CONCEPTUAL FRAMEWORK FOR THE ANALYSIS OF SHEAR DAMAGE IN FOAMED BITUMEN STABILISED MATERIALS

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Abstract: The road building and rehabilitation industry worldwide utilises quality virgin natural aggregate materials, for the construction and maintenance of critical road infrastructure. Depleting natural deposits and limited supplies of high quality aggregates have prompted global emphasis on material selection. The foamed bitumen stabilisation technique offers the industry a sustainable and economical pavement engineering solution. Increased applications involving the enhancement of reclaimed pavement materials and wide range of locally available aggregate materials require pavement practitioners to possess adequate knowledge of its properties, behaviour and performance. Its shear characteristics and damage response have been identified as significant influential factors in determining long term performance. Notwithstanding these, an analysis of existing guidelines and mix design methodologies establish emphasis on stiffness and strength properties, for material characterisation and classification, highlighting the need for further research in modelling performance characteristics. The conceptual framework includes the use of dissipated energy in determining the effect of varying binder and active filler contents on Foamed bitumen stabilised materials (FBSMs) behaviour and performance. This paper highlights significant factors of the study which contribute to the understanding of FBSMs and determination of optimal FBSMs mix formulations.

Keywords: *Bitumen stabilised materials, Dissipated energy, Foamed bitumen stabilisation, Shear characteristics.*

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1. Introduction

Road infrastructure and its networks play a pivotal role in moving people, goods and services and are key to economic development in both developed and developing societies. It is in this regard that they are required to be adequately constructed and maintained. Globally, the road building and rehabilitation industry utilises quality virgin natural aggregate materials, for the construction and upgrade of these elements of critical infrastructure. Increasing concerns of environmental degradation from expanded mineral production, depleting natural deposits and limited supplies of high quality aggregates have prompted global emphasis on material selection. Fortunately, the foamed bitumen stabilisation technique offers the option for the enhancement of reclaimed pavement materials, as well as a range of available aggregate materials [1].

Foamed bitumen stabilisation is utilised for the production of bitumen stabilised materials, which are included in base and subbase layers of stabilised pavement structures. The availability of efficient specialist equipment has supported its increased applications worldwide, through both the cold in plant and cold in place recycling techniques [2]. BSMs produced in the foamed bitumen stabilisation process exhibit increased shear strength, cohesive strength, flexural strength and moisture durability, in its treated form [3]. Accompanying increasing applications of the technology however is emerging intertest from pavement practitioners, into the characteristics, behaviour and long-term performance of the material.

It is in this regard, that this paper identifies a conceptual framework for proposed research into the analysis of shear damage of foamed bitumen stabilised mixes. The proposed investigation aims to evaluate bitumen stabilised materials of varying bitumen binder and active filler contents, towards assessing damage response to increased repetitive loading. Moreover, the study intends to correlate dissipated energy derived from cyclic stress-strain data with measured permanent deformation damage. Examination into the effect of these variable mix compositional factors on dissipated energy capacities, subsequent indication of material ductility and flexibility, are as such proposed as a valuable tool towards material classification. It is expected that this proposed research will be able to highlight key performance characteristics of the variable bitumen stabilised materials and subsequent consideration of these in complementing currently utilised strength and stiffness data for optimal mix formulation designs.

2. Literature Review

2.1 Foamed Bitumen

Foamed bitumen or expanded bitumen is produced when cold water contacts hot bitumen, at temperatures ranging 150 °C to 180 °C, in pressurised chambers of specialist machines. Originally discovered by L Dr Ladis Csanyi over 50 years ago, the initial foaming technique utilising steam injected into hot bitumen was eventually improved by Mobile Oil in the 1960's, which allowed for controlled addition of water to the hot bitumen in an expansion chamber [4]. These were followed by additional developments by specialist equipment manufacturer Wirtgen GmbH in the 1990s, in the production of a metered system, which incorporated the injection of water into hot bitumen, in the presence of pressurised air. This system is included in many of the presently utilised specialised industry foamed bitumen cold recyclers, in the production of a temporary low viscous state of the material, as the bitumen changes from liquid to vapour state, with increased volume [2].

