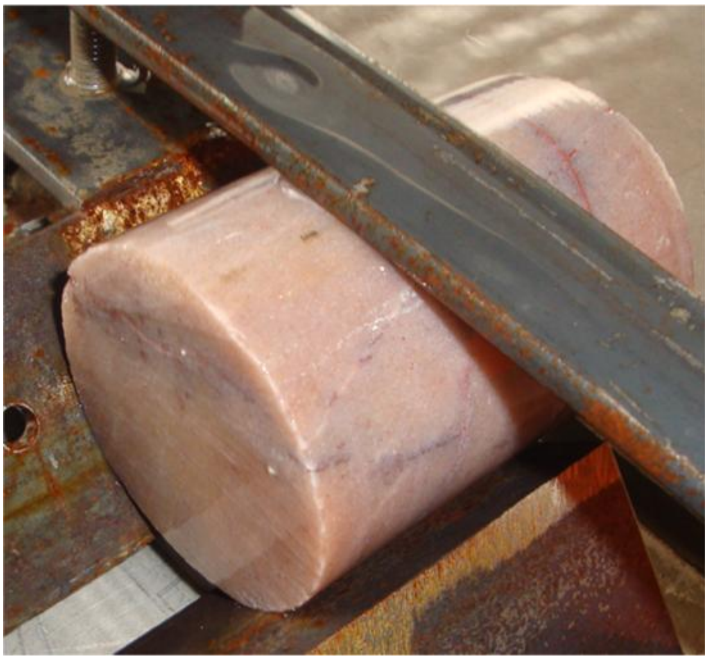


Figure 3-12: Pink Quartzite

Figure 3-13 illustrates how the granites and the quartzites were divided in order to verify if the visual differences made any variance in the BBS.

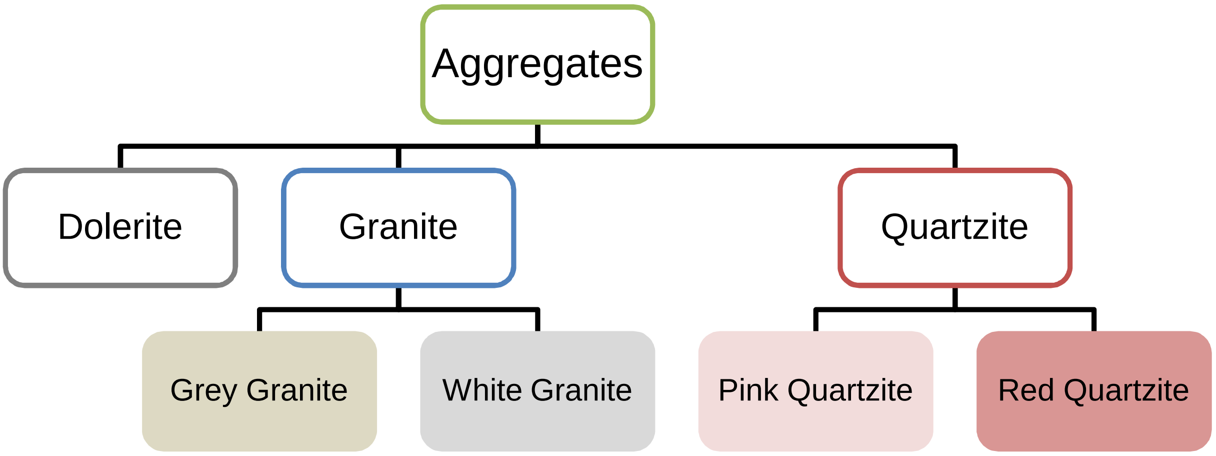


Figure 3-13: Dividing Aggregate Types According to Colour

The granite and quartzite aggregates are acidic and the dolerite is considered to be a basic rock.

Table 3-1: Aggregate Properties

Aggregate	Type of Rock	pH
Granite	Igneous Rock	Acidic
Quartzite	Metamorphic Rock	Acidic
Dolerite	Igneous Rock	Basic

3.3.3 CONDITIONS

Temperature

BBS tests have been done at two different temperatures namely 15 °C and 35 °C. These temperatures represent the approximate average pavement temperatures in South Africa during winter and summer respectively.

Curing Time

Samples were left to cure for 2, 6, and 24 hours respectively. This curing time period represents the time period between constructions of the surface seal and opening to traffic.

3.3.4 TEST SETUP AND SAMPLE PREPARATION

Binder Preparation

Each binder type was heated, in a force draft oven to the relevant temperature similar to what is used in the field prior to application. Table 3-2 shows the relevant application temperatures for various binders.

Table 3-2 Application temperatures of binders (SABITA, 2012)

Binder Type	**Application Temperature [°C]**
80/100 Bitumen	175
S-E1	185
S-R1	200
SC-E1	80
Cat 60	65

Aggregate Preparation

Aggregate cores were received from the various quarries and were approximately 200mm in length and 50mm in diameter. These cores were then cut into discs with a thickness of 20mm using a wet diamond cutting blade as in Figure 3-14.

Figure 3-14: Aggregate Cores Cut into Discs

The rotating cutting blade left an uneven surface on the aggregate discs, so each surface of the discs had to be lapped with a wet diamond 280gr grid (at 300 rpm) to create an even surface. The surface had to be even, but not so smooth as to lose the aggregate properties. See Figures below:

Figure 3-15: Lapping of Quartzite

Figure 3-16: Lapping Device

Figure 3-17: Before and After Lapping – Dolerite

The aggregate discs were all cleaned before testing by placing it in an ultra-sonic water bath for at least 60 minutes at 40°C. Aggregate discs were also cleaned after each test, before being used for succeeding tests. This was done to ensure no binder residue on the testing surface.

Figure 3-18: Ultra-sonic Cleaner Used to Clean Aggregate Discs

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BBS Testing Process

Before each set of tests, the device was calibrated according to the device manufacturing recommendations.

All the aggregate discs were dried and kept in a laboratory oven at 35 degrees Celsius. This will be done to represent a realistic temperature of the pavement during construction and to ensure favourable conditions for the aggregate and binder to bond. The metal pull-off stubs were preheated to 60°C.

Each binder type was heated to the relevant application temperature as indicated in Table 3-2. The hot binder was then applied to the aggregate surface. In case of the bituminous binders the pull-off stub was immediately positioned firmly on top of the binder. The test sample was then cured at the relevant temperature (15°C or 35°C) for a specific curing time (2, 6 or 24 hours).

Due to the water content of the emulsions the aggregate disc with the emulsion was allowed to cure at 35°C for 1 hour before the pull-off stub was attached. The samples were then cured for the remaining time at the relevant curing temperature.

Figure 3-19 to Figure 3-22 illustrates the testing processes for each scenario.

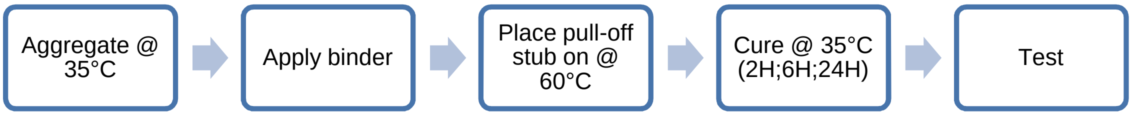

Figure 3-19 Testing Process of Hot Applied Binders at 35°C

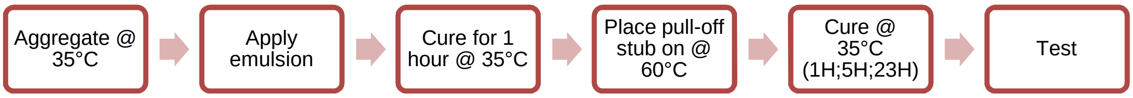

Figure 3-20 Testing Process of Emulsions at 35°C

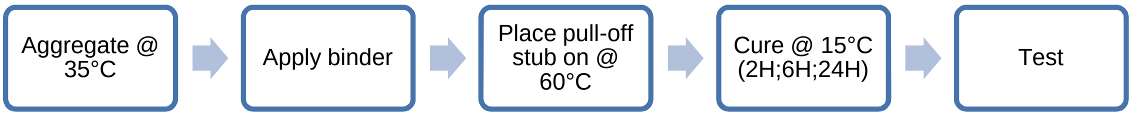

Figure 3-21 Testing Process of Hot Applied Binders at 15°C

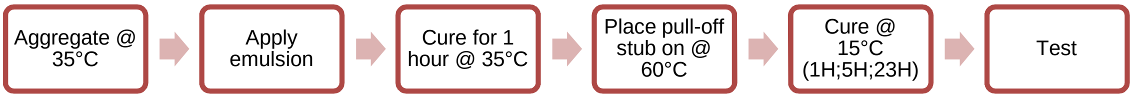

Figure 3-22 Testing Process of Emulsions at 15°C

Each test sample was then removed after curing and tested in the laboratory. The average temperature in the laboratory ranged between 19 and 22°C. It is believed that this did not have a significant influence on the test results due to the short duration of the test.

All the BBS tests were completed between September and December 2012.

3.3.5 DATA

A wide spectrum of variables was researched and therefore most binders used in surface seal applications were investigated. Three of the most widely used aggregate types in South Africa were also studied. These aggregates included both acidic and basic aggregate types. These components of a surface seal were tested at two temperature conditions and a three curing time intervals. It makes this study in terms of BBS of surface seals in South Africa very comprehensive. Therefore, this is good quantitative research.

Because of the number of tests that was carried out and the limited time period in which tests were done, tests were only repeated once. Although test conditions were mirrored and most of the results were similar, some differed significantly. These few tests that showed great differences were repeated in order to obtain a reliable result. In total 319 BBS tests have been carried out.

3.3.6 PRE-ANALYSIS

Loading Rate Adjustment

Seal binders comprise bituminous binders that are viscoelastic, so their responses are temperature and loading rate dependent. Hence, the loading rate or pull out rate of the tests greatly influence the BBS results. The loading rate is determined by calculating the slope of the line between the twenty and eighty percentage marks of the maximum stress value. The loading rates of the BBS tests that have been done range from 400kPa/s to 1200kPa/s, but there were several occurrences where it was lower or higher.

Figure 3-23 shows the loading rate of each BBS test completed for this study. The average loading rate of all the tests was 727 kPa/s.

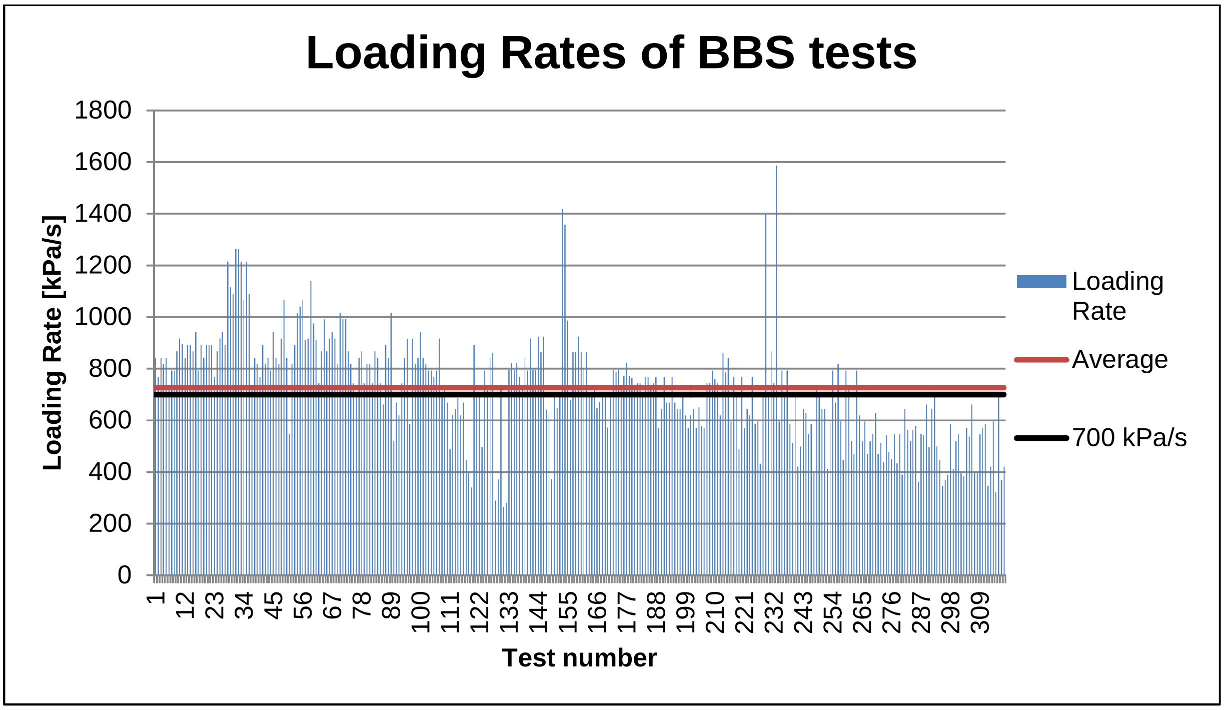

Figure 3-23: Loading Rates of BBS Tests

Although the average of the loading rates was near the desired loading rate, there were significant variations that affected the BBS results.

In order to compare the BBS tests results with each other, it was decided to manipulate the results to a similar loading rate (700 kPa/s). Miller suggested that a power law relationship best describe the relation between the loading rate and pull-out tension. It is worthy to note that Miller did research at much higher loading rates than this study and the power law model was not found best to describe the relation of this study. However, Miller found that loading rates between 690 kPa/s and 1030 kPa/s displays a linear relationship above pull-out tension values of 690 kPa (Greyling, et al., 2010).

Therefore, it was decided to adjust the BBS results by obtaining a linear gradient of the average BBS versus loading rate for each binder and temperature condition. BBS values were then corrected along this gradient.

These visco-elastic properties of binders are greatly influenced by the composition or type of binder as well as temperature. Therefore, binders perform different from each other and also vary in performance at different temperatures.

Each binder type was isolated during a specific temperature and the BBS was plotted against the loading rate as illustrated in Figure 3-24.

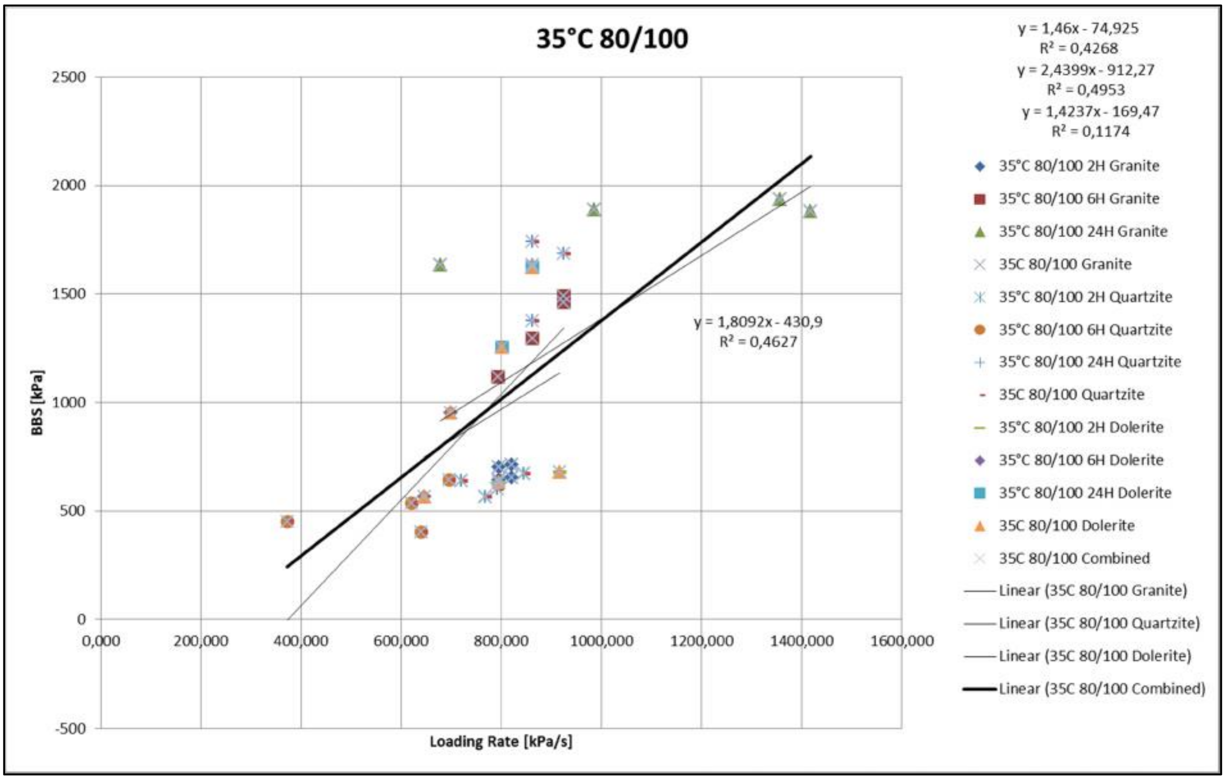

Figure 3-24: BBS versus Loading Rate for 80/100 Pen Bitumen at 35˚C with Gradient

Each graph represents between 18 and 36 tests. A linear trend line was obtained for each binder type to determine the gradient at the two curing temperatures. This gradient is then used to calculate the BBS at a specific loading rate.

The equation below was used to calculate the BBS at the desired loading rate of 700 kPa/s.

$$y_1 = m(x_1 - x_0) + y_0$$

where;

y_1 - *BBS at desired loading rate*

m - *Gradient*

x_1 - *Desired loading rate (700 kPa/s)*

x_0 - *Actual loading rate*

y_0 - *BBS at actual loading rate*

Figure 3-25 below shows the adjusted BBS results at a uniform loading rate.

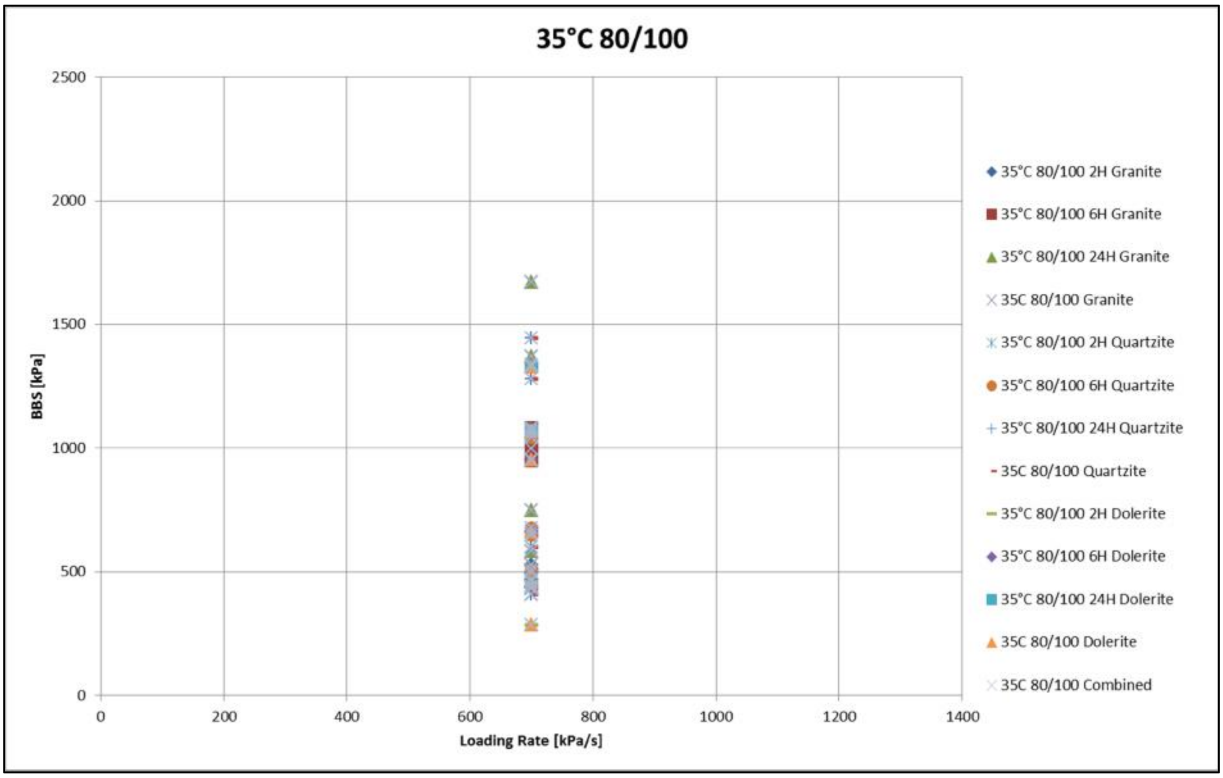

Figure 3-25: Adjusted BBS at 700 kPa/s

This modification to the BBS minimises the effect of loading rate on the results and can therefore be compared in a better manner. The gradients for the various hot applied binders and the emulsions are shown in Table 3-3.

Table 3-3: BBS vs Loading Rate Gradients of Binders

Temperature	Binder	Gradient [s]
15 °C	80/100	1.39
	S-E1	0.45
	S-R1	0.84
	SC-E1	0.9
	CRS 60	0.08
35 °C	80/100	1.81
	S-E1	0.67
	S-R1	0.6
	SC-E1	0.22
	CRS 60	0.26

3.3.7 ANALYSIS

Analysis of Variance

Analysis of variance, or better known as ANOVA, is a statistical method used to tests differences of the means between two or more groups. This method was utilised to analyse the BBS results of this study and confirm certain statements and conclusions.

The conceptual model for ANOVA is a ratio between the differences in the means of the groups and the error variance. In the same way that a variance can be calculated from a set of data, it can be calculated from a set of means. Variance is the square of standard deviation. A higher variance between the means indicates there are bigger differences (Gabrenya, 2003).

The variance between group means is called the between-groups variance. The ratio, or F-value, is the between-groups variance divided by error variance. If this value is large enough ($F > F_{crit}$) we can reject the null hypothesis, which implies the groups are not similar or equal (Gabrenya, 2003). A result is considered statistically significant, when a probability (p-value) is less than a significance level (α-value), and also justifies the rejection of the null hypothesis. The α-value was selected as 0.05.

In the typical application of ANOVA, the null hypothesis is that all groups are basically random samples of the same population. Rejecting the null hypothesis would imply that different treatments result in altered effects (Gelman, 2005).

Sample means must be sufficiently different from each other compared to the error variance within the groups to reject the null hypothesis.

$$F = \frac{Between - Groups\ Variance}{Within - Groups\ (Error) Variance} = \frac{MS\ of\ group}{MS\ of\ error}$$

The within-groups or error variance is the combined variances of the groups.

Microsoft Excel 2010 was utilised to execute the ANOVA and produce a source table to report the result of the analysis. Table 3-4 is an example of the source table.

Table 3-4: Example of ANOVA Source Table

Source of Variation	SS	df	MS	F	P-value	F crit
Sample ($T_1 = T_2$)	63269	1	63269	21,6	5,68E-04	4,75
Columns (2H = 6H = 24H)	38187	2	19094	6,5	0,0122	3,89
Interaction	13868	2	6934	2,4	0,1365	3,89
Within	35226	12	2936			
Total	150550	17				

The values that are coloured in red signals the null hypothesis is rejected, while the values in black suggests the null hypothesis cannot be rejected.

ANOVA makes it possible to the study of the effects of multiple factors or influences. When the experiment includes tests at all combinations of levels of each factor, it is termed factorial. Factorial experiments are more efficient than a series of single factor experiments and the efficiency grows as the number of factors increases. Consequently, factorial designs are heavily used (Montgomery, 2001).

In a multiple factors ANOVA with factors 1, 2 and 3, the ANOVA model includes terms for the main effects (1, 2, 3) and terms for interactions (1*2, 1*3, 2*3, 1*2*3). All terms require hypothesis tests. Testing one factor at a time hides interactions, but produces apparently inconsistent experimental results. The ability to detect interactions is a major advantage of multiple factor ANOVA (Montgomery, 2001).

This study utilised numeral two-way (factorial) ANOVA's as well as limited three-way and four-way ANOVAs. These will be discussed along with the results of the BBS tests.

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Failure Classification

Each test sample was analysed after the test was completed to determine whether failure was adhesive or cohesive. Adhesive failure refers to the breaking of the bond between the aggregate and the binder while cohesive failure refers to the failing of the bond in the binder itself.

Although this is done visually, and is therefore operator dependant, it is fairly obvious to decide whether failure was adhesive or cohesive.

3.4 LIMITATIONS

The absence of a curing chamber with humidity control caused that tests were not cured at a pre-determined humidity. However, it was found by previous research that humidity does not significantly influence the BBS (Greyling, 2012). Therefore the influence of humidity during the BBS tests was not considered.

Bitumen rubber (S-R1) should not be kept or stored for long periods. Due to the nature and duration of the testing proses for this research study, it was impossible to receive a fresh sample of this binder before tests were prepared. All was done to store this binder at recommended temperature and to complete the tests as soon as possible.

The loading rate inconsistency of the testing device influenced the tests, although all tests were done in the recommended loading rate range. However, it would have enhanced the testing procedure if the loading rate was more consistent or variance smaller.

The PATTI device had to be calibrated in order to ensure tests are accurate. This required that the device had to be sent to the U.S.A. and caused a delay in the process.

The fact that the aggregates tested for this study came from sources situated far from the laboratory where tests took place, made it necessary to employ a third party to core, collect and send the aggregates. This process was heavily delayed and caused a significant postponement in the testing process. When these aggregate cores eventually arrived it had to be cut, lapped and then testing could take place.

3.5 EXPECTED RESULTS

- BBS results to improve as curing time is increased
- BBS of hot applied binders higher at low temperatures
- Modified binders to have higher BBS than unmodified binders
- Quartzite to perform better than Granite but both perform better than Dolerite (Basic) with Emulsions (Cationic)

3.6 OVERVIEW OF METHOD

The research design was illustrated and the strength and weaknesses thereof were identified. The instruments used to complete the tests as well as the materials used in this study were discussed. The test procedures and the conditions at which the BBS tests will be performed were also explained.

The data obtained during the study was discussed as well as the pre-analysis method that was performed in order to compare the tests. The analysis of the data was discussed with emphasis on the ANOVA methods.

The limitations of the study were identified and explained and finally the expected results of the study were laid out.

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4. RESULTS

4.1 INTRODUCTION

This chapter contains the BBS results as well as the failure analysis of the tests. The aggregates of the same rock type will be evaluated first to establish if they should be analysed separately or combined. The BBS results of all the tests follow with analysis of each binder type at the various conditions. Finally, the failure analysis of the BBS test will be analysed and discussed.

4.2 EVALUATION OF AGGREGATE TYPES

There were visual differences between the granite and quartzite aggregate samples. These aggregates were of the same origin and mother rock type. Before the BBS results can be analysed, it must first be established how to categorise these aggregates. Below each of these aggregates will be compared at similar conditions.

4.2.1 RESULTS OF AGGREGATE SUB-TYPES

The graph below shows the BBS values of each binder type on grey and white granite for 2, 6 and 24 hours of curing at 15 °C.

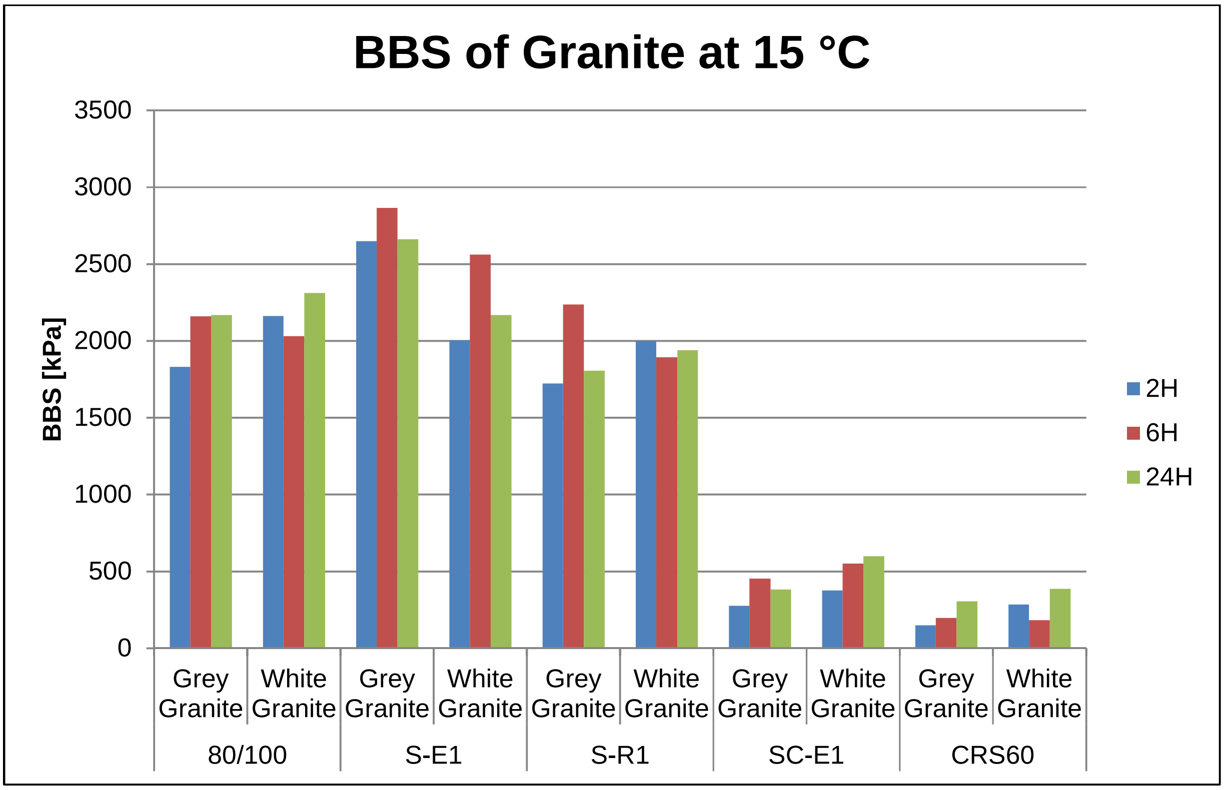

Figure 4-1: BBS Values for Grey and White Granite at 15 °C

Each bar on the graph represents the average of two BBS tests. It is visible that the BBS values only significantly varied between binder types. Below are the ANOVA results of the comparison.

Table 4-1: ANOVA Results Comparing White and Grey Granite at the Various Curing Times at 15 °C

Source of Variation	SS	df	MS	F	P-value	F crit
Sample ($A_1 = A_2$)	5902	1	5902	0,0055	0,9417	4,260
Columns (2H = 6H = 24H)	153547	2	76774	0,0711	0,9316	3,403
Interaction	46755	2	23377	0,0216	0,9786	3,403
Within	25920153	24	1080006			
Total	26126357	29				

It is visible from both Figure 4-1 and Table 4-1 that these two aggregates did not differ to a significant extent. The values for the two granites, with similar binders and curing times, were very similar. The phenomenon repeated itself in the case of quartzite as indicated in Figure 4-2.

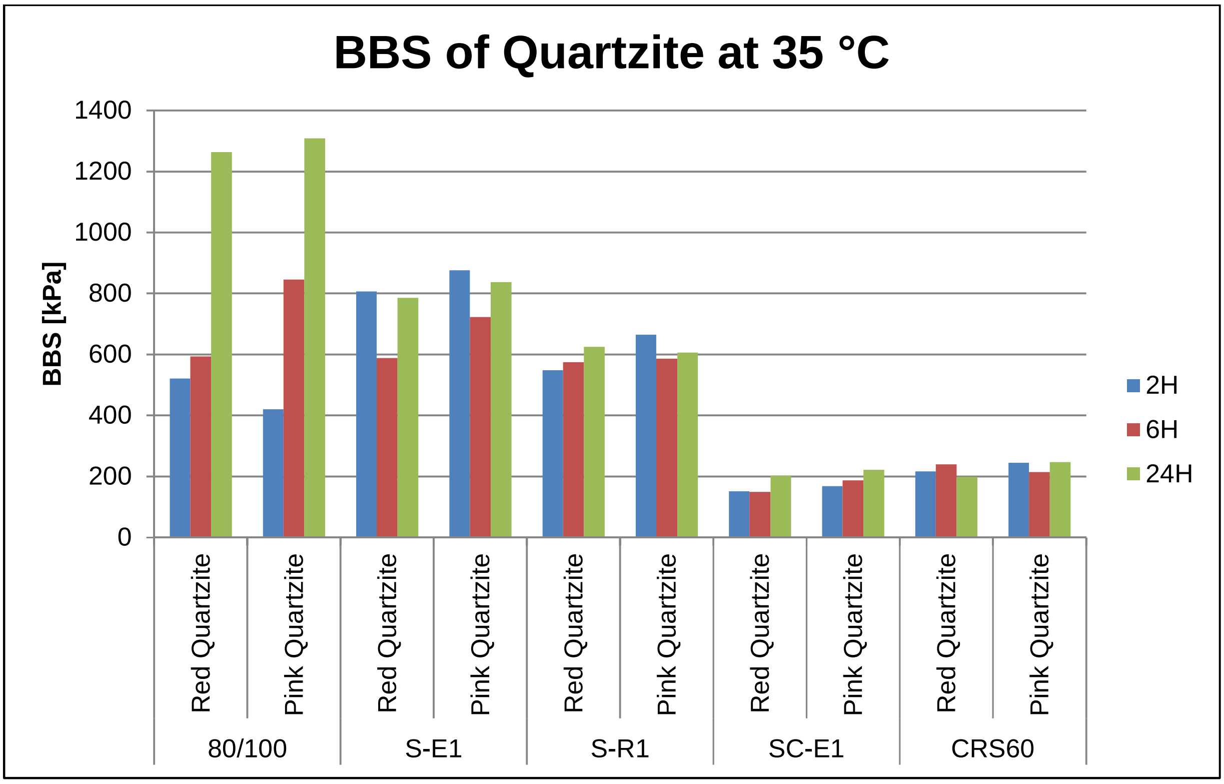

Figure 4-2: BBS Values for Pink and Red Quartzite at 35 °C

Table 4-2: ANOVA Results Comparing Red and Pink Quartzite at the Various Curing Times at 35 °C

Source of Variation	SS	df	MS	F	P-value	F crit
Sample ($A_1 = A_2$)	15641	1	15641	0,1347	0,7168	4,2597
Columns (2H = 6H = 24H)	178682	2	89341	0,7696	0,4743	3,4028
Interaction	4901	2	2450	0,0211	0,9791	3,4028
Within	2786158	24	116090			
Total	2985382	29				

4.2.2 DECISION OF COMBINING AGGREGATES

After it was decided to divide granite and quartzite it became apparent that these aggregates rendered very similar BBS results.

Looking at the ANOVA results it is evident that the P-values are very high, considering the α-value is 0.05. The hypothesis that states that the means of the two samples that are being compared, are equal, cannot be rejected. It was therefore decided to combine test results of these aggregates for each binder type, because of the similar responses. This led to an increased quality of the data for granite and quartzite.

4.3 BITUMEN BOND STRENGTH

Bitumen bond strength is the maximum pull-off strength required to separate the pull-off stub from the bitumen-on-aggregate sample. This is a tensile stress and is measured in kPa.

The comparisons of results are expressed in the form of graphs. Each point on a graph represents the average of the BBS results for the specific aggregates and conditions of curing. The colour of the line represents the aggregate type while the line style represents the binder type. The type of marker at the points represents the temperatures. Below is the key to the graphs.

Key to graphs:

Point Marker – Curing Temperature

■	15 °C
●	35 °C

Line Style – Binder Type

━━━━━━━━━━	80/100 Penetration Grade Bitumen	(80/100)
▬ ▬ ▬ ▬ ▬ ▬ ▬ ▬ ▬ ▬	Polymer Modified Bitumen	(S-E1)
━━ ━━ ━━ ━	Bitumen Rubber	(S-R1)
━━ ▪ ━━ ▪ ━━	Polymer Modified Emulsion	(SC-E1)
▪▪▪▪▪▪▪▪▪▪▪▪▪▪▪▪▪▪	Cationic Spray Grade 60%	(CRS60)

Line Colour – Aggregate Type

▬	Dolerite
▬	Granite
▬	Quartzite

4.3.1 APPLICATION TYPE

Binders can be either hot applied or warm applied (emulsions). The hot applied binders include the 80/100 pen grade bitumen, polymer modified bitumen (S-E1) and bitumen rubber (S-R1). The emulsions used for testing are the polymer modified (SC-E1) and the Cationic Rapid Set Spray Grade (CRS60).

Below are two graphs showing the BBS values versus curing time of all binders for each curing temperature:

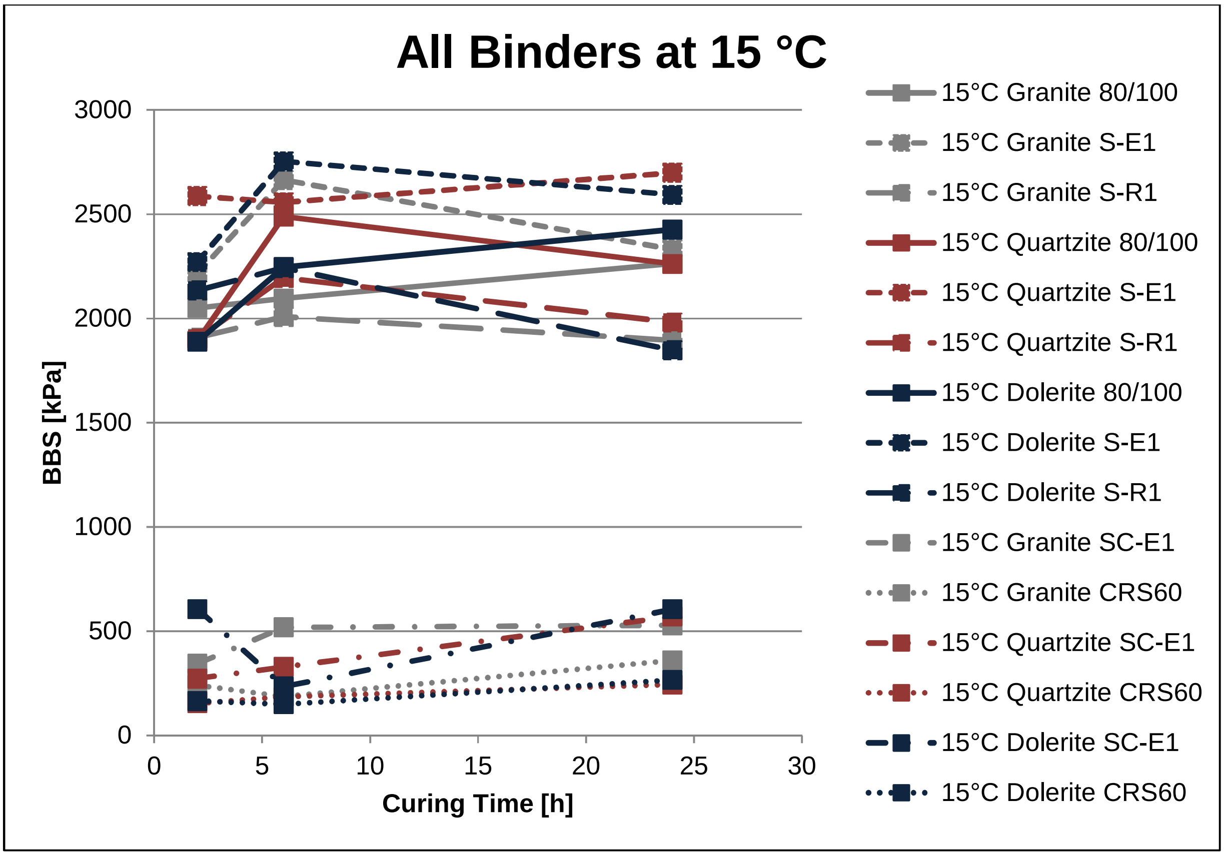

Figure 4-3: BBS versus Curing Time for All Binders at 15 °C

Using analysis of variance (ANOVA) to analyse the null hypothesis that the BBS of HAB equals the BBS of Emulsions the difference is extremely significant.

Table 4-3: Two-way ANOVA with Repetition for HAB versus Emulsions at 15 °C

Source of Variation	SS	df	MS	F	P-value	F crit
Sample (HAB = Em)	16352290	1	16352290	3231,45	5,8E-16	4,75
Columns (2H = 6H = 24H)	72302	2	36151	7,14	0,009	3,89
Interaction	79998	2	39999	7,90	0,006	3,89
Within	60724	12	5060			
Total	16565314	17				

Applying the null hypothesis, which states the means of the BBS results of emulsions equal the means of hot applied binders, the F-value is much larger than the F_{crit}-value and the P-value is extremely small. This confirms a big difference between the BBS of hot applied binders and emulsions. This phenomenon repeats itself at the higher temperature.

