A Mesoscopic-Mechanism-Based Method for Compactability Evaluation of Asphalt Mixtures ‡

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‡More details please check: Yan, Marasteanu, and Le. Mechanism-Based Evaluation of Compactability of Asphalt Mixtures. *Road Mater. Pavement Des.*, 2021.

Research Background

- Importance of compaction: Compaction $\rightarrow$ field density $\rightarrow$ durability.
  - Low field density can lead to many premature pavement distresses, e.g., cracking, moisture damage, raveling and etc.
- Current situation
  - Mixtures are designed to 96% G_{mm} in the lab by Superpave mix design method, while typically can only be constructed to about 93% G_{mm} in the field. In Minnesota, for example, the average field density is 93.4% G_{mm} for 2019 and 2020 projects.*
  - Durability related issues outstripped rutting, becoming the most prevalent distress.
  - Research: limited understanding on compaction process.
- We need to enhance our understanding on compaction process.

* cf. Yan, Marasteanu, Bennett, and Garrity, Field Density Investigation of Asphalt Mixtures in Minnesota, *TRR*, 2021

Gyratory Compaction

In this research, we focus on gyratory compaction in the laboratory setting.

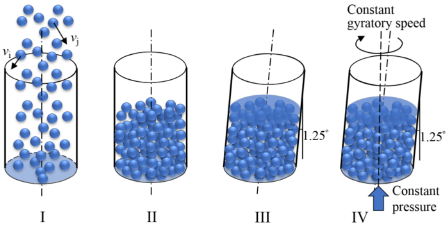
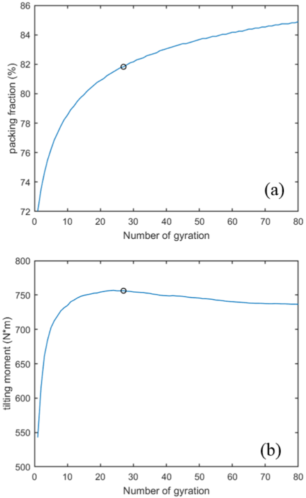


Figure 1: schematic diagram of gyratory compaction produces*

- Loading: Compression + Gyratory Shear.
- Output: Specimen Height + Tilting Moment
  - Specimen Height $\longrightarrow$ Density
  - Tilting Moment $\longrightarrow$ Shear Resistance

*Figure from: Man, *Rheology of Granular-Fluid Systems and its Application in the Compaction of Asphalt Mixtures*. PhD these, University of Minnesota, 2019

Typical Experimental Results of Gyratory Compaction



Some Typical Phenomena:

- Rate of densification decreases with number of gyrations.
- Shear resistance first increases and then decreases with number of gyrations.
- Densification rate increases with the amplitude of gyratory motion. (Similarly, vibration helps field compaction)
- ...

Reasons for these phenomena?

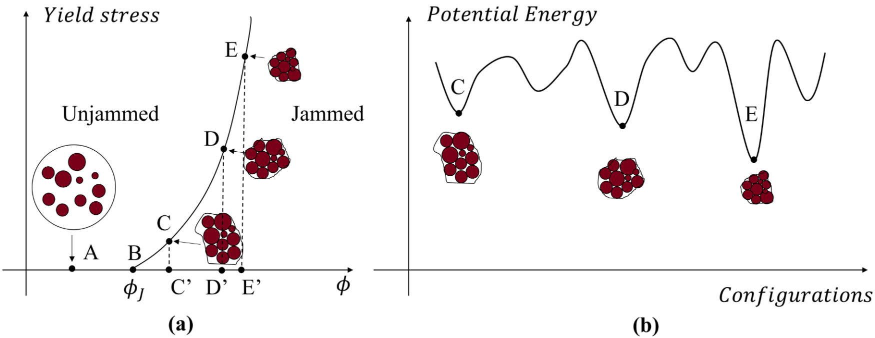
Coupling of Volumetric and Deviatoric Behaviors

- Volumetric behavior: Densification
- Deviatoric behavior: Shear

- Shear $\longrightarrow$ Densification: Amplitude of shear excitation increases rate of densification.
- Densification $\longrightarrow$ Shear: As density increases, the shear resistance first increases and then decreases.

