THERMO-MECHANICS OF ASPHALT MIXES WITH CRUSHED WASTE GLASS AGGREGATES

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Dedicated to

The Almighty Lord, my beloved wife, who has been with me at each step of this journey, and my family to whom I will always be indebted

SUPERVISOR CERTIFICATION

This is to certify that the thesis entitled **"Thermo-mechanics of asphalt mixes with crushed waste glass aggregates"** being submitted by **Mr. Aayush Kumar** to the Indian Institute of Technology Delhi and The University of Queensland for the award of degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. **Mr. Aayush Kumar** has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results contained in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

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ABSTRACT

The increased emphasis on sustainability in pavement construction has led to the incorporation of synthetic alternative aggregates, such as crushed waste glass (CWG) in hot mix asphalt (HMA) production. As the uppermost layer in a pavement structure, asphalt is constantly exposed to traffic loads, fluctuating atmospheric temperatures and varying rainfall conditions. Given that asphalt constitutes the most vulnerable and expensive layer in a pavement structure, ensuring an adequate load-bearing capacity and maintaining structural integrity are critical. Accordingly, a comprehensive understanding of their fracture response when subjected to a combination of mechanical and thermal stresses is essential. This is more crucial when new aggregates (CWG) are explored for use in asphalt mixes, which could influence their properties and prospective on-field performance.

This study focuses on investigating the fracture behaviour and thermo-mechanics of dense graded HMA mixes prepared with varying percentages of CWG, as a replacement for natural fine aggregates (particle size < 4.75 mm and ≥ 0.075 mm). This was achieved using standard testing methods and advanced experimental techniques to evaluate mixture stiffness, fracture response, crack propagation and deformation characteristics under simple and complex stress states. To understand the effect of aggregate morphology on the mechanical performance of asphalt, a detailed aggregate shape characterization study was also carried out. Mesoscale features such as sphericity, roundness and angularity were quantified through image analysis and computational techniques, while the microscale feature – particle roughness was estimated using 3D optical profilometry and the fractal approach. Four mixes with increasing CWG% ranging from 2.5% to 42.5% were designed with unmodified bitumen as per the Marshall method. Specimens prepared at the optimum binder content were further tested for their cracking resistance through the Brazilian and Indirect Tensile Cracking Tolerance (IDEAL-CT) tests. Additionally, a novel stereo high-speed photography technique was used with the

Brazilian tests at – 20°C, 0°C and 60°C temperatures for accurate estimation of crack initiation stresses, crack locations, crack speeds and nature of cracks in the specimens. The IDEAL-CT tests were conducted at room temperature (22°C) on Marshall and Gyratory compacted specimens. The observed fracture response was further studied through thermal parameters of the mixes– thermal conductivity, diffusivity and specific heat capacity, measured using the Transient Plane Source (TPS) method. In addition to cracking, which is a major form of pavement distress, rutting and moisture damage are of significant concern, particularly in regions experiencing high temperatures and rainfall. Therefore, the Hamburg Wheel-Tracking (HWT) tests were conducted to evaluate the rutting and stripping resistance of the mix designs with increasing percentage of CWG.

Following initial investigations into the fracture resistance and thermo-mechanical performance of the mix designs, the ultrasonic pulse velocity (UPV) technique was used for precise identification of crack initiation and crack damage thresholds in the specimens. Unconfined compressive strength (UCS), uniaxial and biaxial compressive tests were conducted on cubical samples, coupled with ultrasonic transducers at room temperature. Further, true triaxial compressive tests were performed and the volumetric strain approach was applied to identify and compare cracking closure, crack initiation, and crack damage thresholds in reference and CWG mixes. Finally, results were fitted to established failure criteria such as the Mogi-linear, Mogi-power and the Drucker-Prager models, offering a deeper understanding of the failure characteristics (compressive and shear dominated) and mechanical behaviour of the mixes.