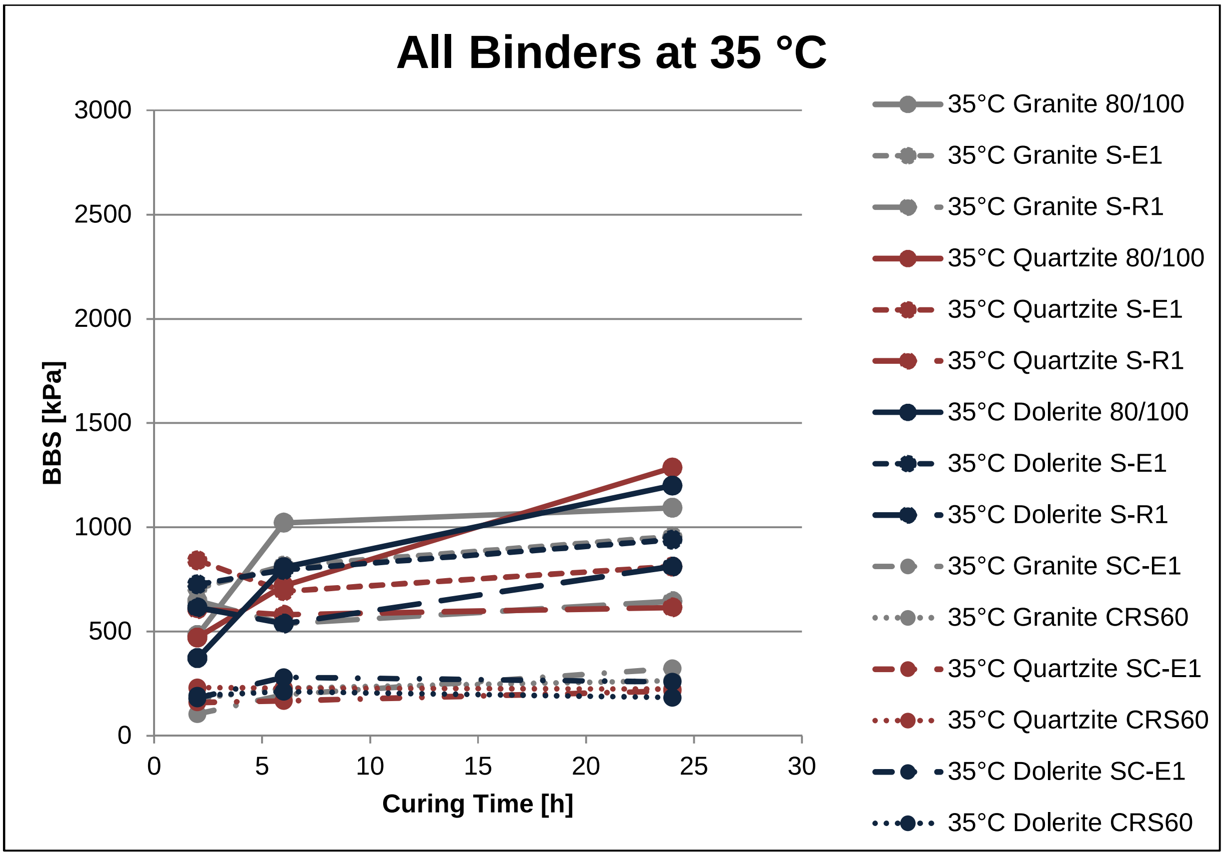

Figure 4-4: BBS versus Curing Time for All Binders at 35 °C

Looking at Figure 4-3 it is clearly visible that the hot applied binders had a higher BBS performance than the emulsions. Although this margin is smaller at the 35 °C curing temperature (Figure 4-4), the emulsions still had weaker bonds than the hot applied binders.

This difference of these binder types at 35 °C is supported by the ANOVA results summarised in Table 4-4 below.

Table 4-4: Two-way ANOVA with Repetition for HAB versus Emulsions at 35 °C

Source of Variation	SS	df	MS	F	P-value	F crit
Sample (HAB = Em)	1316577	1	1316577	726,7	4,17E-12	4,75
Columns (2H = 6H = 24H)	116380	2	58190	32,1	1,52E-05	3,89
Interaction	50067	2	25033	13,8	7,70E-04	3,89
Within	21740	12	1812			
Total	1504764	17				

Due to this large difference between the BBS results of hot applied binders and emulsions, it was decided to divide the binders into these two main categories when comparing.

It is also evident that hot applied binders had higher BBS results at the lower temperature. This will be explained below.

4.3.2 *HOT APPLIED BINDERS*

In this section the hot applied binders were isolated to compare the BBS of the various aggregates.

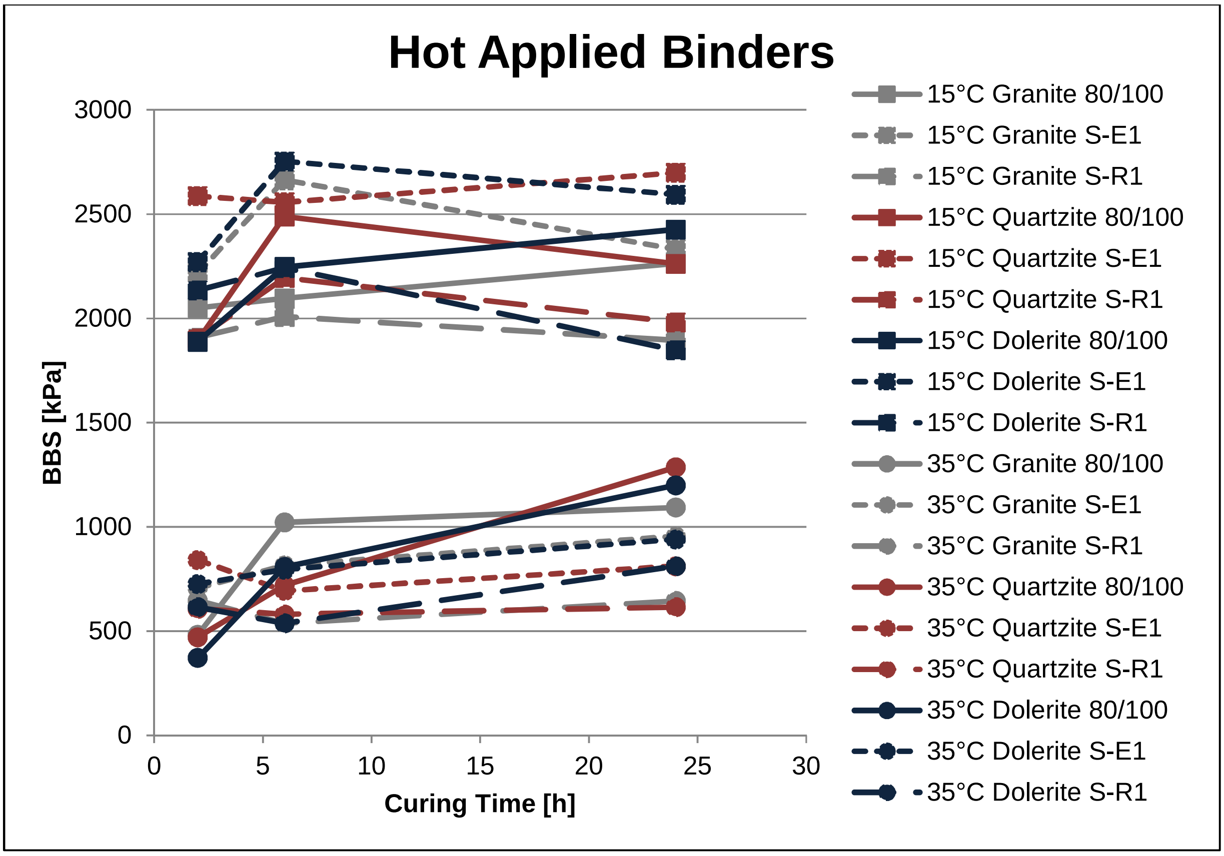

Figure 4-5: BBS results of Hot Applied Binders at Various Curing Intervals

Figure 4-5 highlights the influence of temperature on the BBS results. It is obvious that all the binders had a higher BBS result at lower temperatures.

Table 4-5: Two-way ANOVA with Repetition of 15 °C versus 35 °C for HAB

Source of Variation	SS	df	MS	F	P-value	F crit
Sample ($T_1 = T_2$)	9909325	1	9909325	2517,3	2,58E-15	4,75
Columns (2H = 6H = 24H)	194052	2	97026	24,6	5,63E-05	3,89
Interaction	72640	2	36320	9,2	0,0037	3,89
Within	47239	12	3937			
Total	10223256	17				

Most failure types were cohesive – this means that the bond between the aggregates and the binder was stronger than the binder itself. Therefore the BBS is directly related to the strength of the binder. Bitumen tends to be stiffer at lower temperatures, because of its rheological properties. As the temperature increases the binders become softer and more viscous. This explains why the BBS is much higher at the lower temperatures.

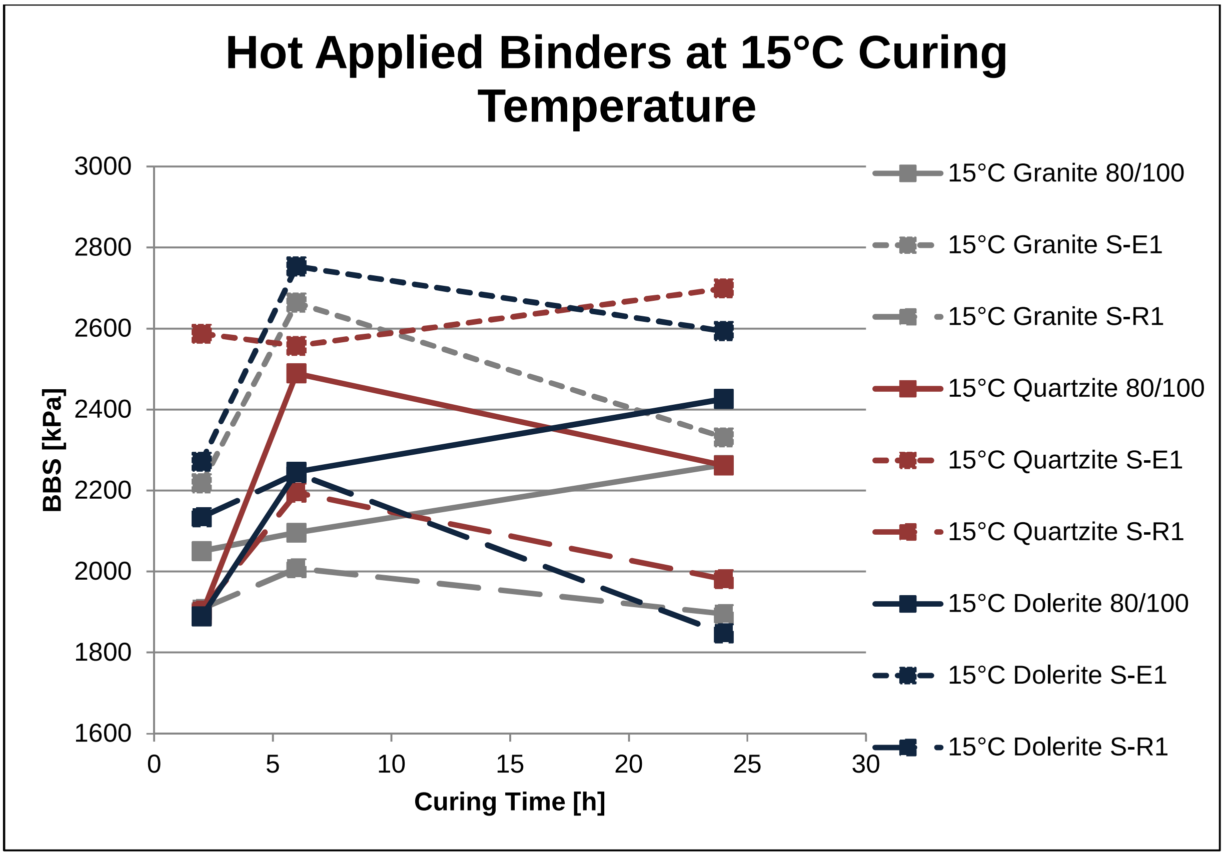

Figure 4-6: BBS results of Hot Applied Binders at 15 °C at Various Curing Intervals

At 15 °C the BBS results seemed to increase as curing time increased, but only when curing time was increased from 2 to 6 hours. It appears as if curing time did not have a positive influence on the BBS when the curing time was further extended to 24 hours. This is not what was expected.

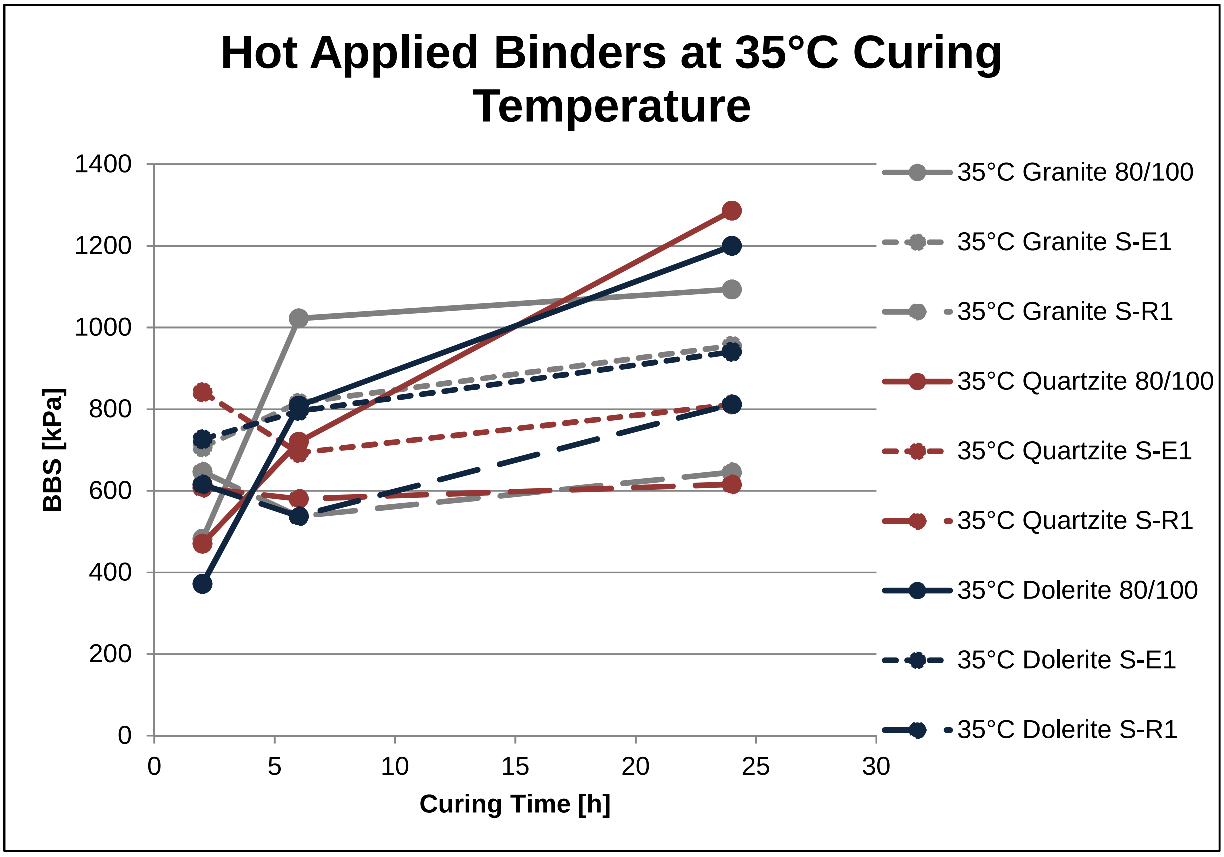

Figure 4-7: BBS results of Hot Applied Binders at 35 °C at Various Curing Intervals

At 35 °C this was less evident. In some cases the BBS results did improve from 2 to 6 hours, but all BBS results improved from 6 to 24 hours of curing.

In order to evaluate the BBS results versus curing time, each binder type will be isolated. Aggregates will also be compared.

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4.3.2.1 80/100 Penetration Grade Bitumen

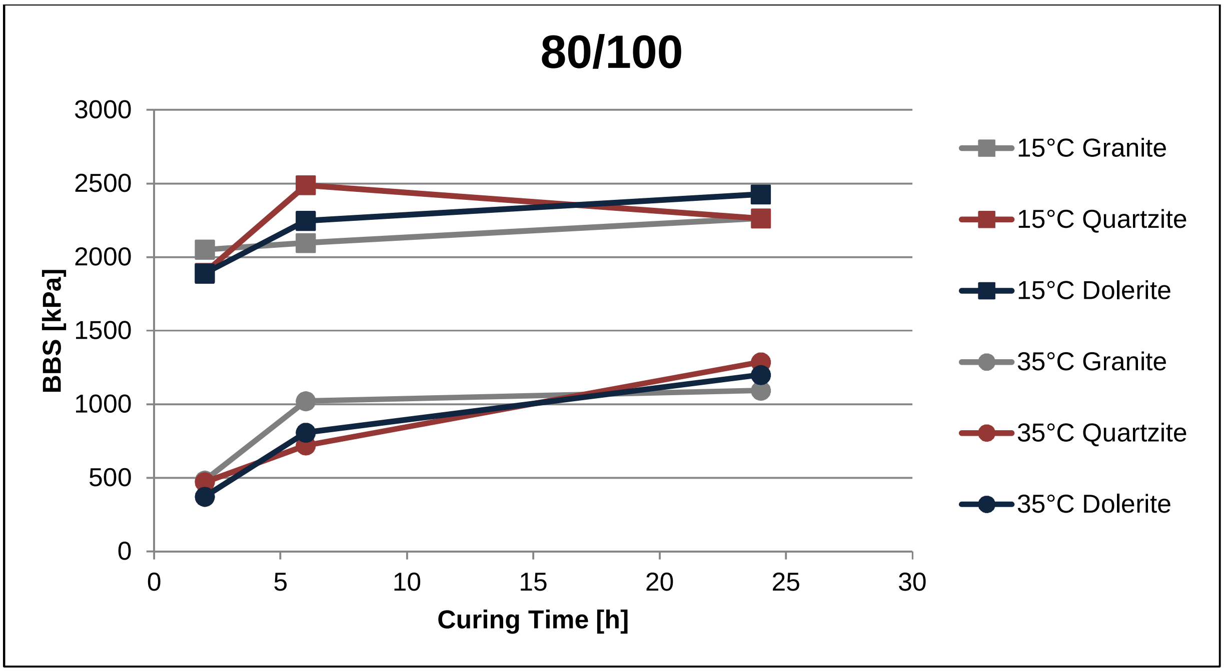

Figure 4-8: BBS versus Curing Time of 80/100 at Both Curing Temperatures

The following information can be derived from Figure 4-8 above and Table 4-6 below:

- Higher BBS result at lower temperature due to visco-elastic properties.
- BBS results improved with curing time in most cases.
- BBS did not improve for quartzite when curing time was extended from 6 to 24 hours. This is because of the very high BBS value at 6 hours of curing.
- Aggregates exhibit similar trends; this is confirmed in the ANOVA results below.
- Curing time had little influence on BBS values.

Table 4-6: ANOVA Results Comparing Aggregates and Curing Times for 80/100 Bitumen

Source of Variation	SS	df	MS	F	P-value	F crit
Sample ($A_1 = A_2 = A_3$)	2752	2	1376	0,0015	0,9985	4,2565
Columns (2H = 6H = 24H)	980308	2	490154	0,5203	0,6112	4,2565
Interaction	41319	4	10330	0,0110	0,9997	3,6331
Within	8479348	9	942150			
Total	9503727	17				

4.3.2.2 Polymer Modified Bitumen (S-E1)

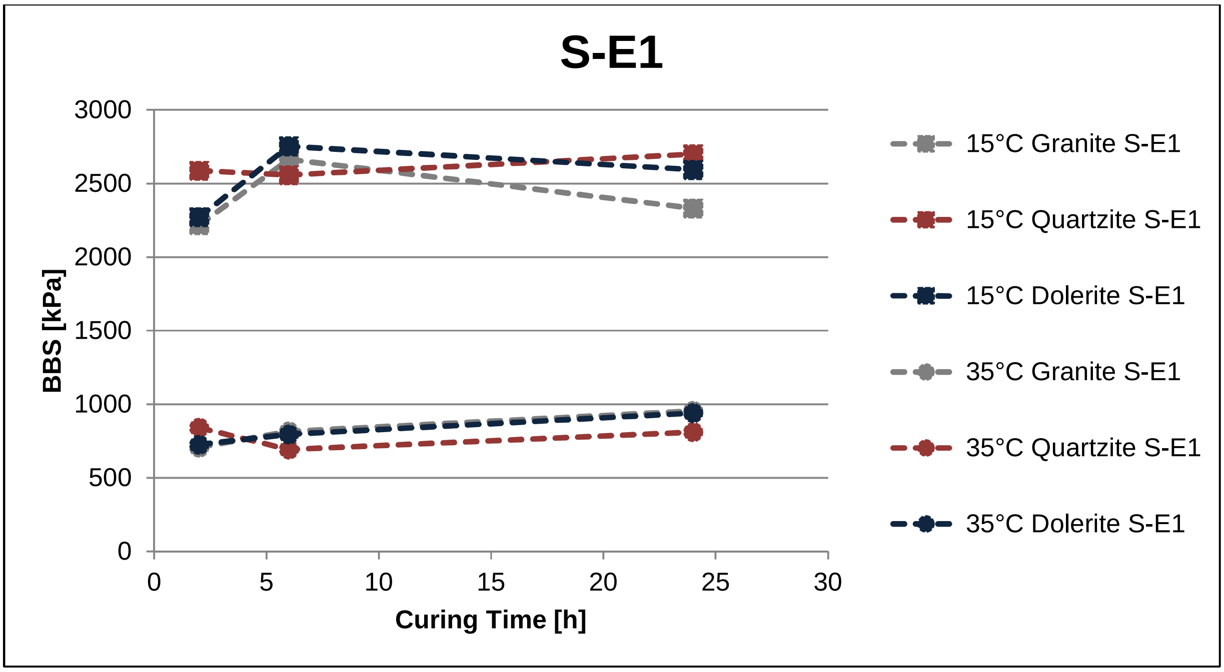

Figure 4-9: BBS versus Curing Time of S-E1 at Both Curing Temperatures

The following information can be derived from Figure 4-9 and Table 4-7:

- Higher BBS values at lower temperature.
- Very high BBS results at 15 °C compared to other binders.
- BBS did not significantly improve as curing time increased at 35 °C.
- Curing time had very slight influence on BBS results.
- All aggregates had similar BBS responses.

Table 4-7: ANOVA Results Comparing Aggregates and Curing Times for S-E1 Binder

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Sample ($A_1 = A_2 = A_3$)	22915	2	11457	0,0077	0,9923	4,2565
Columns (2H = 6H = 24H)	101418	2	50709	0,0343	0,9664	4,2565
Interaction	94320	4	23580	0,0159	0,9994	3,6331
Within	13314646	9	1479405			
Total	13533299	17				

4.3.2.3 Bitumen Rubber (S-R1)

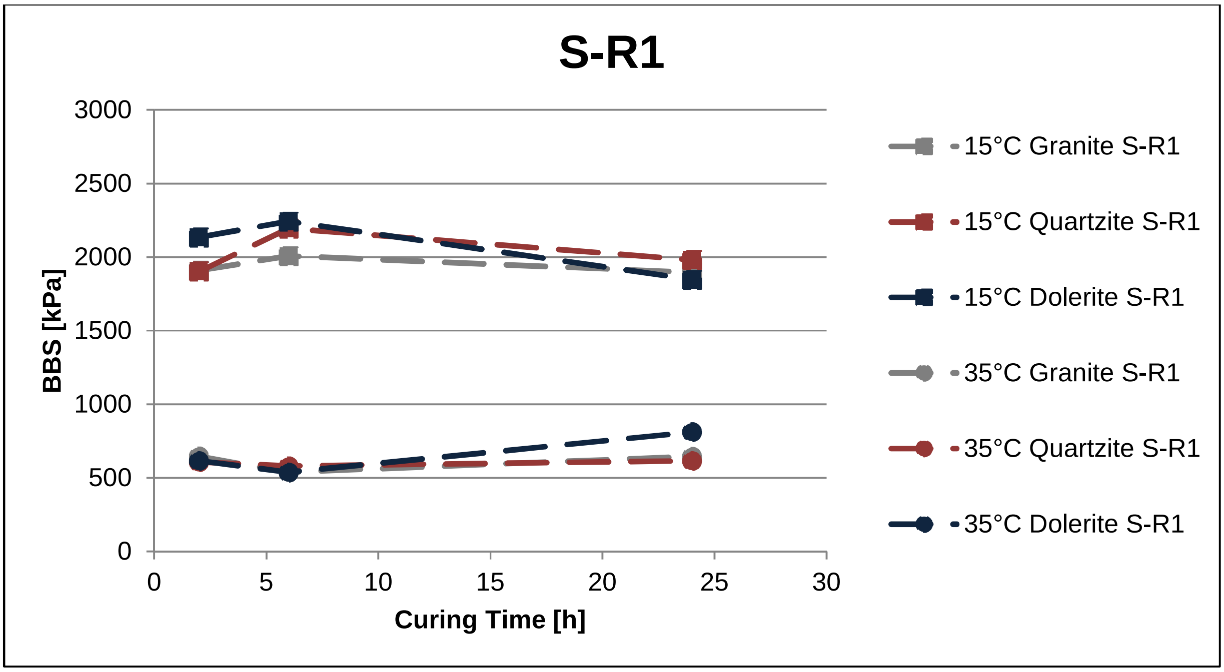

Figure 4-10: BBS versus Curing Time of S-R1 at Both Curing Temperatures

The following information can be derived from Figure 4-10 and Table 4-8:

- Higher BBS results at lower temperature.
- No significant BBS changes as curing time increases.
- All BBS results increased from 2 to 6 hours curing at 15 °C, but then decreased from 6 to 24 hours. BBS decreased from 2 to 6 hours at 35 °C and increased from 6 to 24 hours.
- Lower BBS results than other hot applied binders
- Aggregates had similar BBS responses.

Table 4-8: ANOVA Results Comparing Aggregates and Curing Times for S-R1 Binder

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Sample ($A_1 = A_2 = A_3$)	25178	2	12589	0,0128	0,9873	4,2565
Columns (2H = 6H = 24H)	9710	2	4855	0,0049	0,9951	4,2565
Interaction	12513	4	3128	0,0032	1,0000	3,6331
Within	8876556	9	986284			
Total	8923958	17				

4.3.3 EMULSIONS

Emulsions include Cationic Spray Grade 60% (CRS 60) and Polymer Modified Emulsion (SC-E1) These binders had much lower BBS results and are therefore compared separately. Please note the change in the scale of the graphs.

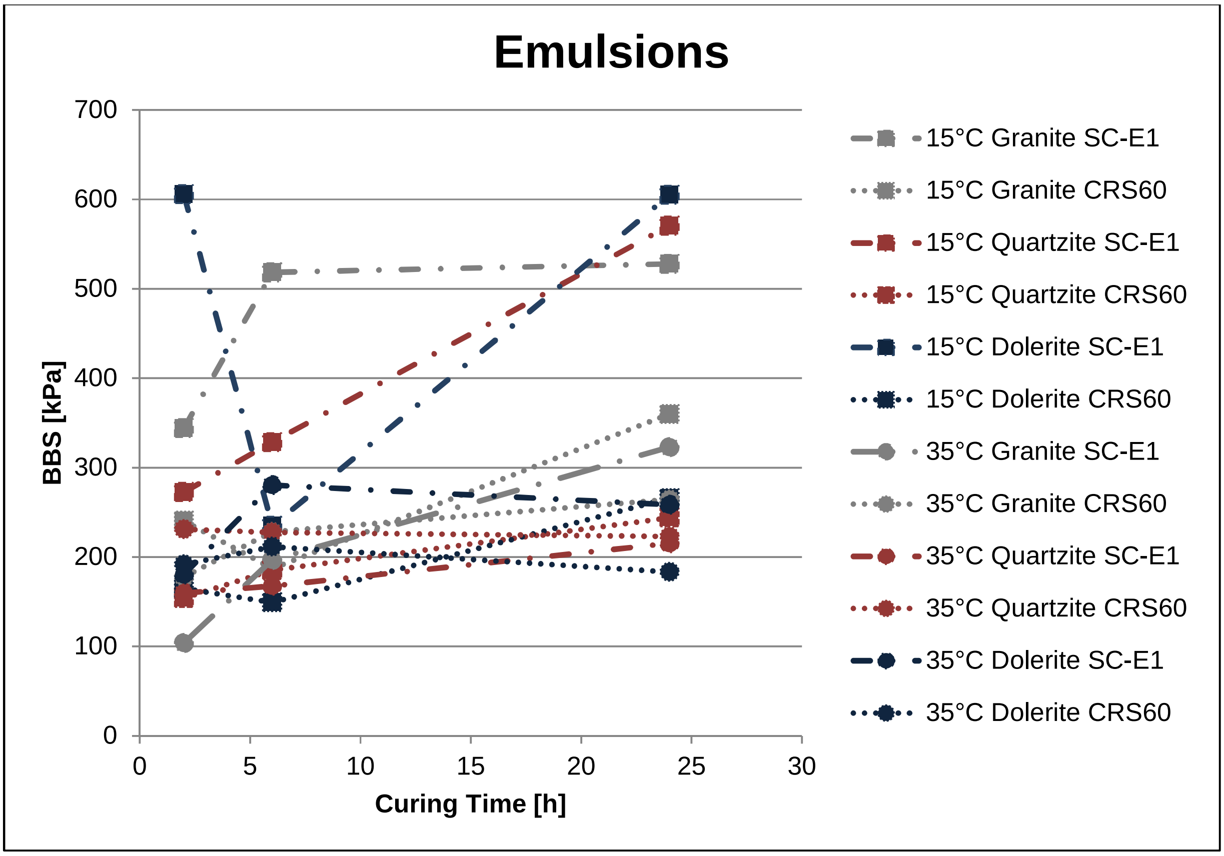

Figure 4-11: BBS versus Curing Time of Emulsions at Both Temperatures

Table 4-9: Two-way ANOVA with Repetition of 15 °C versus 35 °C for Emulsions

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Sample (T_1 = T_2)	63269	1	63269	21,6	5,68E-04	4,75
Columns (2H = 6H = 24H)	38187	2	19094	6,5	0,0122	3,89
Interaction	13868	2	6934	2,4	0,1365	3,89
Within	35226	12	2936			
Total	150550	17				

Looking at Figure 4-11 it is clear that there is a general trend; as the curing time increases, the BBS increases. There is also a significant difference in BBS at the two curing temperatures and is confirmed by the ANOVA results.

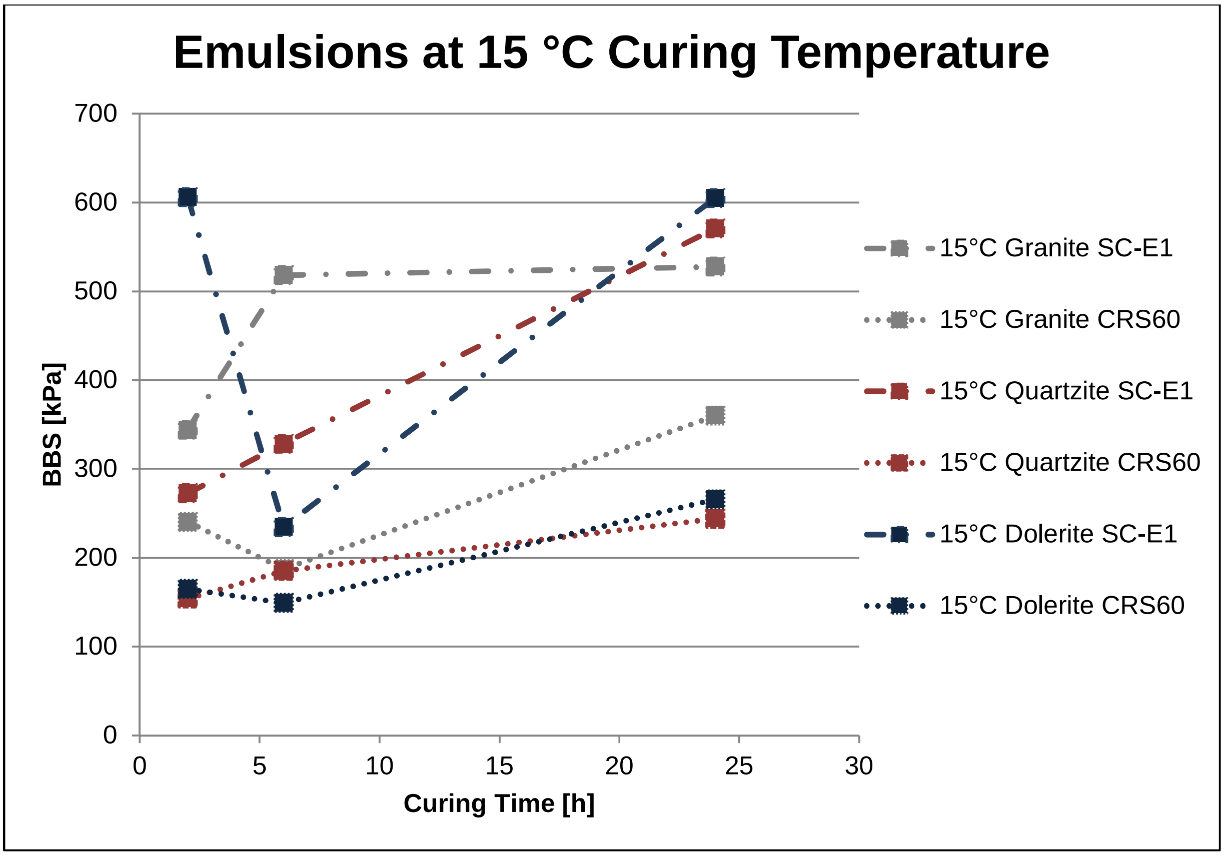

Figure 4-12: BBS versus Curing Time of Emulsions at 15 °C

The BBS results of the polymer modified emulsion were higher than the BBS results of the unmodified emulsion. This case was repeated at every curing interval as well as all aggregates. In general, the BBS results of both binders increased as curing time was increased.

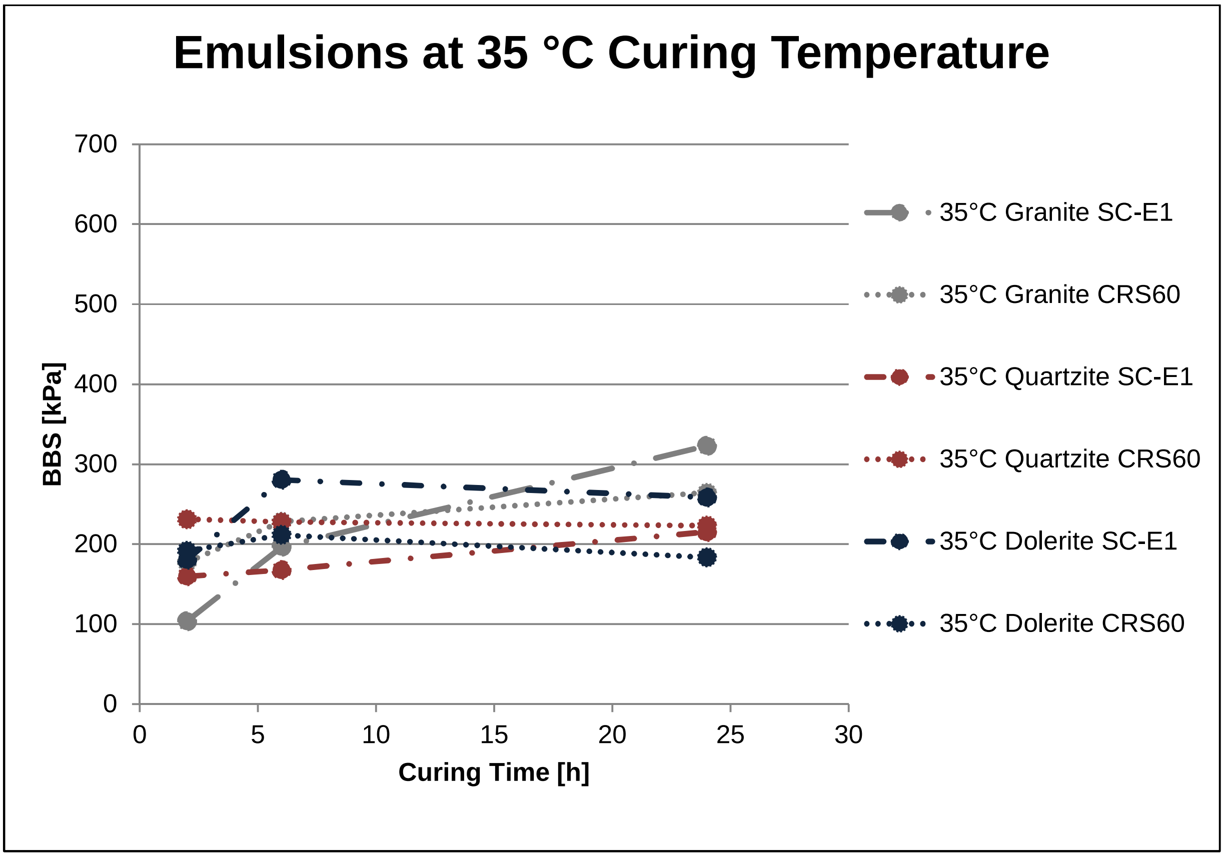

Figure 4-13: BBS versus Curing Time of Emulsions at 35 °C

All the BBS values of the binders in Figure 4-13 are very similar and also very low in comparison with the other BBS results.

In order to compare aggregate types and temperature influence, each binder will be discussed separately.

4.3.3.1 Cationic Spray Grade 60% (CRS60)

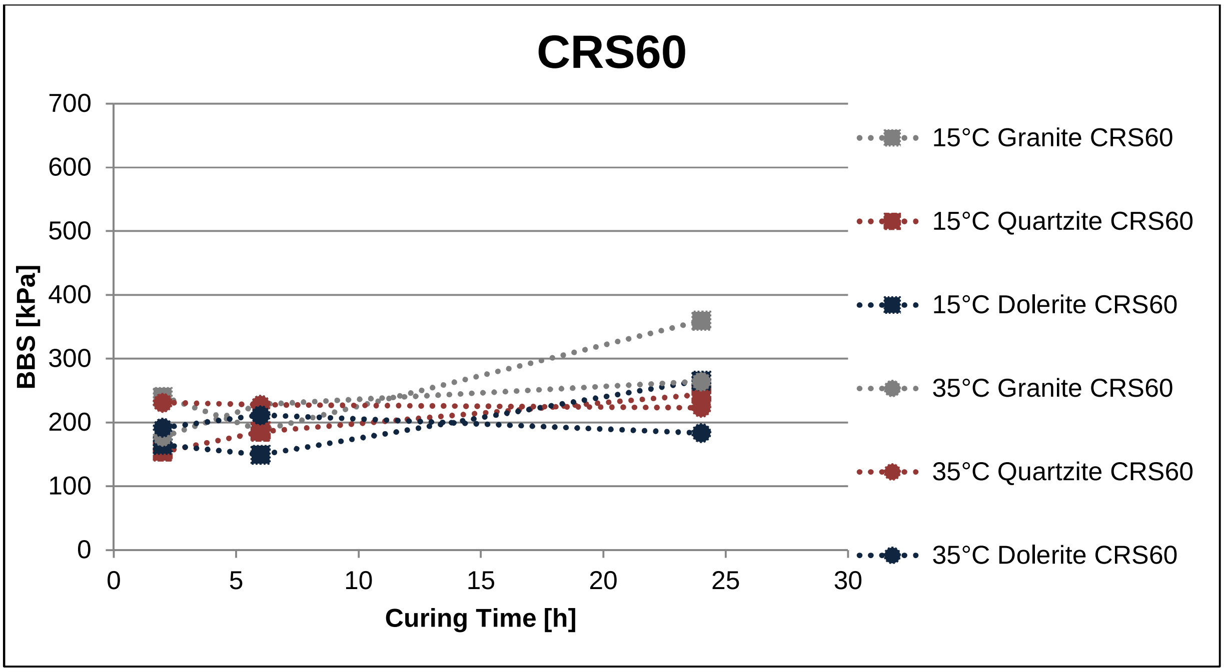

Figure 4-14: BBS versus Curing Time of CRS 60 at Both Curing Temperatures

The following information can be derived from Figure 4-14 above and Table 4-10 below:

- Very low BBS in comparison with other binders.
- No significant differences between BBS results of different curing temperatures.
- No significant BBS changes as curing time increases, except BBS result increased from 6 to 24 hours in the case of granite and dolerite at lower temperature.
- Aggregates had similar BBS responses as indicated below.

Table 4-10: ANOVA Results Comparing Aggregates and Curing Times for CRS 60 Emulsion

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Sample ($A_1 = A_2 = A_3$)	7300	2	3650	1,9168	0,2025	4,2565
Columns (2H = 6H = 24H)	14953	2	7476	3,9261	0,0594	4,2565
Interaction	3869	4	967	0,5079	0,7318	3,6331
Within	17138	9	1904			
Total	43260	17				

4.3.3.2 Polymer Modified KRS 60/30 (SC-E1)

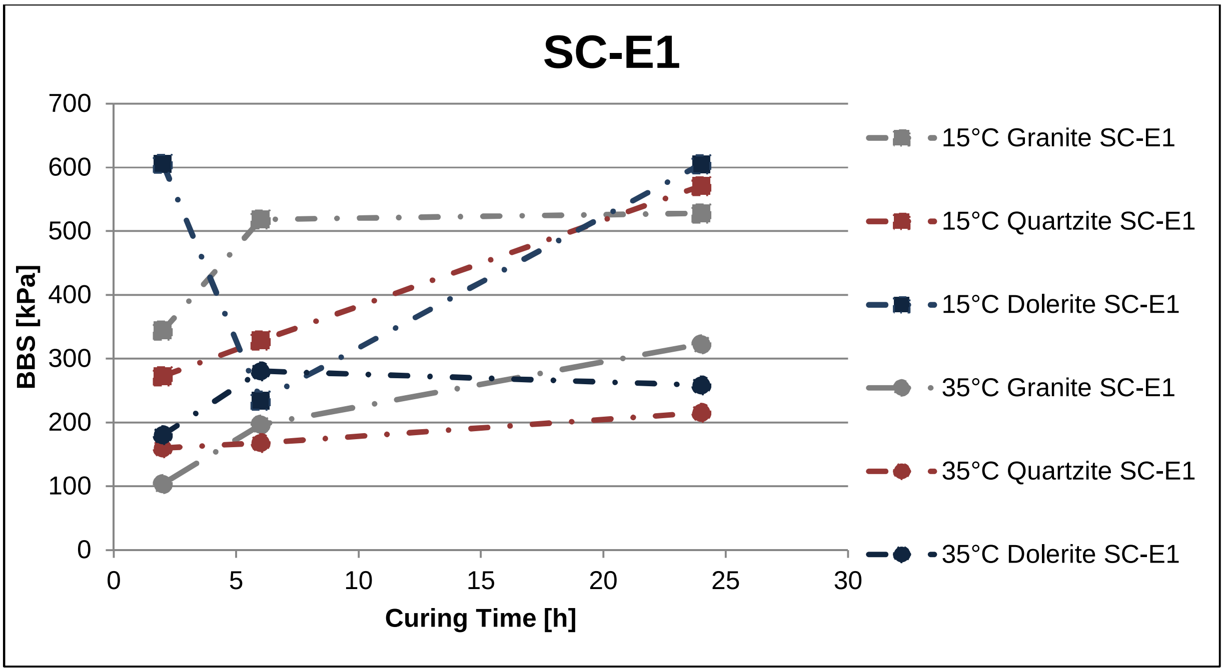

Figure 4-15: BBS versus Curing Time of SC-E1 at Both Curing Temperatures

The following information can be derived from Figure 4-14 above:

- Very low BBS at 35 °C compared to other binders.
- Unusual high BBS value for dolerite at 2 hours and low value at 6 hours.
- BBS results increased as curing time was increased, except for dolerite.
- Higher BBS results at lower temperature for most cases.
- Aggregates had similar BBS responses in most cases.