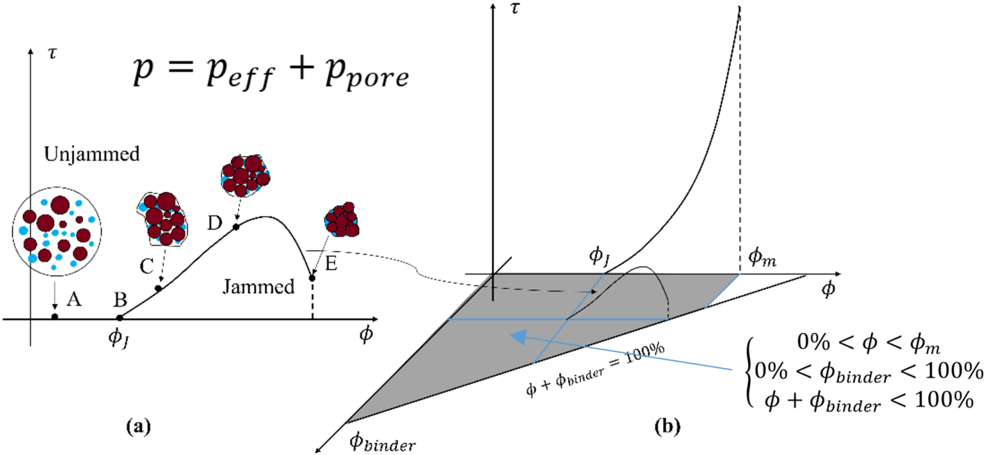
- Origin of the coupling effects: Mesoscopic behavior of aggregates and binder.
- To explain them, we have to resort to mesoscopic physical mechanisms:
  - Jamming of aggregates $\longleftarrow$ inspired by granular physics (Cates et al., 1998; Liu and Nagel, 1998).
  - Binder-aggregate interaction $\longleftarrow$ inspired by critical state soil mechanics (Schofield and Wroth, 1968).

Jamming of Aggregates



- Explains why shear or vibration excitation accelerates compaction.
- Explains the increase in shear resistance with density at the beginning phase of compaction process.
- Cannot explain the decrease in shear resistance in the latter phase of compaction process.

Binder-Aggregate Interaction

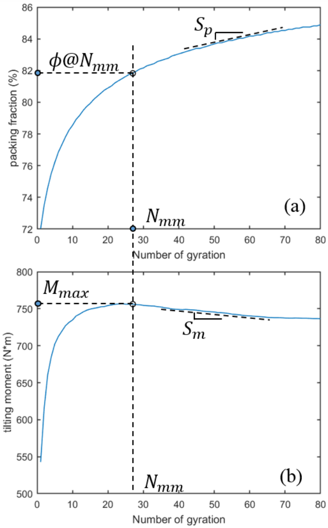


- Explains the decrease in shear resistance in the latter phase of compaction process.

New understanding based on Mesoscopic Mechanisms

Compaction phenomena	**Interpretation based on mechanisms**
Compaction process	Evolution of jammed states of aggregates to denser packings due to shear or vibration excitation
Decrease in the rate of compaction	Aggregate rearrangement (unjamming the system) becomes more difficult as density increases
Increase in shear resistance in the beginning phase	same as above
Decrease in shear resistance in the later phase	Pore pressure builds up which causes the decrease in effective stress in the aggregate skeleton, and thus cause the decrease in shear resistance.

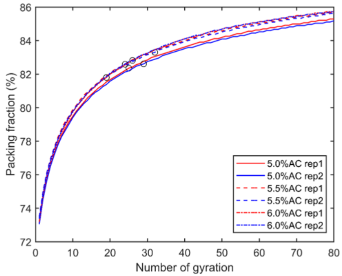
Mechanism-Based Compactability Indices

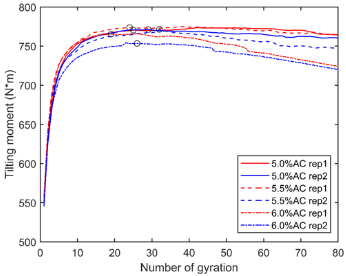


•M_{max}: maximum tilting moment (shear resistance).
•N_{mm}: number of gyrations corresponding to the maximum tilting moment.
•ϕ_{mm}: packing fraction at N_{mm}.
•S_p: slope of ϕ versus N, for $N > N_{mm}$ which characterizes the rate of evolution of jammed states or the rate of densification, after N_{mm} is reached.
•S_m: slope of tilting moment versus N, for $N > N_{mm}$ which characterizes the rate of the decrease in tilting moment, after N_{mm} is reached.
•S_{log}: slope of ϕ versus log$N$, which characterizes the rate of densification.

