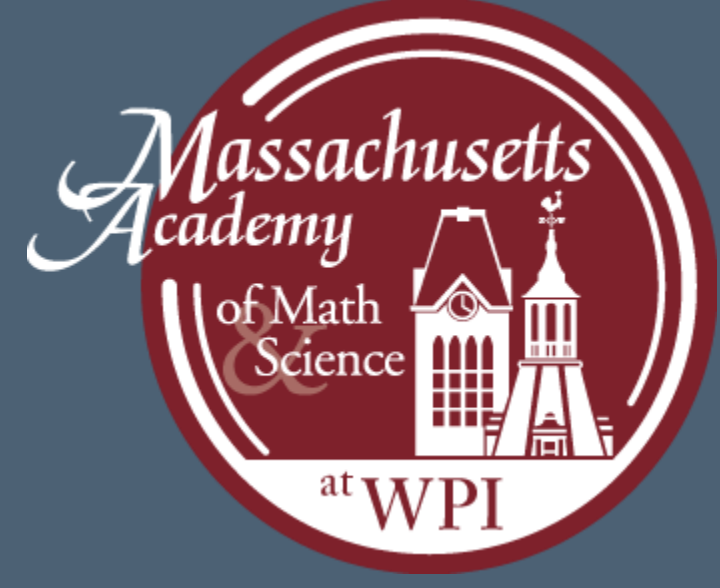


SIMULATING RECYCLED POLYETHYLENE TEREPHTHALATE-MODIFIED WARM MIX ASPHALT



Charles Shi

Advisor: Kevin Crowthers, PhD.



Background

- Plastic pollution is accelerating:** Global plastic production has doubled since 2000 and is projected to triple by 2060 (United Nations Environment Programme, 2025)
- PET dominates waste streams: polyethylene terephthalate (PET) accounts for ~60% of plastic waste (Usman & Kunlin, 2024)
- Warm Mix Asphalt (WMA)** reduces production temperatures by 20–40 °C, **cutting fuel use and emissions** compared to Hot Mix Asphalt (HMA) (Rubio et al., 2012)
- Recycled PET in HMA reinforces binder–aggregate structure while diverting plastic from landfills (Usman & Kunlin, 2024)
- Additives** such as high density polyethylene in HMA have shown to **increase durability** (Chegenizadeh et al., 2021).
- DEM (YADE):** Particle-scale interaction modeling
- FEM (Abaqus):** Macro-scale mechanical and thermal analysis



Research Question

How does the incorporation of **recycled polyethylene terephthalate (PET)** affect the **stiffness, rutting resistance, flexural strength, and thermal conductivity** of warm mix asphalt, as evaluated through simulation?