Table 4-11: Two-Way ANOVA Results Comparing Aggregates and Curing Times for SC-E1 Emulsion

Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Sample ($A_1 = A_2 = A_3$)	17505	2	8753	0,2346	0,7956	4,2565
Columns (2H = 6H = 24H)	72120	2	36060	0,9665	0,4167	4,2565
Interaction	38956	4	9739	0,2610	0,8957	3,6331
Within	335805	9	37312			
Total	464386	17				

4.3.4 DISCUSSION OF ANOVA OF ALL BBS TESTS

An analysis of various was done on all BBS tests to determine the influence of each treatment on the BBS results. A four-way ANOVA was done and the treatments consisted of temperature, binder type, aggregate type and curing time. The tests results were prepared and the analysis was done by the Centre for Statistical Consultation of Stellenbosch University. The result of this analysis is shown in Table 4-12.

It is apparent that the aggregate type did not have a significant influence on the results, while all other treatments did however influence the BBS results. All the interactions with aggregate type also did not have a substantial influence.

Temperature had the biggest influence, followed by binder type and curing time.

Table 4-12: Four-way ANOVA Result of All the BBS Tests Results (Centre for Statistical Consultation, 2014)

Source of Variation	SS	df	MS	F	P-value
Intercept	231895977	1	231895977	5987.099	0.000000
[1] Temperature	50109282	1	50109282	1293.723	0.000000
[2] Binder Type	85964605	4	21491151	554.859	0.000000
[3] Aggregate Type	11520	2	5760	0.149	0.861927
[4] Curing Time	1264002	2	632001	16.317	0.000000
Temperature*Binder Type [1*2]	26758687	4	6689672	172.714	0.000000
Temperature*Aggregate Type [1*3]	61918	2	30959	0.799	0.451295
Binder Type*Aggregate Type [2*3]	205142	8	25643	0.662	0.724346
Temperature*Curing Time [1*4]	203857	2	101928	2.632	0.074844
Binder Type*Curing Time [2*4]	1535315	8	191914	4.955	0.000016
Aggregate Type*Curing Time [3*4]	15924	4	3981	0.103	0.981398
1*2*3	170795	8	21349	0.551	0.816461
1*2*4	776872	8	97109	2.507	0.013326
1*3*4	99243	4	24811	0.641	0.634260
2*3*4	483594	16	30225	0.780	0.706307
1*2*3*4	745390	16	46587	1.203	0.270059
Error	6700742	173	38733		

4.4 FAILURE ANALYSIS

This sub-chapter relates to the type of failure of the test samples. From literature, it was evident that aggregate type and roughness, binder type, curing time and temperature, humidity and moisture will influence the bond between the binder and the aggregate.

Failure mechanisms can be divided into two main categories namely adhesion or cohesion. The figures below illustrate the difference.

Figure 4-16: Example of Adhesive Failure

Figure 4-17: Example of Cohesive Failure

Adhesion failure occurs between the binder and the substrate. This can be seen in Figure 4-16 as there is almost no binder left on the aggregate substrate. Cohesion failure occurs between the binder particles itself. None of the binder is separated from the aggregate substrate in Figure 4-17.

The majority of the failures of the BBS tests that were carried out were cohesive. This means that most failures occurred in the binder itself. From the results of this study it became evident that curing temperature and binder type are the two main variables that influenced the failure type. Figure 4-18 shows the respective percentages of each failure type of all the BBS tests carried out.

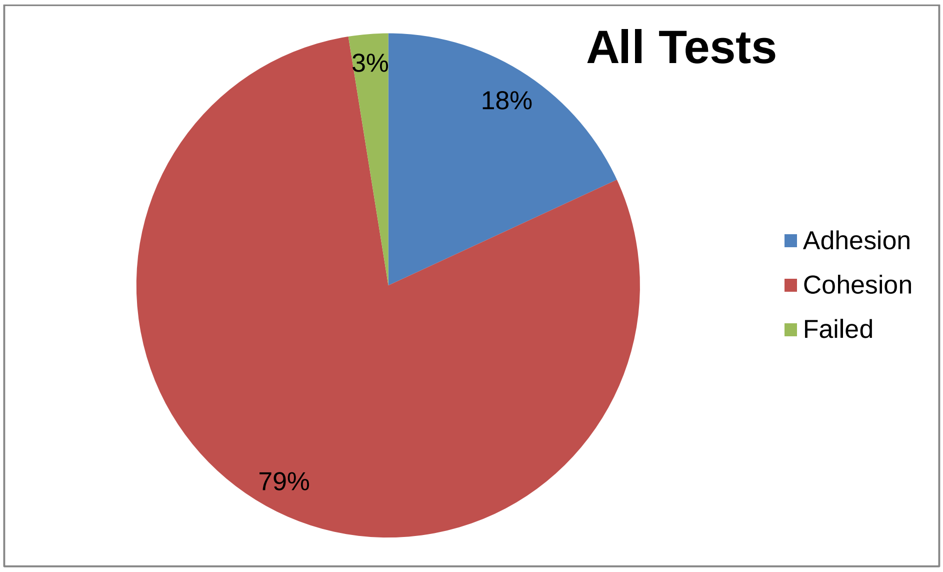

Figure 4-18 Failure Mechanisms of All BBS Tests

4.4.1 INFLUENCING FACTORS

It was revealed in the study that temperature had a significant influence on the adhesive behaviour, due to the rheological and adhesive properties of bitumen. The binder application types (i.e. emulsion or hot applied) also had a substantial effect on the type of failure. Figure 4-19 shows the percentile of failure type for each binder application type and temperature condition.

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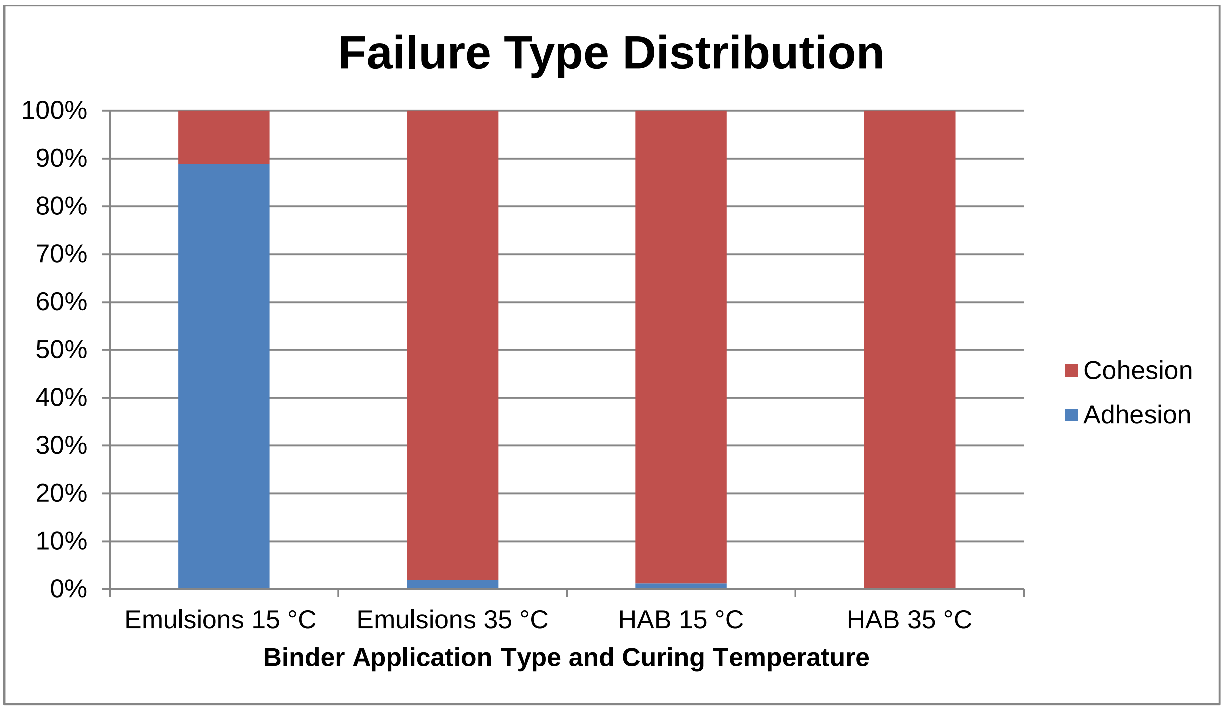

Figure 4-19: Failure Type Sorted According to Binder Application Type and Curing Temperature

The following can be derived from Figure 4-19 above:

- The majority of the failures of emulsions at 15 °C were adhesive.
- Most of the failures of emulsions at 35 °C were cohesive.
- Nearly all the failures of hot applied binders were cohesive at 15 °C.
- All the failures of hot applied binders at 35 °C were cohesive.
- Nearly all adhesive failures occurred at the lower temperature, while almost all the failures at 35 °C were cohesive.

4.4.2 INCOMPLETE TESTS

In total seven tests failed. These failed tests occurred only where emulsions were used as the binder. It is believed that the binder film thickness of the tests that failed were too low. This can be as a result of the evaporation of the water in the emulsion. The emulsions used in this study was prepared by adding 60 % bitumen with 40% water. When this emulsion breaks the water evaporates leaving a 40% reduction in volume. Figure 4-20 illustrates one of these tests.

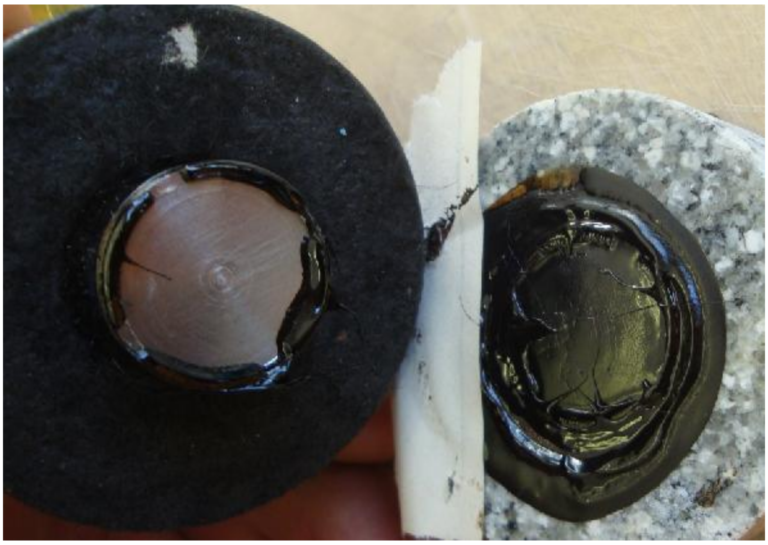

Figure 4-20: Example of a Test Failure

4.5 OVERVIEW OF RESULTS

It was evident that the aggregates from the same mother rock type that differed visually, delivered similar BBS results and therefore these results were combined as one rock type (e.g. granite or quartzite).

The BBS results of each binder type were discussed at the various conditions and combinations thereof. It was clear that the binder application type played a significant role in the BBS results and each application type was discussed separately. It was apparent that the type of aggregate used in the BBS tests did not influence the BBS results significantly. The other influences such as binder type, temperature and curing time did however have an influence of the BBS results.

The types of failures of the BBS tests were discussed and factors influencing this were highlighted.

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5. SYNTHESIS

5.1 INTRODUCTION

In this chapter the results of this study will be compared with what is expected and derived from previous BBS tests. The results will be compared to BBS tests done previously by other students of Stellenbosch University.

Bryce Constable (2009) and André Greyling (2012) did pioneer work in terms of BBS testing at Stellenbosch University. Their research was done solely on the BBS of emulsions to develop a standard test method. The results from their research will be compared and discussed with the work done for this study. Part of this study was overseeing and mentoring two other students namely Riaan Stander (2011) and Shafee Abrahams (2012). These students did BBS testing as part of their final year project in order to obtain their bachelor's degrees in engineering.

Stander (2011) did his study on the influence of fractured surfaces on BBS results. He compared the BBS results of two binders on smooth and fractured surfaces of granite. Abrahams (2012) tested the influence of wet and dry precoating of aggregates on the adhesion properties between aggregates and hot applied binders. These results will also be discussed and compared.

5.2 PREVIOUS BBS TESTS ON EMULSIONS

Greyling (2012) and Constable (2009) did similar BBS tests on emulsions. Constable was a student under the mentorship of Greyling. Therefore, only the tests results of Greyling will be discussed as the results of Constable were incorporated.

The emulsions tested by Greyling were Cationic Spray Grade 65% (CRS 65), Polymer (Styrene-Butadiene-Rubber Latex) Modified Emulsion (SC-E1), Anionic Stable Grade 60% (SS 60) and Anionic Polymer Modified Emulsion (SS 60 + 3% Latex) (Constable & Greyling, 2012). Only the cationic emulsions will be compared and discussed below. The results of Cationic Spray Grade 60% (CRS 60) will be compared to Greyling's CRS 65 and the SBS modified emulsion will be compared to the latex modified CRS 65 of Greyling.

Greyling's (2012) research was carried out on granite and tillite, two aggregate types used in seal construction in South Africa. Granite is an acidic rock type, while tillite is basic. Therefore, the results of tillite will be compared to the results of dolerite in this study. All the tests that will be compared was cured and conducted at 25 °C.

The main difference in methods used by Greyling and this study is the way emulsions were cured before tests were carried out. Greyling cured his tests sample without the pull-off stub for the entire curing period. He then added the pull-off stub and cured the entire setup for 1.5 hours before the samples were tested (Constable & Greyling, 2012). Therefore it is expected that the emulsions used in their research had more exposure to curing that will lead to higher BBS values.

5.2.1 COMPARISON OF RESULTS

Below are the results of Greyling's CRS 65 compared to this study's CRS 60 on granite at the various temperatures. The difference between the two binders is the percentage of bitumen compared to water added in the emulsion.

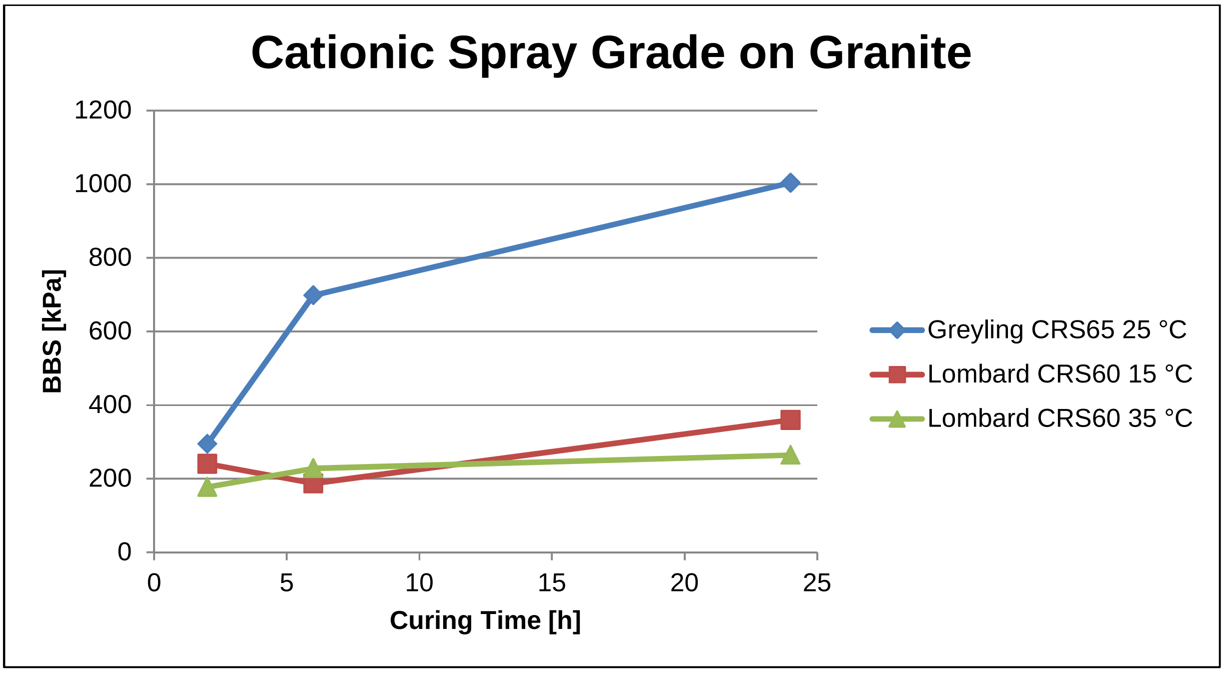

Figure 5-1: BBS versus Curing Time Cationic Spray Grade on Granite for Greyling (2012) and Lombard

The following information can be derived from Figure 5-1 above:

- The BBS values obtained by Greyling are considerably higher than the BBS of this study at extended curing times.
- Very slight increase in BBS of this study as curing time increases for both temperatures.
- Significant BBS increase of Greyling's BBS results as curing time increases.

Below are the results of the polymer modified emulsions on granite at various curing intervals for Greyling and this study. It should be noted that the polymer used to modify the binder Greyling used was Styrene-Butadiene-Rubber (Latex) while the emulsion of this study was modified with SBS. The base bitumen emulsion used for Greyling's binder was CRS 65, while for this study's emulsion CRS 60 was used. This entails that there was 5% more water and less base bitumen used in this study's emulsion than in Greyling's.

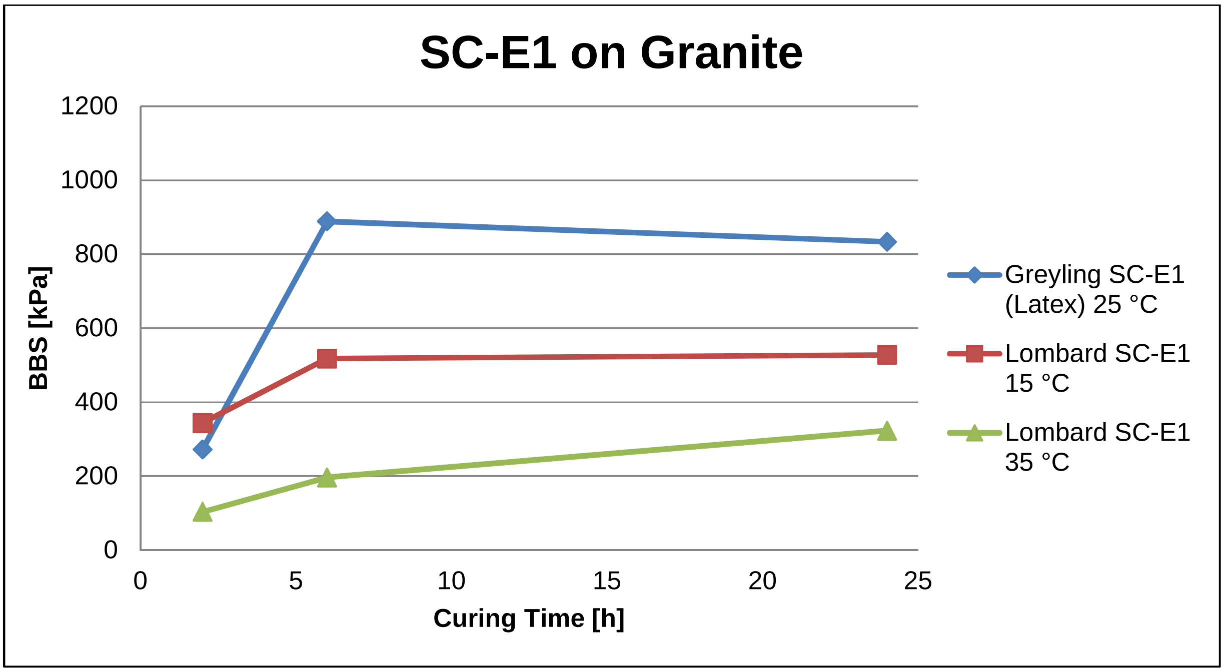

Figure 5-2: BBS versus Curing Time SC-E1 on Granite for Greyling (2012) and Lombard

The following information can be derived from Figure 5-2 above:

- The BBS values of Greyling's study are significantly higher than the BBS values of this study after 6 hours of curing.
- BBS values increases with curing time in this research project, while a slight decrease is noted at Greyling's BBS values from 6 to 24 hours.

Below the BBS results of basic aggregates of Greyling and this study are compared. Greyling used tillite, while dolerite was used in this study.

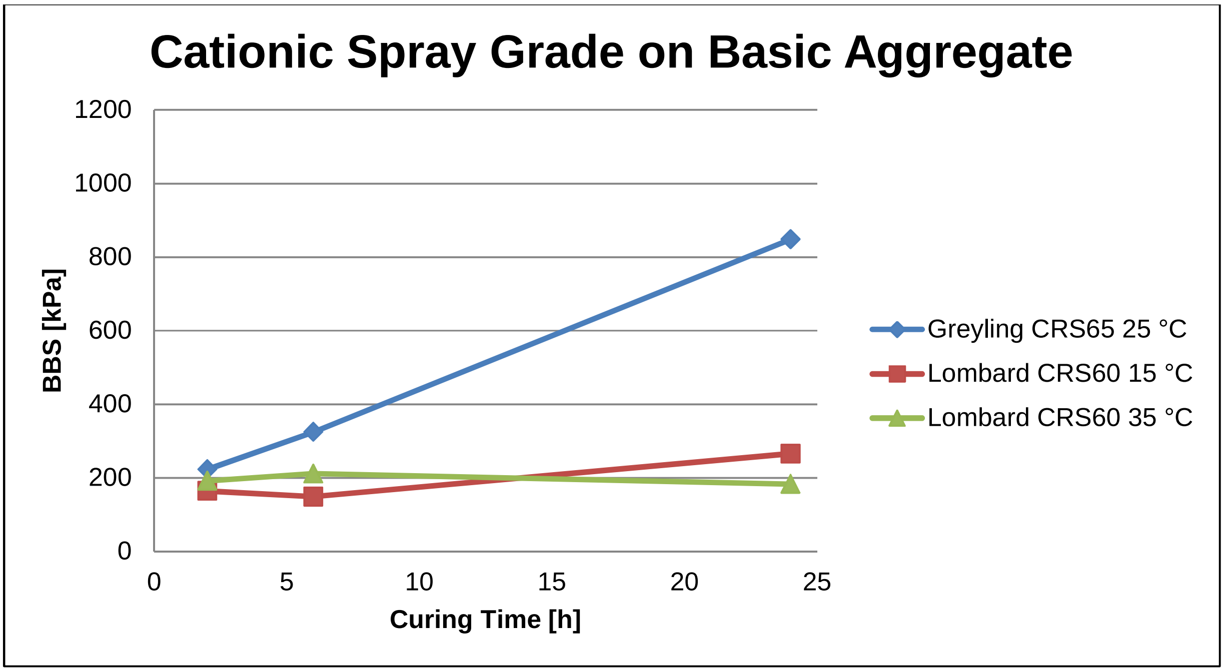

Figure 5-3: BBS versus Curing Time of Cationic Spray Grade on Basic Aggregate for Greyling (2012) and Lombard

The following information can be derived from Figure 5-3 above:

- The BBS values of Greyling are significantly higher than this study at extended curing times.
- Very slight or negligible increase in BBS is noted for this study as curing time increases for both temperatures.
- Significant BBS increase of Greyling's BBS results as curing time increases.

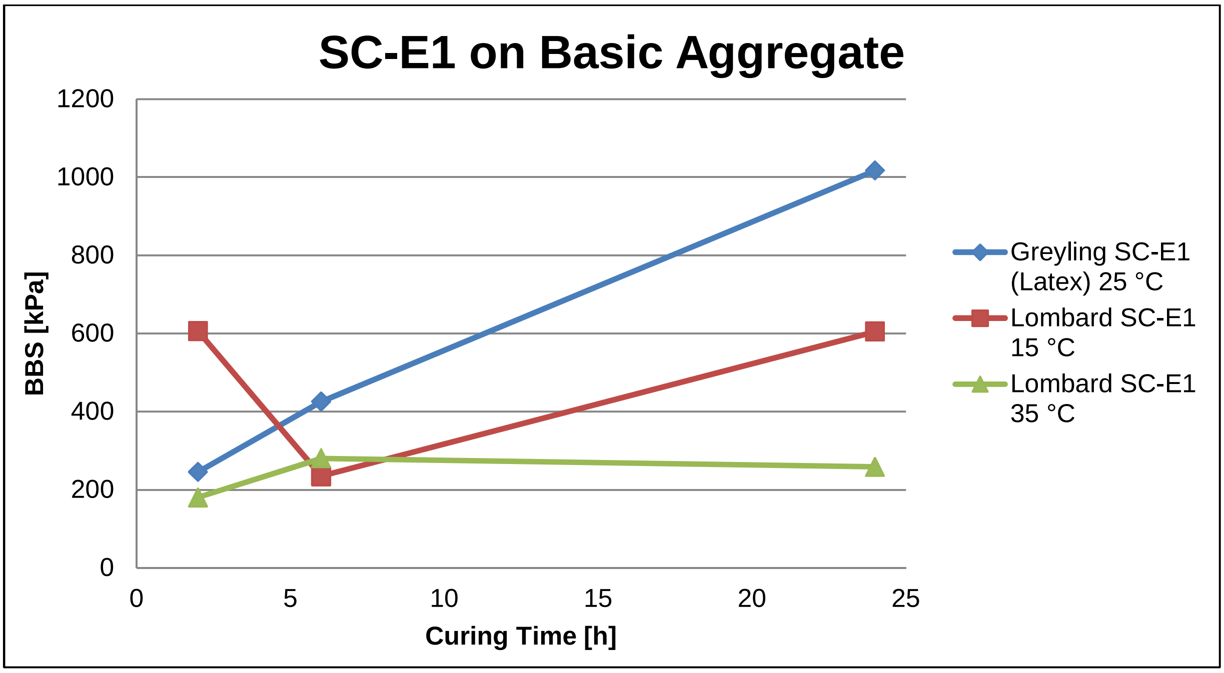

Figure 5-4: BBS versus Curing Time of SC-E1 on Basic Aggregate for Greyling (2012) and Lombard

The following information can be derived from Figure 5-4 above:

- The BBS values of Greyling are significantly higher than this study after 6 hours of curing.
- Unusual BBS result of this study at 2 hours of curing at 15 °C.
- BBS values increase as curing time increases in Greyling’s results, while only the BBS value at the lower temperature increases with curing time in this study.

5.2.2 FINDINGS OF COMPARISON OF GREYLING (2012) AND THIS STUDY

The BBS values for both Greyling (2012) and this research study appeared very similar after two hours of curing. Most BBS values at this two hours curing interval were low (average 254 kPa). These low BBS values after two hours of curing can be expected, because of the water content of the emulsion. It is believed that after this short curing interval, the emulsion has not cured properly and water is still present in the binder. This causes a more viscous binder with decreased strength leading to lower BBS strength.

It is also evident from the results that the BBS values of Greyling's research were significantly higher than the BBS values from this study. This difference can be explained by the different approach in curing of the samples before testing as well as the lesser water content in the emulsions used by Greyling.

The method Greyling used indicated that the test sample be cured for the entire curing time without the pull-off stub, then the stub will be placed on the sample and cured for an additional 1.5 hours. This means that Greyling's samples cured for 1.5 hours longer than the samples of this study. It is believed that the most significant difference in these two methods is not the extended curing time, but rather the curing without the pull-off stub. When the sample is cured with the pull-off stub, the water dispersed in the emulsion has no route or vent to escape from, thus retarding the breaking process. This leads to reduced strength in the binder that leads to a lower BBS value.

5.3 INFLUENCE OF FRACTURED SURFACES

In his final year project, Stander (2011) tested the influence of surface roughness on BBS results. Unfortunately Stander did limited tests, but valuable knowledge was gained during the process.

Using the standard BBS test method, one assumes that a smooth, lapped aggregate surface is the worst case scenario for adhesion between the binder and the aggregate. Theoretically this is valid because of the micro roughness of the aggregate surface. Roughness increases the contact area and adhesion should be effectively improved.

The objective in doing BBS tests on natural fractured aggregate surfaces was to imitate a more realistic surface that exists in the field with seal aggregate comprising fractured faces. This research was conducted with two binder types (80/100 Penetration Grade Bitumen and Anionic Stable Mix 60% Emulsion). Only the 80/100 penetration grade bitumen will be discussed here. Fractured surface tests were conducted only on granite and samples were cured at 35 °C. Curing times were 2 and 12 hours.

Figure 5-5 below shows the results of the BBS tests done on smooth and fractured granite.

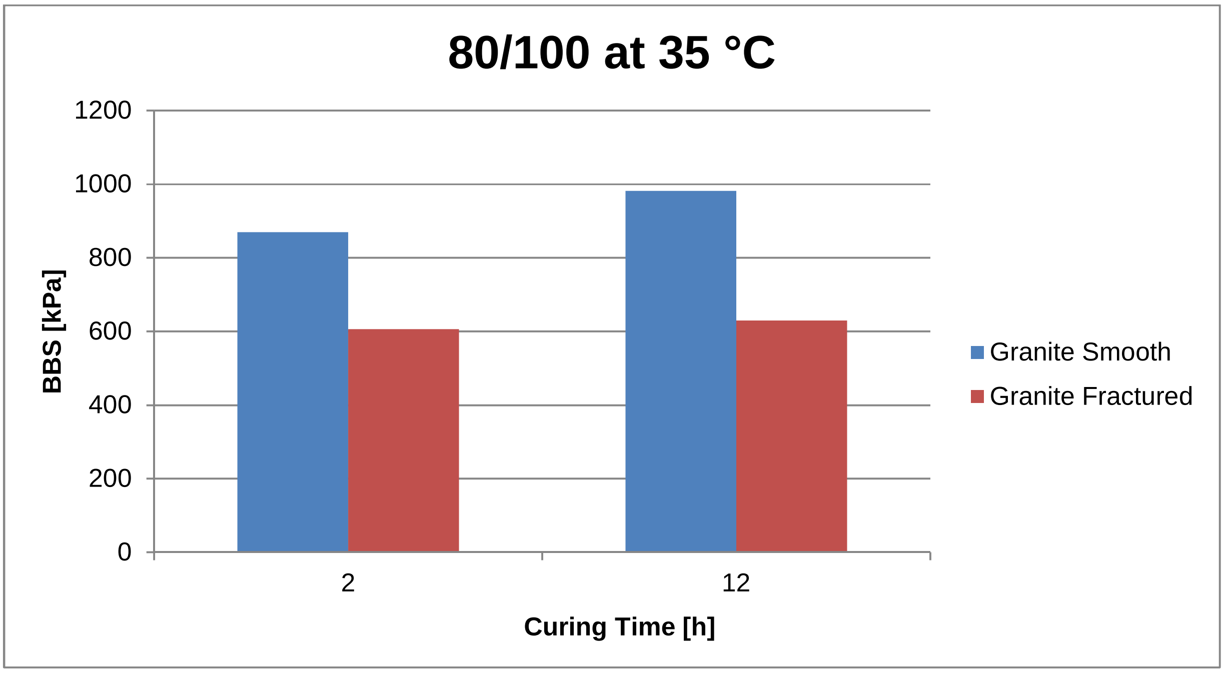

Figure 5-5: BBS versus Curing Time of Smooth and Fractured Granite (Stander, 2011)

The following information can be derived from above:

- Smooth aggregate surfaces yielded higher BBS results than fractured surfaces.
- Slight increase in BBS is noted from 2 to 12 hours of curing of smooth aggregate.
- No significant increase in BBS over curing time is evident for fractured surfaces.

The improved BBS performance of the smooth aggregates initially was considered counter-intuitive, but as Stander investigated further the reason for this became apparent. The stub used in the BBS tests has a smooth contact area. In the case where fractured surfaces were used the smooth contact area of the stub only makes contact with the aggregate stand out points. This creates stress concentration areas underneath the stub and thus reducing the contact area to such an extent that it performs even worse than in the case of smooth surface areas.

This also creates an uneven bitumen film thickness, especially at contact areas where the aggregate touches the stub. At these contact points the binder thickness will effectively be zero and leads to weaker BBS.

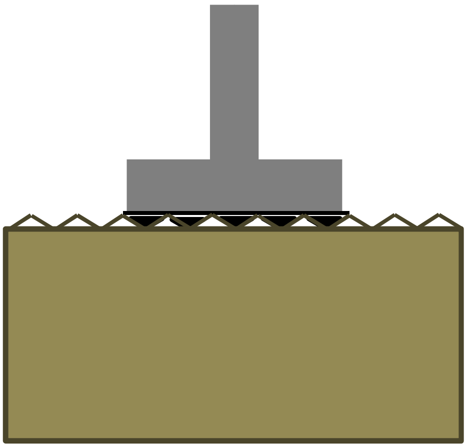

Figure 5-6: Fractured Aggregate Surface creating Pressure Points

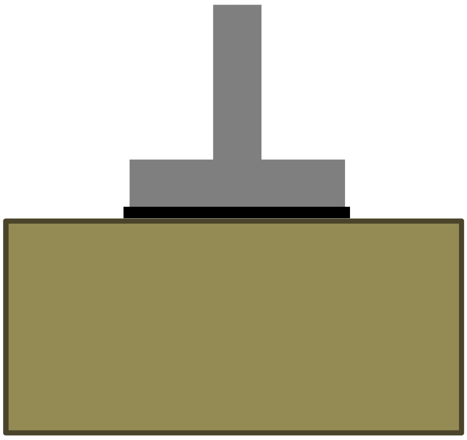

Figure 5-7: Smooth Aggregate Surface

It is intuitive to expect the additional adhesive area to enhance the bond between the aggregate and the binder in comparison with the case of smooth surfaces, and that failures will predominately be cohesive. However the use of fractured surfaces will not necessarily increase the BBS results.

Aggregates surface roughness also differs from each type. Each type of aggregate has a different cleavage or angle of breaking which will cause inconsistent surface areas.

Smooth aggregate surfaces provide a constant surface area in order to compare different types of aggregates. Therefore Stander came to the conclusion that fractured surfaces in BBS testing are not ideal and tests should rather be performed on smooth surfaces (Stander, 2011). The film thickness of the bituminous binder would need to be kept constant in order to facilitate comparable BBS results.

That said, Stander (2011) only conducted a limited amount of tests on a single aggregate type and more research will be required to conclude his findings.

5.3.1 COMPARISON OF RESULTS

Below the results from this study is compared with Stander's tests.

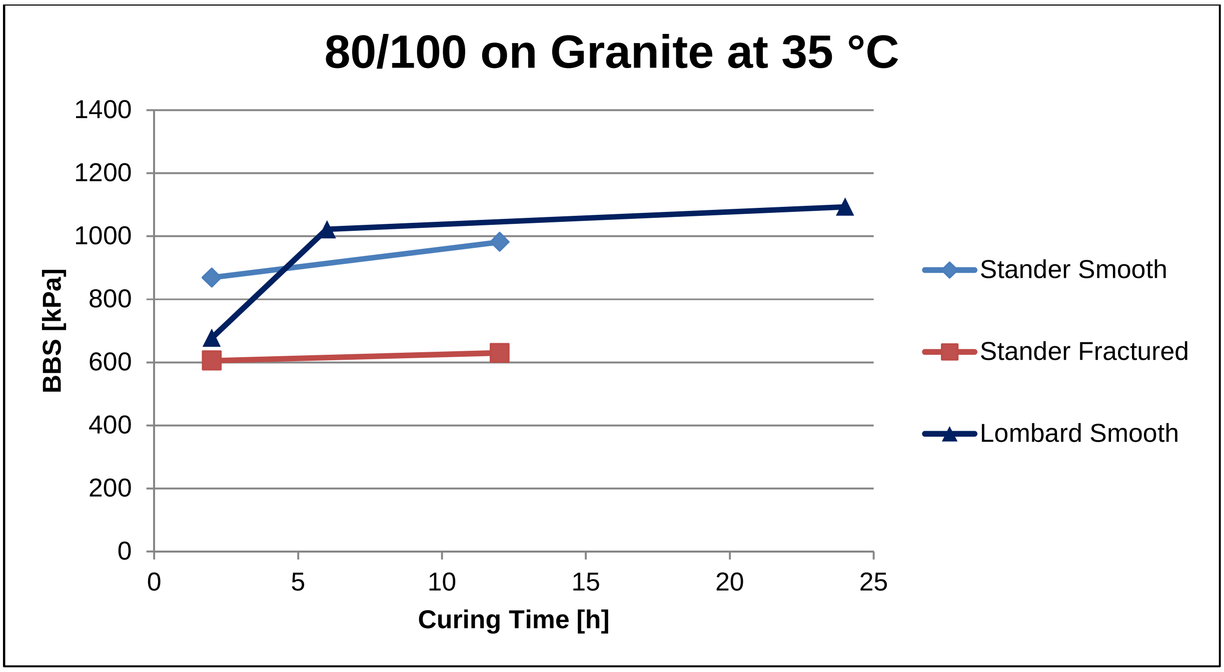

Figure 5-8: BBS versus Curing Time for Lombard and Stander (2011)

Although the curing time intervals for the two studies differed, this graph makes it possible to compare the results. The results in this study were very similar to what Stander attained. It only differed slightly at the 2 hour curing interval.

5.3.2 FINDINGS OF TESTS ON FRACTURES SURFACES

The use of aggregates with fractured surfaces in the BBS test method proved unsuccessful. Aggregate types differ in their composition and surface roughness. This leads to tests with low repeatability and inconsistent binder thickness.

5.4 INFLUENCE OF PRECOATING ON AGGREGATES

Shafee Abrahams (2012) did his research on the influence of precoating on BBS and his findings will be discussed in this section. Abrahams also did tests to see the influence of temperature during the application process. This study was part of an initiative to investigate parameters to improve adhesion properties during winter months. The results will be discussed and compared with this study.

5.4.1 COMPARISON OF RESULTS

All the BBS tests were done on precoated granite. The two hot applied binders used in the study were 80/100 penetration grade bitumen and polymer modified binder (S-E1). The binder was modified with Styrene-Butadiene-Styrene. The precoat used for this study was COLCOTE S^{TM} manufactured by Colas. Abrahams did two tests at the same set of conditions.

Two precoated conditions were tested; wet and dry precoating. The wet precoating condition refers to the process where precoat was applied to the aggregate surface and then cured for 24 hours at 25 °C before the test sample (binder and stub setup) was prepared. The dry condition is when the precoat is applied to the aggregate and then cured for 48 hours at 60 °C before the test sample was prepared. An equal amount (0.1 mm film thickness) of precoat was applied to both conditions (Abrahams, 2012).

Curing conditions refers to the conditions when the binder and stub is already applied to the aggregate and allowed to cure at specific conditions. Abrahams cured his samples at 25 °C, but also cured some samples at 5 and 10 °C. Curing times were 2 and 24 hours and limited tests were cured at 6 and 48 hours.

Abrahams performed all of his tests at relatively low loading rates. The range of loading rates was between 200 and 330 kPa/s and the average was 277 kPa/s. This was only discovered later and was because of a wrong stub diameter setting on the PQG user interface. Despite that the information gathered from his study is still very useful.

The application temperature of hot applied binders varies between 160 and 210 °C when sprayed during construction. The sprayed binder cools down rapidly before aggregate chips are sprayed on top of the binder as illustrated below.

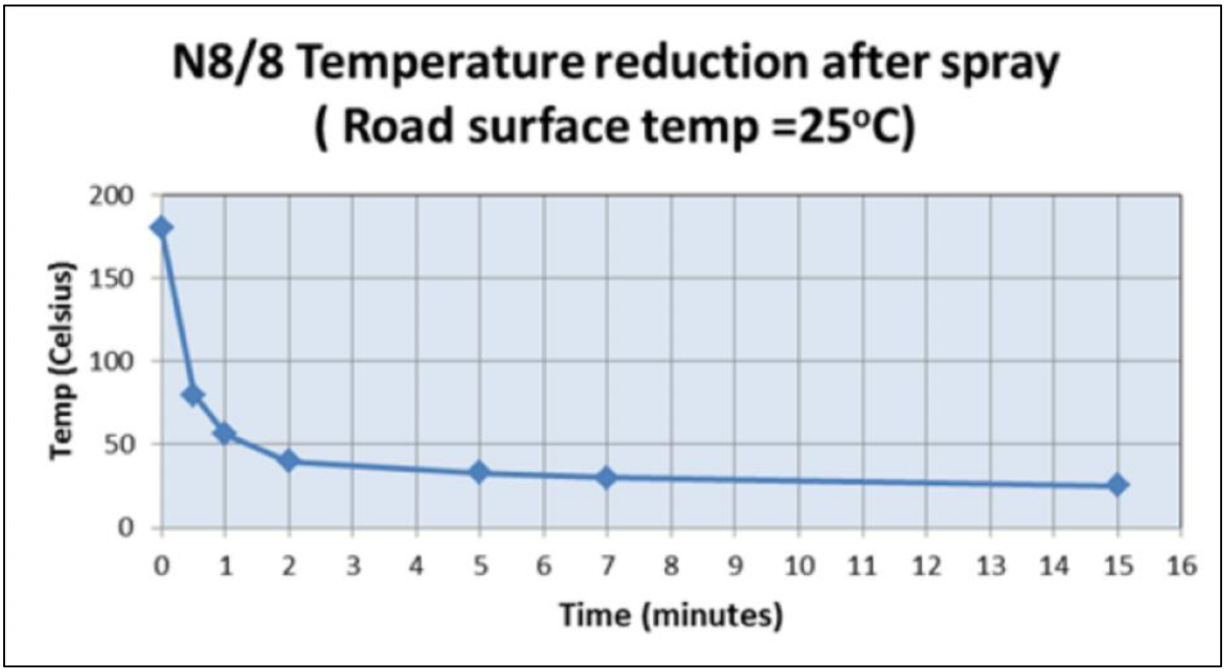

Figure 5-9: Temperature Decrease of Binder during Construction (Van Zyl, et al., 2012)

For this reason Abrahams decided to apply all his binders at an average temperature of 75 °C.