The Marshall test results reveal variations in stability, flow and volumetric properties across mixes with and without CWG. Mixes with increasing CWG are observed to have lower Marshall stability, flow and optimum binder contents but higher stiffness (Marshall Quotient). The IDEAL-CT evaluations show that the Cracking Tolerance index (CT_{index}) and other key fracture parameters are a function of the mix design and specimen size with lower CT_{index} being obtained at higher CWG contents. To follow, the Brazilian tests with high-speed photography provide accurate identification of crack initiation thresholds and estimation of crack speeds which vary with the test temperature and percentage of glass in the samples. Higher ultimate tensile strength and stiffness are observed for mixes with 10% CWG at all test temperatures. Thermal property measurements also provide insights into the observed fracture response by highlighting lower thermal conductivity, diffusivity and specific heat capacities of samples with increasing CWG. Further, the HWT tests demonstrate improved rutting and stripping resistance in mixes with CWG up to an optimum inclusion level of 10%. The above findings on cracking and rutting performance of the mix designs are better interpreted with aggregate shape parameters and their associated effects on mechanical performance.

The ultrasonic pulse velocity (UPV) test offers a novel perspective into crack propagation mechanisms in mixes with and without CWG, depicting variations in wave velocity and energy during uniaxial and biaxial compressive tests. Biaxial test results indicate the strengthening effect of the confining intermediate principal stress (σ_2). Ultimately, the true triaxial compressive tests contribute to a more comprehensive understanding of the strength, deformation characteristics, crack patterns and crack thresholds in mixes with and without CWG, under complex stress states experienced by pavements in the field. Failure criteria assessment also shows differences in degree of fitness for the tested mix designs indicating differences in mechanical response (comparatively ductile reference mixes vs brittle CWG mixes). The findings demonstrate that mixes with CWG (upto 10%) show improved rutting performance compared to reference mixes. However, the stiff and brittle characteristics of mixes with CWG affect their cracking resistance. Overall, the study highlights the feasibility of CWG as a sustainable, yet mechanically distinct alternative aggregate for asphalt production.

ABSTRACT IN HINDI (सारांश)

पेवमेंट निर्माण में सततता (sustainability) पर बढ़ते जोर के परिणामस्वरूप, हॉट मिक्स ऐस्फाल्ट (HMA) के निर्माण में सिंथेटिक वैकल्पिक एग्रीगेट्स, जैसे कि क्रश्ड वेस्ट ग्लास (CWG), का उपयोग किया जाने लगा है। पेवमेंट संरचना की सबसे ऊपरी परत होने के कारण, ऐस्फाल्ट निरंतर यातायात भार, परिवर्तनीय वायुमंडलीय तापमान तथा बदलती वर्षा परिस्थितियों के संपर्क में रहता है। चूँकि ऐस्फाल्ट पेवमेंट संरचना की सबसे अधिक संवेदनशील और महँगी परत होती है, इसलिए पर्याप्त भार-वहन क्षमता सुनिश्चित करना तथा संरचनात्मक अखंडता बनाए रखना अत्यंत आवश्यक है। अतः यांत्रिक एवं तापीय तनावों के संयुक्त प्रभाव में इसकी फ्रैक्चर प्रतिक्रिया की समग्र समझ आवश्यक हो जाती है। यह आवश्यकता तब और अधिक महत्वपूर्ण हो जाती है जब नए एग्रीगेट्स (CWG) को ऐस्फाल्ट मिश्रणों में शामिल किया जाता है, क्योंकि वे मिश्रण के गुणों तथा संभावित फील्ड प्रदर्शन को प्रभावित कर सकते हैं।