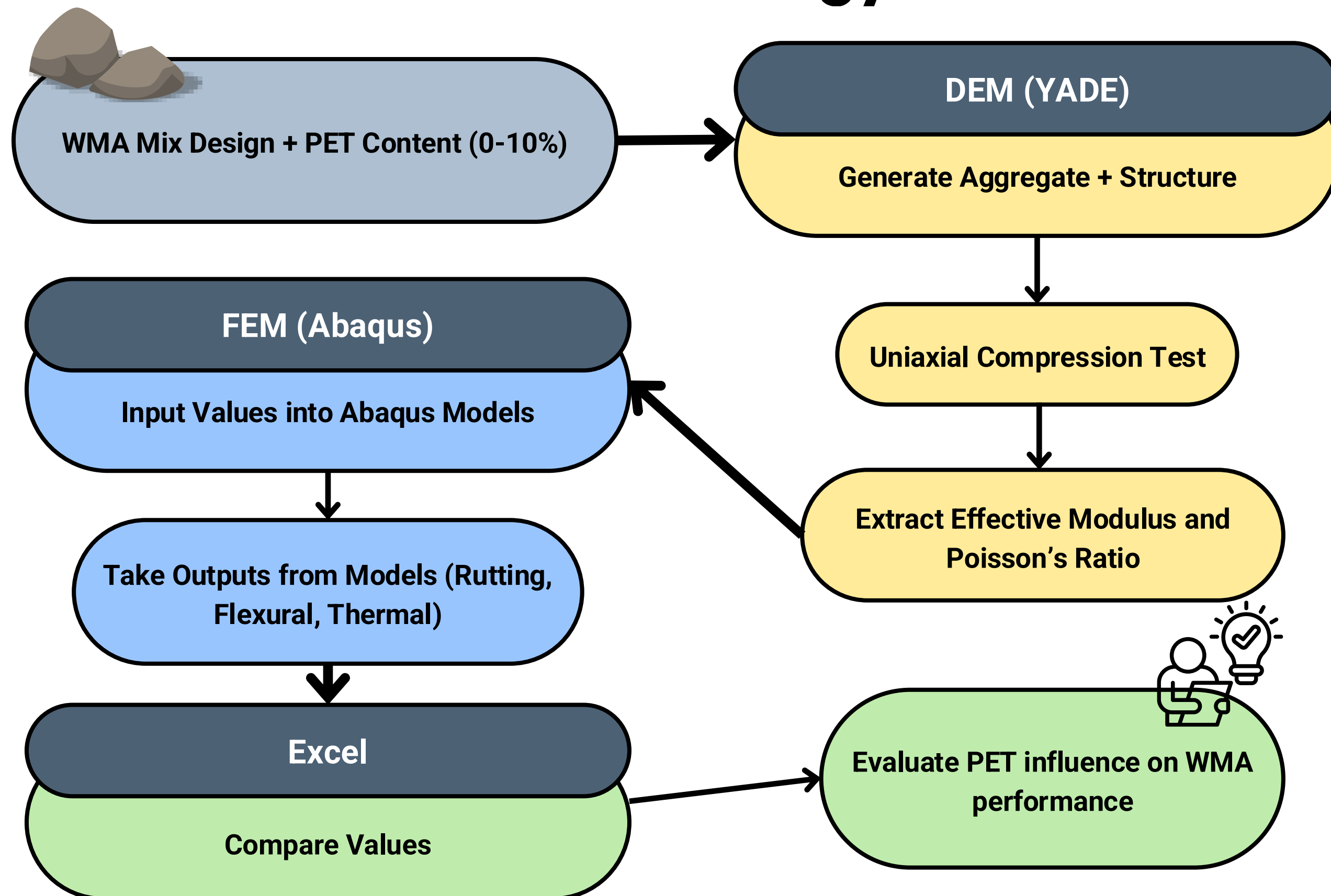
Hypothesis

Recycled polyethylene terephthalate (PET) will improve **stiffness, rutting resistance, and thermal conductivity** of warm mix asphalt while preserving **deformation behavior**, with optimal performance at moderate PET contents.

Results

- DEM Elastic Properties (n = 5 per PET level)**
- Effective modulus increased from 841.8 MPa (0%) to 930.0 MPa (5%), with statistically significant increases at 3% PET ($p < 0.05$) and 5% PET ($p < 0.001$).
 - Poisson's ratio had no statistically significant differences
- Rutting Response (FEM)**
- Rut depths at 800 loading cycles:
- 0%: 2.57 mm
 - 1%: 2.58 mm
 - 2%: 2.47 mm
 - 3%: 2.35 mm
 - 5%: 2.37 mm
 - 10%: 2.83 mm
- Flexural Outputs (FEM)**
- Flexural stress values remained approximately constant at $\sim 1.19 \times 10^6$ Pa for all PET conditions.
 - Midspan displacement decreased from 0.322 mm (0%) to 0.291 mm (5%), with 0.309 mm at 10% PET.
- Thermal Conductivity (FEM)**
- Effective thermal conductivity values (W/m-K):
- 0%: 0.998
 - 1%: 0.983
 - 2%: 0.967
 - 3%: 0.951
 - 5%: 0.917
 - 10%: 0.856