The binder application temperature of this study was identical to the relevant binder application temperature used in practice to ensure that the binder is exposed to the same elements as in the field. These elements include oxidation and influence of the high temperature on the binder itself.

Below are the tests results of Abrahams compared to results of this study.

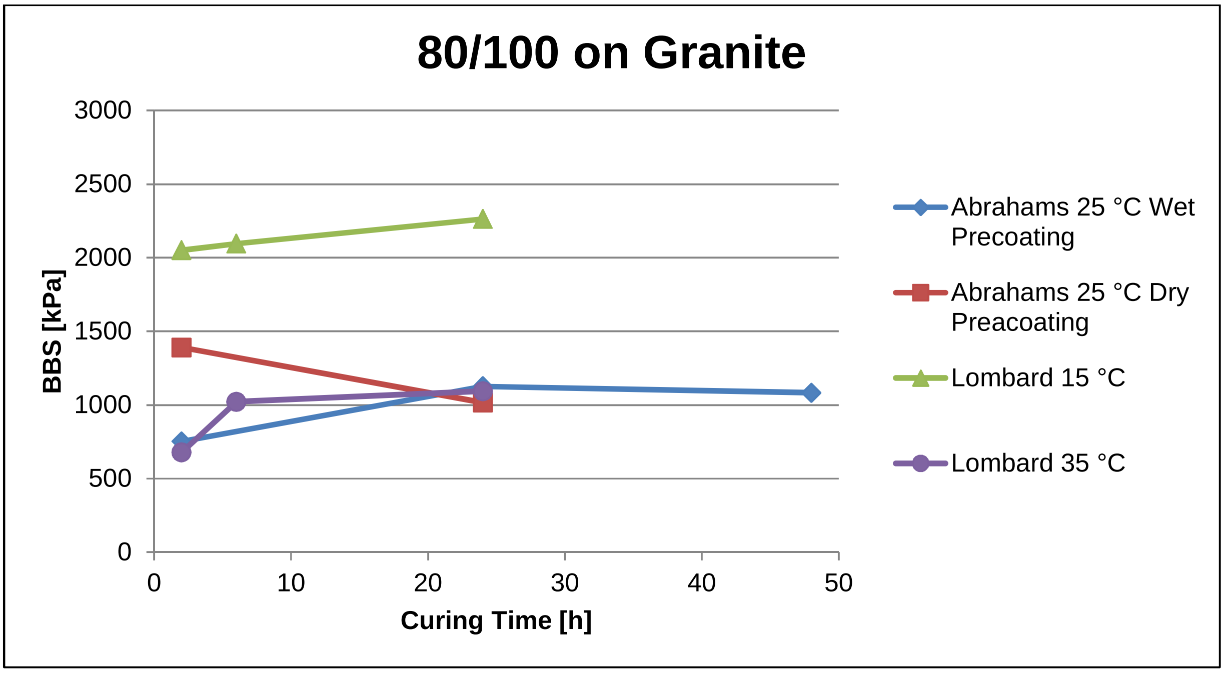

Figure 5-10: BBS versus Curing Time on 80/100 for Abrahams (2012) and Lombard

The following information can be derived from Figure 5-10 above:

- The influence of curing temperature plays significant role in BBS results.
- BBS of wet precoat increased with curing time from 2 to 24 hours, remained similar when cured for longer.
- Dry precoating did not increase in BBS as curing time was extended.

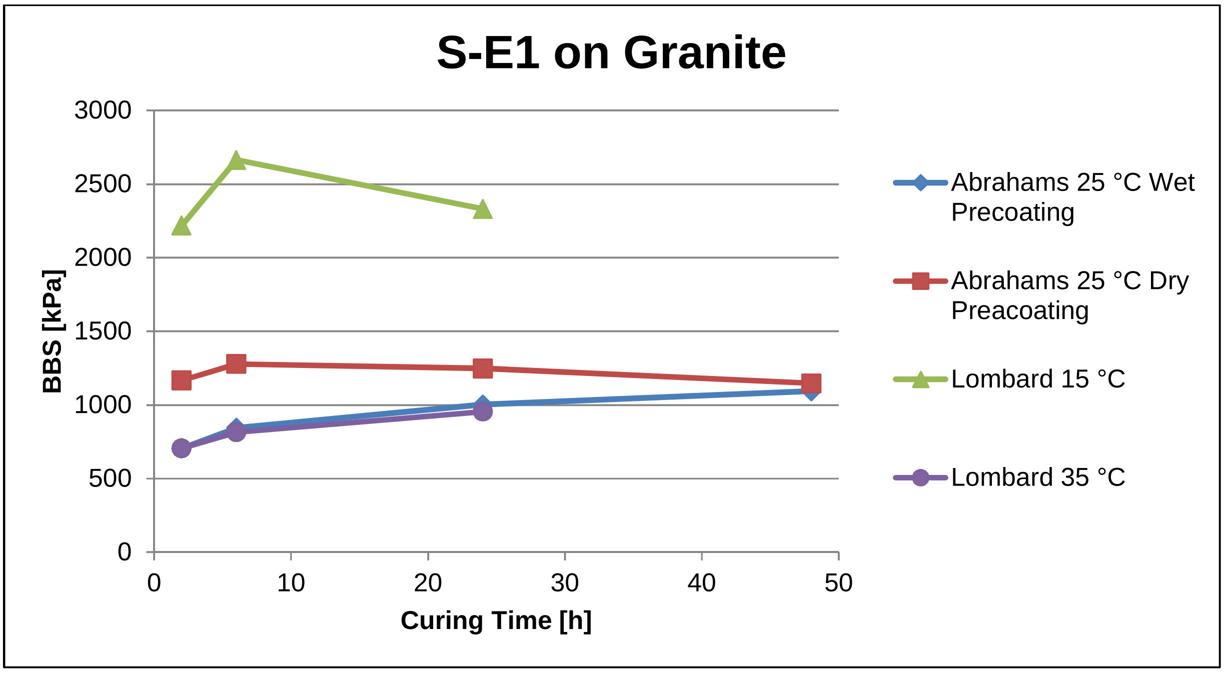

Figure 5-11: BBS versus Curing Time on S-E1 for Abrahams (2012) and Lombard

The following information can be derived from Figure 5-11 above:

- Influence of curing temperature plays most significant role.
- BBS of wet precoat increased with curing time from 2 to 6 and 6 to 24 hours, but increased only slightly when cured for 48 hours.
- Dry precoating only increased in BBS from 2 to 6 hours and then remained or decreased as curing time was extended.
- Similar trends between Abrahams and results of this study.

Note: When considering that loading rates of Abrahams was less than half than the loading rates done for this study, it is evident that precoating does increase the BBS between aggregates and binders.

Wet precoating at 25 °C performs very similar to 35 °C of this study in both binder cases.

Abrahams also did limited tests to determine the influence of very low curing temperatures on the BBS. He did this tests using the SBS polymer modified binder and the dry precoating condition. His tests were completed after two hours of curing and are compared with the results of this study below.

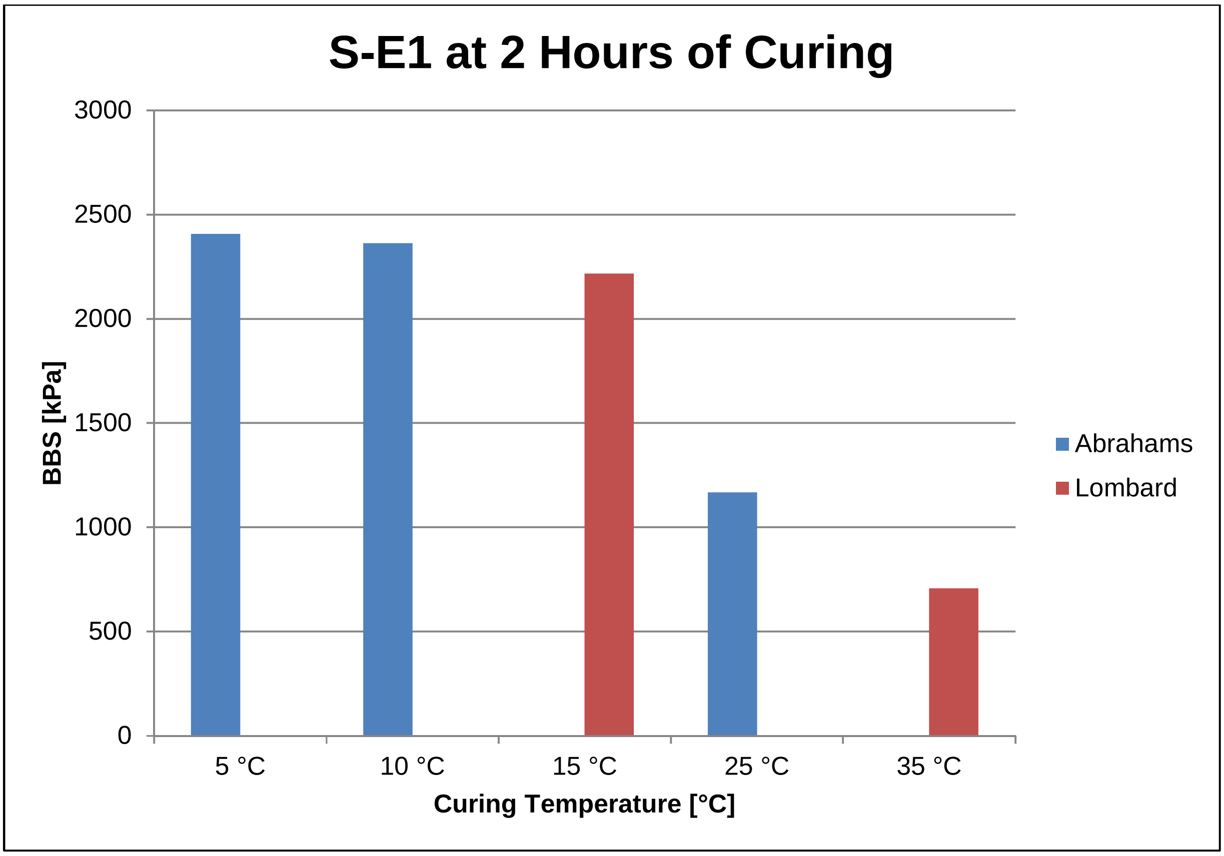

Figure 5-12: BBS verses Curing Temperature of Abrahams and Lombard

The following information can be derived from above:

- BBS increases as curing temperature decreases.
- Smaller BBS increase from 10 °C to 5 °C.
- Similar trends between Abrahams and results of this study.

The influence of the aggregate surface temperature during application was investigated by Abrahams. Tests were done using S-E1 binder and at the dry precoat condition of granite. Two sets of tests were conducted at two curing temperature conditions and two curing times. Below are the results of his findings.

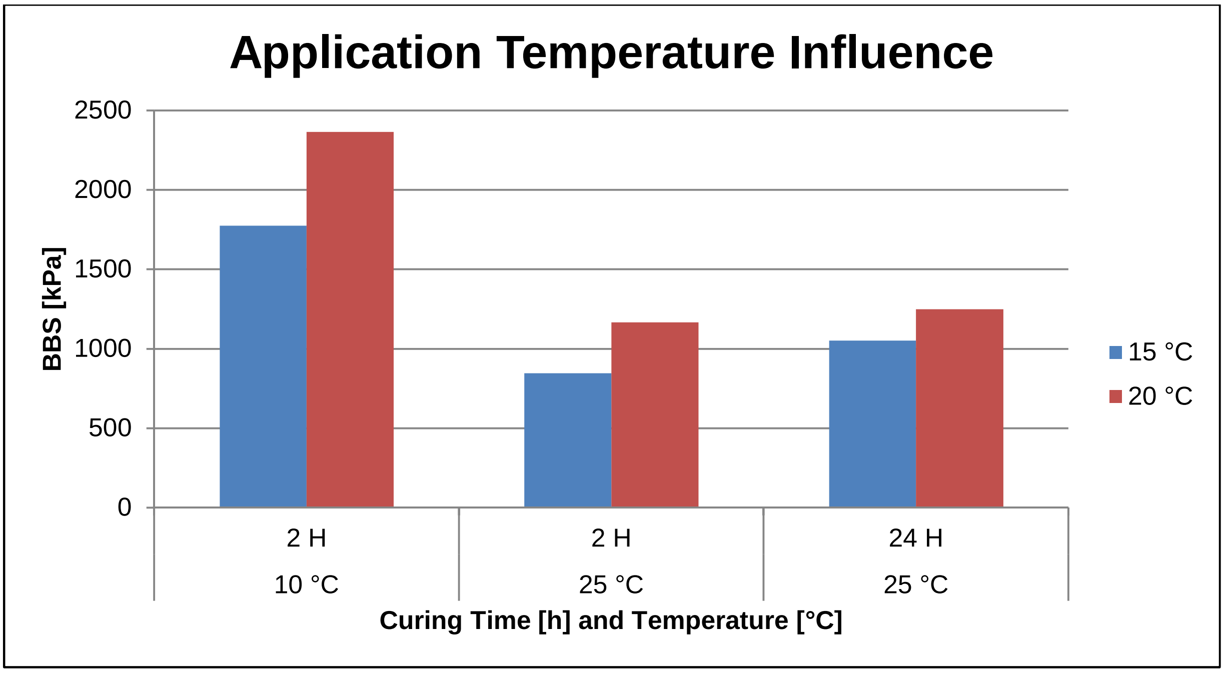

Figure 5-13: Influence of Aggregate Application Temperature on BBS (Abrahams, 2012)

Note: Application temperature refers to the temperature of the aggregate surface during application and not to the binder temperature.

The following information can be derived from above:

- BBS increases as temperature of aggregate at application time increases.

5.4.2 *FINDINGS OF TESTS PERFORMED ON PRECOATED AGGREGATES*

The precoating does increase the BBS results, because of the improved adhesion between the aggregate and the binders. The wet precoating condition performed weaker than the dry precoating condition, but this margin decreased as curing time increased.

Temperature has a more significant influence on the BBS results than the precoating conditions.

5.5 OVERVIEW OF SYNTHESIS

The results of other students were successfully compared to the results of this study.

BBS testing done at Stellenbosch University on emulsions were compared to the results of this study. Tests were also performed on fractured aggregate surfaces and proved unsuccessful. These tests were discussed and the issues involved with fractured surfaces were highlighted and explained. The influence of precoated aggregates used in BBS tests were compared to the results of this study and discussed. All the findings of each comparison were also discussed.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 SUMMARY OF FINDINGS

Loading rate has a significant influence on BBS results. The BBS value increases as the loading rate is increased.

Temperature has a significant influence on BBS results. BBS results were higher at lower temperatures.

Hot applied binders showed the highest BBS results especially at lower temperatures. SBS modified bitumen (S-E1) had the highest BBS at 15 °C. 80/100 pen grade bitumen had the highest BBS at 35 °C.

Emulsions had very low BBS results compared to the hot applied binders. Similar BBS results of Greyling and this study at 2 hours of curing, at both temperature conditions. Greyling's BBS results on emulsions were higher than BBS results of emulsions in this study, at curing times longer than 2 hours.

Most failures for hot applied binders were cohesive. At lower temperature, most failures for emulsions are adhesive. At higher temperature, most failures of all binders were cohesive.

BBS testing on fractured surfaces proved unsuccessful.

Precoating improves the BBS results. Dry precoating has higher BBS results than wet precoating. BBS results improve as curing time of wet precoated aggregates is increased.

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6.2 DISCUSSION OF CHALLENGES

6.2.1 LOADING RATE INCONSISTENCY

The loading rate of the BBS tests varied and made it difficult to compare the test results. However, this problem was minimised by unifying the loading rates as previously explained. Although it improved the reliability of the comparison of the results, it would have been ideal if the loading rates of all the tests were similar.

6.2.2 CURING OF EMULSIONS

It is evident from the BBS results that the emulsions used had very low BBS values at nearly all conditions. This is because of the emulsions did not cure properly. The reason for this is that the emulsion, after being applied to the aggregate, was left to cure without the pull-off stub for only one hour. Then the pull-off stub was applied to the aggregate and binder sample and cured for the remaining curing time. It was believed that the emulsion would cure even further in this condition. The BBS results contradicted this and showed that the emulsion did not cure to reach its maximum strength. Although the emulsions did break, the water in the emulsion did not entirely escape.

The reason for this approach to curing came because of the idea that if the sample was left to cure for too long the binder film thickness would decrease to such an extent that no contact would be made with the pull-off stub. There were a few tests that failed because of this. The problem that would arise if more emulsion is added to the aggregate sample is that excess binder would lead to inaccurate BBS results. Also, it was believed that a rapid setting emulsion would not need more than 1 hour to cure properly.

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6.3 CONCLUSIONS

Although the aggregate type and binder type plays a role in the BBS properties of a surface seal it became apparent that other factors also plays a substantial role, and in some cases even more significantly so. The research objectives of this study are clearly defined in the introduction chapter at the beginning of this report. Each one of the objectives will be dealt with below:

The BBS of various combinations of aggregates and binders were tested and compared. In general, the hot applied binders rendered higher BBS result than the emulsions. The elastomer modified binder (S-E1) performed best at the lower temperature conditions, while the 80/100 penetration grade bitumen had the highest BBS results at 35 °C. These binders (S-E1 and 80/100) both had higher BBS results than bitumen rubber (S-R1). This might have been because of the rubber crumbs in the bitumen rubber.

Comparing emulsions only, the elastomer modified emulsion (SC-E1) had higher BBS results at 15 °C. The BBS results of the emulsions at 35 °C were very similar. To a large extend, the type of aggregate did not influence the BBS results.

A major influence on the BBS results was the binder application type. The hot applied binders had much higher BBS results than the emulsions. Although the BBS results of the various binders used in this study differed from each other, there were certain similarities in the results. These similarities only exist if the binders are of the same application type.

Most failures that occurred where hot applied binders were used were cohesive. Therefore the BBS value is directly related to the strength of the binder. Factors that significantly influenced the hot applied binders’ strength in this study include loading rate, temperature and binder type. Curing time did play a role, but not to the same extent. This was predicted, as hot applied binders do not require breaking or release entrapped water or other substances that reduces strength. The hot applied binders only had to cool down (from application temperature) to reach optimum strength at the particular test temperature.

Bitumen is a visco-elastic material and will therefore be affected by temperature and loading rate. Although the loading rate was corrected in order to compare the BBS results, the influence on the binder strength cannot be neglected. As the loading rate is increased the binder strength will increase. The effect of temperature on the BBS results in this study was evident. The BBS results were much higher at the lower temperature conditions.

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The majority of failures of emulsions at 35 °C were also cohesive and the BBS results can be explained similarly as above. However, the BBS values of the emulsions tested at this condition were much lower than those of the hot applied binders at the same conditions. It is believed that the emulsions did not break to the full extend and that water was still present in the binder at the time of testing. The presence of the water in the binder reduces binder strength. Curing time did influence the BBS results of the emulsions; there was a general trend that as the curing time is increased the BBS results increased.

It was interesting to note that most failures were adhesive in the cases where emulsions were cured and tested at 15 °C. As discussed, this was not the case when hot applied binders were used. The main difference between these binder types is the presence of water in the binder as well as the application temperatures of the binders. The factors that influence the BBS results in the case where adhesive failures occurred differ from those of cohesive failure. If adhesion failure occurs it entails that the binder strength was greater than the bond between the binder and the aggregate. Evidently temperature plays a role, but factors such as binder type, aggregate type and the presence of water also affects this.

The results of this study were also compared to the BBS results of other students. The BBS results of the emulsions of this study were lower at extended curing times than the results of the predecessors. However, the results after 2 hours of curing were very similar. This is due to the same reason as discussed; the emulsions used in the tests of this study did not break properly. The BBS results of the hot applied binders correlated with those of other students. The results confirmed the effect of temperature on the BBS results. It also became evident that the temperature of the aggregate at the time of application plays a role; the BBS results increase as the aggregate temperature at application increases.

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6.4 FUTURE RESEARCH

LOADING RATE

It would be ideal to perform all BBS tests at a predetermined similar loading rate. This is not always possible, but great care should be taken before each test is performed to ensure an accurate and uniform loading rate. The air supply to the device should be kept at a constant pressure. The Coefficient of Variation of the loading rate should be kept at a minimum.

The loading rate replicates the rate at which motor vehicles apply a pull-off force on the aggregate chippings in a seal. This will vary according to motor vehicle speed, acceleration and spin. A study to determine the loading rate that vehicles perform on seals would give great insight into actual loading rates experienced in the field.

CURING OF EMULSIONS

The method of curing the emulsion should be adapted to ensure that emulsions have properly broken and all excess water have evaporated at the time of testing. It will lead to optimum binder strength and therefore results of hot applied binders can be compared with emulsions in a better manner.

FRACTURED SURFACES

A more detailed study on the influence of fractured surfaces would be valuable, especially if the fractured surface can be controlled.

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APPENDICES

OF

INFLUENCE OF SURFACE SEAL VARIABLES ON BITUMEN BOND STRENGTH PROPERTIES

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CONTENTS

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A. BITUMEN BOND STRENGTH TESTS RESULTS

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Table 1: BBS Results of 80/100 Bitumen at 15 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
15°C	80/100	2H	Granite	GG1	842,442	2029,004	1831
15°C	80/100	2H	Granite	G15a	768,109	2148,247	2054
15°C	80/100	2H	Granite	G27a	842,442	2465,324	2267
15°C	80/100	2H	Quartzite	RQ1b	817,665	1524,933	1361
15°C	80/100	2H	Quartzite	RQ4b	842,442	1869,111	1671
15°C	80/100	2H	Quartzite	Q10a	718,554	2449,064	2423
15°C	80/100	2H	Quartzite	Q13a	792,887	2245,809	2117
15°C	80/100	2H	Dolerite	D	792,887	2367,762	2239
15°C	80/100	2H	Dolerite	D25a	867,220	1771,548	1539
15°C	80/100	6H	Granite	GG2a	916,776	2644,189	2343
15°C	80/100	6H	Granite	GG3a	895,073	2248,519	1977
15°C	80/100	6H	Granite	G12b	842,442	1898,921	1701
15°C	80/100	6H	Granite	G16a	891,998	2630,638	2364
15°C	80/100	6H	Quartzite	RQ5b	891,998	2262,07	1995
15°C	80/100	6H	Quartzite	RQ7b	867,220	2915,195	2683
15°C	80/100	6H	Quartzite	Q15b	941,553	2820,343	2485
15°C	80/100	6H	Quartzite	Q17b	792,887	2923,325	2794
15°C	80/100	6H	Dolerite	D21b	891,998	2281,04	2014
15°C	80/100	6H	Dolerite	D22a	842,442	2676,709	2479
15°C	80/100	24H	Granite	GG1b	891,998	2435,514	2169
15°C	80/100	24H	Granite	G19a	891,998	2524,946	2258
15°C	80/100	24H	Granite	G30a	891,998	2630,638	2364
15°C	80/100	24H	Quartzite	RQ3a	768,109	2234,969	2140
15°C	80/100	24H	Quartzite	RQ4b	867,220	2581,857	2349
15°C	80/100	24H	Quartzite	Q8a	916,776	2663,159	2362
15°C	80/100	24H	Quartzite	Q9a	941,553	2533,076	2197
15°C	80/100	24H	Dolerite	D15b	891,998	2470,745	2204

Table 2: BBS Results of S-E1 at 15 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
15°C	S-E1	2H	Granite	GG3a	1214,110	2879,964	2649
15°C	S-E1	2H	Granite	G7a	1115,000	1771,548	1585
15°C	S-E1	2H	Granite	G32a	1090,220	2595,407	2420
15°C	S-E1	2H	Quartzite	RQ3a	1263,660	2955,846	2702
15°C	S-E1	2H	Quartzite	RQ8a	1263,660	2758,011	2504
15°C	S-E1	2H	Quartzite	Q5a	1214,110	2942,295	2711
15°C	S-E1	2H	Quartzite	Q12b	1065,440	2595,407	2431
15°C	S-E1	2H	Dolerite	D1a	1214,110	1963,963	1733
15°C	S-E1	2H	Dolerite	D9b	1090,220	2985,656	2810
15°C	S-E1	6H	Granite	GG1b	718,554	2874,544	2866
15°C	S-E1	6H	Granite	G15b	842,442	2771,562	2707
15°C	S-E1	6H	Granite	G23a	817,665	2470,745	2418
15°C	S-E1	6H	Quartzite	RQ3b	768,109	2389,443	2359
15°C	S-E1	6H	Quartzite	RQ8a	891,998	2866,414	2780
15°C	S-E1	6H	Quartzite	Q5b	817,665	2527,656	2475
15°C	S-E1	6H	Quartzite	Q10a	842,442	2679,419	2615
15°C	S-E1	6H	Dolerite	D1a	792,887	2606,248	2564
15°C	S-E1	6H	Dolerite	D9b	941,553	3050,698	2942
15°C	S-E1	24H	Granite	GG3a	842,442	2725,49	2661
15°C	S-E1	24H	Granite	G8b	817,665	2595,407	2542
15°C	S-E1	24H	Granite	G30b	916,776	1888,081	1791
15°C	S-E1	24H	Quartzite	RQ5b	1065,440	2928,745	2764
15°C	S-E1	24H	Quartzite	RQ7b	842,442	2636,058	2572
15°C	S-E1	24H	Quartzite	Q7b	545,110	2676,709	2746
15°C	S-E1	24H	Quartzite	Q16b	817,665	2766,141	2713
15°C	S-E1	24H	Dolerite	D2a	891,998	2565,597	2479
15°C	S-E1	24H	Dolerite	D4a	1015,890	2850,153	2708

Table 3: BBS Results of S-R1 at 15 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
15°C	S-R1	2H	Granite	GG2a	1040,660	2010,034	1724
15°C	S-R1	2H	Granite	G1b	1065,440	2115,726	1809
15°C	S-R1	2H	Granite	G14a	910,581	2367,762	2191
15°C	S-R1	2H	Quartzite	RQ2b	916,776	1858,27	1676
15°C	S-R1	2H	Quartzite	RQ6a	1139,780	2180,768	1811
15°C	S-R1	2H	Quartzite	Q9b	975,623	2205,158	1974
15°C	S-R1	2H	Quartzite	Q14a	910,581	2329,821	2153
15°C	S-R1	2H	Dolerite	D14b	743,332	2123,856	2087
15°C	S-R1	2H	Dolerite	D20b	867,220	2321,691	2181
15°C	S-R1	6H	Granite	GG1a	991,109	2481,585	2237
15°C	S-R1	6H	Granite	G13a	867,220	2503,265	2363
15°C	S-R1	6H	Granite	G15b	916,776	1606,234	1424
15°C	S-R1	6H	Quartzite	RQ3a	941,553	2218,709	2016
15°C	S-R1	6H	Quartzite	RQ8a	916,776	2424,673	2243
15°C	S-R1	6H	Quartzite	Q8a	817,665	2411,123	2312
15°C	S-R1	6H	Quartzite	Q11a	1015,890	2473,455	2208
15°C	S-R1	6H	Dolerite	D10a	991,109	2595,407	2351
15°C	S-R1	6H	Dolerite	D25b	991,109	2378,602	2134
15°C	S-R1	24H	Granite	GG4a	867,220	1947,702	1807
15°C	S-R1	24H	Granite	G13a	817,665	2066,945	1968
15°C	S-R1	24H	Granite	G14a	743,332	1947,702	1911
15°C	S-R1	24H	Quartzite	RQ2b	693,776	1720,057	1725
15°C	S-R1	24H	Quartzite	RQ6a	842,442	2251,229	2132
15°C	S-R1	24H	Quartzite	Q2b	867,220	2083,206	1943
15°C	S-R1	24H	Quartzite	Q3a	743,332	2161,797	2125
15°C	S-R1	24H	Dolerite	D7a	817,665	1779,678	1681
15°C	S-R1	24H	Dolerite	D24b	817,665	2113,016	2014

Table 4: BBS Results of SC-E1 at 15 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
15°C	SC-E1	2H	Granite	GG1a	743,332	316,244	277
15°C	SC-E1	2H	Granite	G14a	867,22	554,73	404
15°C	SC-E1	2H	Granite	G27a	842,442	478,848	351
15°C	SC-E1	2H	Quartzite	RQ5a	743,332	373,156	334
15°C	SC-E1	2H	Quartzite	Q2a	661,383	253,913	289
15°C	SC-E1	2H	Quartzite	Q14b	891,998	367,736	195
15°C	SC-E1	2H	Dolerite	D6a	842,442	757,985	630
15°C	SC-E1	2H	Dolerite	D9a	1015,89	866,387	582
15°C	SC-E1	6H	Granite	GG5a	520,332	291,854	454
15°C	SC-E1	6H	Granite	G3a	668,998	451,748	480
15°C	SC-E1	6H	Granite	G20b	619,443	549,31	622
15°C	SC-E1	6H	Quartzite	RQ1a	743,332	335,215	296
15°C	SC-E1	6H	Quartzite	RQ4a	842,442	400,256	272
15°C	SC-E1	6H	Quartzite	Q5a	914,553	476,138	283
15°C	SC-E1	6H	Quartzite	Q9b	585,374	359,605	463
15°C	SC-E1	6H	Dolerite	D2b	914,553	383,996	191
15°C	SC-E1	6H	Dolerite	D18a	817,665	383,996	278
15°C	SC-E1	24H	Granite	GG5b	842,442	511,369	383
15°C	SC-E1	24H	Granite	G3a	941,553	904,328	687
15°C	SC-E1	24H	Granite	G20a	842,442	641,452	513
15°C	SC-E1	24H	Quartzite	RQ1a	817,665	668,553	563
15°C	SC-E1	24H	Quartzite	RQ4a	792,887	489,688	406
15°C	SC-E1	24H	Quartzite	Q2a	792,887	554,73	471
15°C	SC-E1	24H	Quartzite	Q3b	768,109	904,328	843
15°C	SC-E1	24H	Dolerite	D13b	792,887	641,452	558
15°C	SC-E1	24H	Dolerite	D18a	916,776	847,417	652

Table 5: BBS Results of CRS60 at 15 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
15°C	CRS60	2	Granite	GG3b	708,793	150,931	150
15°C	CRS60	2	Granite	G9a	718,54	278,304	277
15°C	CRS60	2	Granite	G25a	668,998	291,854	294
15°C	CRS60	2	Quartzite	RQ3b	487,939	104,86	122
15°C	CRS60	2	Quartzite	RQ8a	622,071	88,599	95
15°C	CRS60	2	Quartzite	Q3a	644,221	316,244	321
15°C	CRS60	2	Quartzite	Q16b	686,161	77,759	79
15°C	CRS60	2	Dolerite	D3a	619,443	183,451	190
15°C	CRS60	2	Dolerite	D13b	668,998	137,38	140
15°C	CRS60	6	Granite	GG2a	445,999	178,031	198
15°C	CRS60	6	Granite	G3b	396,443	118,41	143
15°C	CRS60	6	Granite	G5a	340,225	191,582	220
15°C	CRS60	6	Quartzite	RQ2a	891,998	262,043	247
15°C	CRS60	6	Quartzite	RQ6a	693,776	272,883	273
15°C	CRS60	6	Quartzite	Q10a	693,776	121,12	122
15°C	CRS60	6	Quartzite	Q13a	495,554	83,179	100
15°C	CRS60	6	Dolerite	D14a	792,887	129,25	122
15°C	CRS60	6	Dolerite	D20a	718,554	178,031	177
15°C	CRS60	24	Granite	GG4b	842,442	316,244	305
15°C	CRS60	24	Granite	G17b	859,605	438,197	425
15°C	CRS60	24	Granite	G22a	289,717	316,244	349
15°C	CRS60	24	Quartzite	RQ6a	371,666	102,149	128
15°C	CRS60	24	Quartzite	Q4a	718,554	354,185	353
15°C	CRS60	24	Quartzite	Q12b	264,94	215,972	251
15°C	CRS60	24	Dolerite	D11b	281,847	232,233	266

Table 6: BBS Results of 80/100 Bitumen at 35 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
35°C	80/100	2H	Granite	GG1a	795,615	701,073	528
35°C	80/100	2H	Granite	GG3a	820,477	714,624	497
35°C	80/100	2H	Granite	G1a	795,615	641,452	468
35°C	80/100	2H	Granite	G3b	820,477	655,002	437
35°C	80/100	2H	Quartzite	RQ7a	768,109	565,57	442
35°C	80/100	2H	Quartzite	RQ8a	721,028	638,742	601
35°C	80/100	2H	Quartzite	Q9a	845,339	671,263	408
35°C	80/100	2H	Quartzite	Q10a	792,887	600,801	433
35°C	80/100	2H	Dolerite	D9a	916,776	679,393	287
35°C	80/100	2H	Dolerite	D10a	795,615	630,612	458
35°C	80/100	6H	Granite	GG1a	794,291	1120,334	950
35°C	80/100	6H	Granite	GG4a	924,899	1489,987	1083
35°C	80/100	6H	Granite	G9a	863,239	1295,079	1000
35°C	80/100	6H	Granite	G10a	924,908	1463,103	1056
35°C	80/100	6H	Quartzite	RQ1a	640,555	402,966	511
35°C	80/100	6H	Quartzite	RQ6a	621,578	535,76	678
35°C	80/100	6H	Quartzite	Q2a	372,945	451,748	1044
35°C	80/100	6H	Quartzite	Q3a	696,165	641,452	648
35°C	80/100	6H	Dolerite	D12a	646,440	565,57	663
35°C	80/100	6H	Dolerite	D13a	698,976	952,31	954
35°C	80/100	24H	Granite	GG2b	1418,183	1882,45	583
35°C	80/100	24H	Granite	GG5a	1356,523	1936,217	748
35°C	80/100	24H	Granite	G34a	986,569	1889,171	1370
35°C	80/100	24H	Granite	G35a	678,257	1633,774	1673
35°C	80/100	24H	Quartzite	RQ2a	863,248	1741,31	1446
35°C	80/100	24H	Quartzite	RQ3a	863,248	1375,73	1080
35°C	80/100	24H	Quartzite	Q7a	924,908	1687,542	1280
35°C	80/100	24H	Quartzite	Q8a	863,239	1633,774	1338
35°C	80/100	24H	Dolerite	D24a	801,587	1254,753	1071
35°C	80/100	24H	Dolerite	D25a	863,239	1624,406	1329

Table 7: BBS Results of S-E1 at 35 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
35°C	S-E1	2H	Granite	GG3b	689,836	701,073	708
35°C	S-E1	2H	Granite	G2b	696,156	720,044	723
35°C	S-E1	2H	Granite	G4a	721,028	703,783	690
35°C	S-E1	2H	Quartzite	RQ4b	646,431	736,304	772
35°C	S-E1	2H	Quartzite	RQ5b	671,303	823,026	842
35°C	S-E1	2H	Quartzite	Q4a	696,165	901,618	904
35°C	S-E1	2H	Quartzite	Q5b	696,165	844,707	847
35°C	S-E1	2H	Dolerite	D7a	571,844	627,902	714
35°C	S-E1	2H	Dolerite	D8a	696,165	736,304	739
35°C	S-E1	6H	Granite	G15a	795,615	850,127	786
35°C	S-E1	6H	Granite	G20a	788,391	904,328	845
35°C	S-E1	6H	Quartzite	RQ7a	795,615	698,363	634
35°C	S-E1	6H	Quartzite	Q9a	770,752	814,896	767
35°C	S-E1	6H	Quartzite	Q10a	820,447	757,985	677
35°C	S-E1	6H	Dolerite	D14a	770,752	809,476	762
35°C	S-E1	6H	Dolerite	D15a	763,746	871,807	829
35°C	S-E1	24H	Granite	G1b	718,554	936,849	924
35°C	S-E1	24H	Granite	G3b	743,332	1015,441	986
35°C	S-E1	24H	Quartzite	RQ4a	743,332	795,926	767
35°C	S-E1	24H	Quartzite	RQ5a	693,776	801,346	806
35°C	S-E1	24H	Quartzite	Q6a	768,109	912,458	867
35°C	S-E1	24H	Quartzite	Q14b	768,109	852,837	807
35°C	S-E1	24H	Dolerite	D9b	718,554	926,009	914
35°C	S-E1	24H	Dolerite	D10b	743,332	996,47	967

Table 8: BBS Results of S-R1 at 35 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
35°C	S-R1	2H	Granite	G25a	768,109	630,612	590
35°C	S-R1	2H	Granite	G32b	569,888	625,192	703
35°C	S-R1	2H	Quartzite	RQ4a	644,221	503,239	537
35°C	S-R1	2H	Quartzite	RQ8a	768,109	600,801	560
35°C	S-R1	2H	Quartzite	Q14a	668,998	589,961	609
35°C	S-R1	2H	Quartzite	Q15b	668,998	703,783	722
35°C	S-R1	2H	Dolerite	D15a	768,109	625,192	584
35°C	S-R1	2H	Dolerite	D24a	668,998	627,902	647
35°C	S-R1	6H	Granite	GG3b	644,221	549,31	583
35°C	S-R1	6H	Granite	G7b	644,221	386,706	420
35°C	S-R1	6H	Granite	G13b	693,776	606,221	610
35°C	S-R1	6H	Quartzite	RQ2b	619,443	508,659	557
35°C	S-R1	6H	Quartzite	RQ5b	569,888	514,079	592
35°C	S-R1	6H	Quartzite	Q3b	619,443	435,487	484
35°C	S-R1	6H	Quartzite	Q8a	644,221	655,002	688
35°C	S-R1	6H	Dolerite	D23b	569,888	459,878	538
35°C	S-R1	24H	Granite	GG2a	650,415	598,091	628
35°C	S-R1	24H	Granite	GG4b	578,710	497,819	571
35°C	S-R1	24H	Granite	G14b	569,888	562,86	641
35°C	S-R1	24H	Granite	G23b	743,332	768,825	743
35°C	S-R1	24H	Quartzite	RQ3b	743,332	739,014	713
35°C	S-R1	24H	Quartzite	RQ6a	792,887	592,671	537
35°C	S-R1	24H	Quartzite	Q11a	760,494	505,949	470
35°C	S-R1	24H	Quartzite	Q13a	743,332	768,825	743
35°C	S-R1	24H	Dolerite	D18a	619,443	763,405	812

Table 9: BBS Results of SC-E1 at 35 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
35°C	SC-E1	2H	Granite	G32a	859,605	107,57	72
35°C	SC-E1	2H	Granite	G35a	785,272	153,641	135
35°C	SC-E1	2H	Quartzite	RQ5b	842,442	175,321	144
35°C	SC-E1	2H	Quartzite	RQ7b	594,665	134,67	158
35°C	SC-E1	2H	Quartzite	Q7a	768,109	150,931	136
35°C	SC-E1	2H	Quartzite	Q11a	693,776	199,712	201
35°C	SC-E1	2H	Dolerite	D9b	487,939	153,641	200
35°C	SC-E1	2H	Dolerite	D16a	768,109	175,321	160
35°C	SC-E1	6H	Granite	GG1a	569,888	191,582	220
35°C	SC-E1	6H	Granite	G23a	644,221	83,179	95
35°C	SC-E1	6H	Granite	G27a	619,443	256,623	274
35°C	SC-E1	6H	Quartzite	RQ3a	768,109	156,351	141
35°C	SC-E1	6H	Quartzite	RQ6a	587,05	131,96	157
35°C	SC-E1	6H	Quartzite	Q9b	594,665	218,682	242
35°C	SC-E1	6H	Quartzite	Q13a	431,624	71,865	131
35°C	SC-E1	6H	Dolerite	D1b	693,776	218,682	220
35°C	SC-E1	6H	Dolerite	D19b	563,689	310,824	341
35°C	SC-E1	24H	Granite	GG3a	693,776	210,552	212
35°C	SC-E1	24H	Granite	G8a	867,22	389,416	353
35°C	SC-E1	24H	Granite	G24a	743,332	413,807	404
35°C	SC-E1	24H	Quartzite	RQ7a	1585,77	397,546	203
35°C	SC-E1	24H	Quartzite	Q5b	594,665	134,67	158
35°C	SC-E1	24H	Quartzite	Q15b	792,887	305,404	285
35°C	SC-E1	24H	Dolerite	D13b	688,523	229,522	232
35°C	SC-E1	24H	Dolerite	D14b	792,887	305,404	285

Table 10: BBS Results of CRS60 at 35 °C

Temperature	Binder	Curing Time	Aggregate	Agg Number	Loading Rate	Tensile Yield Strength	BBS at 700kPa
35°C	CRS60	2H	Granite	GG1a	585,374	112,99	143
35°C	CRS60	2H	Granite	GG5a	512,717	129,25	178
35°C	CRS60	2H	Granite	G19b	693,776	150,931	153
35°C	CRS60	2H	Granite	G23b	421,221	164,481	237
35°C	CRS60	2H	Quartzite	RQ7a	498,652	164,481	217
35°C	CRS60	2H	Quartzite	RQ8a	644,221	202,422	217
35°C	CRS60	2H	Quartzite	Q8b	628,735	262,043	281
35°C	CRS60	2H	Quartzite	Q9b	545,11	169,901	210
35°C	CRS60	2H	Dolerite	D13a	585,374	164,481	194
35°C	CRS60	2H	Dolerite	D18b	396,443	110,28	189
35°C	CRS60	6H	Granite	G9b	693,776	305,404	307
35°C	CRS60	6H	Granite	G20b	644,221	134,67	149
35°C	CRS60	6H	Quartzite	RQ1a	644,221	256,623	271
35°C	CRS60	6H	Quartzite	RQ8b	411,93	134,67	210
35°C	CRS60	6H	Quartzite	Q4b	594,665	286,434	314
35°C	CRS60	6H	Quartzite	Q6a	792,887	140,09	116
35°C	CRS60	6H	Dolerite	D12b	668,998	215,972	224
35°C	CRS60	6H	Dolerite	D23b	817,665	229,522	199
35°C	CRS60	24H	Granite	GG2a	594,665	270,173	298
35°C	CRS60	24H	Granite	G13b	445,999	121,12	187
35°C	CRS60	24H	Granite	G28b	792,887	332,505	308
35°C	CRS60	24H	Quartzite	RQ1a	718,554	281,014	276
35°C	CRS60	24H	Quartzite	RQ4b	520,332	75,049	122
35°C	CRS60	24H	Quartzite	Q12b	470,777	205,132	265
35°C	CRS60	24H	Quartzite	Q14b	792,887	253,913	230
35°C	CRS60	24H	Dolerite	D12b	619,443	121,12	142
35°C	CRS60	24H	Dolerite	D25a	520,332	178,031	225

