

# 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  $\geq 0.075$  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  $-20^{\circ}\text{C}$ ,  $0^{\circ}\text{C}$  and  $60^{\circ}\text{C}$  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 ( $22^{\circ}\text{C}$ ) on Marshall and Gyrotory 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 ( $\sigma_2$ ). 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.