The rupturing of the bitumen bubbles during agitation with aggregates in mixing, creates splinters which adhere to the finer particles of the parent aggregate. The result is the production of a bituminous mastic between the foamed bitumen and fine particles. Upon compaction, this mastic binds the uncoated coarse particles of the aggregate together at contact points, creating a non-continuously bound FBSM layer [3].

Figure 1: Foamed Bitumen Sample

2.2 Foamed Bitumen Stabilised Materials (FBSMs)

FBSMs are identified by the Asphalt Academy [3] to exhibit maintained unbound granular characteristics, but with a notable improvement in cohesive strength and accompanied reduced moisture sensitivity. They do not display a predominantly black appearance and are not tacky to the touch, as common with the bound asphaltic concrete material. These inherent characteristics have been established by the Asphalt Academy [3] to be as a result of the action of the mastic connecting the coarse particles at contact points which leads to a consequential slight darkening of the material, with minimal coating of the larger sized aggregate particles.

2.2.1 *Microstructure of FBSMs*

The microstructure of BSMs has been theorised from imaging studies by Fu [5] to consist of three phases inclusive of an uncoated large aggregate phase, a mastic phase and uncoated mineral filler phase. A parallel description of FBSMs have been presented by Jenkins and Collings [6], which identify significant distinction in microstructure to the other traditionally utilised bound and unbound pavement materials. This has been attributed to bonding of the largely uncoated coarse aggregate skeleton at the specific contact points, created by dispersed bitumen-fine filler mastic. The result is a material classified by Jenkins and Collings [6] as non-continuously bound, displaying increased cohesion, minimal reduction in internal angle of friction, and an increased flexural strength.

Figure 2: Section through BSM core sample

Resulting from its conceptualised microstructure, existing guidelines on the use FBSMs such as that established by the Asphalt Academy [3] and the Wirtgen Gmbh [2] categorise FBSMs mid-spec between the unbound granular aggregate and the bound asphaltic concrete. The characteristics of these FBSMs are consistent for those with low bitumen and low cement contents, as utilized in some of the many economical viable, state of the art pavement engineering applications. These materials are described as exhibiting stress dependent behaviour alike granular unbound materials but with improved moisture and flexibility from dispersed bitumen mastic. This description in existing guidelines [3,6] characterises FBSMs as analogous to an enhanced unbound granular aggregate, however exhibiting increased cohesion, maintained granular interlock and subsequent stress-dependent behaviour, this as opposed to rigid behaviour, displayed by a bound asphaltic concrete or cement stabilized material.

2.2.2 Shear Behaviour of FBSMs

Current bitumen stabilised material guidelines [2,3], laboratory research by Jenkins [7], Ebels [8], Dal Ben [9] and review of long term pavement data [6] have identified the development of permanent shear strains as a dominant response of the material to repetitive loading. As a result of stress stiffening response displayed, permanent deformation has been established as a significant failure response of the FBSMs under repetitive loading [4]. The development of permanent shear strains and a subsequent long term permanent deformation response of FBSMs have been established from past laboratory research [7,8,9] to be dependent of the shear characteristics of the stabilised material. Analysis of the materials response to laboratory cyclic loading has identified stress dependent behaviour and the influence of deviator stress ratio on permanent deformation development, with accumulated shear deformation, subsequently largely influenced by the material's shear properties. It is in this regard that current mix design methodologies utilise shear properties in the classification of BSMs and subsequent differentiator of its performance of these materials [2,3].

2.2.3 FBSM Mix Design Methodologies

Accompanying an increase in applications of the foamed bitumen stabilization technology worldwide, is the availability of material data, laboratory research findings, pavement performance and construction experiences, which have been incorporated in the generation of manuals of design criteria, quality control and testing procedures. Commonly referenced among these manuals are those developed from South African research [3] and that from German manufacturer Wirtgen Gmbh [2], the latter of which also based on recommendations from South African researchers. Moreover, FBSMs have been established by Arevalo [10] as a mixture of parent aggregate, foamed bitumen and active filler, the properties and amounts of these elements established as significantly influencing the characteristics of the treated material.