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B. ANOVA RESULTS BY CENTRE FOR STATISTICAL CONSULTATION, 2014

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a. 4-WAY ANOVA (DATA BBS LERICHELOMBARD)

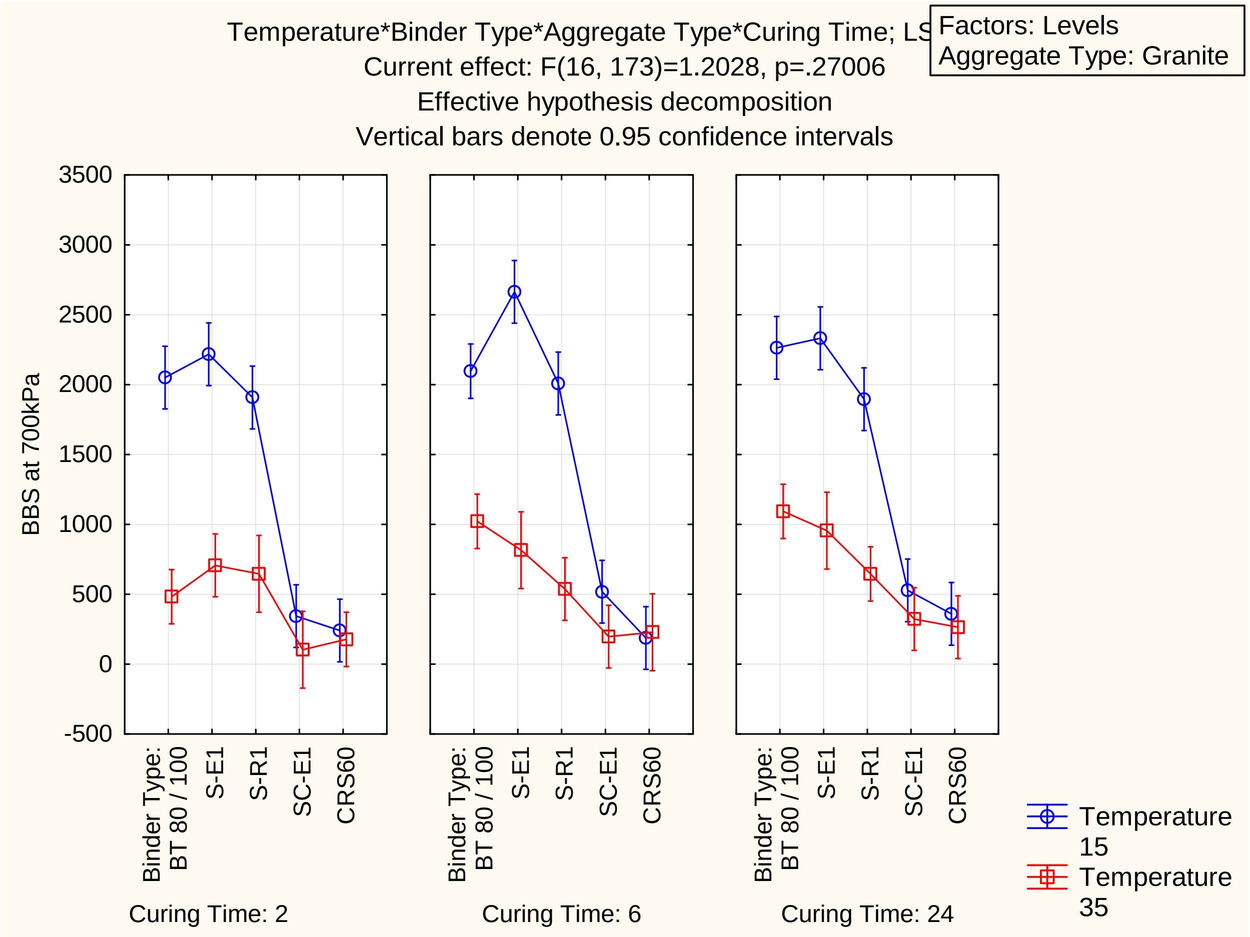
ANOVA RESULTS 1: DATA BBS LERICHELOMBARD

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

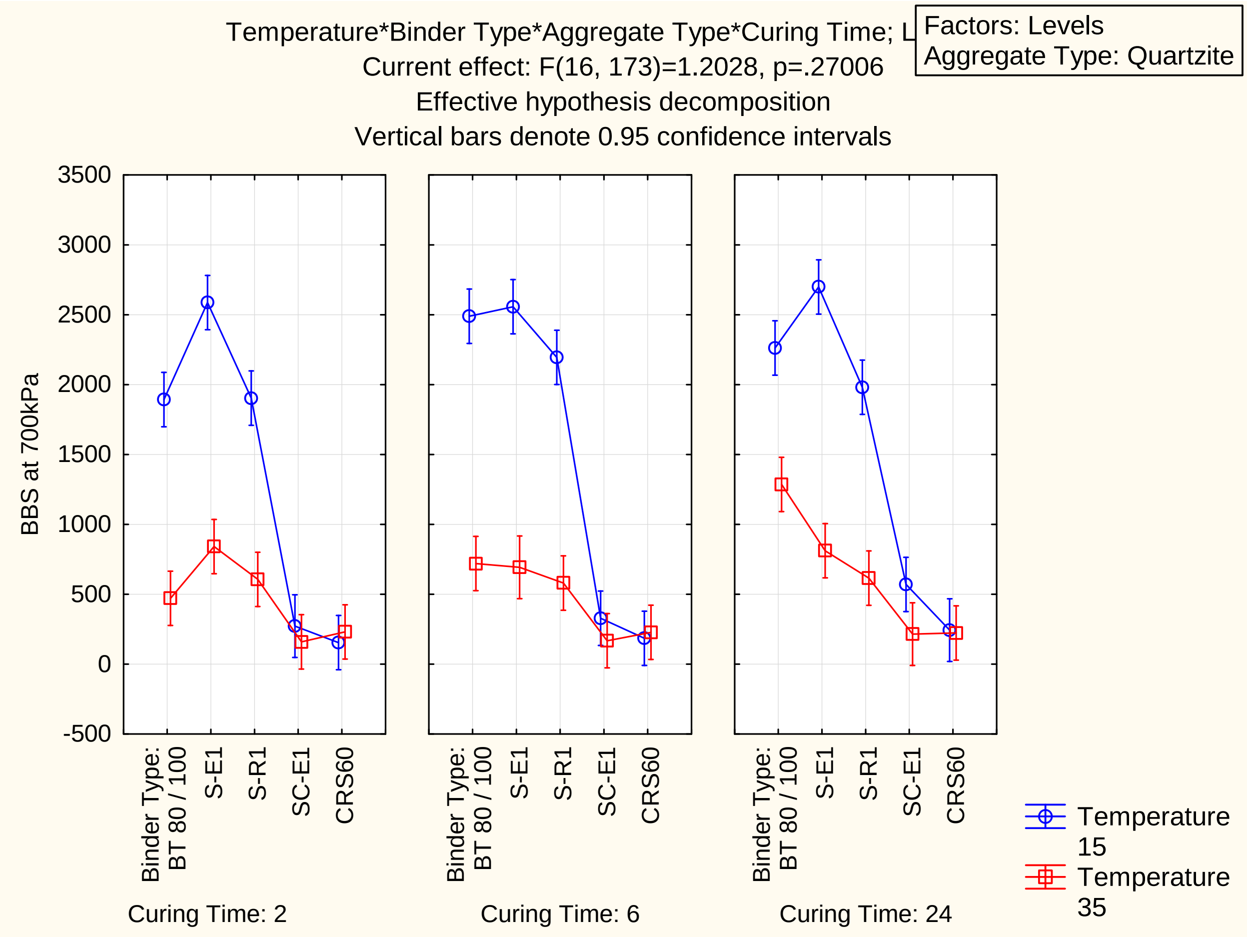
Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova 201408
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	231895977	1	231895977	5987.099	0.000000
{1}Temperature	50109282	1	50109282	1293.723	0.000000
{2}Binder Type	85964605	4	21491151	554.859	0.000000
{3}Aggregate Type	11520	2	5760	0.149	0.861927
{4}Curing Time	1264002	2	632001	16.317	0.000000
Temperature*Binder Type	26758687	4	6689672	172.714	0.000000
Temperature*Aggregate Type	61918	2	30959	0.799	0.451295
Binder Type*Aggregate Type	205142	8	25643	0.662	0.724346
Temperature*Curing Time	203857	2	101928	2.632	0.074844
Binder Type*Curing Time	1535315	8	191914	4.955	0.000016
Aggregate Type*Curing Time	15924	4	3981	0.103	0.981398
Temperature*Binder Type*Aggregate Type	170795	8	21349	0.551	0.816461
Temperature*Binder Type*Curing Time	776872	8	97109	2.507	0.013326
Temperature*Aggregate Type*Curing Time	99243	4	24811	0.641	0.634260
Binder Type*Aggregate Type*Curing Time	483594	16	30225	0.780	0.706307
1*2*3*4	745390	16	46587	1.203	0.270059
Error	6700742	173	38733		

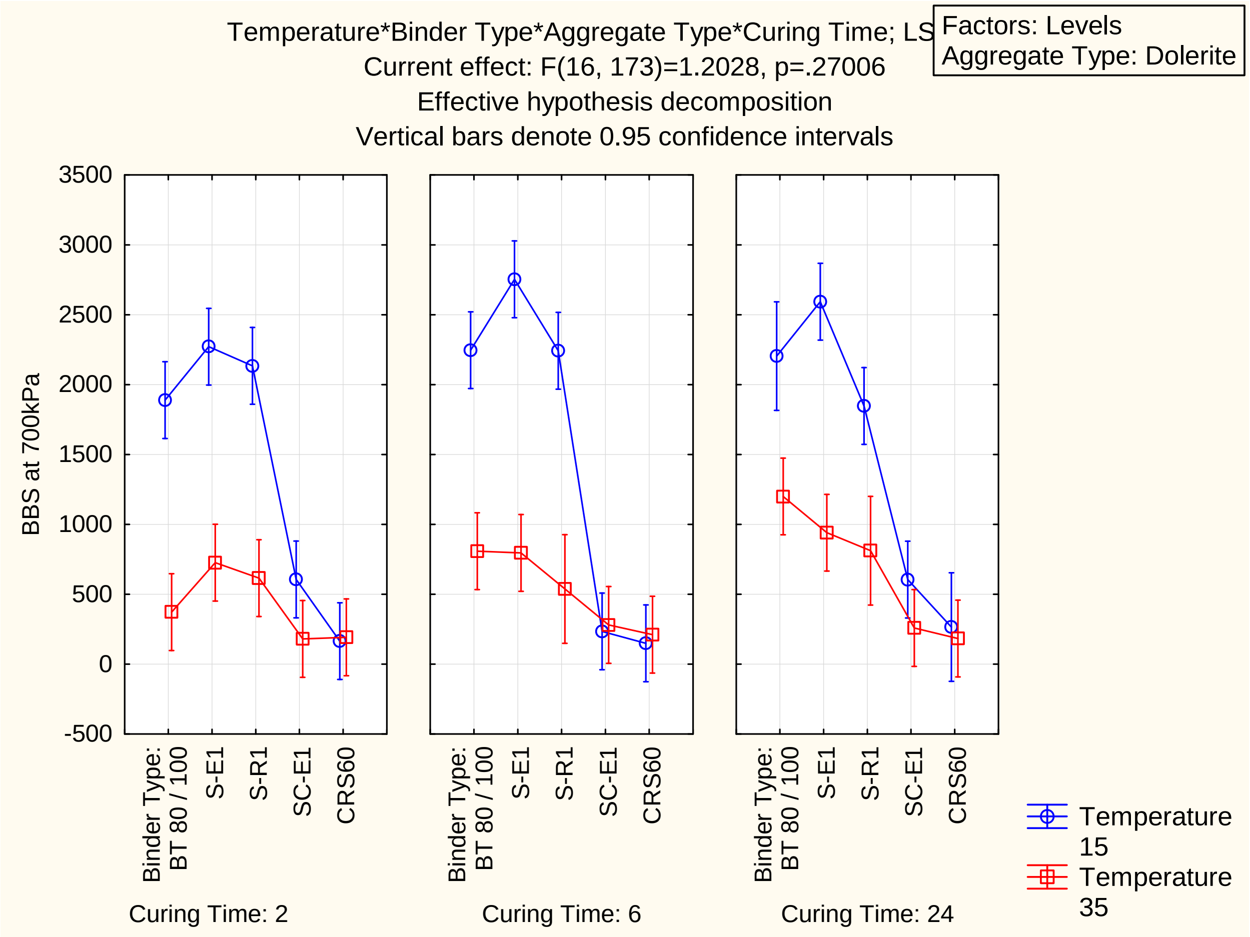
Temperature*Binder Type*Aggregate Type*Curing Time; LS Means



Temperature*Binder Type*Aggregate Type*Curing Time; LS Means



Temperature*Binder Type*Aggregate Type*Curing Time; LS Means



Temperature*Binder Type*Aggregate Type*Curing Time; LS Means (DATA BBS LeRicheLombard)

Temperature*Binder Type*Aggregate Type*Curing Time; LS Means (DATA BBS LeRicheLombard)

Current effect: F(16, 173)=1.2028, p=.27006

Effective hypothesis decomposition

Cell No.	Temperature	Binder Type	Aggregate Type	Curing Time	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	BT 80 / 100	Granite	2	2050.638	113.6260	1826.366	2274.910	3
2	15	BT 80 / 100	Granite	6	2096.231	98.4030	1902.006	2290.456	4
3	15	BT 80 / 100	Granite	24	2263.489	113.6260	2039.217	2487.761	3
4	15	BT 80 / 100	Quartzite	2	1893.116	98.4030	1698.891	2087.341	4
5	15	BT 80 / 100	Quartzite	6	2489.187	98.4030	2294.962	2683.412	4
6	15	BT 80 / 100	Quartzite	24	2262.219	98.4030	2067.994	2456.444	4
7	15	BT 80 / 100	Dolerite	2	1888.881	139.1629	1614.205	2163.556	2
8	15	BT 80 / 100	Dolerite	6	2246.439	139.1629	1971.763	2521.114	2
9	15	BT 80 / 100	Dolerite	24	2203.868	196.8060	1815.418	2592.318	1
10	15	S-E1	Granite	2	2217.740	113.6260	1993.468	2442.012	3
11	15	S-E1	Granite	6	2663.818	113.6260	2439.546	2888.090	3

12	15	S-E1	Granite	24	2331.460	113.6260	2107.188	2555.732	3
13	15	S-E1	Quartzite	2	2587.117	98.4030	2392.892	2781.342	4
14	15	S-E1	Quartzite	6	2557.209	98.4030	2362.984	2751.434	4
15	15	S-E1	Quartzite	24	2698.964	98.4030	2504.739	2893.189	4
16	15	S-E1	Dolerite	2	2271.335	139.1629	1996.660	2546.011	2
17	15	S-E1	Dolerite	6	2753.224	139.1629	2478.548	3027.900	2
18	15	S-E1	Dolerite	24	2593.600	139.1629	2318.925	2868.276	2
19	15	S-R1	Granite	2	1907.837	113.6260	1683.565	2132.108	3
20	15	S-R1	Granite	6	2007.999	113.6260	1783.727	2232.270	3
21	15	S-R1	Granite	24	1895.549	113.6260	1671.277	2119.821	3
22	15	S-R1	Quartzite	2	1903.525	98.4030	1709.300	2097.750	4
23	15	S-R1	Quartzite	6	2194.694	98.4030	2000.469	2388.919	4
24	15	S-R1	Quartzite	24	1981.251	98.4030	1787.026	2175.476	4
25	15	S-R1	Dolerite	2	2134.342	139.1629	1859.666	2409.017	2
26	15	S-R1	Dolerite	6	2242.473	139.1629	1967.797	2517.149	2
27	15	S-R1	Dolerite	24	1847.508	139.1629	1572.833	2122.184	2

28	15	SC-E1	Granite	2	344.042	113.6260	119.771	568.314	3
29	15	SC-E1	Granite	6	518.339	113.6260	294.067	742.611	3
30	15	SC-E1	Granite	24	527.785	113.6260	303.513	752.057	3
31	15	SC-E1	Quartzite	2	272.588	113.6260	48.316	496.860	3
32	15	SC-E1	Quartzite	6	328.521	98.4030	134.296	522.746	4
33	15	SC-E1	Quartzite	24	570.726	98.4030	376.501	764.951	4
34	15	SC-E1	Dolerite	2	605.937	139.1629	331.261	880.612	2
35	15	SC-E1	Dolerite	6	234.498	139.1629	-40.178	509.174	2
36	15	SC-E1	Dolerite	24	605.086	139.1629	330.410	879.762	2
37	15	CRS60	Granite	2	240.461	113.6260	16.189	464.733	3
38	15	CRS60	Granite	6	187.137	113.6260	-37.135	411.408	3
39	15	CRS60	Granite	24	359.781	113.6260	135.510	584.053	3
40	15	CRS60	Quartzite	2	154.058	98.4030	-40.167	348.283	4
41	15	CRS60	Quartzite	6	185.304	98.4030	-8.921	379.529	4
42	15	CRS60	Quartzite	24	243.964	113.6260	19.693	468.236	3
43	15	CRS60	Dolerite	2	164.878	139.1629	-109.798	439.554	2

44	15	CRS60	Dolerite	6	149.183	139.1629	-125.493	423.859	2
45	15	CRS60	Dolerite	24	265.685	196.8060	-122.765	654.135	1
46	35	BT 80 / 100	Granite	2	482.474	98.4030	288.249	676.700	4
47	35	BT 80 / 100	Granite	6	1022.056	98.4030	827.831	1216.281	4
48	35	BT 80 / 100	Granite	24	1093.515	98.4030	899.290	1287.740	4
49	35	BT 80 / 100	Quartzite	2	470.962	98.4030	276.737	665.187	4
50	35	BT 80 / 100	Quartzite	6	720.094	98.4030	525.869	914.319	4
51	35	BT 80 / 100	Quartzite	24	1286.213	98.4030	1091.988	1480.438	4
52	35	BT 80 / 100	Dolerite	2	372.289	139.1629	97.613	646.964	2
53	35	BT 80 / 100	Dolerite	6	808.339	139.1629	533.663	1083.014	2
54	35	BT 80 / 100	Dolerite	24	1199.912	139.1629	925.236	1474.588	2
55	35	S-E1	Granite	2	706.732	113.6260	482.460	931.004	3
56	35	S-E1	Granite	6	815.585	139.1629	540.910	1090.261	2
57	35	S-E1	Granite	24	955.413	139.1629	680.737	1230.089	2
58	35	S-E1	Quartzite	2	841.478	98.4030	647.253	1035.703	4
59	35	S-E1	Quartzite	6	693.026	113.6260	468.754	917.298	3

60	35	S-E1	Quartzite	24	811.610	98.4030	617.385	1005.835	4
61	35	S-E1	Dolerite	2	726.320	139.1629	451.644	1000.996	2
62	35	S-E1	Dolerite	6	795.585	139.1629	520.909	1070.260	2
63	35	S-E1	Dolerite	24	940.508	139.1629	665.832	1215.183	2
64	35	S-R1	Granite	2	646.503	139.1629	371.827	921.179	2
65	35	S-R1	Granite	6	537.635	113.6260	313.364	761.907	3
66	35	S-R1	Granite	24	645.547	98.4030	451.322	839.772	4
67	35	S-R1	Quartzite	2	606.897	98.4030	412.672	801.122	4
68	35	S-R1	Quartzite	6	580.358	98.4030	386.132	774.583	4
69	35	S-R1	Quartzite	24	615.608	98.4030	421.383	809.833	4
70	35	S-R1	Dolerite	2	615.415	139.1629	340.739	890.091	2
71	35	S-R1	Dolerite	6	537.945	196.8060	149.495	926.395	1
72	35	S-R1	Dolerite	24	811.739	196.8060	423.289	1200.189	1
73	35	SC-E1	Granite	2	103.669	139.1629	-171.007	378.345	2
74	35	SC-E1	Granite	6	196.668	113.6260	-27.604	420.939	3
75	35	SC-E1	Granite	24	322.941	113.6260	98.669	547.213	3

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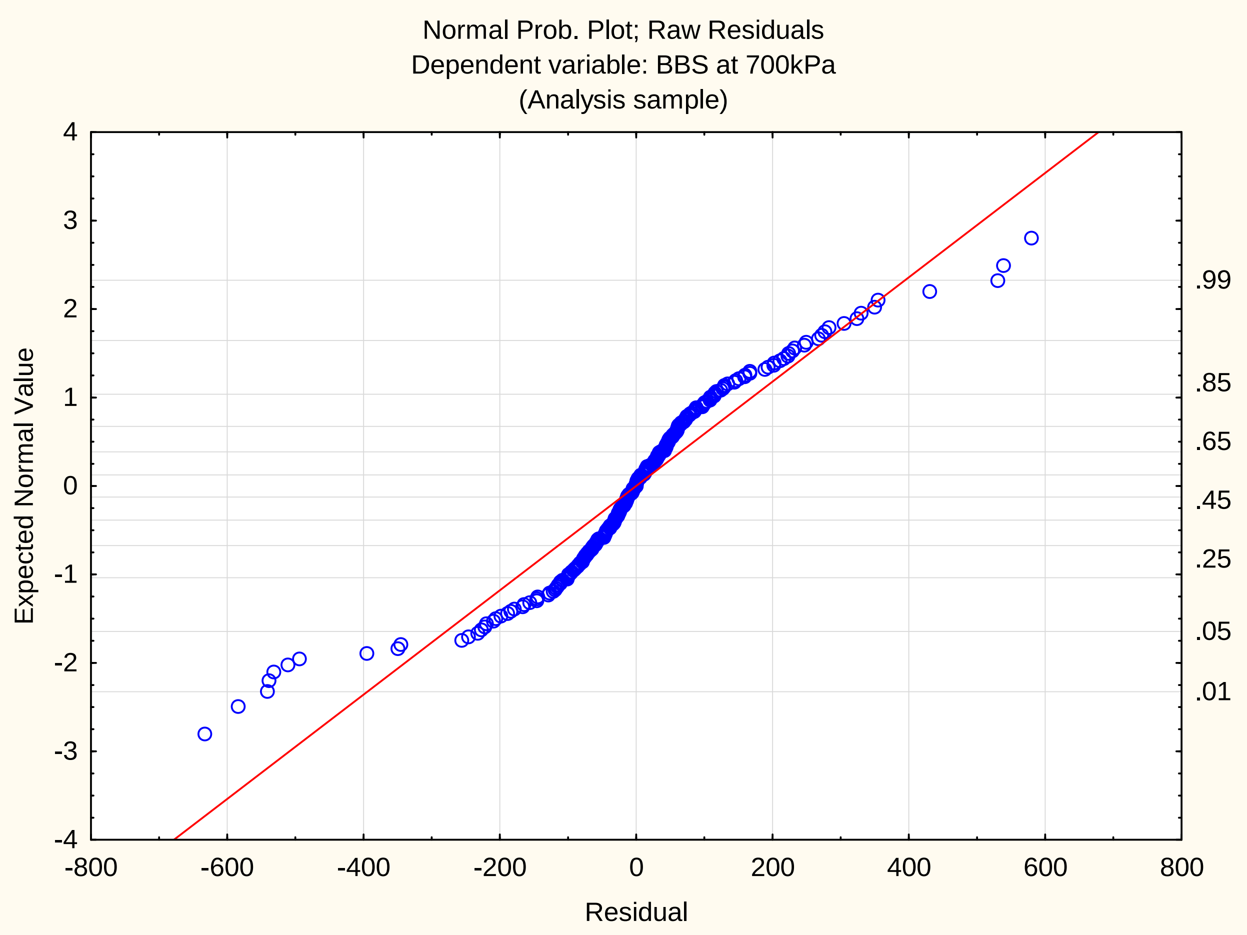
76	35	SC-E1	Quartzite	2	159.714	98.4030	-34.511	353.939	4
77	35	SC-E1	Quartzite	6	167.735	98.4030	-26.490	361.960	4
78	35	SC-E1	Quartzite	24	215.163	113.6260	-9.109	439.435	3
79	35	SC-E1	Dolerite	2	180.316	139.1629	-94.360	454.991	2
80	35	SC-E1	Dolerite	6	280.432	139.1629	5.756	555.108	2
81	35	SC-E1	Dolerite	24	258.508	139.1629	-16.168	533.184	2
82	35	CRS60	Granite	2	177.562	98.4030	-16.663	371.787	4
83	35	CRS60	Granite	6	228.097	139.1629	-46.578	502.773	2
84	35	CRS60	Granite	24	264.358	113.6260	40.086	488.630	3
85	35	CRS60	Quartzite	2	231.125	98.4030	36.900	425.350	4
86	35	CRS60	Quartzite	6	227.614	98.4030	33.389	421.839	4
87	35	CRS60	Quartzite	24	223.111	98.4030	28.886	417.336	4
88	35	CRS60	Dolerite	2	191.744	139.1629	-82.931	466.420	2
89	35	CRS60	Dolerite	6	211.481	139.1629	-63.195	486.157	2
90	35	CRS60	Dolerite	24	183.405	139.1629	-91.271	458.080	2

Normal Prob. Plot; Raw Residuals



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b. 3-WAY ANOVA (DATA BBS LERICHELOMBARD)

ANOVA RESULTS 1: DATA BBS LERICHELOMBARD

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova 2014 Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	179424241	1	179424241	2520.986	0.000000
Temperature	36397138	1	36397138	511.395	0.000000
Application Type	85448274	1	85448274	1200.584	0.000000
Aggregate Type	9136	2	4568	0.064	0.937851
Temperature*Application Type	26191965	1	26191965	368.008	0.000000
Temperature*Aggregate Type	35791	2	17895	0.251	0.777878
Application Type*Aggregate Ty	96885	2	48443	0.681	0.507225
Temperature*Application Type*	135700	2	67850	0.953	0.386850
Error	17864237	251	71172		

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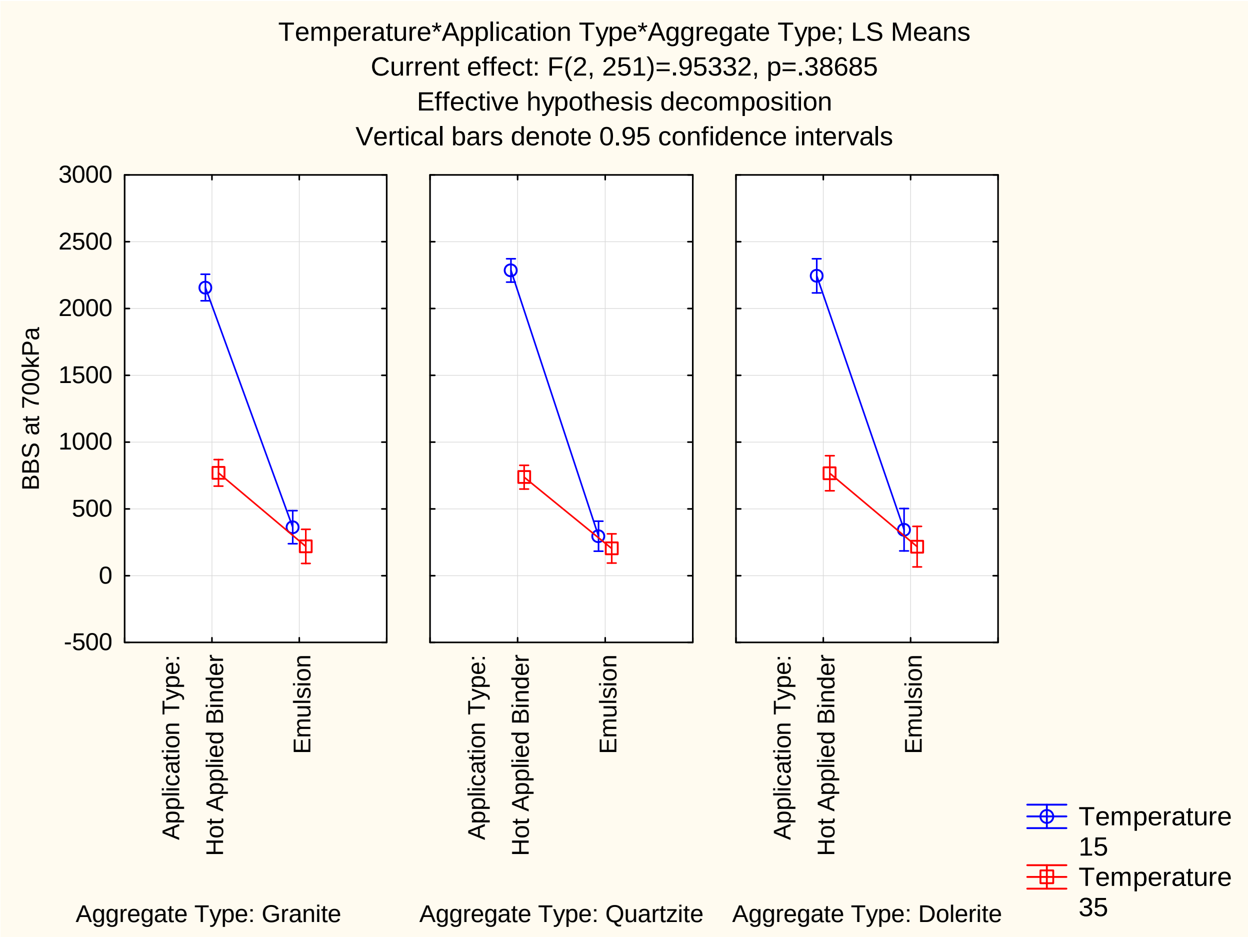
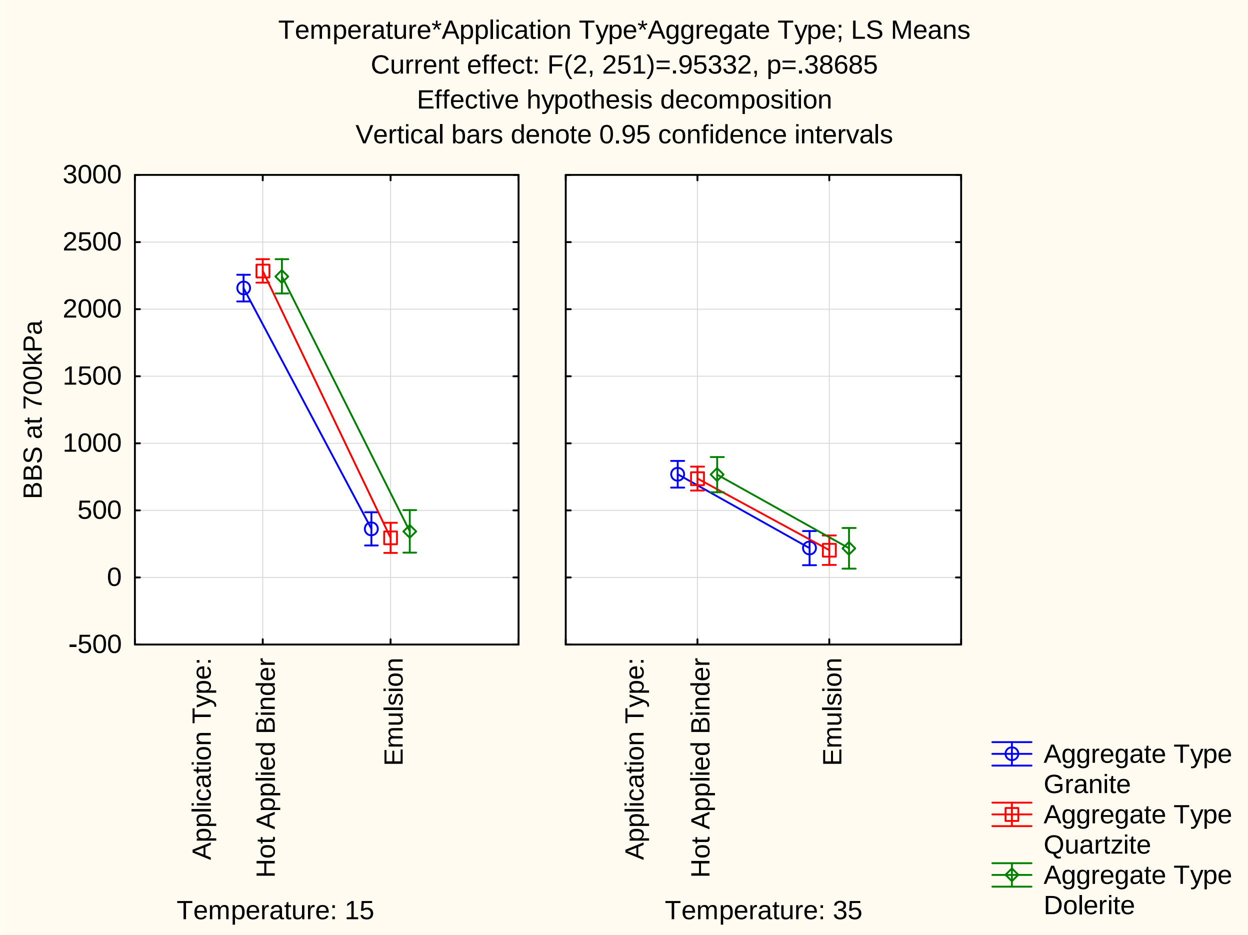
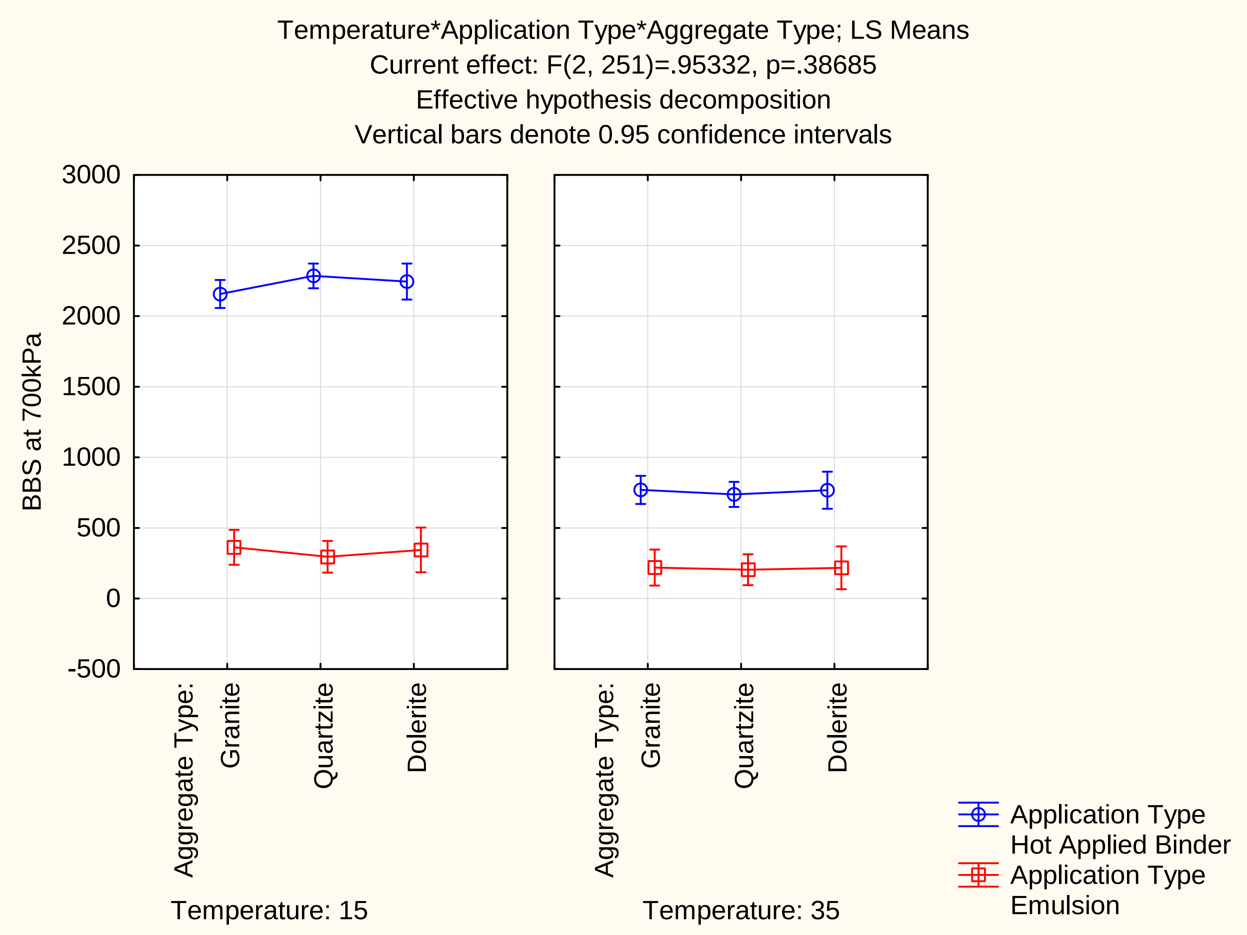
Temperature*Application Type*Aggregate Type; LS Means



Temperature*Application Type*Aggregate Type; LS Means



Temperature*Application Type*Aggregate Type; LS Means

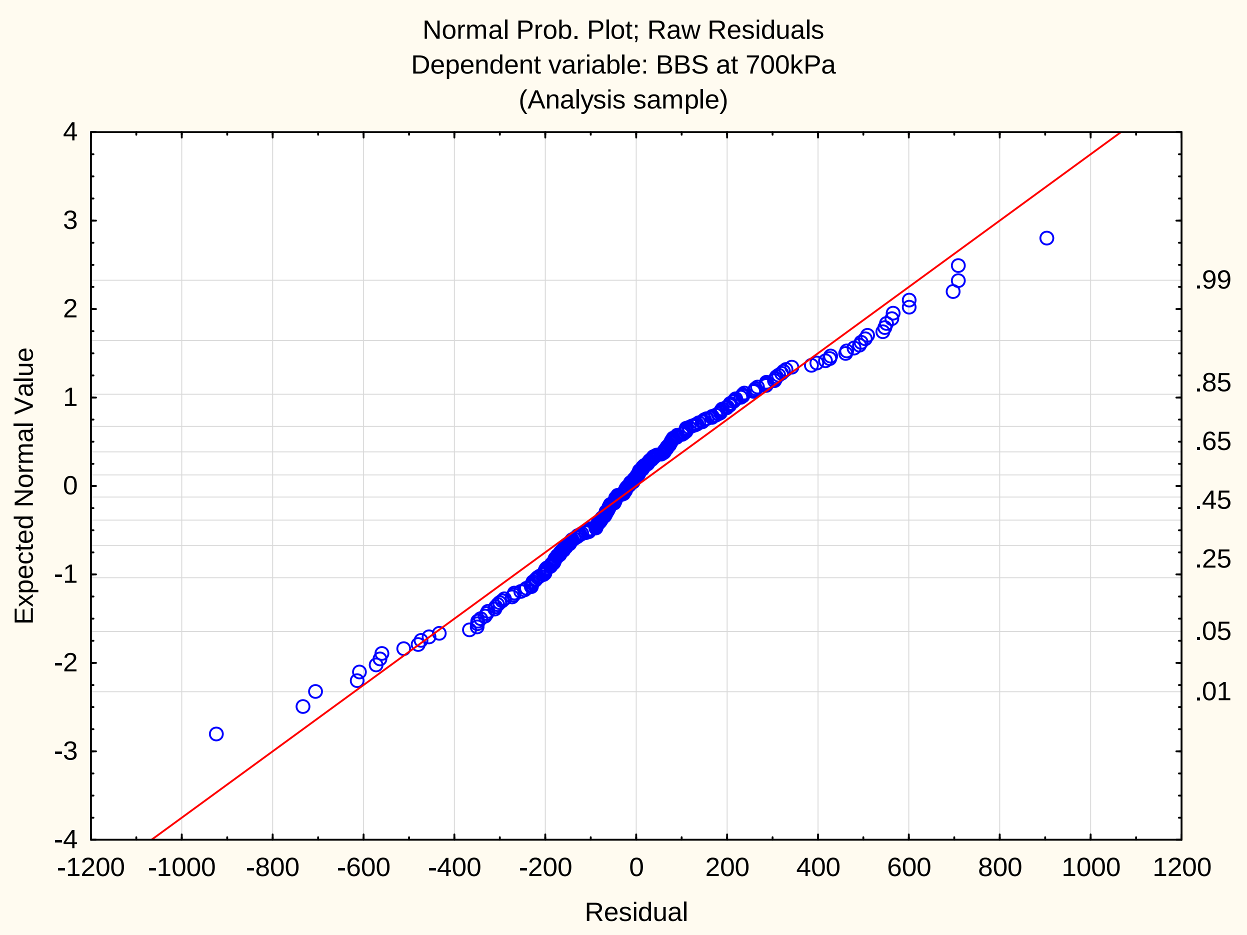


Temperature*Application Type*Aggregate Type; LS Means (DATA BBS LeRicheLombard)

Temperature*Application Type*Aggregate Type; LS Means (DATA InputAnova 20140820.sta)
Current effect: F(2, 251)=.95332, p=.38685
Effective hypothesis decomposition