Methodology



FEM Models

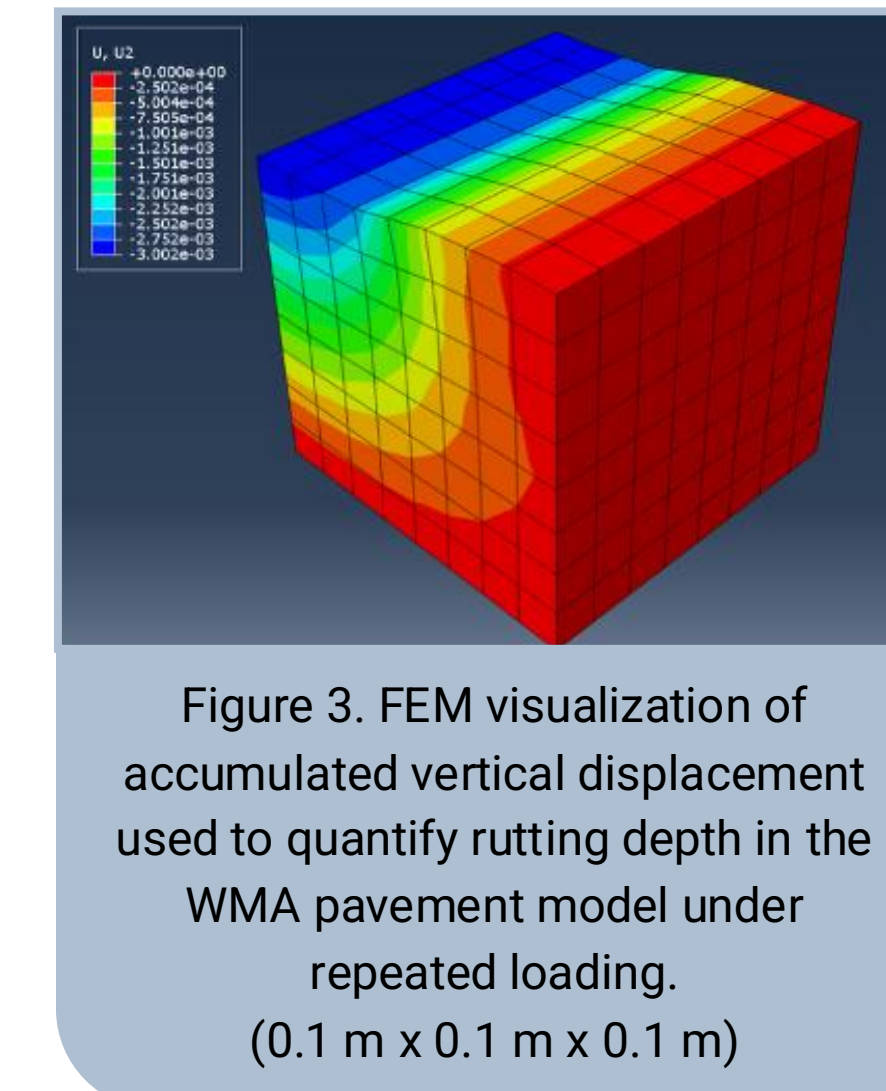


Figure 4. FEM stress contour and deformed shape of the PET-modified WMA beam model under three-point bending, showing tensile and compressive stress distribution during flexural loading. (0.3 m x 0.05 m x 0.05 m)

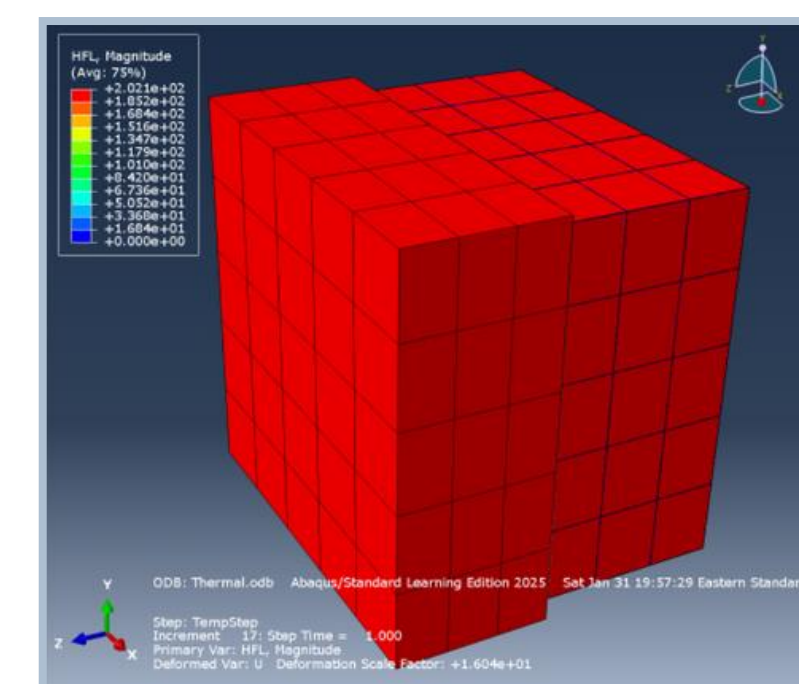
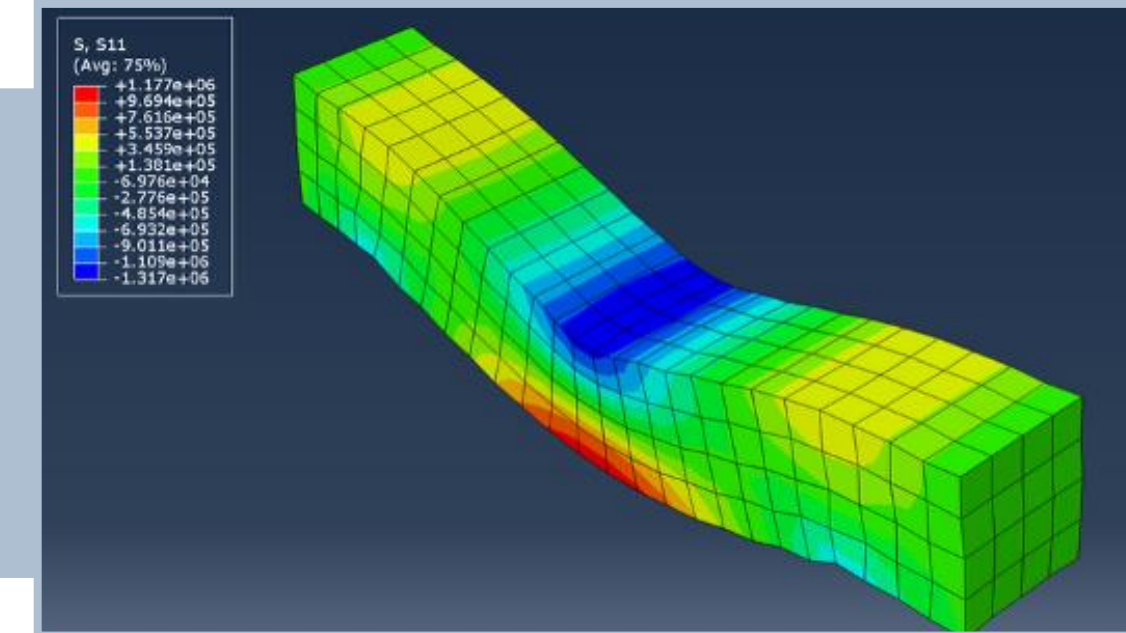