The impacts of these individual components on the properties of the stabilised mixes have been highlighted in findings of studies by global researchers. Recommended grading charts for parent material suitability, developed in early stages of technology [7] and adopted in existing guidelines identify optimal performance with gradations in proximity to the maximum density curve and a sufficient filler content within range 4% -12% [2,3]. Past investigations into the influence of binder content on mix characteristics have also established improved cohesion and strength properties with increased binder to an optimum value, above which friction angle reduces and a decrease in shear strength results[7].Notably, active filler content is not selected as a variable in the design process with a restricted maximum value of 1% recognised as a measure of caution against expected increased stiffness, reduced flexibility and decrease in effectiveness of bituminous properties [3]. Previous investigations have however indicated increased cohesion, tensile strengths, moisture durability and improved permanent deformation resistance with the incorporation of active filler [8,10].

Ultimately, existing mix design methodologies currently utilize mix strength properties, in the determination of optimum formulations for stabilized materials. These established processes [2,3] involve investigations into the strength characteristics of the mixes implemented at varied binder contents within a recommended range and a constant active filler content, constrained to 1%. The mix's optimum binder content is subsequently selected at a suitable binder content providing strength values exceeding that of minimum recommended strength criteria, with cost also an influential measure in the selection, once criteria are exceeded.

2.3 Research Gap

Foamed bitumen stabilisation exists as a sustainable, effective pavement engineering solution in the construction and rehabilitation of critical road infrastructure. Major advantages of its application include its use in stabilised systems of reduced thicknesses, improved durability and potential for enhancement and inclusion of low quality parent material aggregates [3]. Owing to its conceptualised microstructure, FBSMs are characterised as displaying enhanced granular characteristics, with permanent deformation established as its critical response to in service loading.

Inherently, current mix design methodologies from established material guidelines utilise strength and stiffness characteristics for classifying FBSMs and input into structural design [2,3]. Notwithstanding this, performance of the material during its service life and recognition of the incremental permanent deformation damage with increased repetitive loading is a significant aspect for its classification. It is therefore proposed that characterisation of the damage response of the uniquely classified FBSM and assessment into the impact of mix variables on this performance characteristic, can significantly contribute to the existing body of knowledge of foamed bitumen technology. Notably, the value of damage theory has been previously established from past research into pavement materials, with its application highlighting its effectiveness in characterising material degradation and providing key indicator of distress development, for materials in service [11].

2.3.1 Damage in Pavement Materials

Damage mechanics is referred to as the study of the mechanism of deterioration of a material under loading [12]. Past studies into damage progression of commonly utilised pavement materials include those carried out on bound materials subject to cumulative fatigue damage such as asphalt mixes [13,14], in addition to those investigating permanent strain response of unbound granular aggregates [15].

Characterization of damage response of pavement materials has been highlighted as a critical factor in determining long term performance and predicting design life of the materials. Studies such as that by Ghuzlan and Carpenter [13] and Maggiore et al [14], into flexural fatigue damage have established the effectiveness of damage in improving fatigue life estimation as well as enhancing classification of differently graded and variable binder content asphalt mixtures. Similarly, research such as that by Tao et al [15] have identified the value of damage characterisation of unbound granular aggregates in classifying pavement base aggregates based on permanent strain accumulation and stable/unstable behaviour differentiation.

2.3.2 Dissipated Energy in Material Damage Analysis

Applications of Dissipated Energy in pavement material damage analysis has been attributed to its simplicity and ability to effectively identify progressive damage, in response to cyclic loading. Advantages of its application in asphalt fatigue damage analysis includes addressing limitations within the largely descriptive phenomenological based method and subjective fracture mechanics crack propagation approach of analysis [13]. Similarly, its use in characterising damage progression within unbound granular aggregates allows for determining more accurately transition zones between stable and unstable Shakedown responses. Applications of Dissipated Energy in past research has exhibited its efficiency in identifying possible points of microstructural adjustments, eliminating ambiguity in classifying some responses of variable materials within the three ranges of unbound granular aggregates, displaying permanent strain development in theorised Shakedown response [15].