Cell No.	Temperature	Application Type	Aggregate Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	Hot Applied Binder	Granite	2157.161	50.41692	2057.867	2256.455	28
2	15	Hot Applied Binder	Quartzite	2285.254	44.46355	2197.684	2372.823	36
3	15	Hot Applied Binder	Dolerite	2244.675	64.70397	2117.243	2372.107	17
4	15	Emulsion	Granite	362.924	62.88095	239.083	486.766	18
5	15	Emulsion	Quartzite	295.641	56.87796	183.622	407.659	22
6	15	Emulsion	Dolerite	344.077	80.43759	185.658	502.496	11
7	35	Hot Applied Binder	Granite	769.374	50.41692	670.080	868.668	28
8	35	Hot Applied Binder	Quartzite	737.484	45.09427	648.673	826.296	35
9	35	Hot Applied Binder	Dolerite	766.651	66.69532	635.297	898.005	16
10	35	Emulsion	Granite	219.158	64.70397	91.726	346.590	17
11	35	Emulsion	Quartzite	203.595	55.62774	94.038	313.152	23
12	35	Emulsion	Dolerite	217.648	77.01313	65.973	369.322	12

Normal Prob. Plot; Raw Residuals



c. 2-WAY ANOVA PER AGGREGATE TYPE (DATA BBS LERICHELOMBARD)

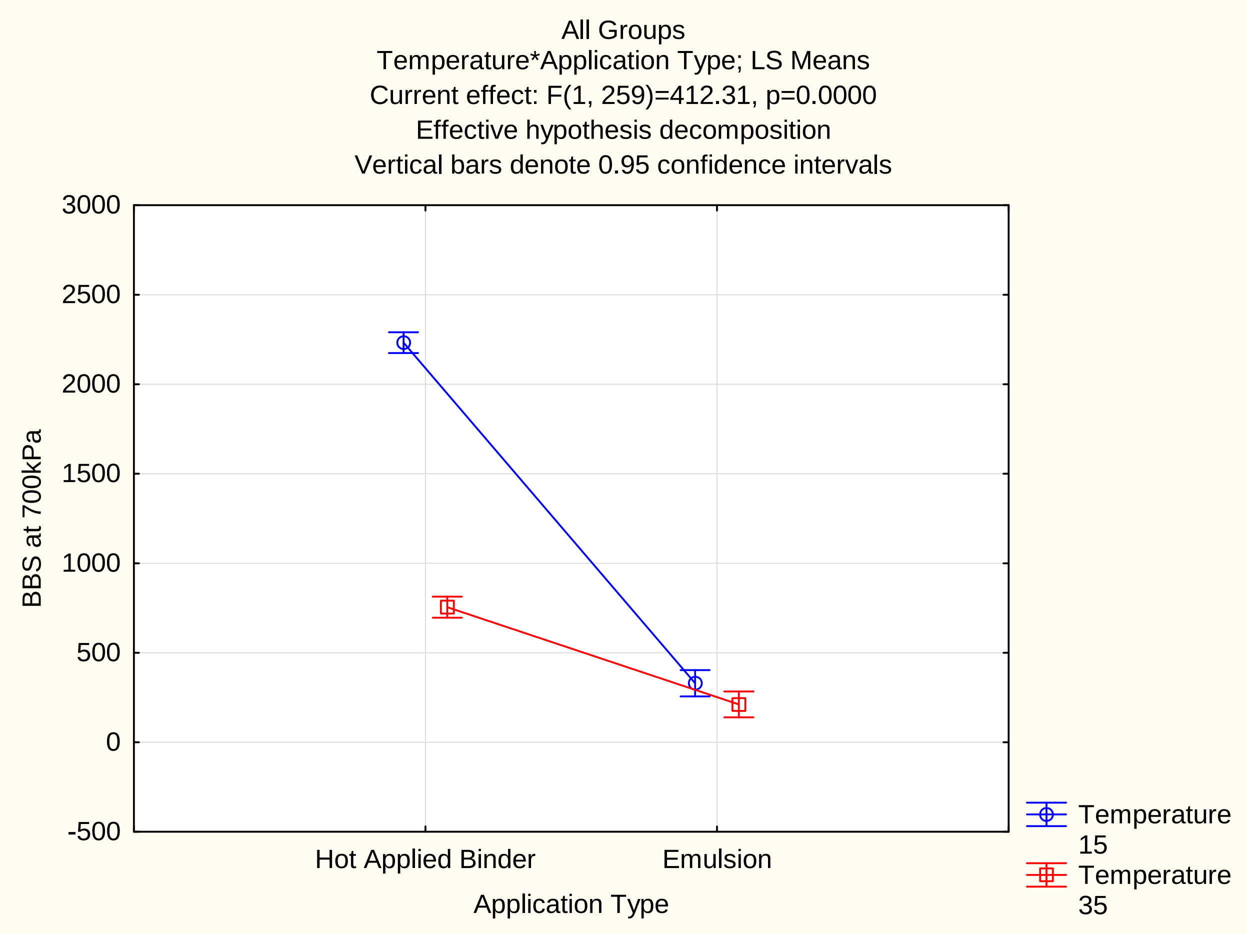
ANOVA RESULTS 1: DATA BBS LERICHELOMBARD

All Groups

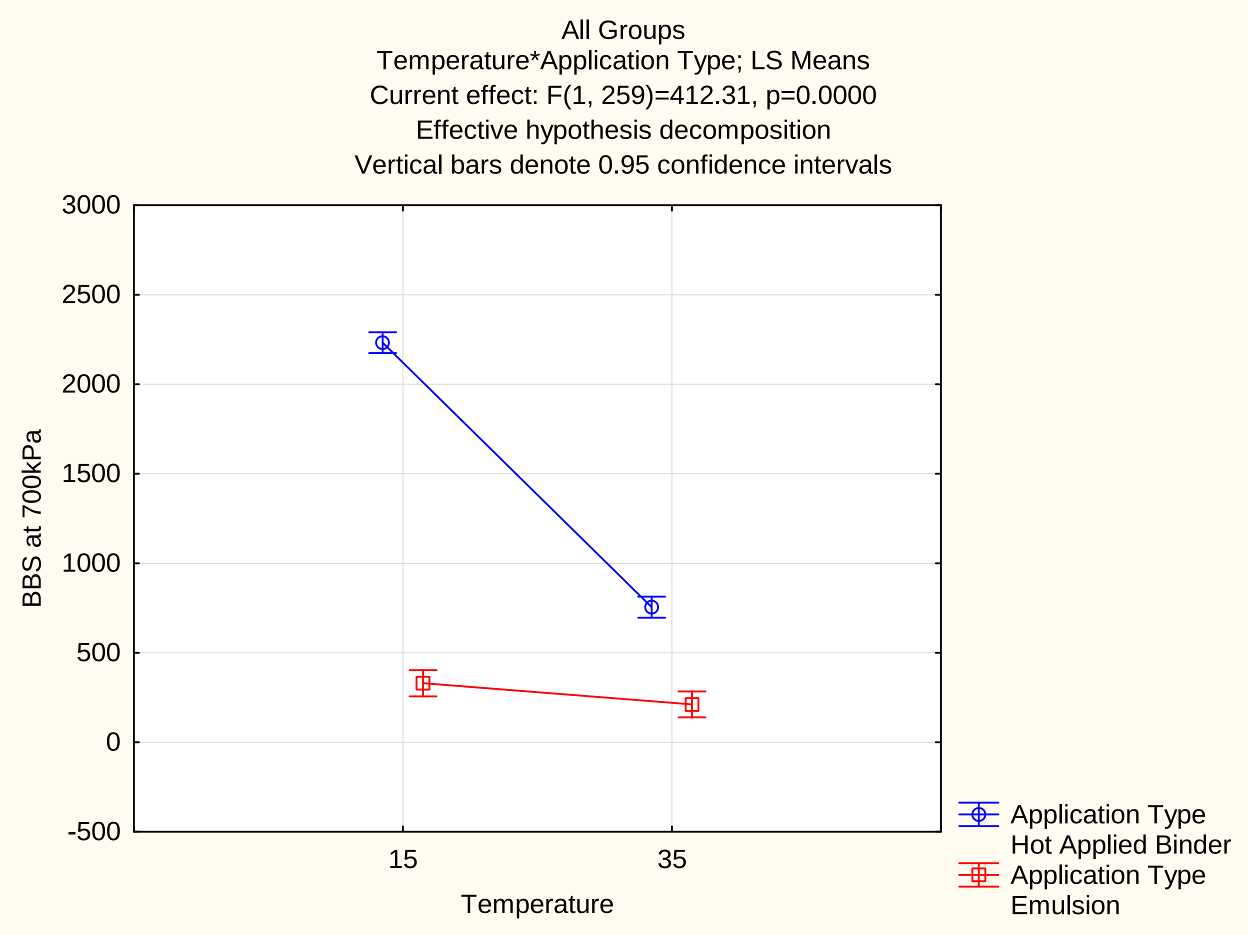
Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

Effect	All Groups Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova Sigma-restricted parameterization Effective hypothesis decomposition				
	SS	Degr. of Freedom	MS	F	p
Intercept	195061648	1	195061648	2776.625	0.00
Temperature	39882080	1	39882080	567.706	0.00
Application Type	93667071	1	93667071	1333.314	0.00
Temperature*Application Type	28965102	1	28965102	412.307	0.00
Error	18195097	259	70251		

*Temperature*Application Type; LS Means*



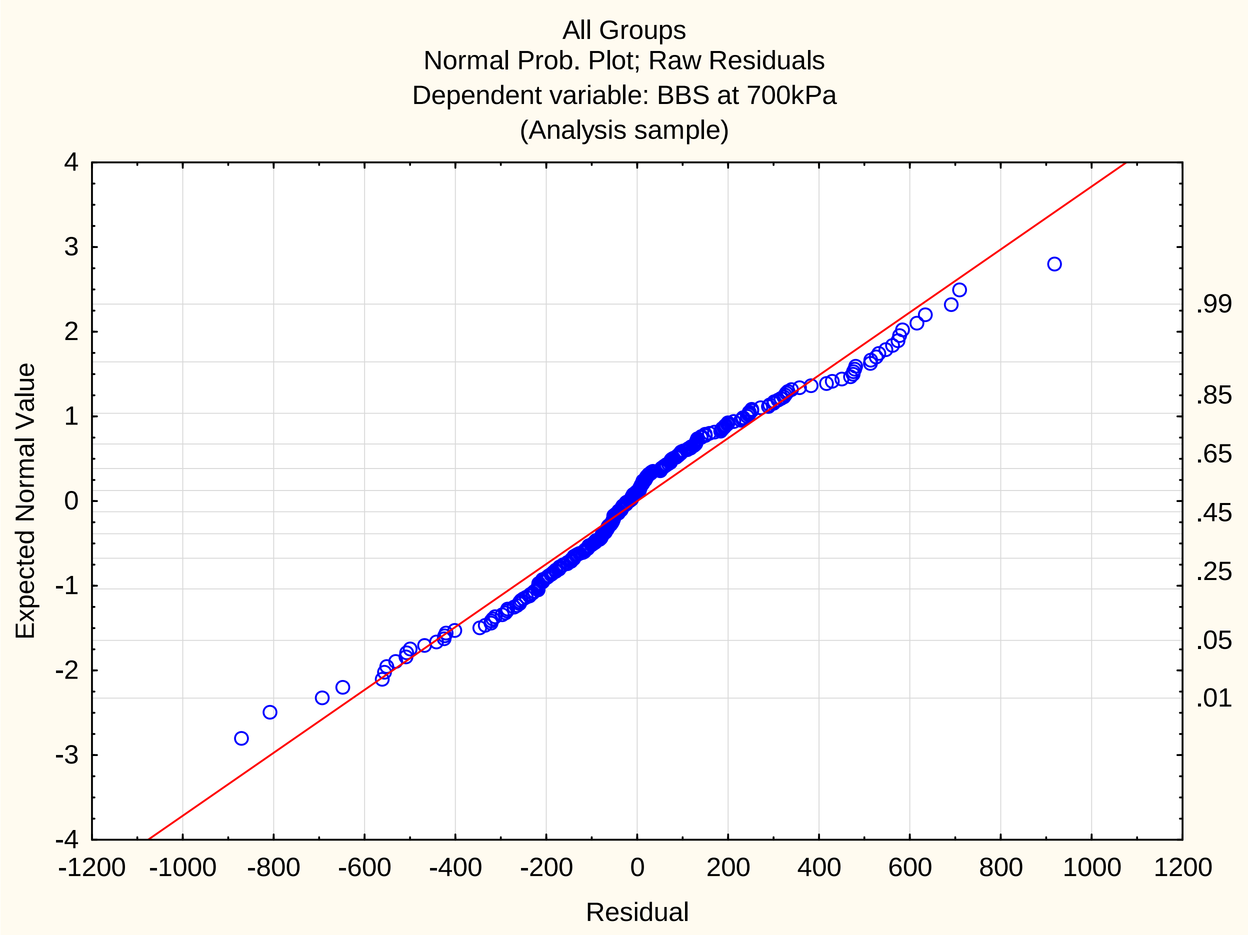
*Temperature*Application Type; LS Means*



Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

	All Groups Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta) Probabilities for Post Hoc Tests Error: Between MS = 70251., df = 259.00					
Cell No.	Temperature	Application Type	{1} 2232.5	{2} 329.83	{3} 754.69	{4} 211.93
1	15	Hot Applied Binder		0.000000	0.000000	0.000000
2	15	Emulsion	0.00		0.000000	0.148938
3	35	Hot Applied Binder	0.00	0.000000		0.000000
4	35	Emulsion	0.00	0.148938	0.000000	

Normal Prob. Plot; Raw Residuals

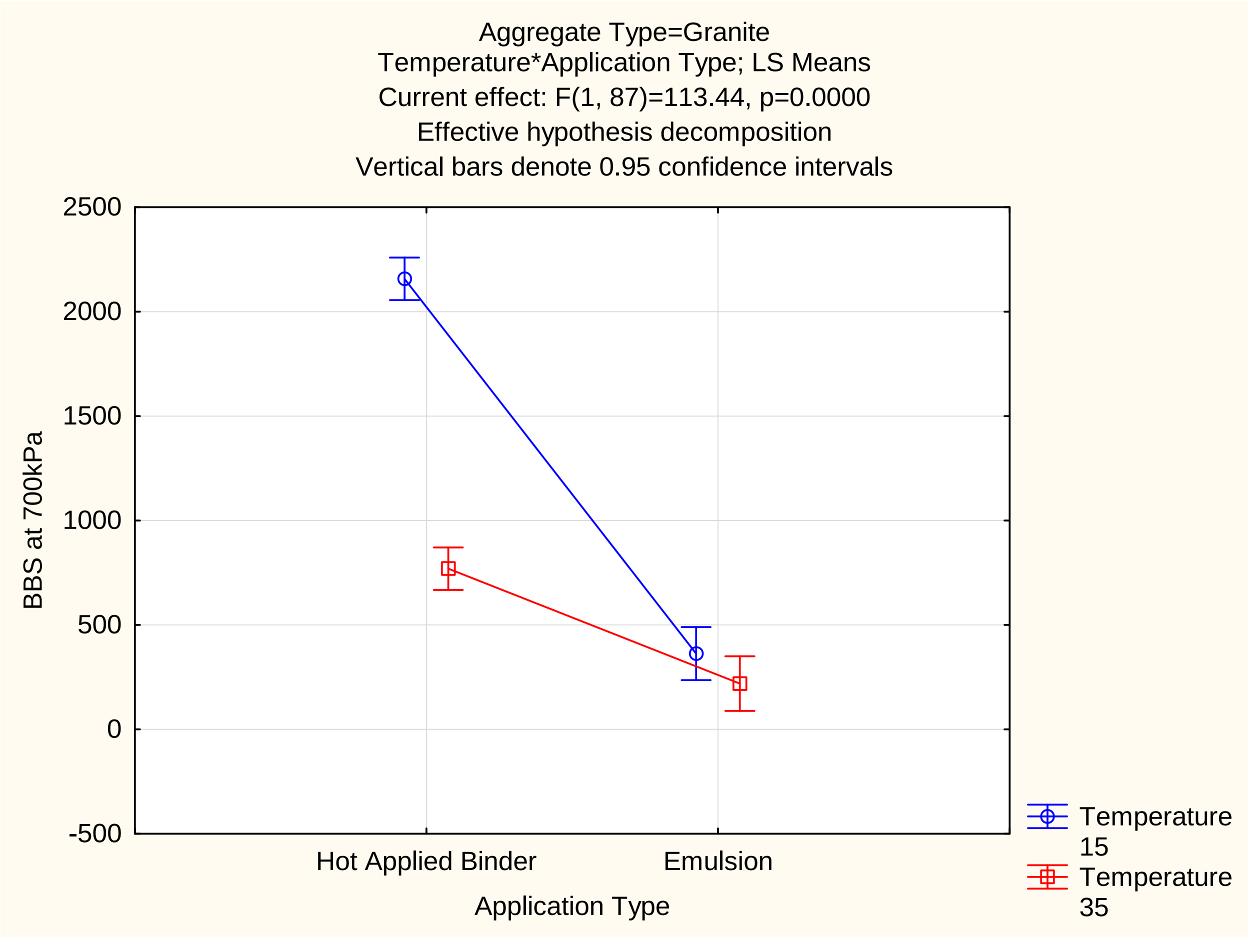


Aggregate Type=Granite

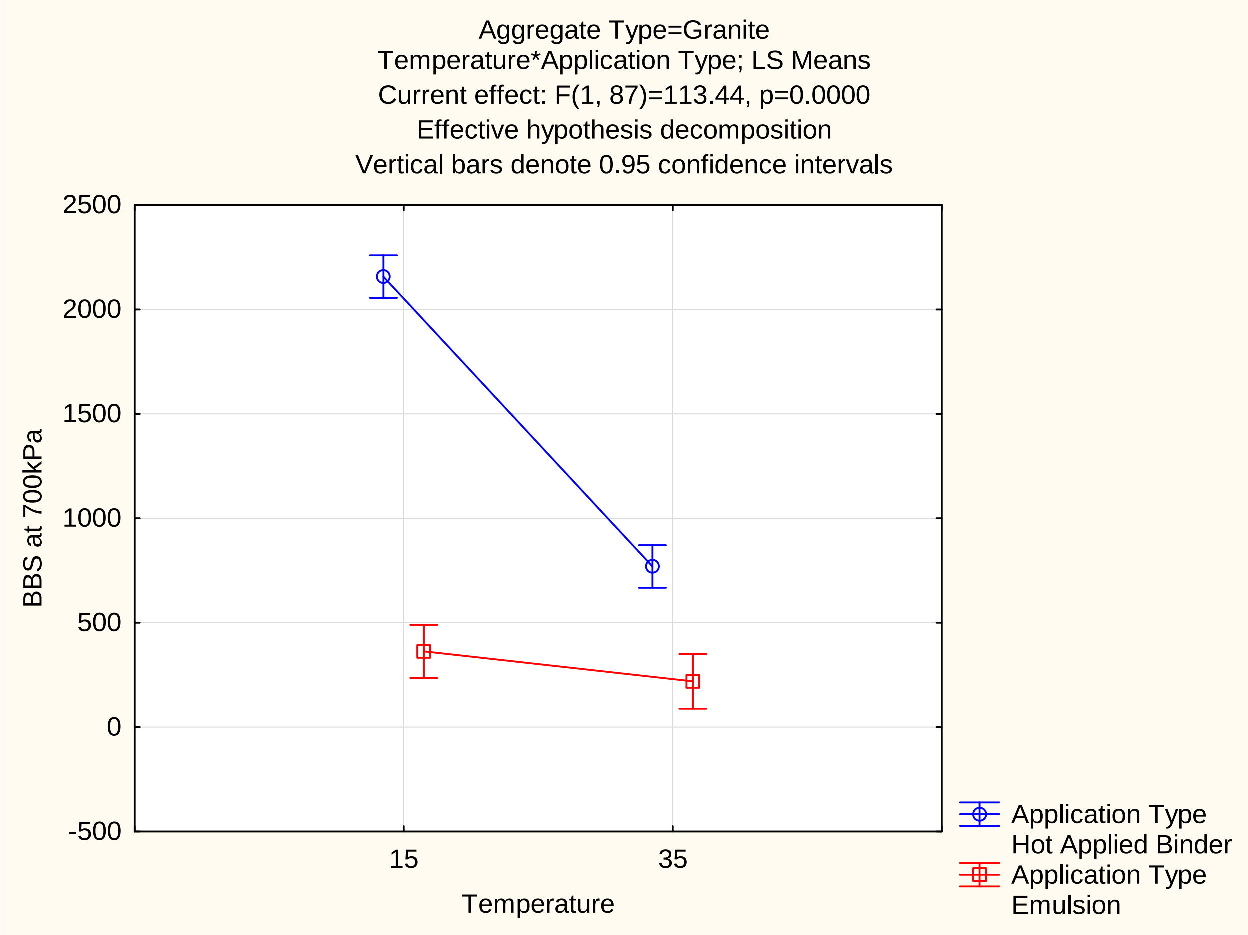
Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Aggregate Type=Granite Univariate Tests of Significance for BBS at 700kPa (DATA InputAno Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	66253432	1	66253432	902.3679	0.00
Temperature	12624110	1	12624110	171.9396	0.00
Application Type	29581458	1	29581458	402.8978	0.00
Temperature*Application Type	8328976	1	8328976	113.4402	0.00
Error	6387692	87	73422		

*Temperature*Application Type; LS Means*



*Temperature*Application Type; LS Means*

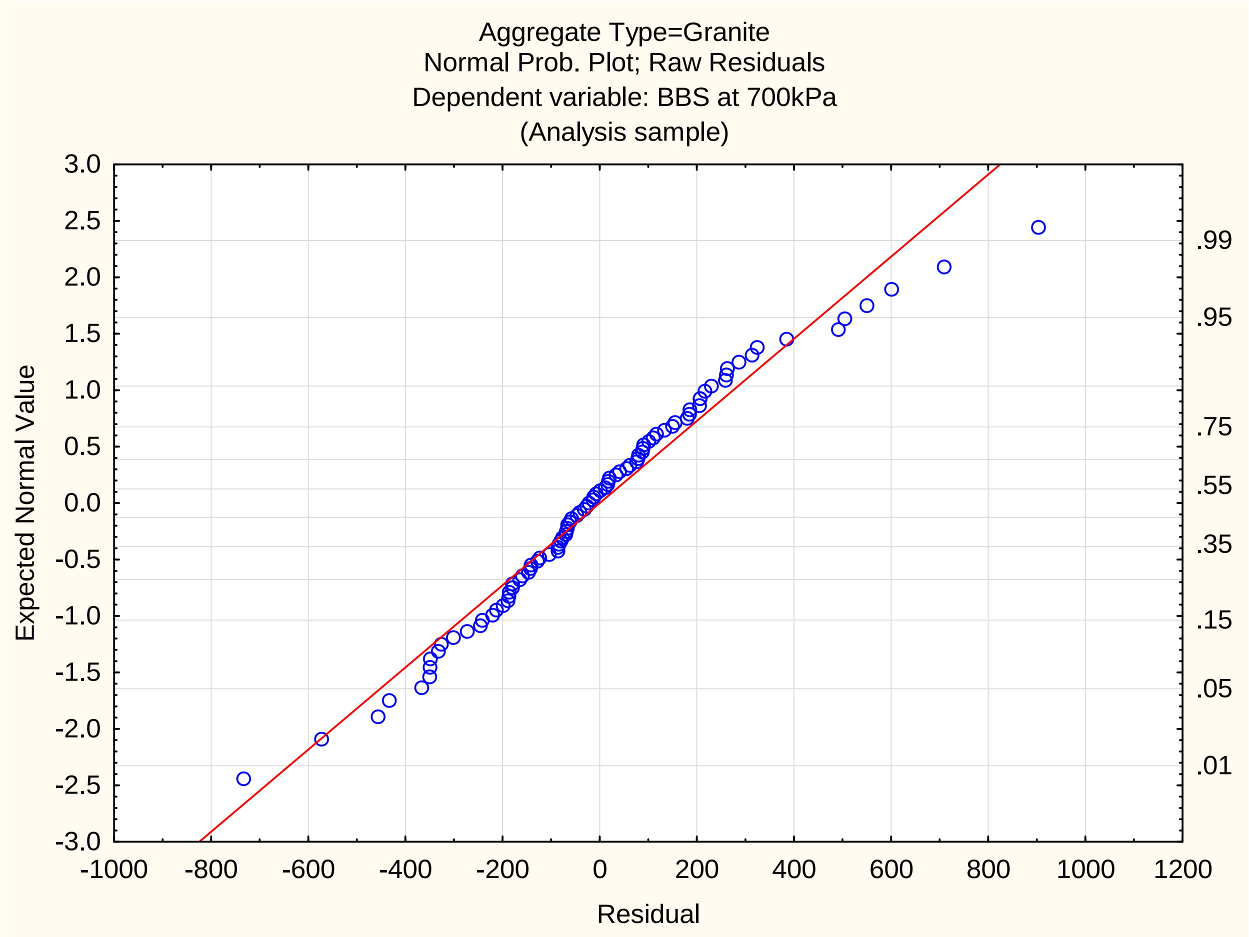


Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

Aggregate Type=Granite
Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta)
Probabilities for Post Hoc Tests
Error: Between MS = 73422., df = 87.000

Cell No.	Temperature	Application Type	{1} 2157.2	{2} 362.92	{3} 769.37	{4} 219.16
1	15	Hot Applied Binder		0.000000	0.000000	0.000000
2	15	Emulsion	0.00		0.000020	0.721927
3	35	Hot Applied Binder	0.00	0.000020		0.000000
4	35	Emulsion	0.00	0.721927	0.000000	

Normal Prob. Plot; Raw Residuals



Aggregate Type=Quartzite

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Aggregate Type=Quartzite Univariate Tests of Significance for BBS at 700kPa (DATA InputAno Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	85380824	1	85380824	1263.708	0.00
Temperature	18508777	1	18508777	273.946	0.00
Application Type	43832440	1	43832440	648.757	0.00
Temperature*Application Type	14586326	1	14586326	215.890	0.00
Error	7567136	112	67564		

*Temperature*Application Type; LS Means*

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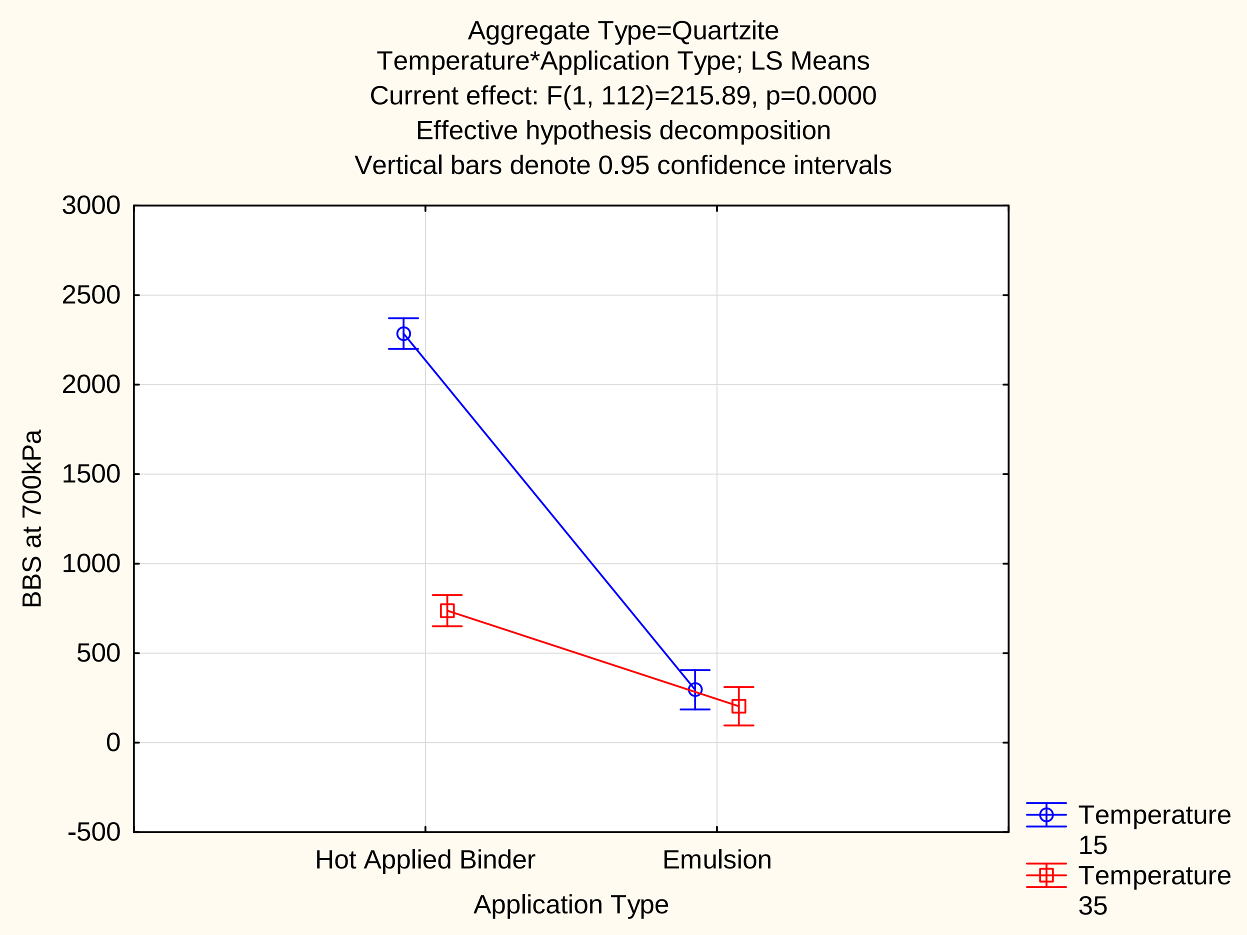
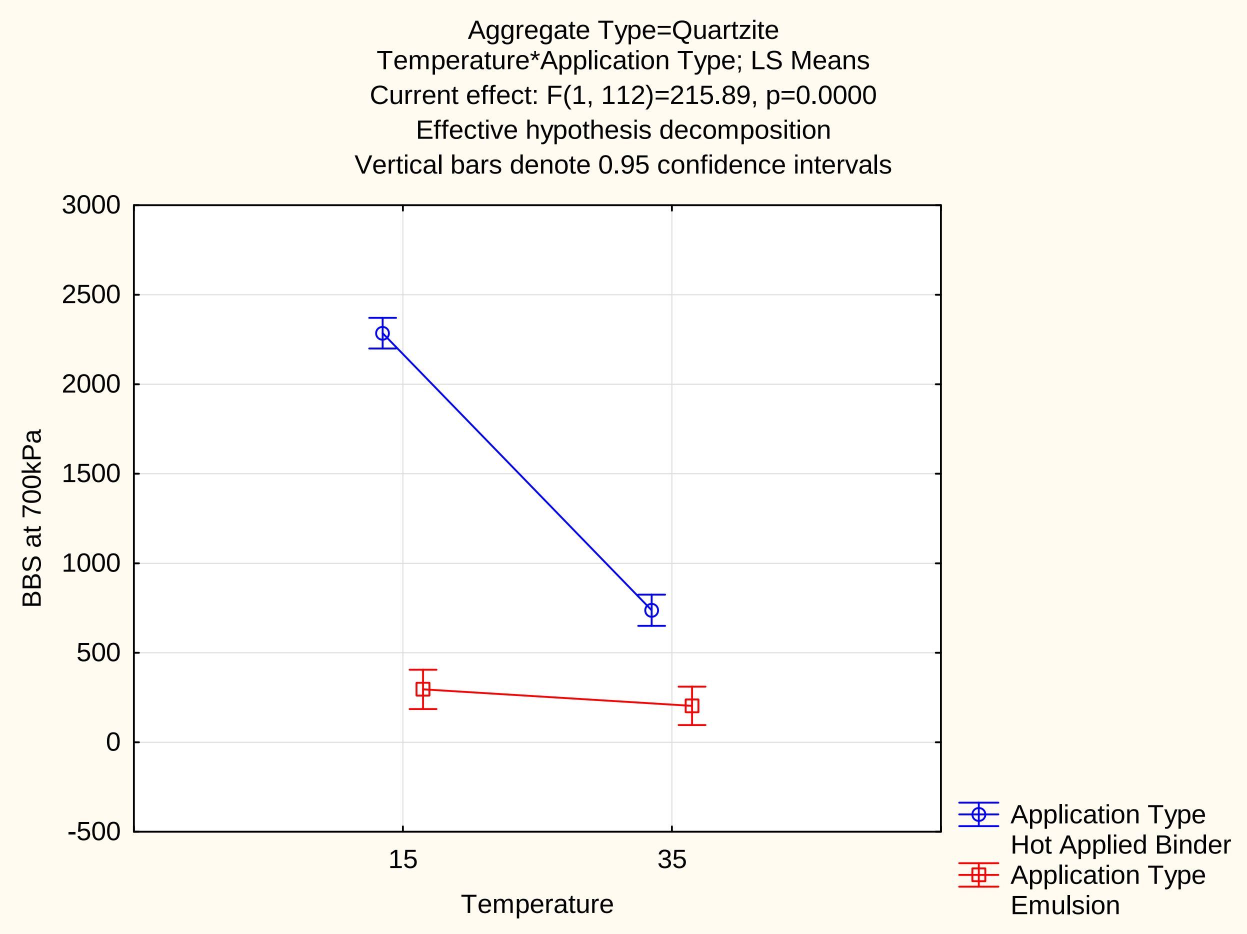


*Temperature*Application Type; LS Means*



Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

Aggregate Type=Quartzite
Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta)
Probabilities for Post Hoc Tests
Error: Between MS = 67564., df = 112.00

Cell No.	Temperature	Application Type	{1} 2285.3	{2} 295.64	{3} 737.48	{4} 203.59
1	15	Hot Applied Binder		0.000000	0.000000	0.000000
2	15	Emulsion	0.00		0.000000	1.000000
3	35	Hot Applied Binder	0.00	0.000000		0.000000
4	35	Emulsion	0.00	1.000000	0.000000	

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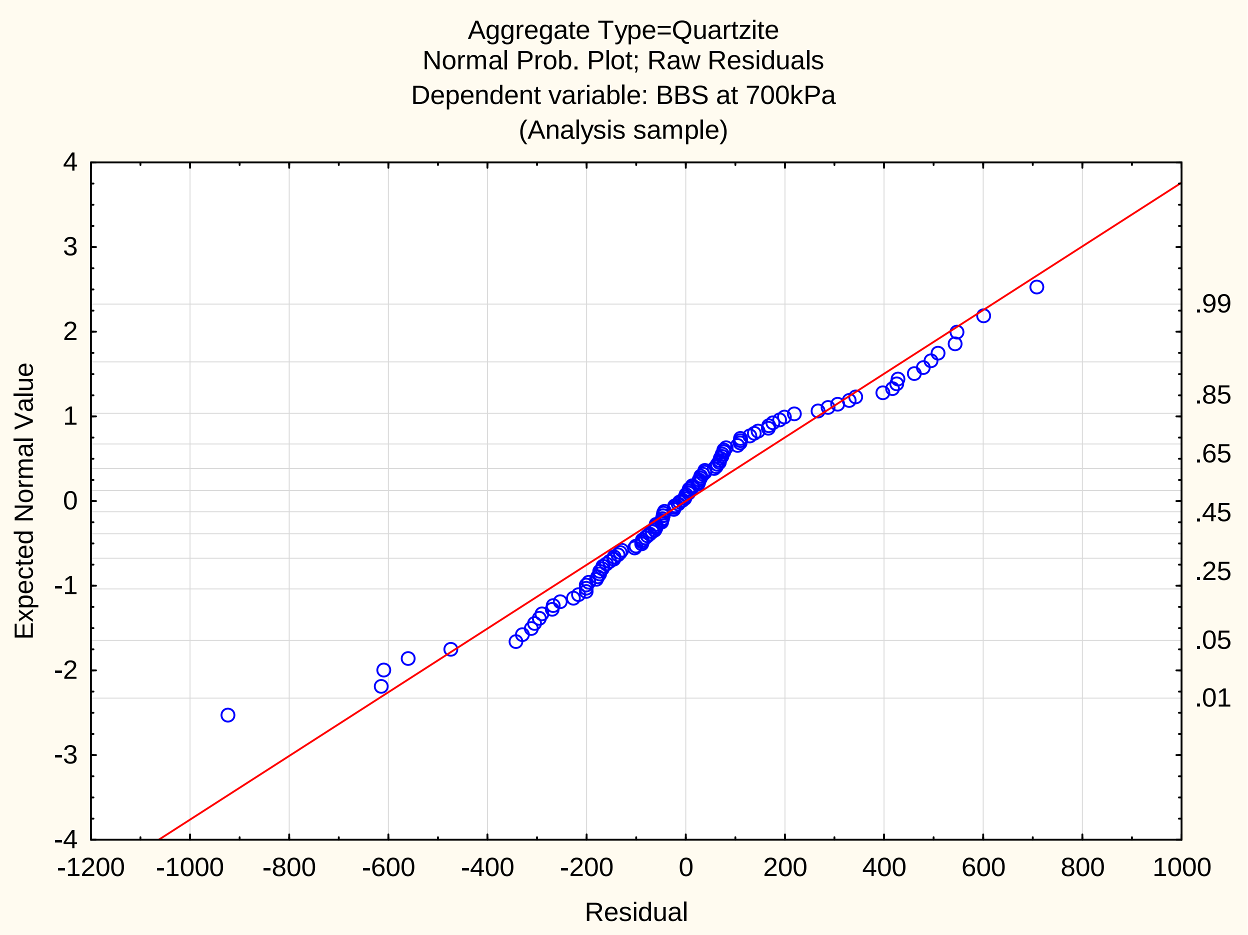
Normal Prob. Plot; Raw Residuals

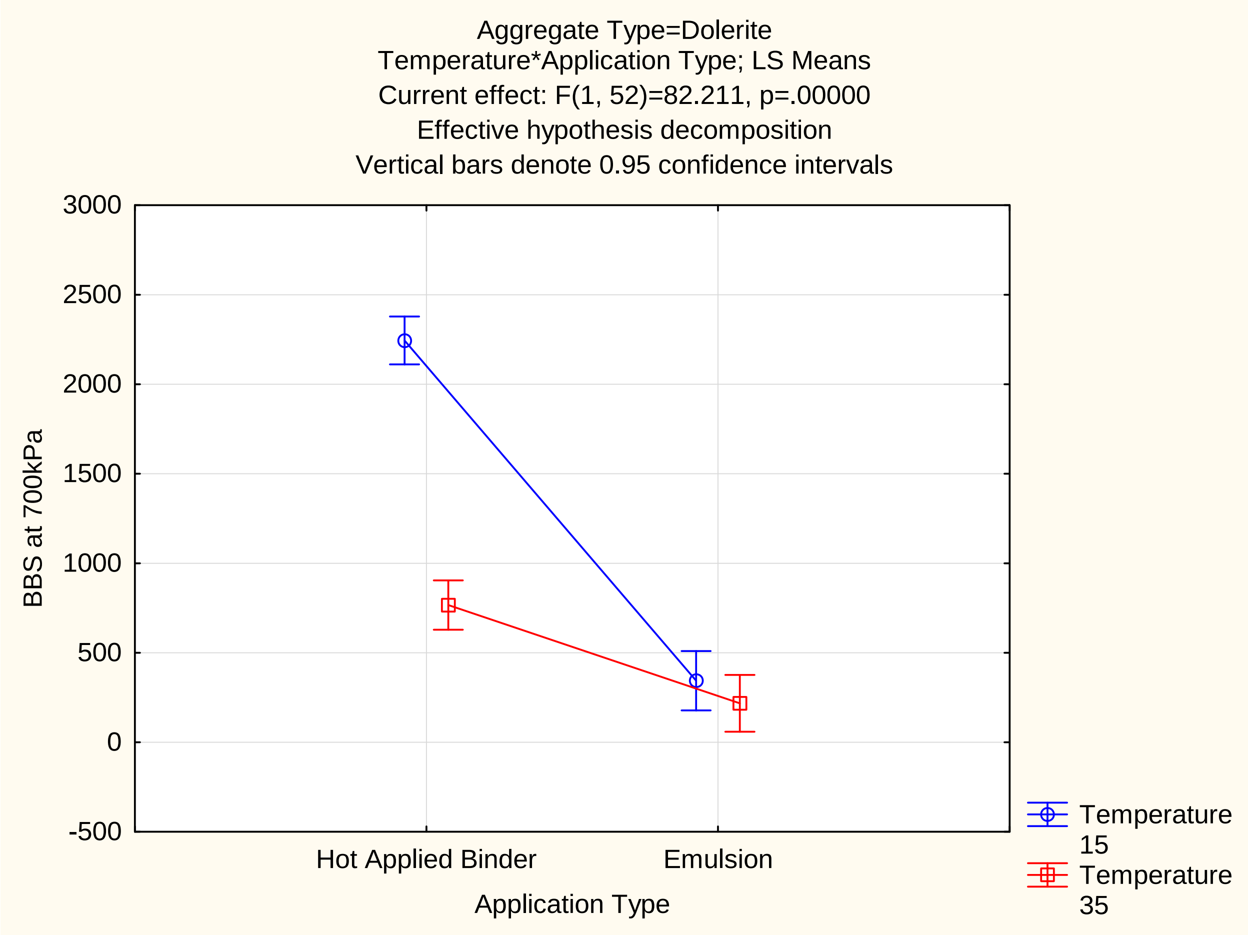


Aggregate Type=Dolerite

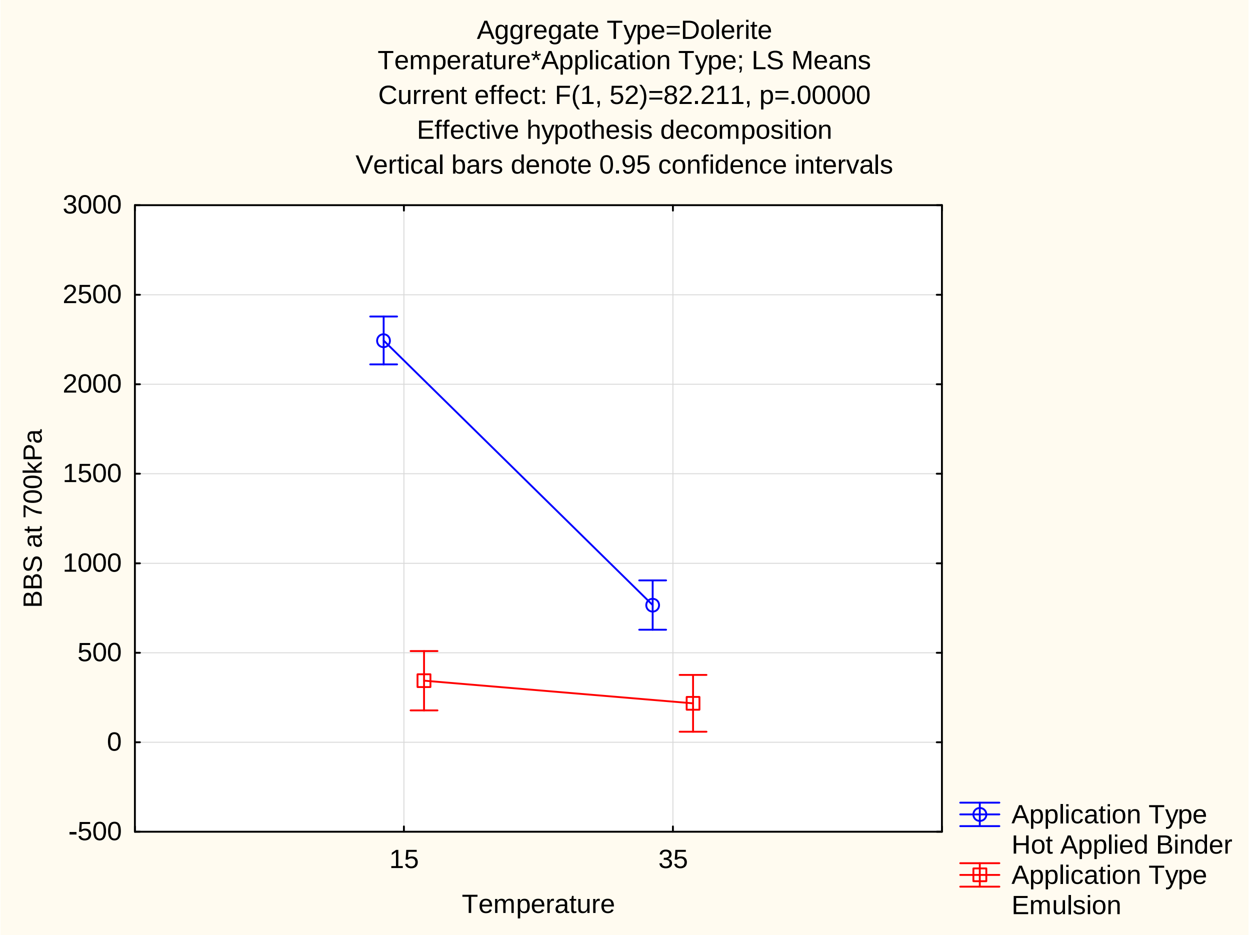
Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Aggregate Type=Dolerite Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova 20 Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	43194048	1	43194048	574.5346	0.000000
Temperature	8709630	1	8709630	115.8489	0.000000
Application Type	20301885	1	20301885	270.0403	0.000000
Temperature*Application Type	6180708	1	6180708	82.2111	0.000000
Error	3909409	52	75181		