Figure 5. FEM heat flux magnitude contours in the WMA model under steady-state thermal loading. Heat flux outputs were extracted to calculate effective thermal conductivity using Fourier's law. (0.1 m x 0.1 m x 0.1 m)

Analysis + Findings

- Effective modulus **increased** and rutting depth **decreased** at moderate PET dosages.
 - Flexural strength was **maintained**, while midspan deflection **decreased** up to 5% PET, indicating increased stiffness under bending.
 - Thermal conductivity **decreased** steadily with PET
 - Poisson's ratio remained **stable**, indicating PET primarily alters stiffness rather than deformation.
- Optimal PET content \approx 3–5% improves stiffness and rutting resistance while reducing thermal conductivity, with minimal impact on flexural strength.**

Cost-Benefit Analysis + Implications

Assumes standard U.S. lane-km (3.6 m wide, 5 cm lift per lane-km) (American Association of State Highway and Transportation Officials, 2013).

Table 1. Estimated recycled PET diverted from landfills per lane-kilometer of pavement at varying PET contents, including approximate equivalent numbers of PET bottles.

PET Content	PET Used (tons)	Approx. Bottles Diverted*
0%	0	0
3%	~12-15	~1.2 million
5%	~20-22	~2.0 million
10%	~40	~4.0 million

- Benefits**
- ~2 million bottles diverted per lane-km
 - Reduced natural aggregate use
 - WMA: ~20–30% lower fuel use and CO₂ (Rubio et al. 2012)
 - Improved rutting resistance → potential service-life extension

- Tradeoffs**
- Possible microplastic release from pavement wear
 - Lower thermal conductivity:
 - Beneficial in cold climates (thermal insulation)
 - May retain heat in hot climates; rutting damage

- Net Impact**
- Increased stiffness with preserved flexural strength
 - Slightly higher upfront cost
 - Likely positive lifecycle performance—sustainability balance

- Implications**
- PET-modified WMA offers a path to reuse plastic waste while improving rutting resistance and stiffness.
 - The novel DEM–FEM framework enables low-cost optimization of sustainable pavement materials.