यह अध्ययन प्राकृतिक महीन एग्रीगेट्स (कण आकार < 4.75 मिमी एवं ≥ 0.075 मिमी) के आंशिक प्रतिस्थापन के रूप में विभिन्न प्रतिशतों में CWG के उपयोग से तैयार किए गए डेंस ग्रेडेड HMA मिश्रणों के फ्रैक्चर व्यवहार एवं थर्मो-मैकेनिकल गुणों की जाँच पर केंद्रित है। इसके लिए मानक परीक्षण विधियों तथा उन्नत प्रायोगिक तकनीकों का उपयोग किया गया, जिससे सरल एवं जटिल तनाव अवस्थाओं में मिश्रण की कठोरता, फ्रैक्चर प्रतिक्रिया, क्रैक प्रसार तथा विकृति विशेषताओं का मूल्यांकन किया जा सके। ऐस्फाल्ट के यांत्रिक प्रदर्शन पर एग्रीगेट आकृति के प्रभाव को समझने हेतु एक विस्तृत एग्रीगेट आकार विशेषता अध्ययन भी किया गया। मेसो-स्केल विशेषताओं जैसे स्फेरिसिटी, राउंडनेस एवं एंगुलैरिटी को इमेज विश्लेषण एवं संगणकीय तकनीकों द्वारा मात्रात्मक रूप से निर्धारित किया गया, जबकि माइक्रो-स्केल विशेषता अर्थात कण खुरदरापन (particle roughness) का आकलन 3-D ऑप्टिकल प्रोफिलोमेट्री एवं फ्रैक्टल पद्धति द्वारा किया गया।

2.5% से 42.5% तक बढ़ते CWG प्रतिशत के साथ चार मिश्रणों का डिज़ाइन अनमॉडिफ़ाइड बिटुमेन के साथ मार्शल विधि के अनुसार किया गया। इष्टतम बाइंडर सामग्री पर तैयार नमूनों को ब्राज़ीलियन परीक्षण तथा इंडायरेक्ट टेन्साइल क्रैकिंग टॉलरेंस (IDEAL-CT) परीक्षणों के माध्यम से उनकी क्रैकिंग प्रतिरोध क्षमता के लिए आगे परखा गया। इसके अतिरिक्त, –20°C, 0°C तथा 60°C तापमानों पर ब्राज़ीलियन परीक्षणों के साथ एक नवीन स्टीरियो हाई-स्पीड फ़ोटोग्राफी तकनीक का उपयोग किया गया, जिससे क्रैक आरंभ तनाव, क्रैक स्थान, क्रैक वेग तथा नमूनों में बनने वाले क्रैक्स की प्रकृति का सटीक आकलन संभव हो सका। IDEAL-CT परीक्षण कमरे के तापमान (22°C) पर मार्शल एवं जाइरेटरी कॉम्पैक्टेड नमूनों पर किए गए।

प्रेक्षित फ्रैक्चर प्रतिक्रिया का आगे अध्ययन मिश्रणों के तापीय गुणों—तापीय चालकता, तापीय प्रसरणशीलता एवं विशिष्ट ऊष्मा धारिता—के माध्यम से किया गया, जिन्हें ट्रांज़िएंट प्लेन सोर्स (TPS) विधि से मापा गया। क्रैकिंग के अतिरिक्त, जो पेवमेंट क्षति का एक प्रमुख रूप है, रटिंग एवं नमी क्षति भी विशेष रूप से उच्च तापमान एवं अधिक वर्षा वाले क्षेत्रों में गंभीर चिंता का विषय हैं। अतः CWG के बढ़ते प्रतिशत के साथ मिश्रण डिज़ाइनों की रटिंग एवं स्ट्रिपिंग प्रतिरोध क्षमता के मूल्यांकन हेतु हैम्बर्ग व्हील-ट्रैकिंग (HWT) परीक्षण किए गए।