*Temperature*Application Type; LS Means*



*Temperature*Application Type; LS Means*



Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

Aggregate Type=Dolerite
Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta)
Probabilities for Post Hoc Tests
Error: Between MS = 75181., df = 52.000

Cell No.	Temperature	Application Type	{1} 2244.7	{2} 344.08	{3} 766.65	{4} 217.65
1	15	Hot Applied Binder		0.000000	0.000000	0.000000
2	15	Emulsion	0.00		0.001489	1.000000
3	35	Hot Applied Binder	0.00	0.001489		0.000018
4	35	Emulsion	0.00	1.000000	0.000018	

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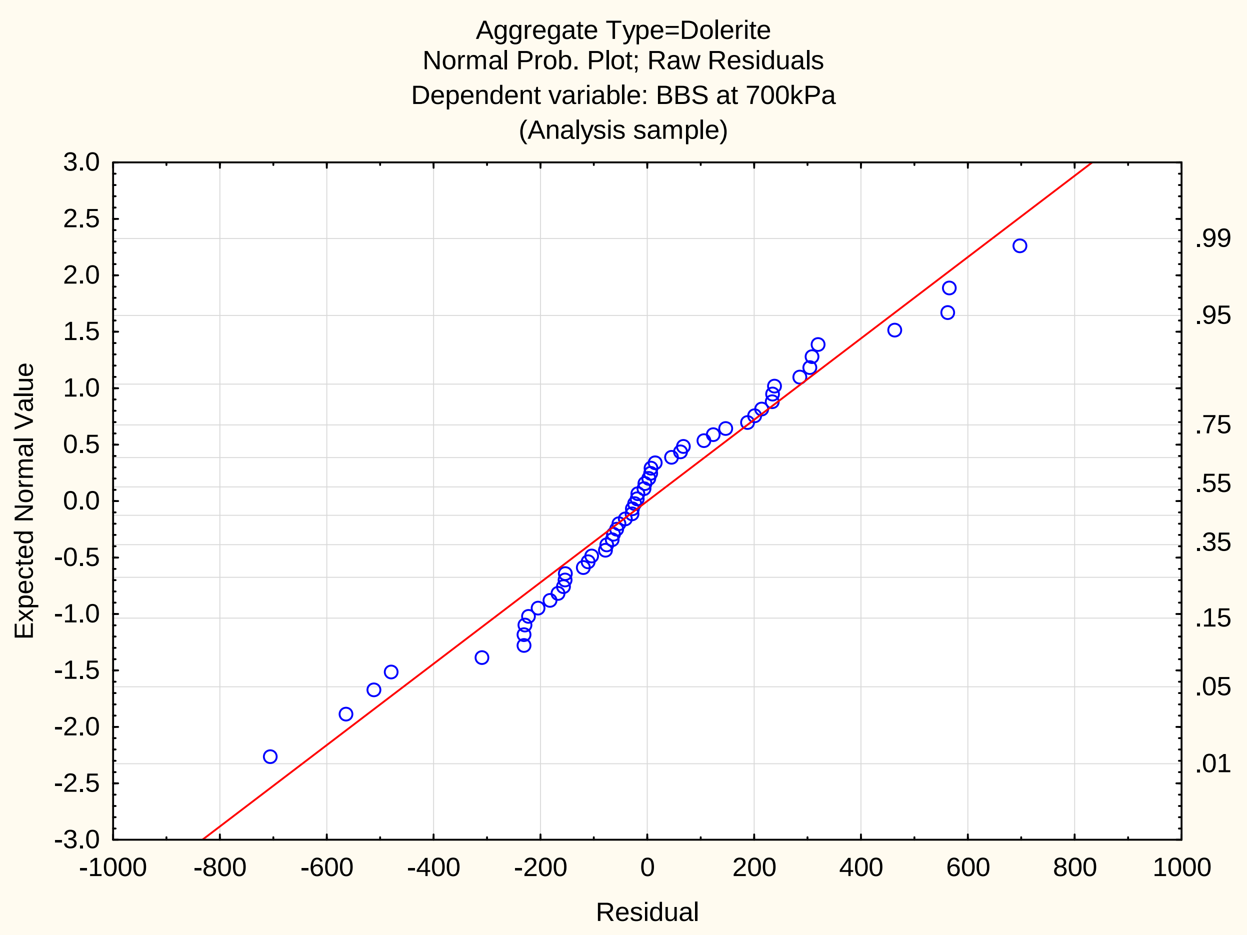
Normal Prob. Plot; Raw Residuals



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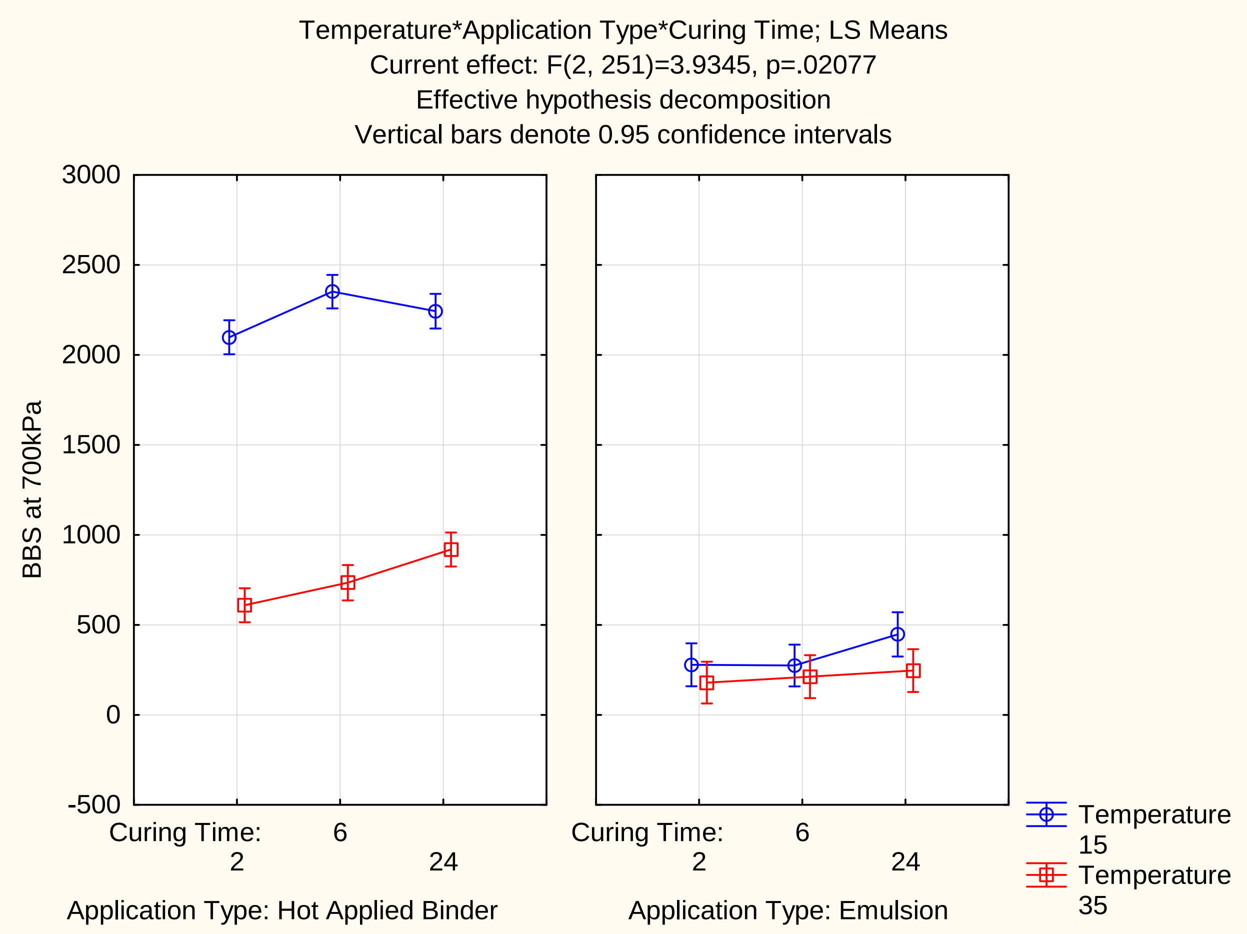
d. 3-WAY ANOVA (DATA BBS LERICHELOMBARD)

ANOVA RESULTS 1: DATA BBS LERICHELOMBARD

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova 20140 Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	195036830	1	195036830	3130.758	0.000000
Temperature	39922892	1	39922892	640.848	0.000000
Application Type	93090694	1	93090694	1494.305	0.000000
Curing Time	1255647	2	627823	10.078	0.000062
Temperature*Application Type	28773439	1	28773439	461.875	0.000000
Temperature*Curing Time	62164	2	31082	0.499	0.607780
Application Type*Curing Time	329116	2	164558	2.642	0.073234
Temperature*Application Type*Curing	490217	2	245108	3.935	0.020773
Error	15636548	251	62297		

Temperature*Application Type*Curing Time; LS Means



Temperature*Application Type*Curing Time; LS Means (DATA BBS LeRicheLombard)

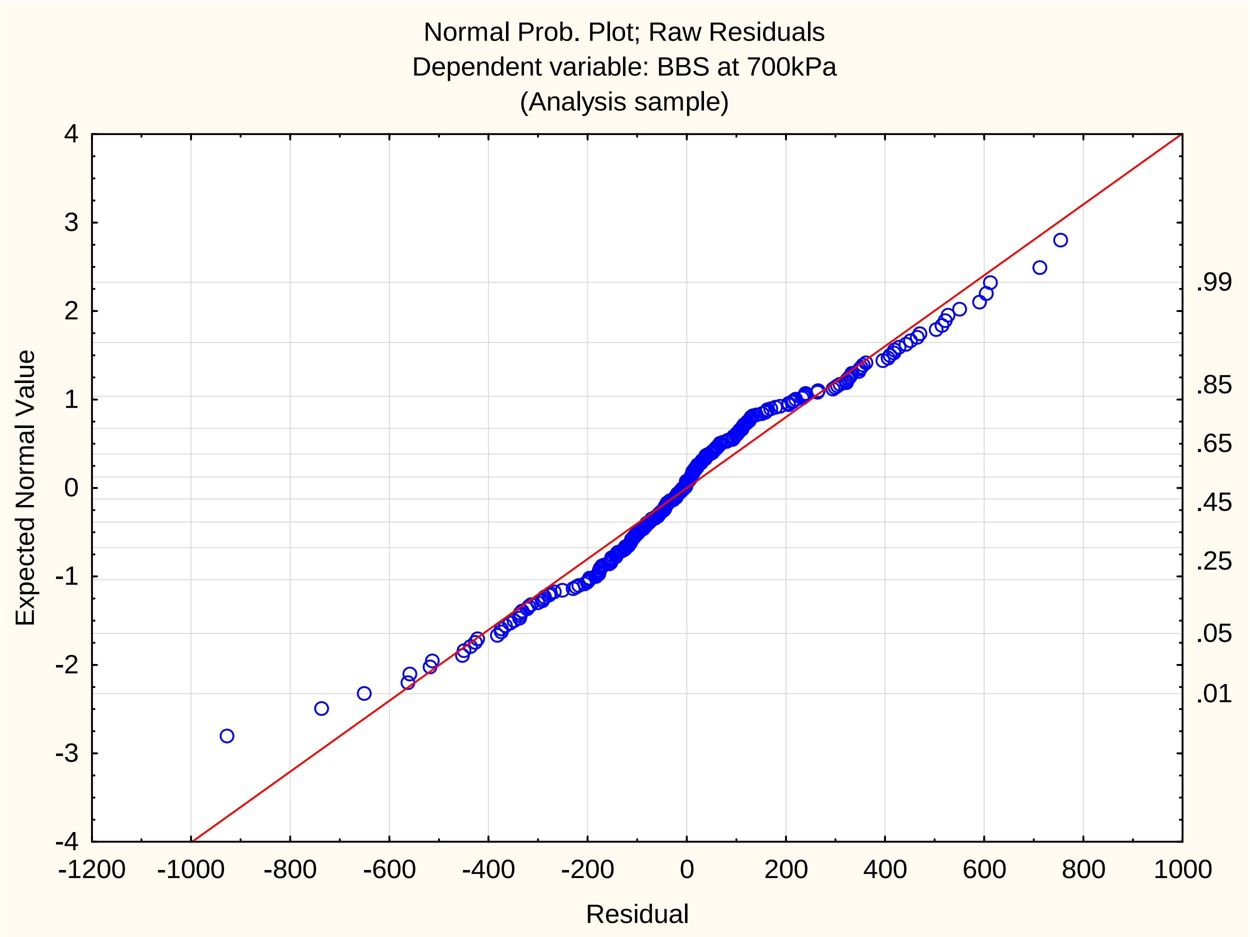
Temperature*Application Type*Curing Time; LS Means (DATA InputAnova 20140820.sta)
Current effect: F(2, 251)=3.9345, p=.02077
Effective hypothesis decomposition

Cell No.	Temperature	Application Type	Curing Time	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	Hot Applied Binder	2	2098.252	48.03433	2003.650	2192.853	27
2	15	Hot Applied Binder	6	2351.750	47.16877	2258.853	2444.647	28
3	15	Hot Applied Binder	24	2243.358	48.94935	2146.954	2339.762	26
4	15	Emulsion	2	278.184	60.53536	158.962	397.406	17
5	15	Emulsion	6	274.394	58.82979	158.531	390.257	18
6	15	Emulsion	24	447.085	62.39842	324.194	569.976	16
7	35	Hot Applied Binder	2	609.204	48.03433	514.602	703.805	27
8	35	Hot Applied Binder	6	734.359	49.91874	636.046	832.672	25
9	35	Hot Applied Binder	24	919.014	48.03433	824.412	1013.616	27
10	35	Emulsion	2	179.170	58.82979	63.307	295.033	18
11	35	Emulsion	6	212.436	60.53536	93.214	331.658	17
12	35	Emulsion	24	246.097	60.53536	126.875	365.319	17

Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

Cell No.	Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta) Probabilities for Post Hoc Tests Error: Between MS = 62297., df = 251.00														
	Temperature	Application Type	Curing Time	{1} 2098.3	{2} 2351.8	{3} 2243.4	{4} 278.18	{5} 274.39	{6} 447.08	{7} 609.20	{8} 734.36	{9} 919.01	{10} 179.17	{11} 212.4	{12} 246.10
1	15	Hot Applied Binder	2		0.014	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	15	Hot Applied Binder	6	0.014		1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	15	Hot Applied Binder	24	1.000	1.000		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	15	Emulsion	2	0.000	0.000	0.000		1.000	1.000	0.002	0.000	0.000	1.000	1.000	1.000
5	15	Emulsion	6	0.000	0.000	0.000	1.000		1.000	0.001	0.000	0.000	1.000	1.000	1.000
6	15	Emulsion	24	0.000	0.000	0.000	1.000	1.000		1.000	0.026	0.000	0.132	0.490	1.000
7	35	Hot Applied Binder	2	0.000	0.000	0.000	0.002	0.001	1.000		1.000	0.001	0.000	0.000	0.000
8	35	Hot Applied Binder	6	0.000	0.000	0.000	0.000	0.000	0.026	1.000		0.540	0.000	0.000	0.000
9	35	Hot Applied Binder	24	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.540		0.000	0.000	0.000
10	35	Emulsion	2	0.000	0.000	0.000	1.000	1.000	0.132	0.000	0.000	0.000		1.000	1.000
11	35	Emulsion	6	0.000	0.000	0.000	1.000	1.000	0.490	0.000	0.000	0.000	1.000		1.000
12	35	Emulsion	24	0.000	0.000	0.000	1.000	1.000	1.000	0.000	0.000	0.000	1.000	1.000	

Normal Prob. Plot; Raw Residuals



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e. 2-WAY ANOVA PER CURING TIME (DATA BBS LERICHELOMBARD)

ANOVA RESULTS 1: DATA BBS LERICHELOMBARD

All Groups

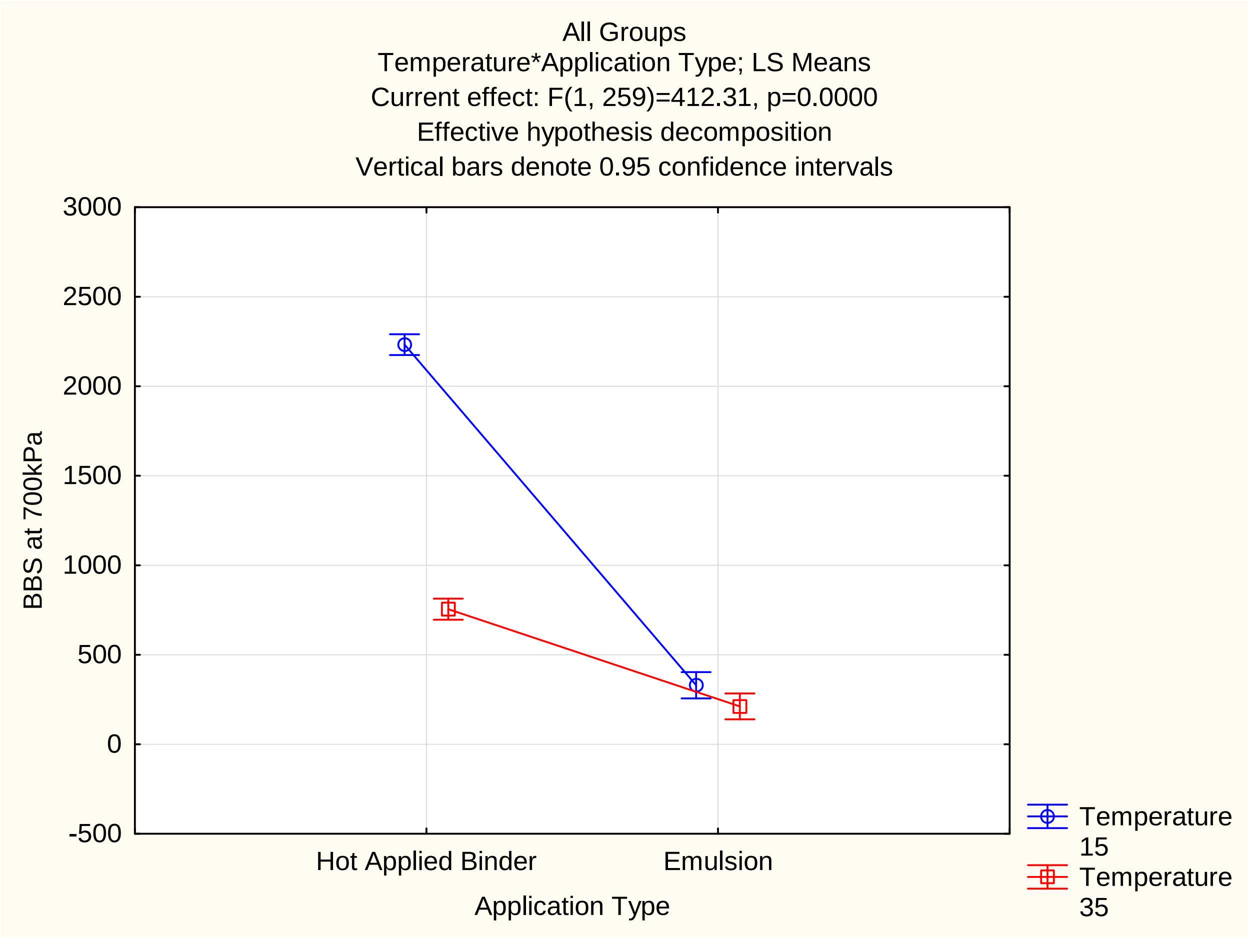
Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	All Groups Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	195061648	1	195061648	2776.625	0.00
Temperature	39882080	1	39882080	567.706	0.00
Application Type	93667071	1	93667071	1333.314	0.00
Temperature*Application Type	28965102	1	28965102	412.307	0.00
Error	18195097	259	70251		

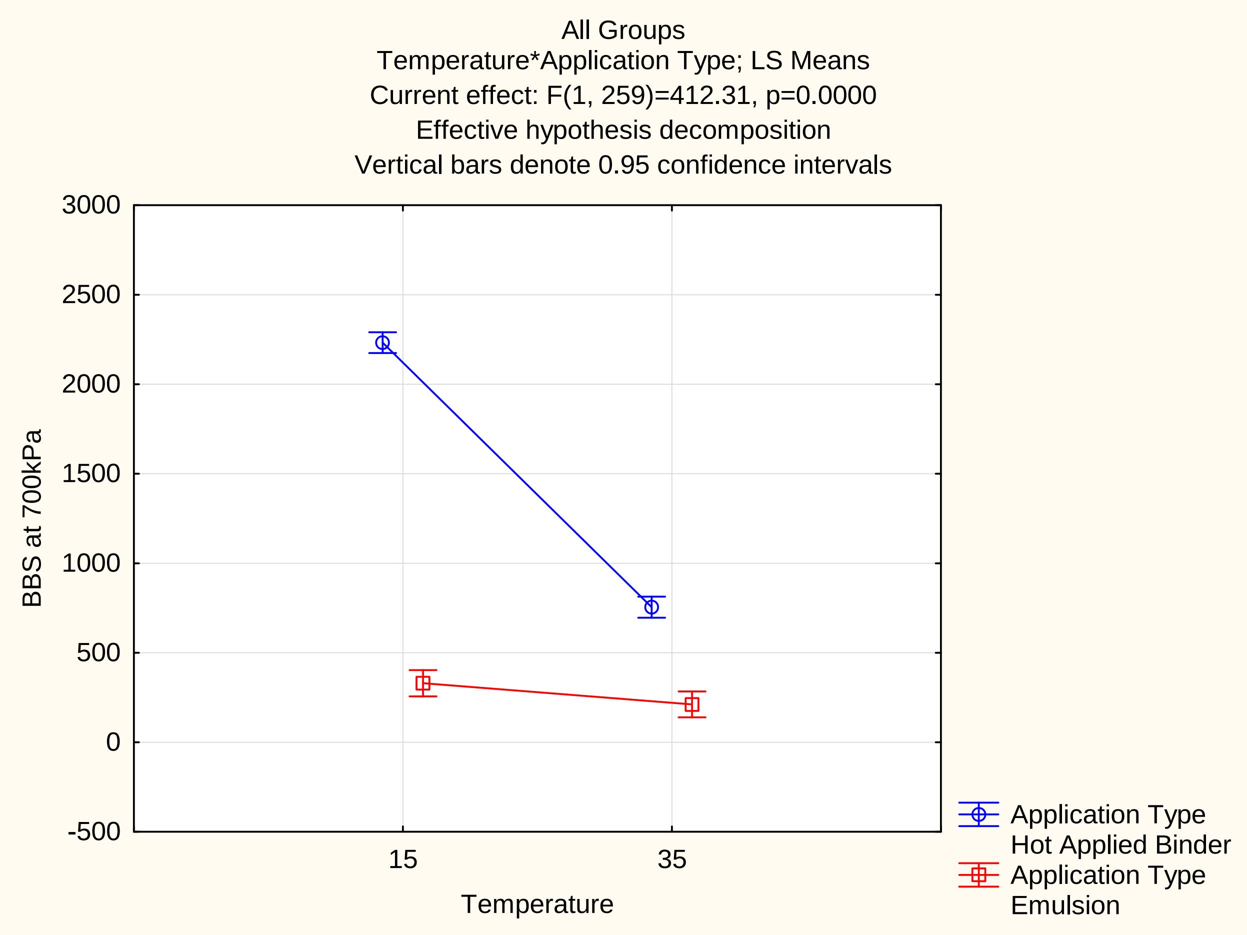
*Temperature*Application Type; LS Means (DATA BBS LeRicheLombard)*

	All Groups Temperature*Application Type; LS Means (DATA InputAnova 20140820.sta) Current effect: F(1, 259)=412.31, p=0.0000 Effective hypothesis decomposition						
Cell No.	Temperature	Application Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	Hot Applied Binder	2232.458	29.44997	2174.466	2290.450	81
2	15	Emulsion	329.835	37.11438	256.750	402.919	51
3	35	Hot Applied Binder	754.694	29.82042	695.973	813.416	79
4	35	Emulsion	211.926	36.75578	139.547	284.304	52

*Temperature*Application Type; LS Means*



*Temperature*Application Type; LS Means*



Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

All Groups
Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta)
Probabilities for Post Hoc Tests
Error: Between MS = 70251., df = 259.00

Cell No.	Temperature	Application Type	{1} 2232.5	{2} 329.83	{3} 754.69	{4} 211.93
1	15	Hot Applied Binde		0.000000	0.000000	0.000000
2	15	Emulsio	0.00		0.000000	0.148938
3	35	Hot Applied Binde	0.00	0.000000		0.000000
4	35	Emulsio	0.00	0.148938	0.000000	

Curing Time=2

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

Curing Time=2
Univariate Tests of Significance for BBS at 700kPa (DATA InputAno
Sigma-restricted parameterization
Effective hypothesis decomposition

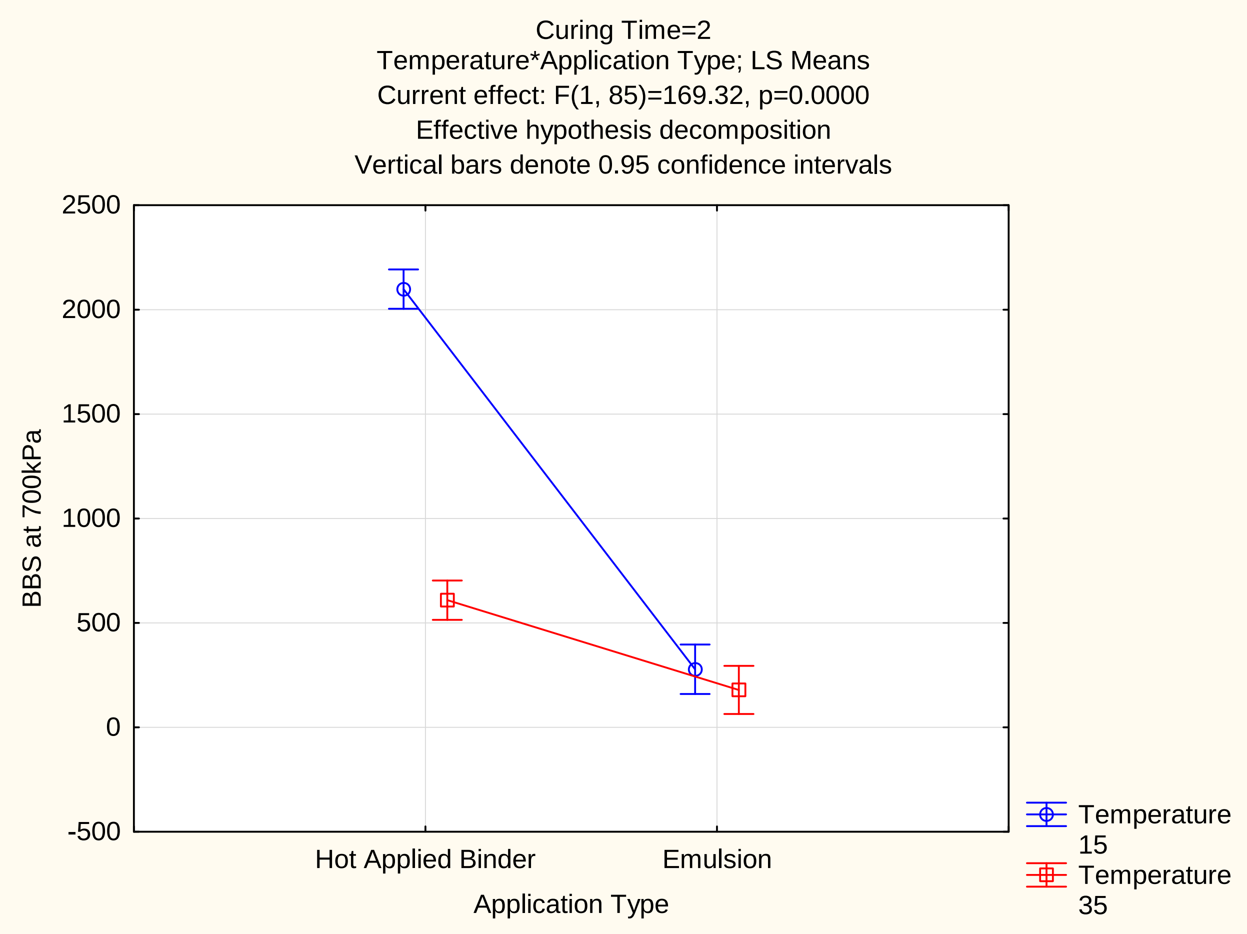
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	53148590	1	53148590	877.7246	0.00
Temperature	13382323	1	13382323	221.0029	0.00
Application Type	26865843	1	26865843	443.6771	0.00
Temperature*Application Type	10252914	1	10252914	169.3222	0.00
Error	5146979	85	60553		

*Temperature*Application Type; LS Means (DATA BBS LeRicheLombard)*

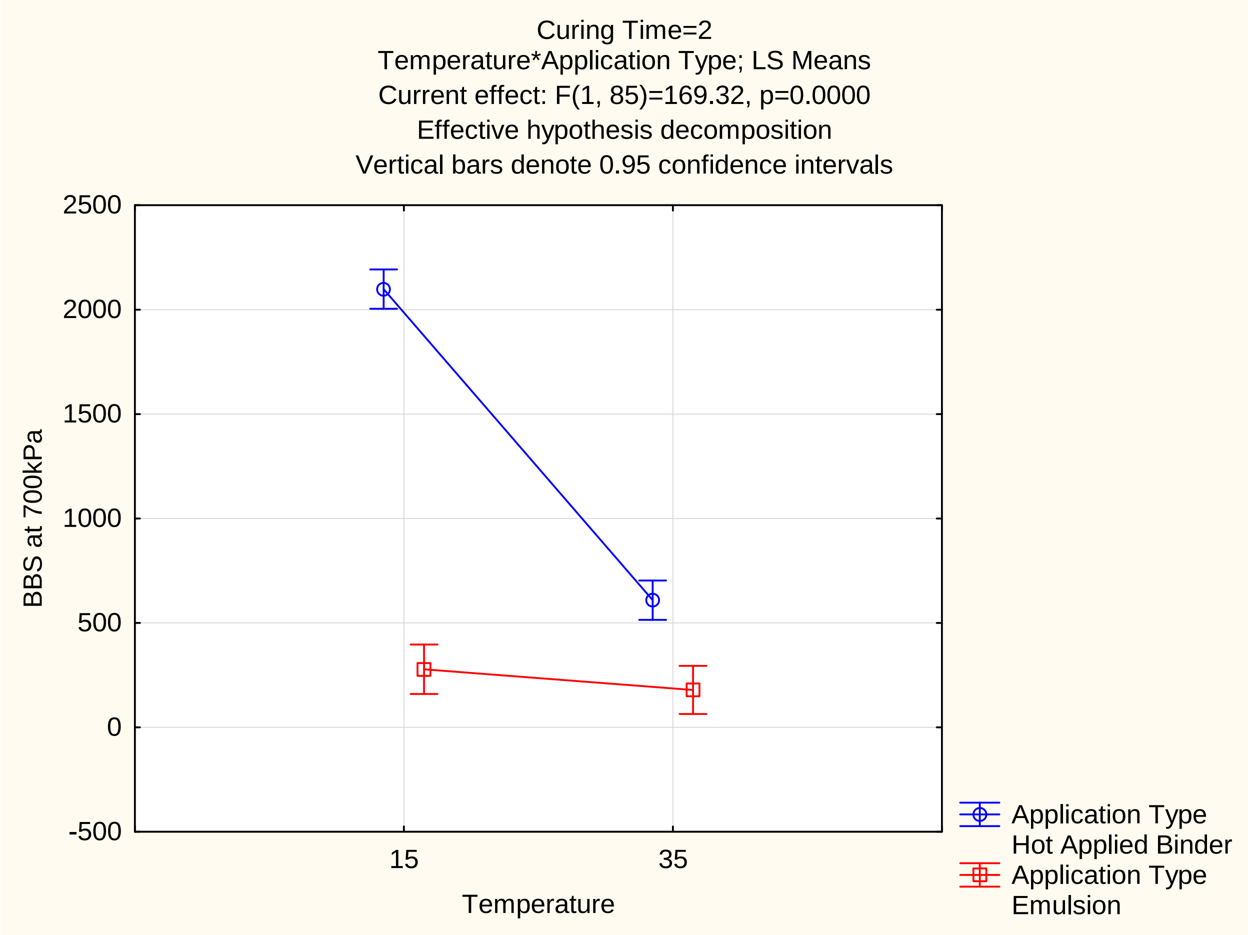
Curing Time=2
Temperature*Application Type; LS Means (DATA InputAnova 20140820.sta)
Current effect: F(1, 85)=169.32, p=0.0000
Effective hypothesis decomposition

Cell No.	Temperature	Application Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	Hot Applied Binder	2098.252	47.35707	2004.093	2192.410	27
2	15	Emulsion	278.184	59.68185	159.521	396.848	17
3	35	Hot Applied Binder	609.204	47.35707	515.045	703.362	27
4	35	Emulsion	179.170	58.00033	63.850	294.490	18

*Temperature*Application Type; LS Means*



*Temperature*Application Type; LS Means*



Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

Curing Time=2
Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta)
Probabilities for Post Hoc Tests
Error: Between MS = 60553., df = 85.000

Cell No.	Temperature	Application Type	{1} 2098.3	{2} 278.18	{3} 609.20	{4} 179.17
1	15	Hot Applied Binder		0.000000	0.000000	0.000000
2	15	Emulsion	0.00		0.000230	1.000000
3	35	Hot Applied Binder	0.00	0.000230		0.000001
4	35	Emulsion	0.00	1.000000	0.000001	

Curing Time=6

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

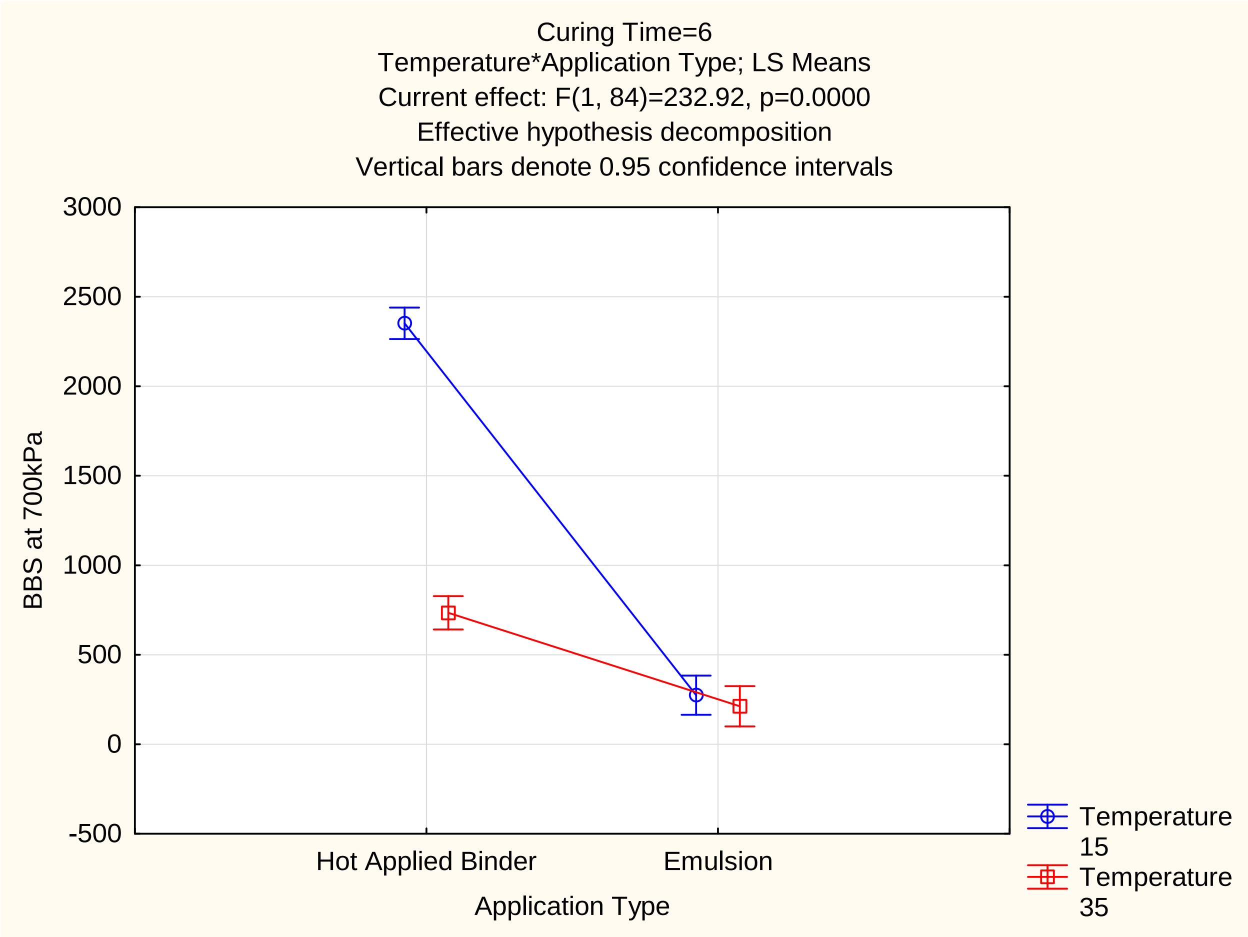
Curing Time=6
Univariate Tests of Significance for BBS at 700kPa (DATA InputAnov
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	67155921	1	67155921	1228.999	0.00
Temperature	14835930	1	14835930	271.508	0.00
Application Type	35541761	1	35541761	650.438	0.00
Temperature*Application Type	12727293	1	12727293	232.918	0.00
Error	4589993	84	54643		