*Assuming ~10g per PET bottle

DEM Data

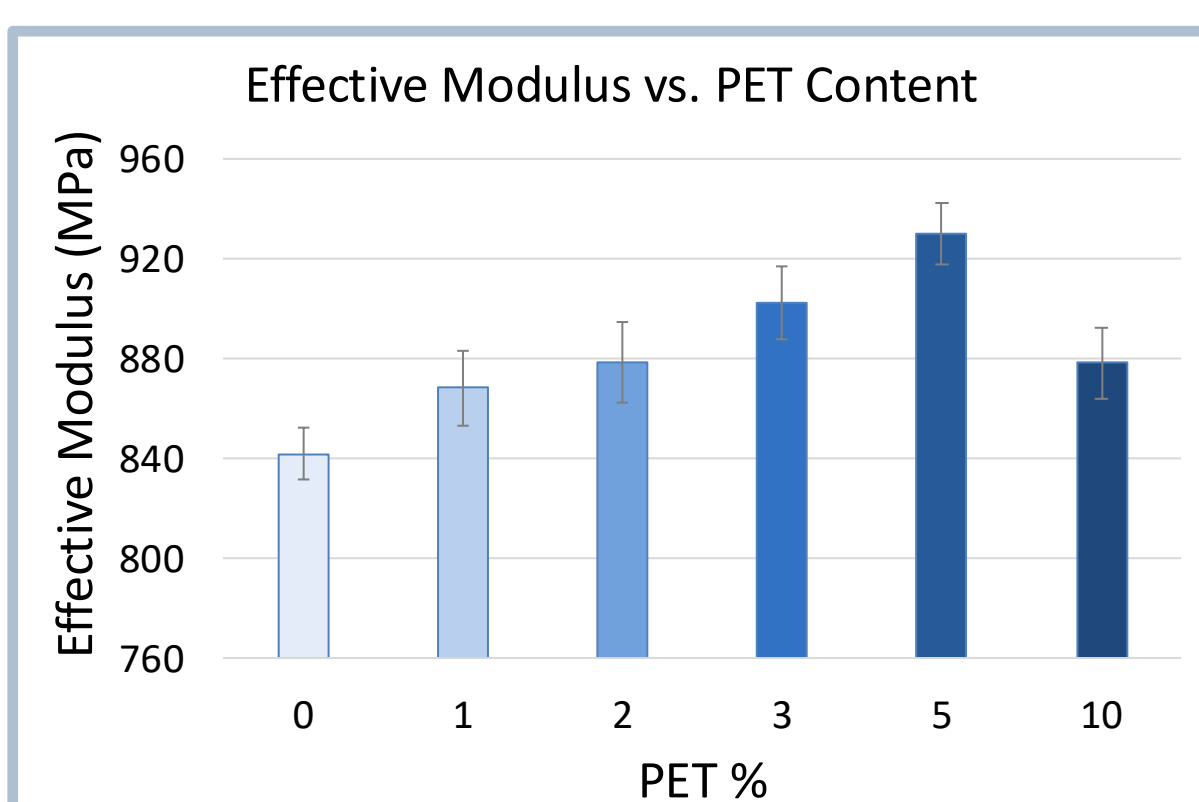


Figure 1. Effective modulus versus PET content for warm mix asphalt obtained from DEM uniaxial compression simulations. Bars show mean values from five randomized packings; error bars represent \pm SEM.