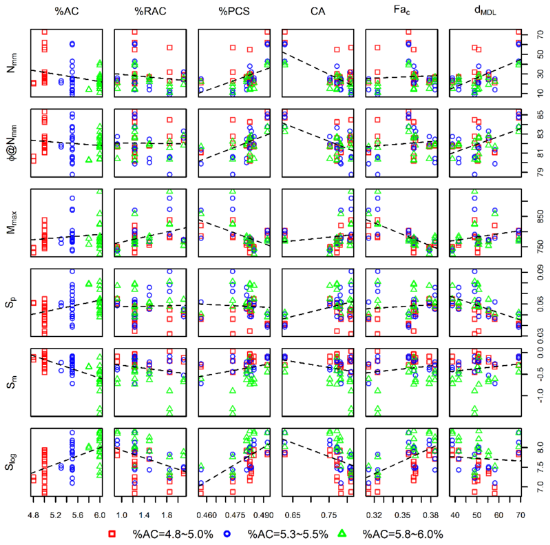
Case Study – Characterize the Compactability of MnROAD Mixtures

- Seven mixtures were studied. Gyratory compaction data in their mix design phase were collected.
- The mixtures have:
  - same aggregate angularity,
  - different gradations.
  - Three binder content levels were tried in their design phase.
- Compactability were evaluated by the proposed mechanism-based indices.
- Correlations between compactability and material composition were then analyzed.





Correlations between Compactability and Material Properties



- Some correlations are identified.
  - %AC $\leftrightarrow S_{log}$
  - %AC $\leftrightarrow S_m$
  - ...
- The correlations are consistent with the inference based on the proposed mesoscopic mechanisms.
- The correlations are of great help for design more compactable mixtures

Conclusions

- Two physical mechanisms were proposed to explain the compaction process from mesoscopic level.
  - Jamming of aggregates.
  - Binder-aggregate interaction.
- Based on the mechanisms, six indices were proposed to characterize gyratory compaction data and to evaluate the compactability of mixtures. They are advantageous since they have clear physical meanings.
- By the proposed indices, compactability of real mixtures were characterized. Some correlations were identified between compactability and material properties, which are of great help for designing more compactable mixtures.
- The proposed mechanisms shed light on the modeling of compaction process.

Please check this paper for more details of this research: Yan, Marasteanu, and Le. Mechanism-Based Evaluation of Compactability of Asphalt Mixtures. *Road Mater. Pavement Des.*, 2021.

Current Progress

Modeling the gyratory compaction based on the mesoscopic mechanisms

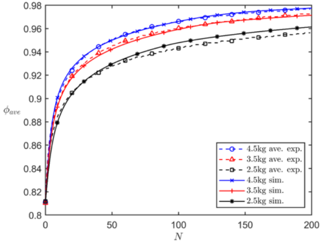
- Nonlocalilty of aggregate rearrangements (jamming).

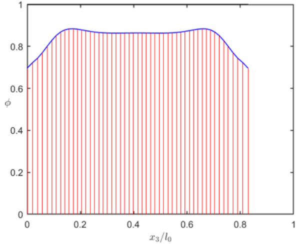
$$\bar{\phi}(x,t) = \int_{-\infty}^{\infty} \alpha(x-x')\,\phi(x',t)\,dx'$$

- Rate of densification $\longleftarrow$ transition rate between jammed states due to the excitation of gyratory shear.

$$\frac{\partial \dot{x}}{\partial x} = -C_1 \exp\left(-C_2(\bar{\phi}-\phi_t)^k\right)$$

- Simulation Results:
  - Simulate the shape of compaction curve for different specimen sizes: larger specimen is easier to compact.
  - Simulate the density profile: density is higher in the middle while is lower at the two ends.





Yan, Marasteanu, and Le, One-Dimensional Nonlocal Model for Gyratory Compaction of Hot Asphalt Mixtures, Submitted to *J. Eng. Mech.*

Thank you!