Mechanism-Based Evaluation of Compactability of Asphalt Mixtures

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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
  - In the US, mixtures are designed to 96% G_{mm} in the lab by Superpave design method, while typically can only be constructed to about 93% G_{mm} in the field after construction (Yan et al., 2021)[1].
  - Mix design: Compaction is not given enough consideration.
  - Research: having very limited understanding.
- Clearly, compaction need to be improved in practice. To do that, we need first enhance our understanding on compaction process.

[1] Yan, Marasteanu, Bennett, and Garrity, *Field Density Investigation of Asphalt Mixtures in Minnesota*, TRR, 2021

Gyratory Compaction

In this research, we focus on using gyratory compaction method in the laboratory to study compaction process.

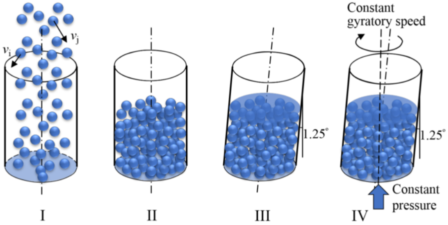
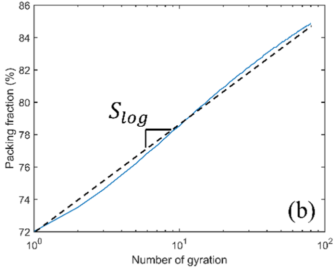


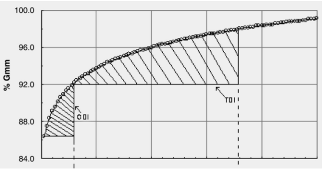
Figure 1: schematic diagram of gyratory compaction produces (Teng, 2019)

- Loading: compression + gyratory shear.
- Size of specimen: diameter = 150mm, height ≈ 110 mm.
- Output: specimen height and tilting moment at each gyration.

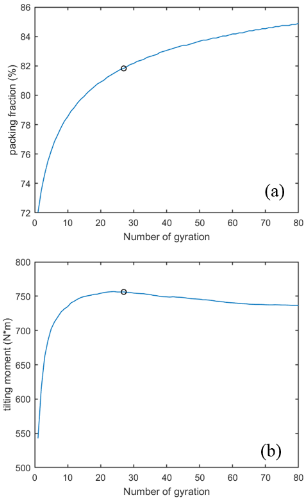
Some Previous Understandings of Gyratory Compaction

- Linear relationship between density and and logarithm of number of gyrations (Moutier, 1974)
- Energy indices: Energy dissipation during compaction (Guler et al., 2000, Stakston and Bahia, 2003; Faheem and Bahia, 2004; Dessouky et al., 2004)
- Locking point: at certain number of gyrations aggregates interlock with each other and further compaction of mixture becomes very hard (Vavrik and Carpenter, 1998)





Typical Experimental Results of Gyratory Compaction



Typical phenomena of gyratory compaction:

- Rate of densification is the highest at the beginning and decreases with number of gyrations.
- Shear resistance (tilting moment) first increases and then decreases with number of gyrations.
- Rate of densification increases with the amplitude of gyratory shear.
- ...

Reasons for these phenomena?

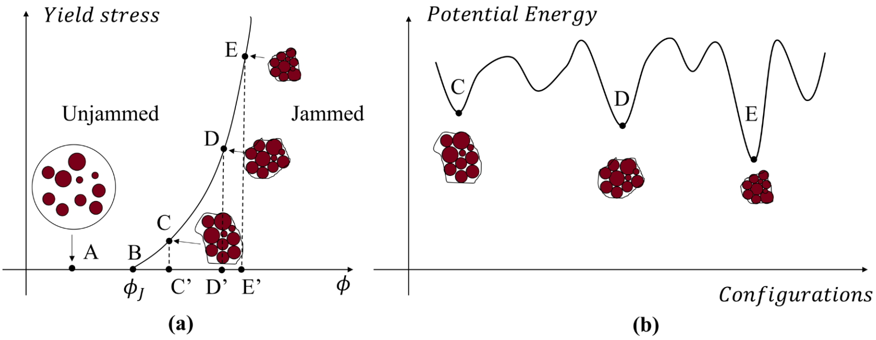
Coupling of Volumetric and Deviatoric Behaviors