Significantly, cyclic loading of materials under repetitive loading result in the generation of non-linear stress strain curves, in the form of hysteric loops [Fig. 3]. Repeated loading of constant magnitude and subsequent increased strain over time is theorised to consist of a combination of recovered and permanent strain.

In previous studies involving Dissipated Energy analysis of bound and unbound pavement materials, the area under the hysteresis loop is postulated to be representative of the energy dissipated in a load cycle and its determination utilised in assessing the material's response to load repetitions [15]. Moreover, Dissipated Energy has been utilised in the analysis of permanent strain development for both fatigue degradation studies in asphalt mixes and permanent deformation response evaluation of granular aggregates. In both instances, Dissipated Energy - permanent strain relationships were examined to characterise the incremental responses of variable materials subject to cyclic loadings, towards material classification and categorisation.

2.3.3 Addressing the Research Gap

A review of existing literature has identified the effectiveness of foamed bitumen and FBSMs in pavement construction and rehabilitation. Whilst current mix design methodologies emphasise stiffness and strength characteristics for material classification, consideration of incremental response to loading can add to the material design process. As established from previously highlighted literature, permanent deformation is recognised as a critical distress response of FBSMs [2,3,6,7]. Significantly, Dissipated Energy has been identified as an effective tool for analysing damage response in pavement materials. In this regard, this paper establishes a theoretical framework for proposed investigative study, which aims to utilise Dissipated Energy in analysing shear damage and subsequent permanent deformation development of variable constituted FBSMs, towards improving classification and categorisation of the material.

3. Methodology

The conceptual framework for this intended study proposes the use of Dissipated Energy as an analytical tool for analysing the shear damage in FBSMS. The details of the design of this proposed study are as outlined in the following aspects of the methodology.

3.1 Aim of Study

The aim of this proposed study is to analyse the shear damage of bitumen stabilised materials using Dissipated Energy principles.

3.2 Objectives of Study

The primary focus of this proposed laboratory study involves an analysis into the damage response of FBSMs. As such, one of the enlisted objectives of this study is to measure the FBSM strength values that define the engineering behaviour BSM-Crushed blue limestone materials in the laboratory, towards characterising mixes investigated. In addition, considering the focus of the research in exploring aspects of material deterioration of cyclically loaded FBSMs, another objective of the proposed study proceeds to determine the Dissipated Energy from obtained laboratory stress-strain data and its correlation with the permanent deformation damage measured. In its application, the use of Dissipated Energy as a tool of analysis is suggested for indication of responsive changes in the material with repetitive loading and characterisation of its degradation, consistent with permanent shear strain development. Further to establishing the relationship between Dissipated Energy and permanent deformation, an investigation into the effect of selected mix variables on the attained damage response of the materials as a subsequent objective of the study, intends to examine the influence of these mix factors on its behaviour and performance. This measure is aimed at exploring the impact of varying binder contents, active filler type and active filler content increases on permanent deformation response attributed to shear damage with increasing load cycles and is proposed to augment the process for classification of the materials in the design formulation procedures.

3.3 Scope of Study

The study into analysis of shear damage of FBSM proposes investigation into the laboratory behaviour of variable constituted FBSMs with emphasis on evaluating material damage, through an examination of the permanent strain response to cyclic loading and characterisation by computation of Dissipated Energy. The aggregate material selected for this study is that commonly utilised in pavement foamed bitumen stabilisation and recycling applications in the form of granular crushed stone base aggregate, sourced from a crushed blue limestone quarry, with extraction from within the Trinidad Northern Range. Foamed bitumen stabilising agents for the exercise are to be produced using a Wirtgen laboratory foaming unit, capable of effectively simulate foamed bitumen production processes on the large field construction machines, with cement and lime selected as active filler types.