मिश्रण डिज़ाइनों की फ्रैक्चर प्रतिरोध क्षमता एवं थर्मो-मैकेनिकल प्रदर्शन पर प्रारंभिक जाँच के पश्चात, नमूनों में क्रैक आरंभ एवं क्रैक क्षति सीमाओं की सटीक पहचान के लिए अल्ट्रासोनिक पल्स वेलोसिटी (UPV) तकनीक का उपयोग किया गया। कमरे के तापमान पर क्यूबिकल नमूनों पर अनकॉन्फ़ाइंड कंप्रेसिव स्ट्रेंथ (UCS), यूनिआक्सियल एवं बायैक्सियल संपीडन परीक्षण किए गए, जिन्हें अल्ट्रासोनिक ट्रांसड्यूसर्स के साथ जोड़ा गया। इसके अतिरिक्त, ट्रू ट्रायैक्सियल संपीडन परीक्षण किए गए तथा वॉल्यूमेट्रिक स्ट्रेन दृष्टिकोण को अपनाकर रेफ़रेंस एवं CWG मिश्रणों में क्रैक क्लोज़र, क्रैक इनिशिएशन एवं क्रैक डैमेज सीमाओं की पहचान एवं तुलना की गई। अंततः, परिणामों को स्थापित

विफलता मानदंडों जैसे मोगी-लीनियर, मोगी-पावर तथा ड्रकर-प्रेगर मॉडलों के साथ फिट किया गया, जिससे मिश्रणों के विफलता गुणधर्मों एवं यांत्रिक व्यवहार की गहन समझ प्राप्त हो सकी।

मार्शल परीक्षण परिणाम CWG के साथ एवं बिना CWG वाले मिश्रणों में स्थिरता, फ्लो एवं वॉल्यूमेट्रिक गुणों में भिन्नता दर्शाते हैं। CWG की मात्रा बढ़ने के साथ मिश्रणों में कम मार्शल स्थिरता, फ्लो एवं इष्टतम बाइंडर सामग्री, किंतु अधिक कठोरता देखी गई। IDEAL-CT मूल्यांकन से यह स्पष्ट होता है कि क्रैकिंग टॉलरेंस इंडेक्स (CT_{index}) एवं अन्य प्रमुख फ्रैक्चर पैरामीटर मिश्रण डिज़ाइन एवं नमूना आकार पर निर्भर करते हैं, तथा उच्च CWG सामग्री पर कम CT_{index} प्राप्त होता है। आगे, हाई-स्पीड फ़ोटोग्राफी के साथ किए गए ब्राज़ीलियन परीक्षण विभिन्न तापमानों एवं ग्लास प्रतिशत के साथ क्रैक आरंभ सीमाओं की सटीक पहचान तथा क्रैक वेग के आकलन को संभव बनाते हैं। सभी परीक्षण तापमानों पर 10% CWG वाले मिश्रणों में अधिक अंतिम तन्य शक्ति एवं कठोरता देखी गई।

तापीय गुणों के मापन से भी प्रेक्षित फ्रैक्चर प्रतिक्रिया की व्याख्या में सहायता मिलती है, क्योंकि बढ़ते CWG प्रतिशत के साथ नमूनों में तापीय चालकता, प्रसरणशीलता एवं विशिष्ट ऊष्मा धारिता कम पाई गई। इसके अतिरिक्त, HWT परीक्षणों से यह प्रदर्शित होता है कि 10% तक के इष्टतम CWG सम्मिश्रण पर मिश्रणों में रटिंग एवं स्ट्रिपिंग प्रतिरोध में सुधार होता है। क्रैकिंग एवं रटिंग प्रदर्शन से संबंधित उपर्युक्त निष्कर्षों की बेहतर व्याख्या एग्रीगेट आकार पैरामीटरों तथा उनके यांत्रिक प्रदर्शन पर प्रभाव के संदर्भ में की जा सकती है।