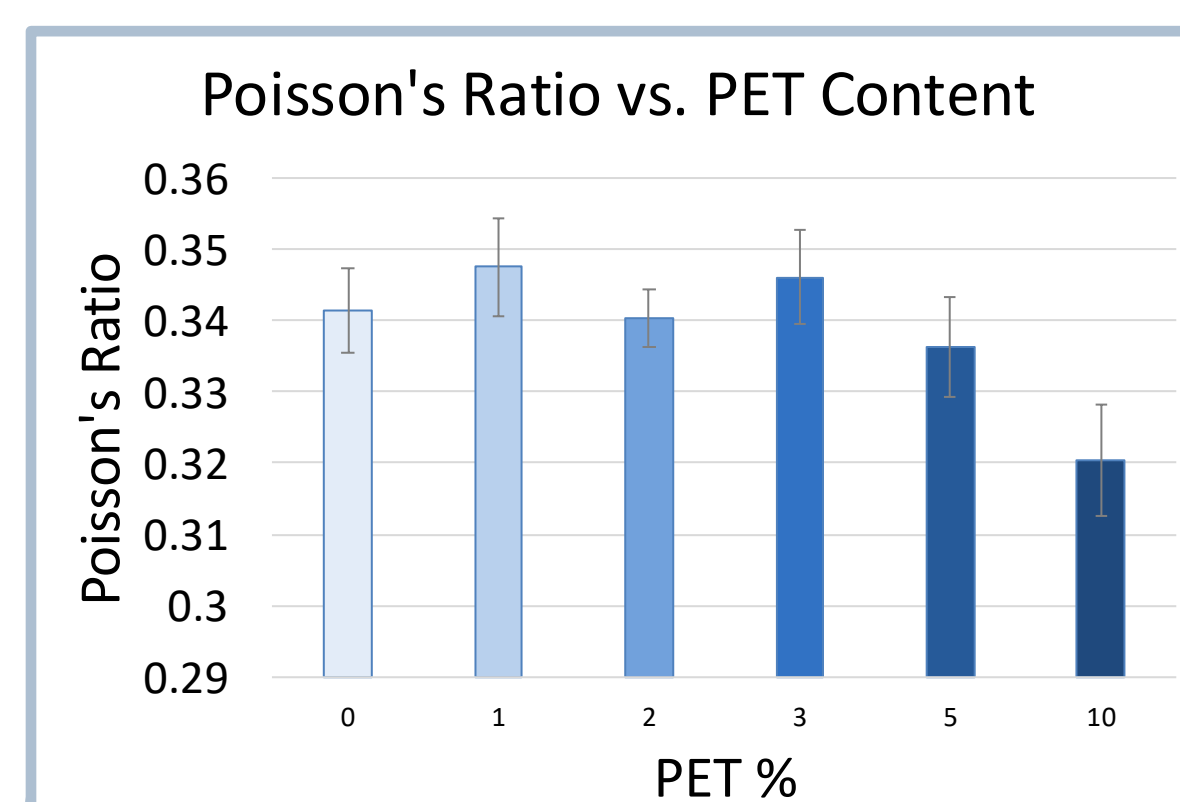


Figure 2. Poisson's ratio versus PET content for warm mix asphalt obtained from DEM uniaxial compression simulations. Bars show mean values from five randomized packings; error bars represent \pm SEM.