3.4 Experimental Design

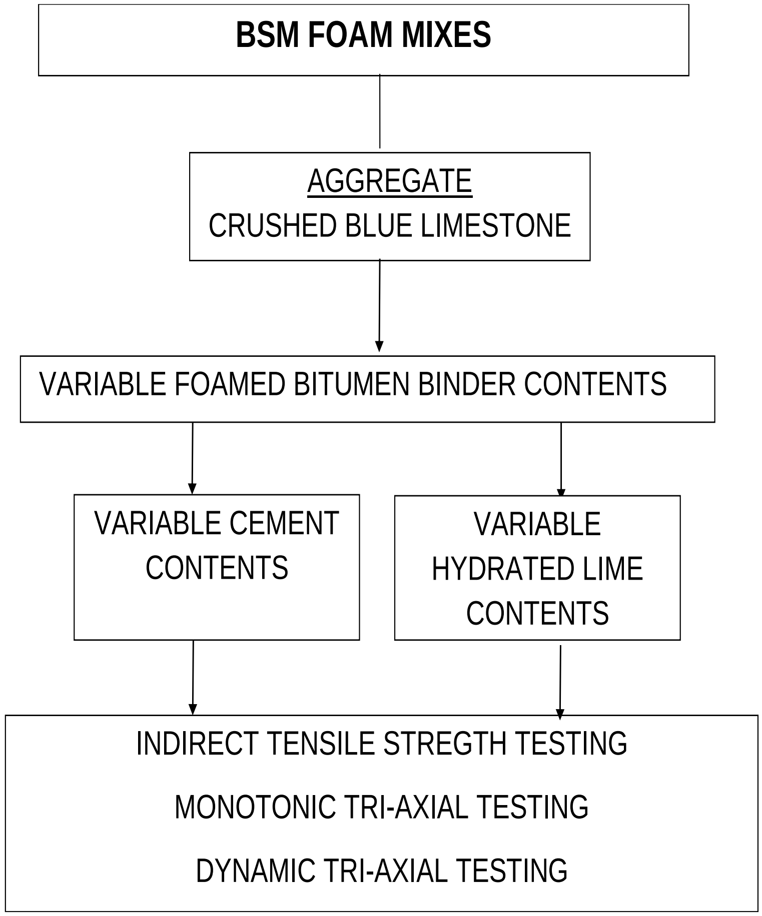

Figure 3: Proposed Experimental Design

4. Discussion

This proposed study into the analysis of shear damage in FBSMs focuses on establishing correlation between measured Dissipated Energy and permanent shear strain accumulation and permanent deformation response with repeated loading. In this regard a significant aspect of the intended analysis of obtained stress strain data from dynamic cyclic tri-axial test involves determination of Dissipated Energy for the variable mixes investigated. Subsequent examinations of permanent strain-dissipated energy relationships are proposed to identify incremental changes in behaviour of the material. An evaluation of the permanent strain rate against dissipated energies, at the varying stages of loading will also be used to establish that portion of the energy causing damage in the various mixes. In addition, it is projected that obtained DE would be used for investigating the impact of mix variables on its damage response. The effect of strength characteristics used in current classification criteria [2,3] including shear parameters cohesion and friction angle of variable mixes on observed Dissipated Energy response and incremental damage progression are also intended for examination. This activity is proposed to investigate the significance of these currently used design indicators on the damage response of variable constitute BSM mixes.

5. Conclusion

In summary, applications of foamed bitumen stabilisation technology and the use of FBSMs as a pavement engineering solution is supported by its effectiveness in enhancing properties of a range of available aggregate materials. Existing material guidelines, manuals and previous investigations by researchers worldwide have described FBSMs as a uniquely classified material, displaying granular characteristics but with improved shear properties from increased cohesion. Accompanying increased applications is the significance of knowledge of the material's characteristics, behaviour and critically its long-term performance. Current mix design methodologies emphasise strength characteristics in the design of these materials with recommended strength criteria for its classification.

Performance characteristics of the material exists as a significant factor in applications of the technology and the stabilised material. It is in this regard that this paper presents a conceptual framework for proposed laboratory analysis of shear damage and subsequent permanent deformation accumulation, for variable foamed bitumen stabilised material mixes. The proposed use of Dissipated Energy as a tool of analysing this shear damage is aimed at characterising the incremental permanent strain response of the material to cyclic loading. This initiative is expected to contribute to the existing body of knowledge of this material by characterising the material's long-term deterioration as well as evaluating the influence of mix variables on the material response, towards completing classification criteria currently being used.

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