UPV परीक्षण CWG के साथ एवं बिना CWG वाले मिश्रणों में क्रैक प्रसार तंत्र की एक नवीन दृष्टि प्रस्तुत करता है, जिसमें यूनिआक्सियल एवं बायैक्सियल संपीडन परीक्षणों के दौरान तरंग वेग एवं ऊर्जा में भिन्नताएँ प्रदर्शित होती हैं। बायैक्सियल परीक्षण परिणाम मध्यवर्ती प्रमुख संपीडन तनाव (σ_2) के परिबंधन प्रभाव को दर्शाते हैं। अंततः, ट्रू ट्रायैक्सियल संपीडन परीक्षण फील्ड में पेवमेंट द्वारा अनुभव की जाने वाली जटिल तनाव अवस्थाओं के अंतर्गत CWG के साथ एवं बिना CWG वाले मिश्रणों की शक्ति, विकृति विशेषताओं, क्रैक पैटर्न तथा क्रैक सीमाओं की अधिक व्यापक समझ प्रदान करते हैं।

विफलता मानदंडों के आकलन से परीक्षण किए गए मिश्रण डिज़ाइनों की उपयुक्तता की डिग्री में भी अंतर दिखाई देता है, जो यांत्रिक प्रतिक्रिया में भिन्नता को दर्शाता है (तुलनात्मक रूप से अधिक नमनीय रेफ़रेंस मिश्रण बनाम अधिक भंगुर CWG मिश्रण)। निष्कर्ष दर्शाते हैं कि 10% तक CWG वाले मिश्रणों में रेफ़रेंस मिश्रणों की तुलना में बेहतर रटिंग प्रदर्शन प्राप्त होता है। तथापि, CWG युक्त मिश्रणों की कठोर एवं भंगुर प्रकृति उनकी क्रैकिंग प्रतिरोध क्षमता को प्रभावित करती है। समग्र रूप से, यह अध्ययन ऐस्फाल्ट उत्पादन के लिए CWG को एक सतत, किंतु यांत्रिक रूप से भिन्न वैकल्पिक एग्रीगेट के रूप में अपनाने की व्यवहार्यता को रेखांकित करता है।

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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(Aayush Kumar)

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LIST OF SYMBOLS

a_i	Angle between the planes that bound the i^{th} corner of a particle
q_c	Cut-off wave vector
C_o	Intercept of the power spectral density vs. q plot
S_q	Root mean square roughness
$S_{q,frac}$	Fractal roughness
B_{ev}	Effective binder volume
m_{75}	Post-peak slope
l_{75}	Displacement at 75% of the peak load
G_f	Fracture energy
σ_1 , ε_1	Major principal stress and strain respectively
σ_2, ε_2	Intermediate principal stress and strain respectively
σ_3, ε_3	Minor principal stress and strain respectively
ε_v	Volumetric strain
σ_{oct}	Octahedral shear stress
$\sigma_{m,2}$	Mean effective stress
$\theta°$	Lode Angle
I_1	First invariant of Cauchy's stress tensor
J_1, J_2 , J_3	First second and third stress invariants of the deviatoric stress tensor respectively

LIST OF ACRONYMS

HMA	Hot Mix Asphalt
RAP	Reclaimed Asphalt Pavement
CR	Crushed Rock
CWG	Crushed Waste Glass
BGF	Bag House Fines
BIC	Bayesian Information Criteria
TPM	Triangular Prism Method
PSD	Power Spectral Density
VMA	Voids in Mineral Aggregate
VFB	Voids Filled with Bitumen
MQ	Marshall Quotient
ANOVA	Analysis of Variance
HSD	Honest Significant Difference
SD	Standard Deviation
COV	Coefficient of Variation
IDT	Indirect Tensile Test
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
CT	Cracking Tolerance
UTS	Ultimate Tensile Strength
TPS	Transient Plane Source
HWT	Hamburg Wheel Tracking
SIP	Stripping Inflection Point
NDE	Non-Destructive Evaluation

UCS	Unconfined Compressive Strength
UPV	Ultrasonic Pulse Velocity
CC	Crack Closure
CI	Crack Initiation
CD	Crack Damage
VSM	Volumetric Strain Method
RMSE	Root Mean Square Error
ARE	Average Relative Error
CM	Compressive Meridian
MEPDG	Mechanistic Empirical Pavement Design Guide