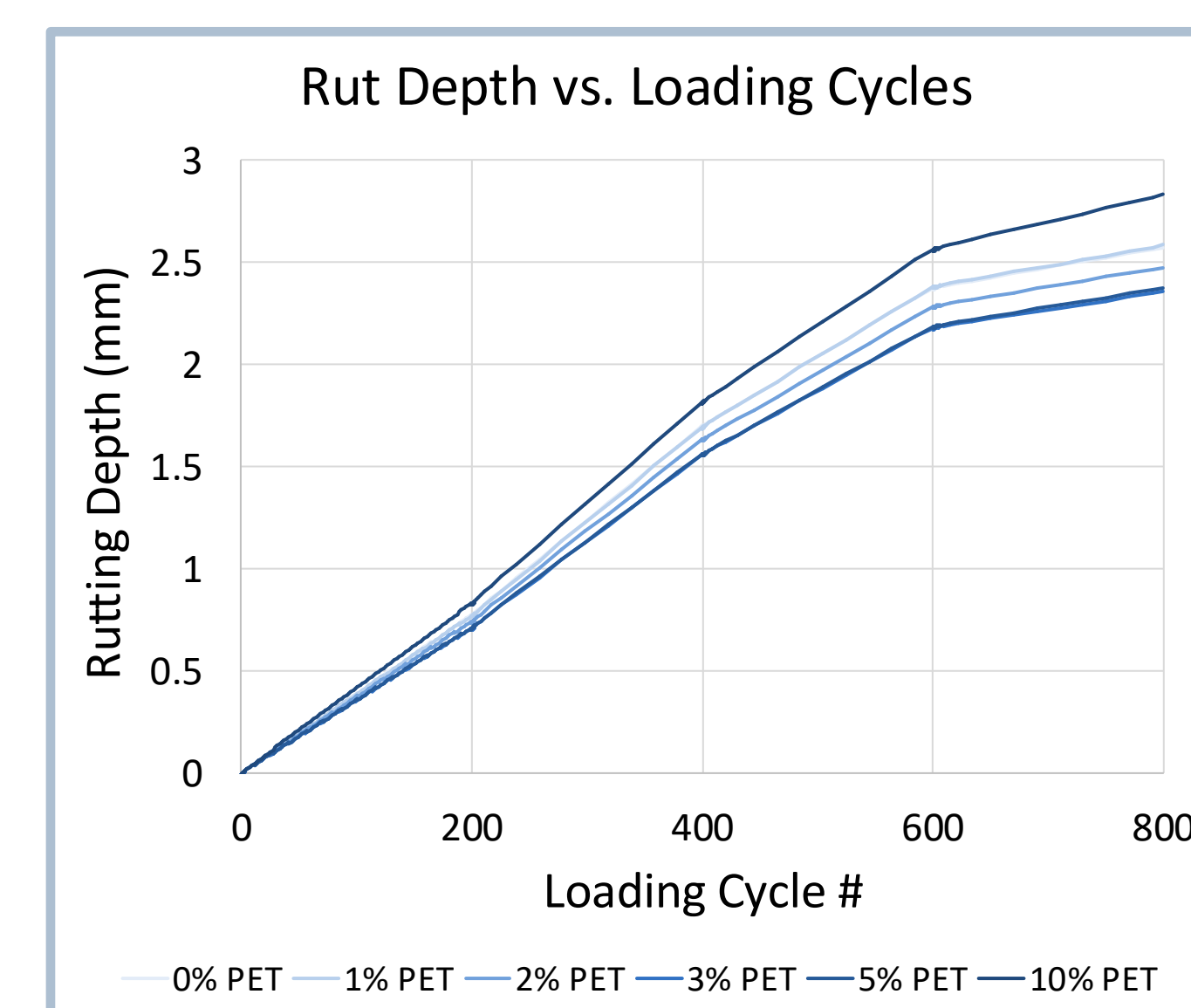


Figure 6: Rutting depth as a function of loading cycles for warm mix asphalt containing 0–10% recycled PET. Curves represent FEM-predicted accumulated surface displacement under repeated vertical loading up to 800 cycles for each PET content.

FEM Data

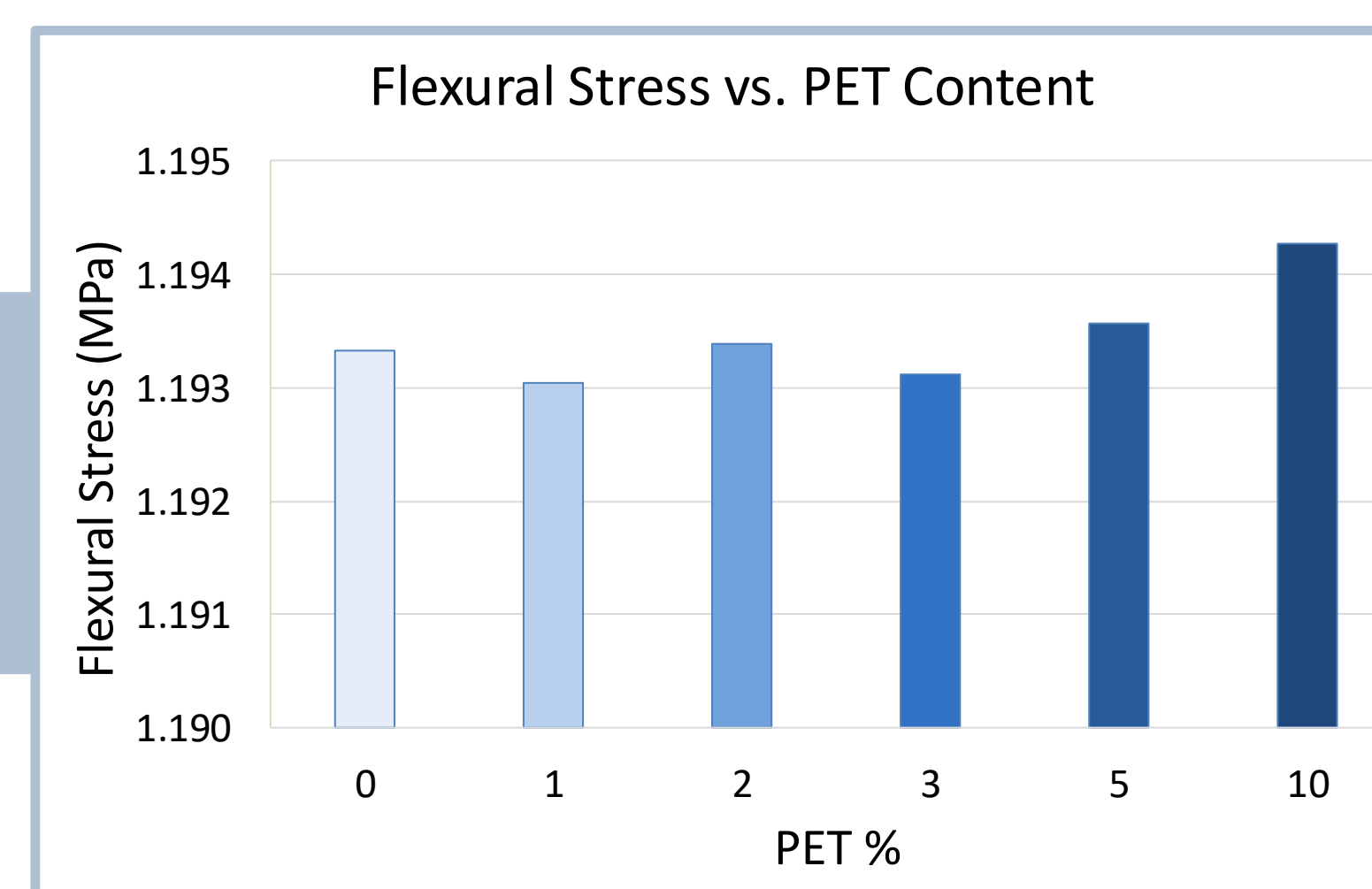


Figure 7. Flexural stress versus PET content for warm mix asphalt, obtained from FEM beam simulations under identical geometry and loading conditions.