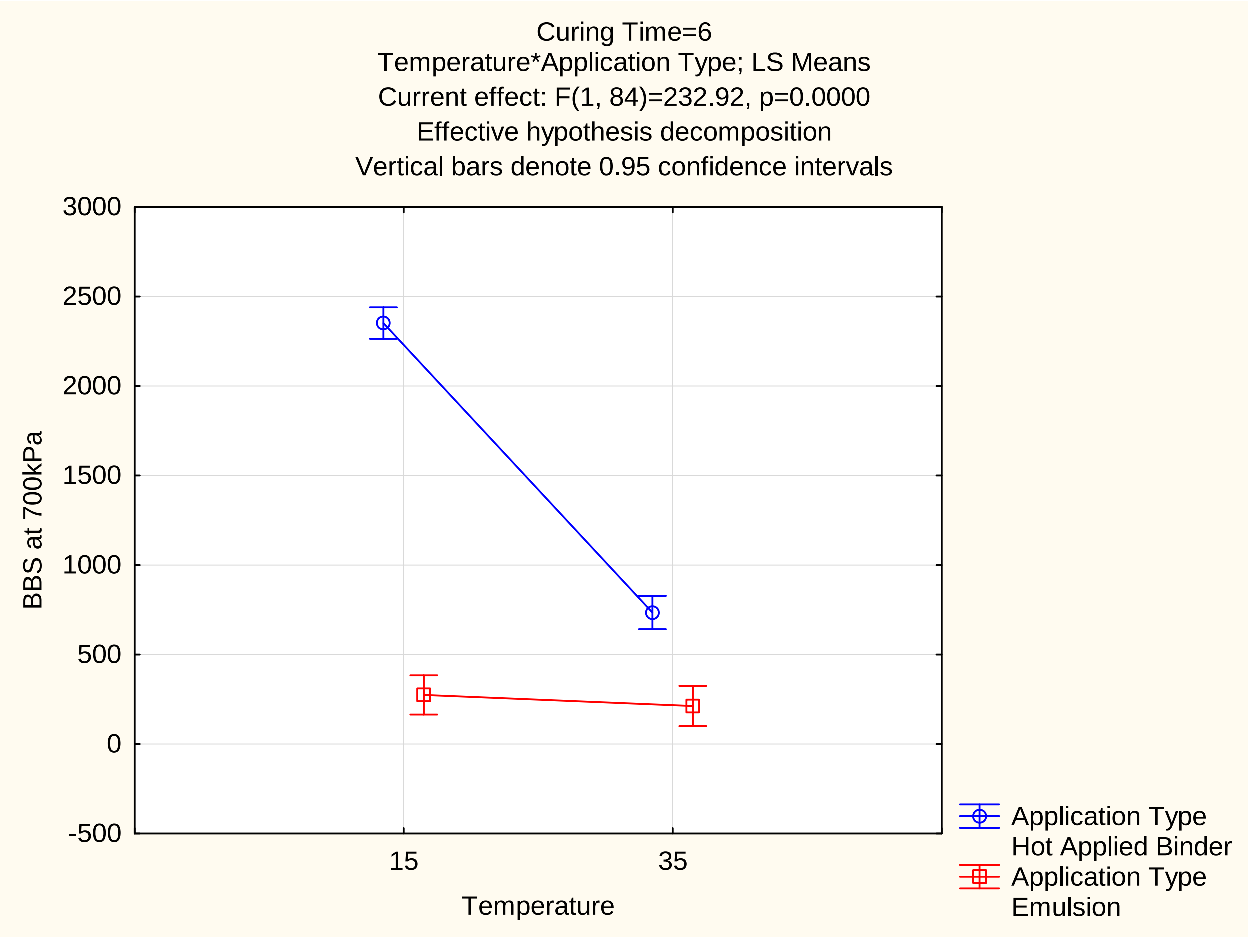
*Temperature*Application Type; LS Means (DATA BBS LeRicheLombard)*

	Curing Time=6 Temperature*Application Type; LS Means (DATA InputAnova 20140820.sta) Current effect: F(1, 84)=232.92, p=0.0000 Effective hypothesis decomposition						
Cell No.	Temperature	Application Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	Hot Applied Binder	2351.750	44.17610	2263.901	2439.599	28
2	15	Emulsion	274.394	55.09727	164.827	383.961	18
3	35	Hot Applied Binder	734.359	46.75159	641.388	827.330	25
4	35	Emulsion	212.436	56.69463	99.693	325.180	17

*Temperature*Application Type; LS Means*



*Temperature*Application Type; LS Means*



Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

Curing Time=6
Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta)
Probabilities for Post Hoc Tests
Error: Between MS = 54643., df = 84.000

Cell No.	Temperature	Application Type	{1} 2351.8	{2} 274.39	{3} 734.36	{4} 212.44
1	15	Hot Applied Binder		0.000000	0.000000	0.000000
2	15	Emulsion	0.00		0.000000	1.000000
3	35	Hot Applied Binder	0.00	0.000000		0.000000
4	35	Emulsion	0.00	1.000000	0.000000	

Curing Time=24

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

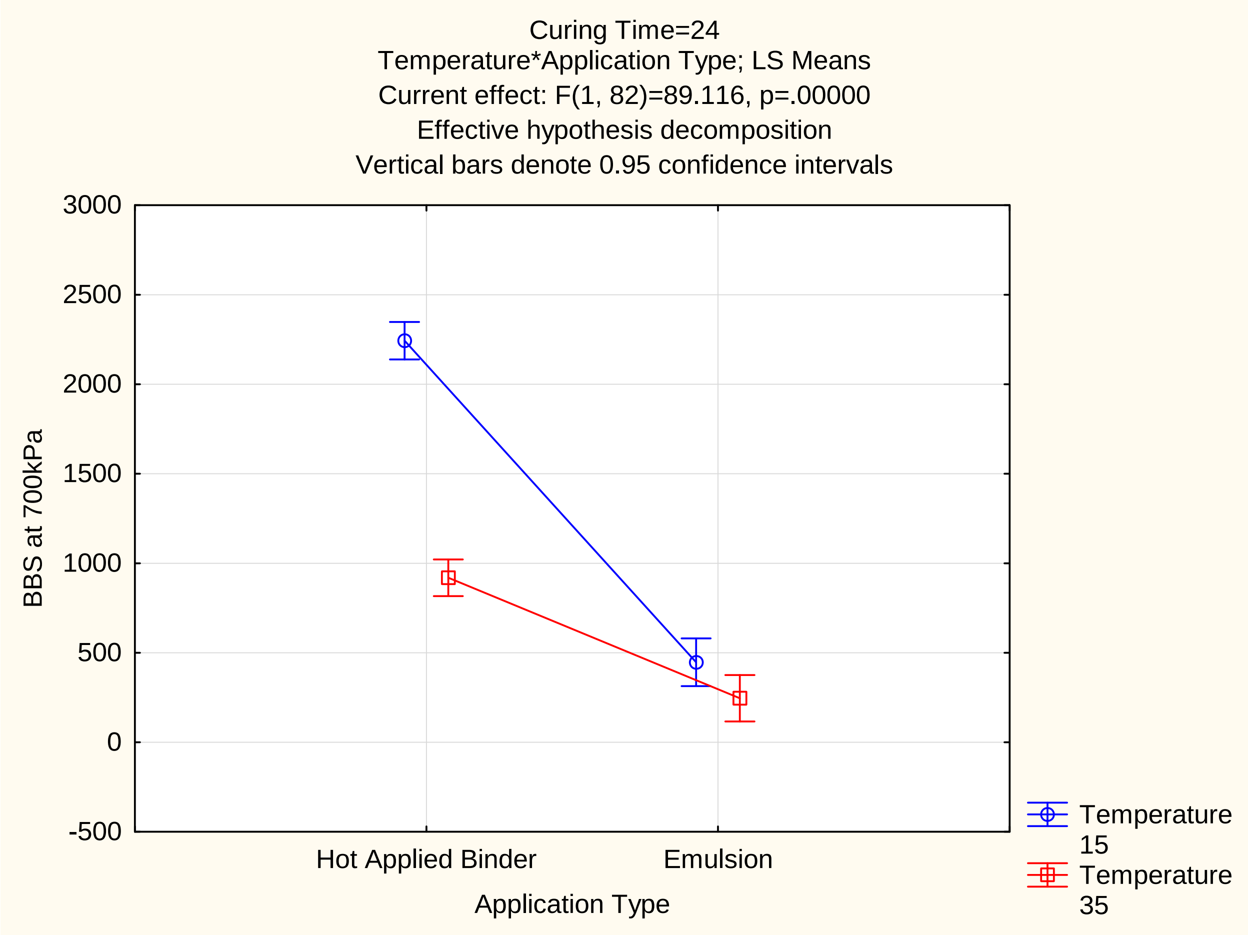
Curing Time=24
Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova 20
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	75526575	1	75526575	1049.767	0.000000
Temperature	11821013	1	11821013	164.304	0.000000
Application Type	30976697	1	30976697	430.555	0.000000
Temperature*Application Type	6411532	1	6411532	89.116	0.000000
Error	5899576	82	71946		

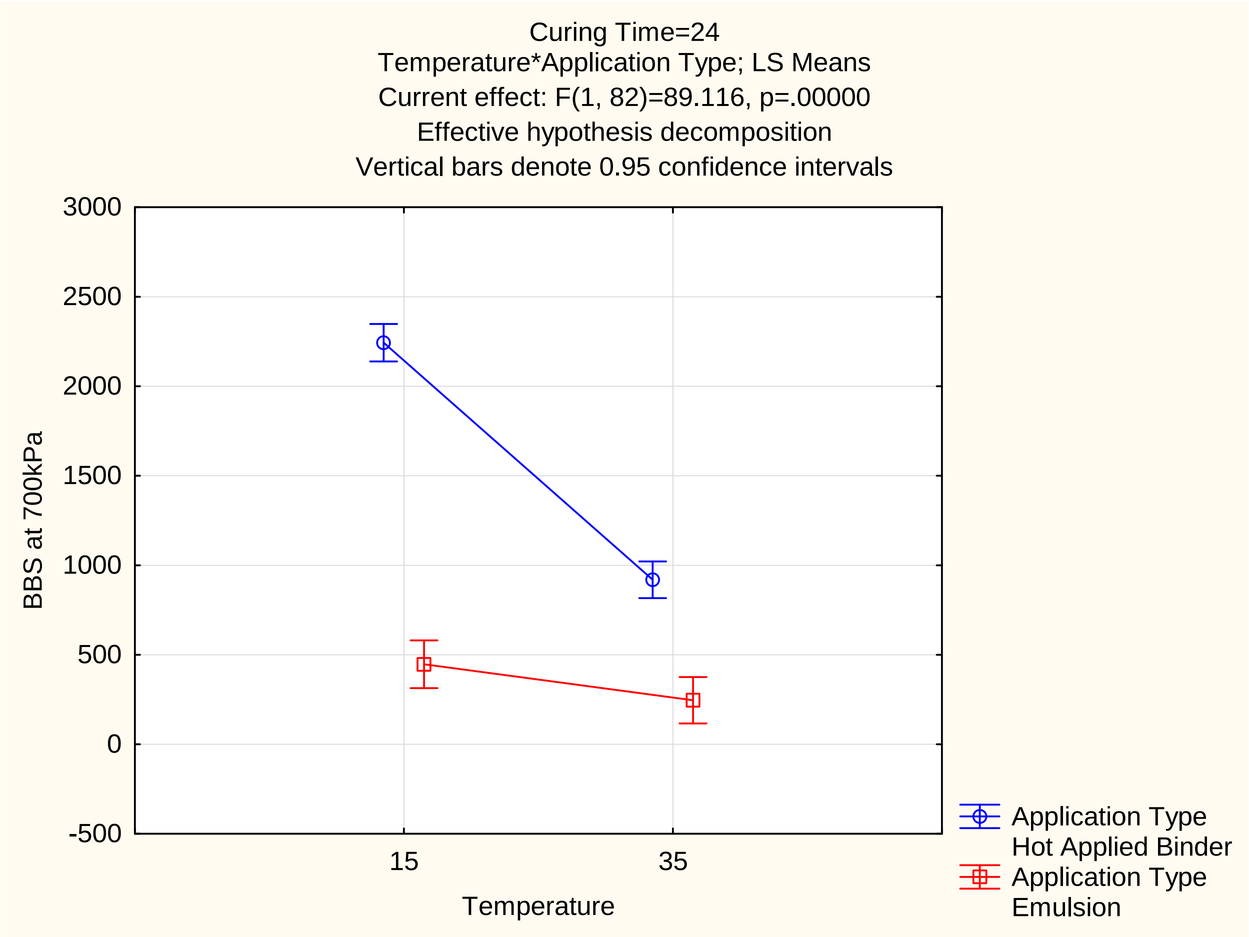
*Temperature*Application Type; LS Means (DATA BBS LeRicheLombard)*

Cell No.	Curing Time=24 Temperature*Application Type; LS Means (DATA InputAnova 20140820.sta) Current effect: F(1, 82)=89.116, p=.00000 Effective hypothesis decomposition Temperature	Application Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	Hot Applied Binder	2243.358	52.60376	2138.713	2348.004	26
2	15	Emulsion	447.085	67.05690	313.687	580.482	16
3	35	Hot Applied Binder	919.014	51.62043	816.324	1021.703	27
4	35	Emulsion	246.097	65.05475	116.683	375.512	17

*Temperature*Application Type; LS Means*



*Temperature*Application Type; LS Means*



Bonferroni test; variable BBS at 700kPa (DATA BBS LeRicheLombard)

Curing Time=24
Bonferroni test; variable BBS at 700kPa (DATA InputAnova 20140820.sta)
Probabilities for Post Hoc Tests
Error: Between MS = 71946., df = 82.000

Cell No.	Temperature	Application Type	{1} 2243.4	{2} 447.08	{3} 919.01	{4} 246.10
1	15	Hot Applied Binder		0.000000	0.000000	0.000000
2	15	Emulsion	0.00		0.000002	0.206390
3	35	Hot Applied Binder	0.00	0.000002		0.000000
4	35	Emulsion	0.00	0.206390	0.000000	

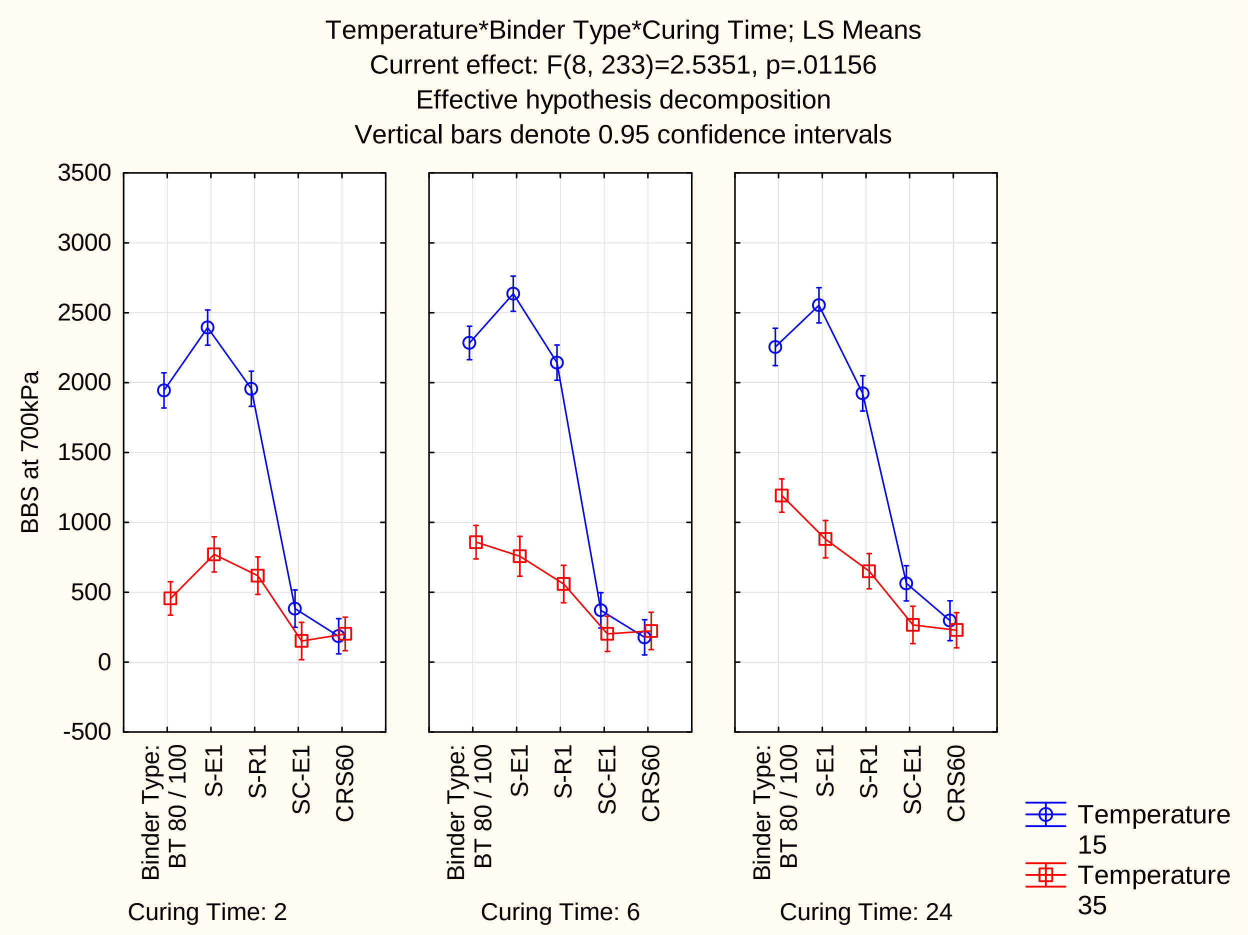
f. 3-WAY ANOVA (DATA BBS LERICHELOMBARD)

ANOVA RESULTS 1: DATA BBS LERICHELOMBARD

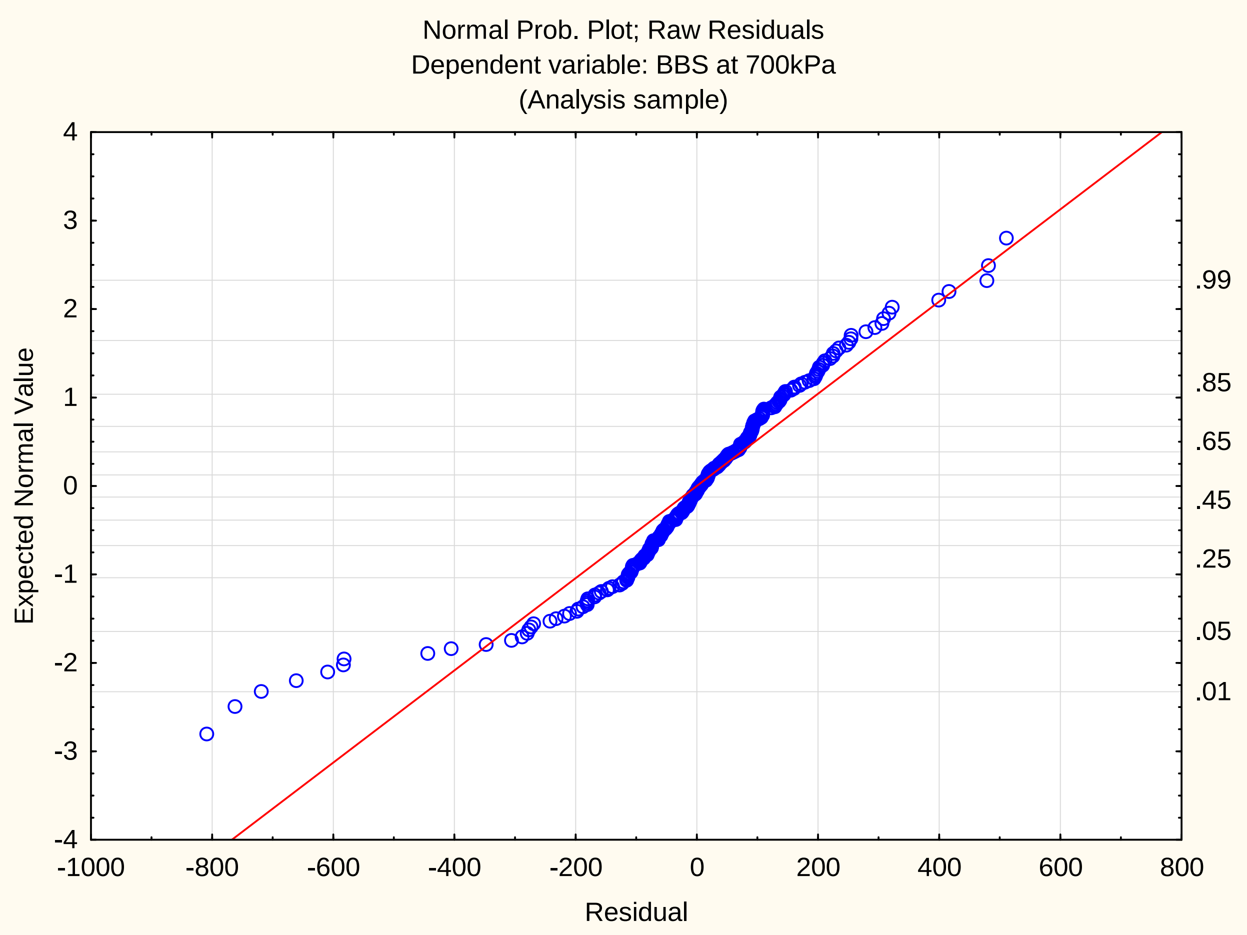
Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova 20140 Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	262130455	1	262130455	7112.504	0.000000
Temperature	57180849	1	57180849	1551.514	0.000000
Binder Type	95933777	4	23983444	650.754	0.000000
Curing Time	1376020	2	688010	18.668	0.000000
Temperature*Binder Type	30255750	4	7563938	205.236	0.000000
Temperature*Curing Time	174403	2	87202	2.366	0.096099
Binder Type*Curing Time	1736372	8	217046	5.889	0.000001
Temperature*Binder Type*Curing Time	747448	8	93431	2.535	0.011558
Error	8587187	233	36855		

Temperature*Binder Type*Curing Time; LS Means



Normal Prob. Plot; Raw Residuals



g. 2-way ANOVA per Curing Time (DATA BBS LeRicheLombard)

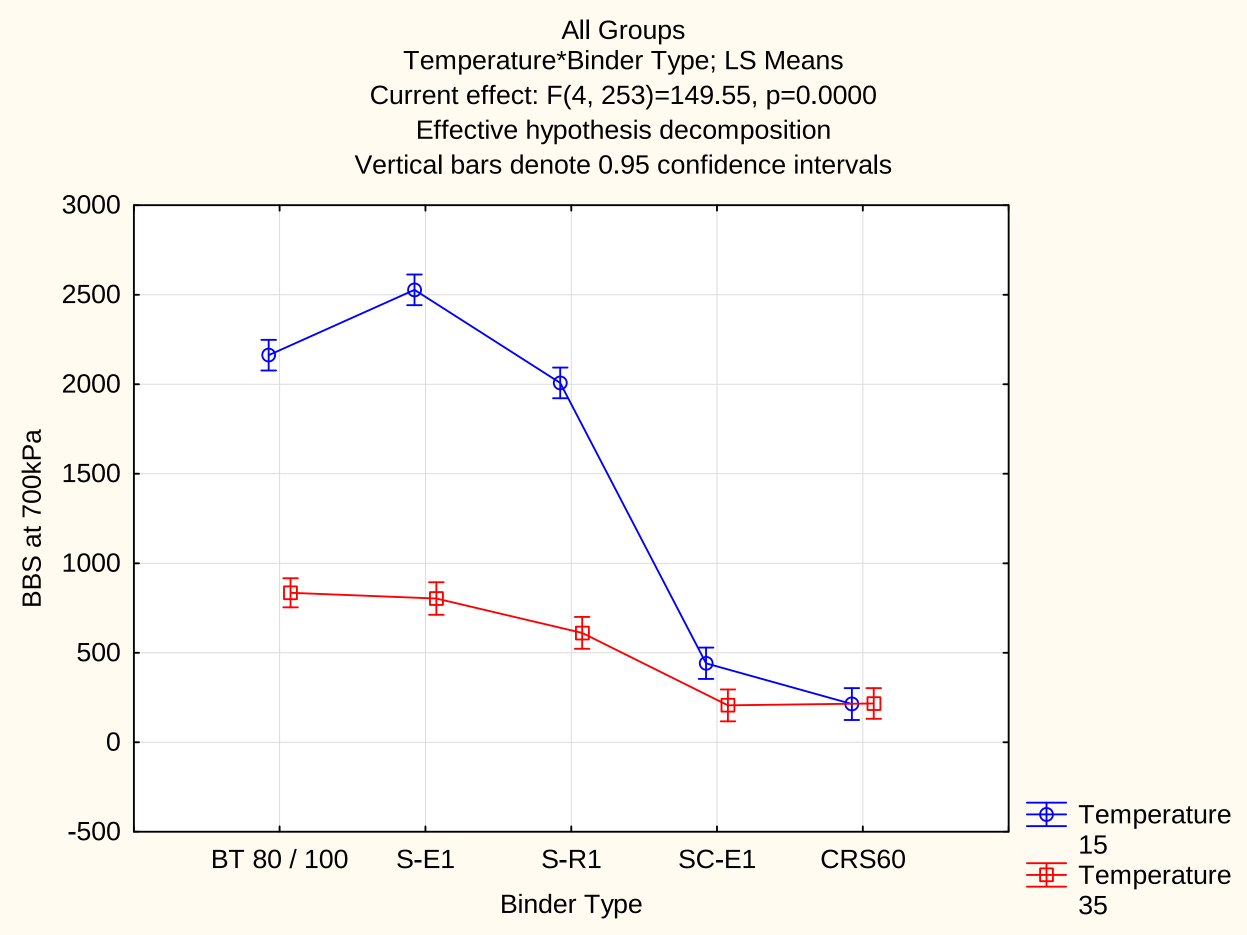
ANOVA Results 1: DATA BBS LeRicheLombard

All Groups

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	All Groups Univariate Tests of Significance for BBS at 700kPa (DATA InputAnova Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	263407347	1	263407347	5161.102	0.00
Temperature	57376556	1	57376556	1124.214	0.00
Binder Type	96850433	4	24212608	474.413	0.00
Temperature*Binder Type	30530006	4	7632502	149.548	0.00
Error	12912369	253	51037		

*Temperature*Binder Type; LS Means*



*Temperature*Binder Type; LS Means (DATA BBS LeRicheLombard)*

All Groups
Temperature*Binder Type; LS Means (DATA InputAnova 20140820.sta)
Current effect: F(4, 253)=149.55, p=0.0000
Effective hypothesis decomposition

Cell No.	Temperature	Binder Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	BT 80 / 100	2162.219	43.47713	2076.595	2247.842	27
2	15	S-E1	2527.723	43.47713	2442.100	2613.347	27
3	15	S-R1	2007.432	43.47713	1921.809	2093.056	27
4	15	SC-E1	441.396	44.30534	354.142	528.650	26
5	15	CRS60	213.811	45.18275	124.829	302.794	25
6	35	BT 80 / 100	835.411	41.24602	754.182	916.640	30
7	35	S-E1	803.269	46.11446	712.452	894.086	24
8	35	S-R1	611.203	45.18275	522.220	700.185	25
9	35	SC-E1	206.398	45.18275	117.416	295.381	25
10	35	CRS60	217.044	43.47713	131.420	302.667	27

Curing Time=2

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Curing Time=2 Univariate Tests of Significance for BBS at 700kPa (DATA InputAno Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	72623056	1	72623056	1728.681	0.00
Temperature	19243604	1	19243604	458.065	0.00
Binder Type	28495006	4	7123751	169.570	0.00
Temperature*Binder Type	10533833	4	2633458	62.685	0.00
Error	3318843	79	42011		

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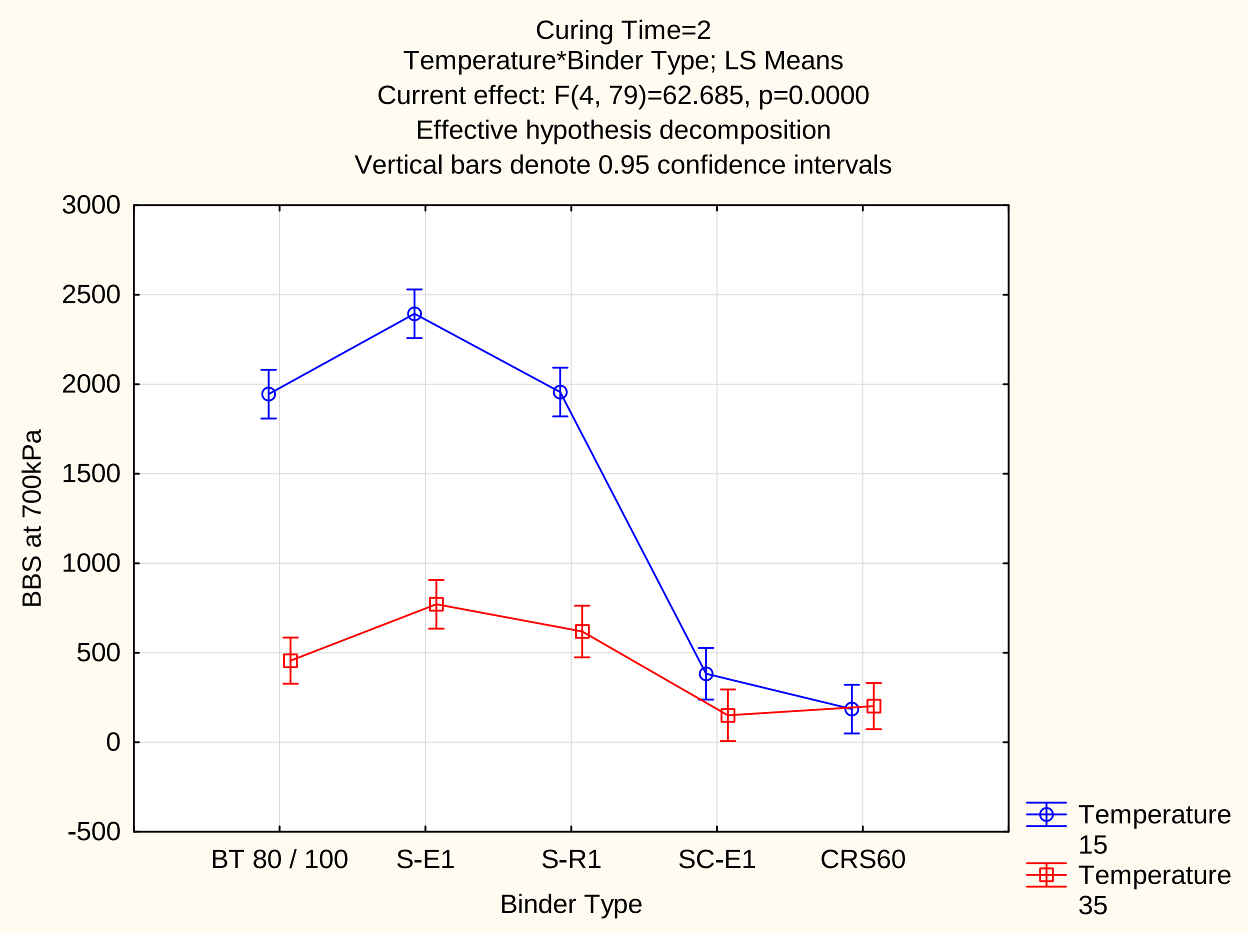
*Temperature*Binder Type; LS Means*



*Temperature*Binder Type; LS Means (DATA BBS LeRicheLombard)*

Curing Time=2
Temperature*Binder Type; LS Means (DATA InputAnova 20140820.sta)
Current effect: F(4, 79)=62.685, p=0.0000
Effective hypothesis decomposition

Cell No.	Temperature	Binder Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	BT 80 / 100	1944.682	68.32168	1808.691	2080.673	9
2	15	S-E1	2393.818	68.32168	2257.827	2529.809	9
3	15	S-R1	1956.255	68.32168	1820.264	2092.246	9
4	15	SC-E1	382.720	72.46609	238.480	526.961	8
5	15	CRS60	185.263	68.32168	49.272	321.254	9
6	35	BT 80 / 100	455.832	64.81564	326.820	584.845	10
7	35	S-E1	770.972	68.32168	634.981	906.963	9
8	35	S-R1	618.928	72.46609	474.688	763.168	8
9	35	SC-E1	150.853	72.46609	6.613	295.093	8
10	35	CRS60	201.824	64.81564	72.812	330.836	10

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Curing Time=6

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Curing Time=6 Univariate Tests of Significance for BBS at 700kPa (DATA InputAno Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	90819622	1	90819622	2486.131	0.00
Temperature	21861525	1	21861525	598.446	0.00
Binder Type	36192336	4	9048084	247.686	0.00
Temperature*Binder Type	13132614	4	3283154	89.874	0.00
Error	2849380	78	36531		

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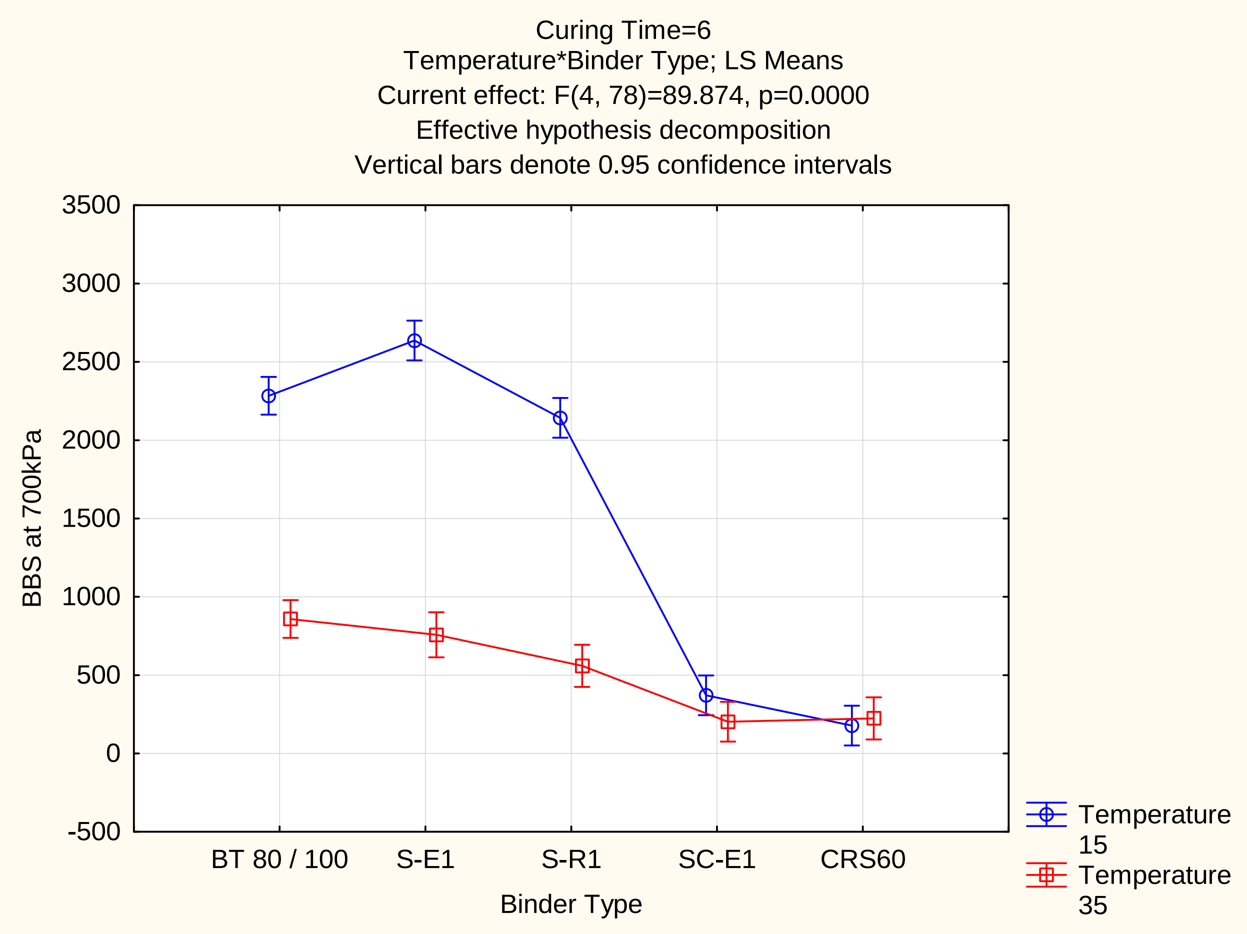
Temperature*Binder Type; LS Means



*Temperature*Binder Type; LS Means (DATA BBS LeRicheLombard)*

Curing Time=6
Temperature*Binder Type; LS Means (DATA InputAnova 20140820.sta)
Current effect: F(4, 78)=89.874, p=0.0000
Effective hypothesis decomposition

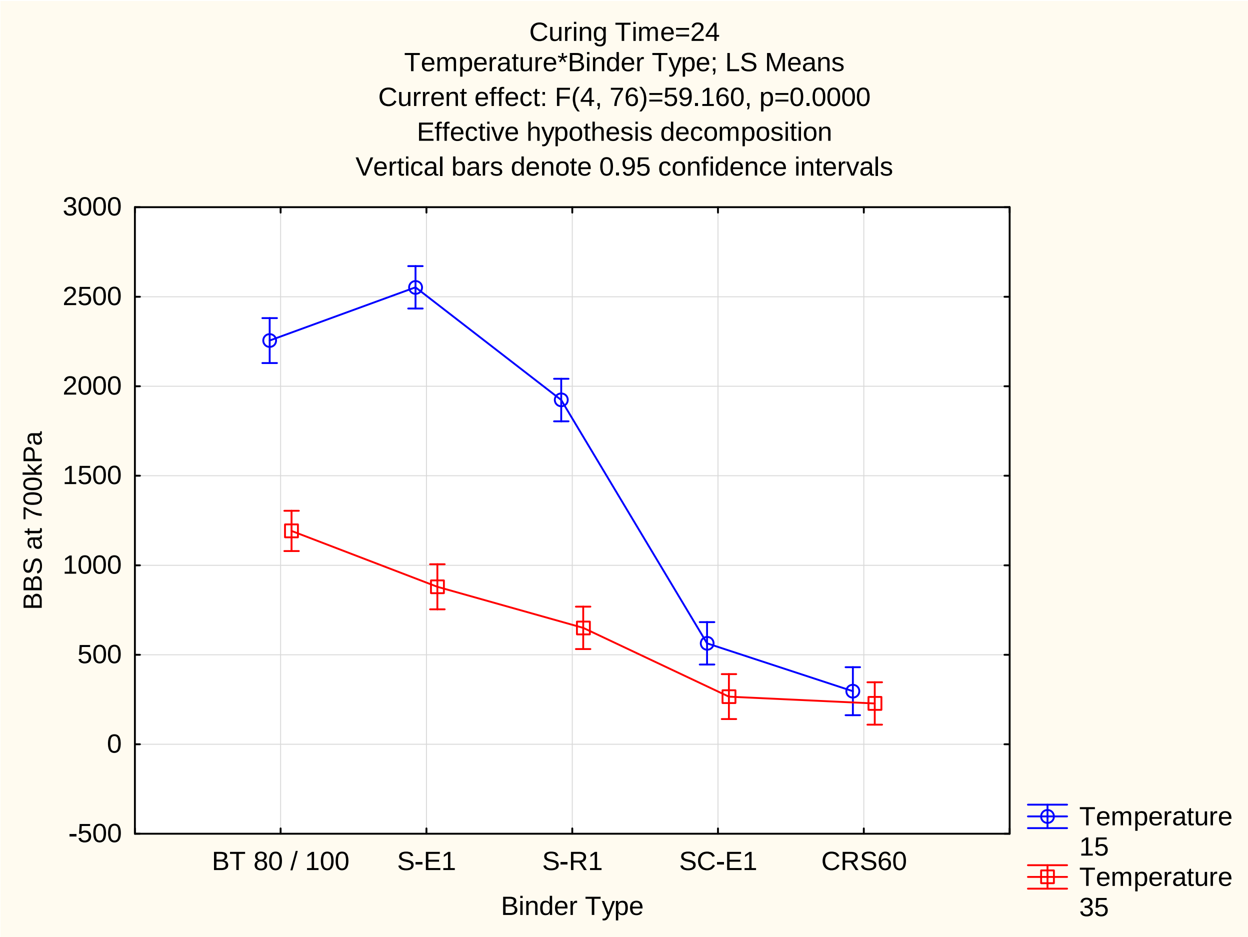
Cell No.	Temperature	Binder Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	BT 80 / 100	2283.455	60.44048	2163.127	2403.783	10
2	15	S-E1	2636.304	63.70986	2509.468	2763.141	9
3	15	S-R1	2143.080	63.70986	2016.243	2269.916	9
4	15	SC-E1	370.899	63.70986	244.063	497.736	9
5	15	CRS60	177.888	63.70986	51.051	304.725	9
6	35	BT 80 / 100	858.528	60.44048	738.200	978.855	10
7	35	S-E1	757.346	72.24019	613.526	901.165	7
8	35	S-R1	559.035	67.57451	424.505	693.566	8
9	35	SC-E1	202.423	63.70986	75.586	329.259	9
10	35	CRS60	223.701	67.57451	89.171	358.232	8

Curing Time=24

Univariate Tests of Significance for BBS at 700kPa (DATA BBS LeRicheLombard)

	Curing Time=24 Univariate Tests of Significance for BBS at 700kPa (DATA InputAno Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	99567775	1	99567775	3128.261	0.00
Temperature	16314514	1	16314514	512.576	0.00
Binder Type	32973966	4	8243492	258.997	0.00
Temperature*Binder Type	7531883	4	1882971	59.160	0.00
Error	2418964	76	31828		

*Temperature*Binder Type; LS Means*



*Temperature*Binder Type; LS Means (DATA BBS LeRicheLombard)*

Curing Time=24
Temperature*Binder Type; LS Means (DATA InputAnova 20140820.sta)
Current effect: F(4, 76)=59.160, p=0.0000
Effective hypothesis decomposition

Cell No.	Temperature	Binder Type	BBS at 700kPa Mean	BBS at 700kPa Std.Err.	BBS at 700kPa -95.00%	BBS at 700kPa +95.00%	N
1	15	BT 80 / 100	2255.401	63.07582	2129.775	2381.028	8
2	15	S-E1	2553.049	59.46845	2434.607	2671.490	9
3	15	S-R1	1922.963	59.46845	1804.521	2041.405	9
4	15	SC-E1	564.048	59.46845	445.607	682.490	9
5	15	CRS60	296.703	67.43089	162.403	431.003	7
6	35	BT 80 / 100	1191.874	56.41673	1079.510	1304.237	10
7	35	S-E1	879.785	63.07582	754.159	1005.411	8
8	35	S-R1	650.707	59.46845	532.265	769.148	9
9	35	SC-E1	266.416	63.07582	140.790	392.042	8
10	35	CRS60	228.037	59.46845	109.595	346.478	9