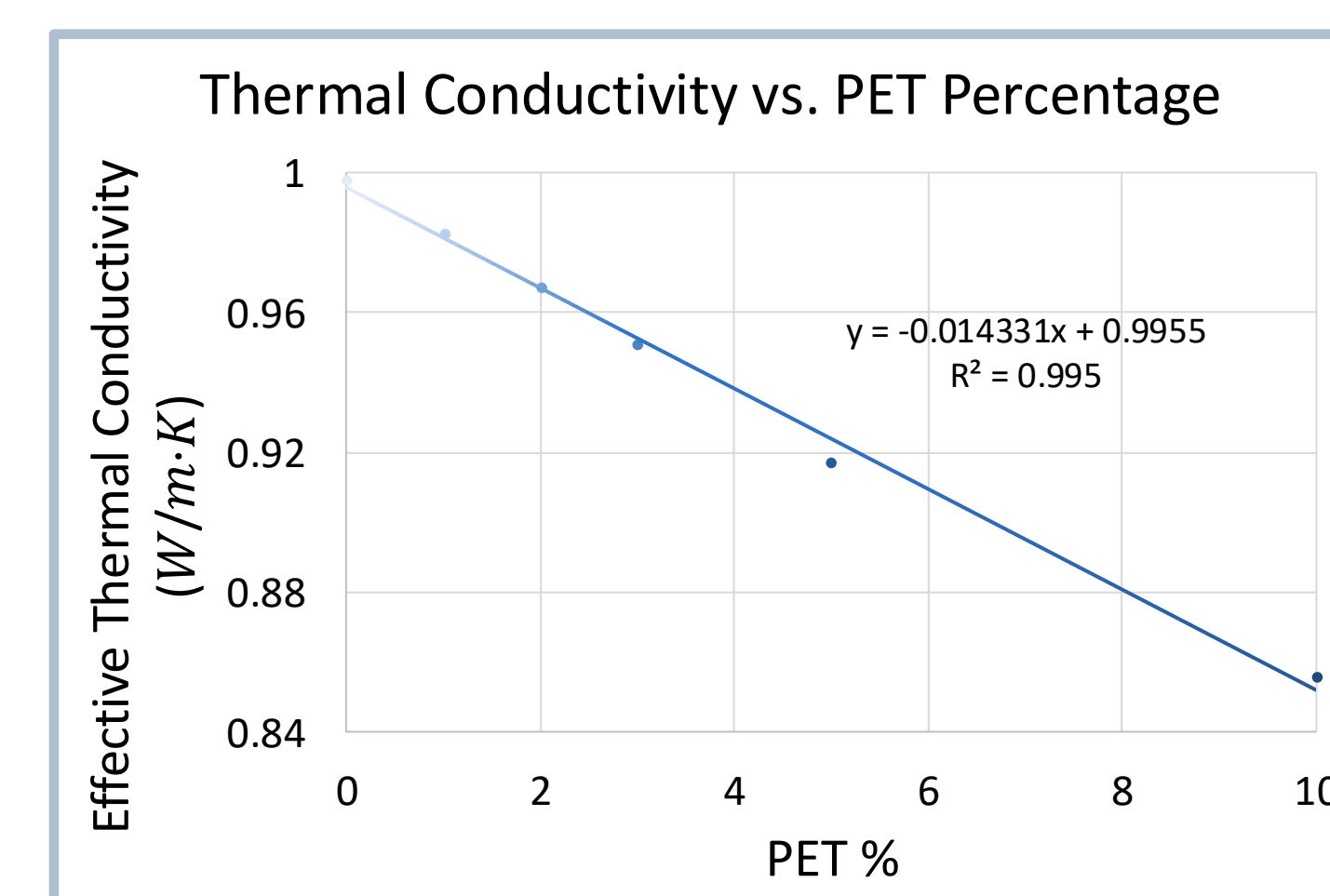


Figure 8. Effective thermal conductivity of warm mix asphalt as a function of recycled PET content (0–10%), obtained from FEM heat transfer simulations. Points represent FEM-derived values; the solid line indicates linear regression.

Future Work

- Quantify **microplastic runoff** from PET-modified pavements to assess long-term environmental impact.
- Perform full **life-cycle cost analysis** using AASHTOWare Pavement ME
- Refine **optimal PET content** across wider PET ranges
- Validate** models with laboratory testing, including rutting, flexural, and thermal experiments.