- Volumetric behavior: densification
- Deviatoric behavior: shear

- Shear $\longrightarrow$ densification: rate of densification increases with the increasing amplitude of distortion
- Densification $\longrightarrow$ shear: the shear resistance first increases and then decreases with the increase in density

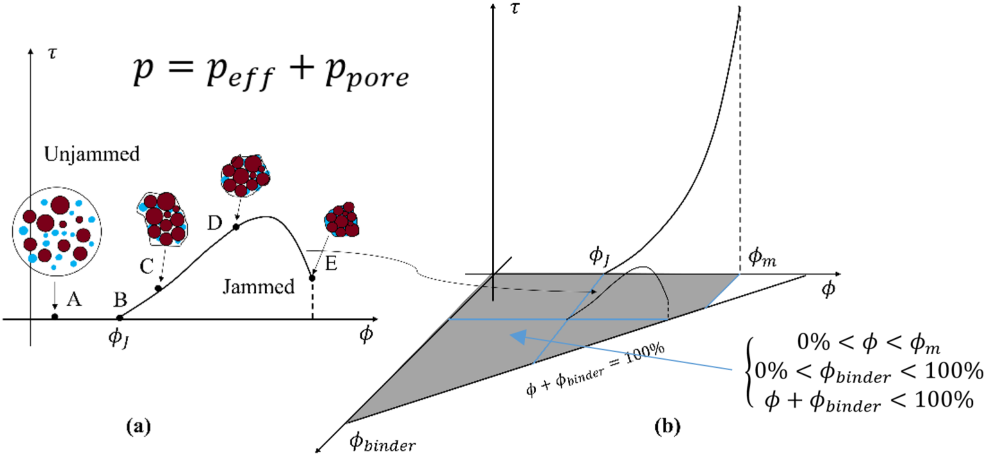
- These coupling effects originate from the mesoscopic behavior of material components. To explain them, we have to resort to mesoscopic physical mechanisms:
  - Jamming of aggregates $\longleftarrow$ inspired by granular physics (Cates et al., 1998; Liu and Nagel, 1998).
  - Binder-aggregate interaction $\longleftarrow$ 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

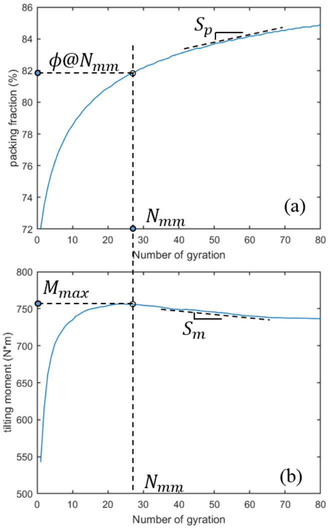


- Explains the decrease in shear resistance in the latter phase of compaction process.

Interpretation of Compaction Process by 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.

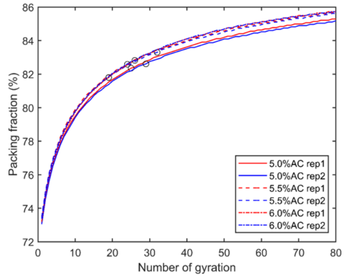
Mechanism-Based Compactability Indices

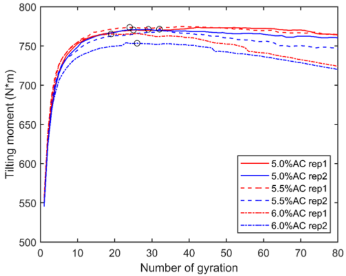


- M_{max}: maximum tilting moment (shear resistance).
- N_{mm}: number of gyrations corresponding to the maximum tilting moment.
- ϕ_{mm}: packing fraction at N_{mm}.
- S_p: slope of ϕ versus N, for $N > N_{mm}$ which characterizes the rate of evolution of jammed states or the rate of densification,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

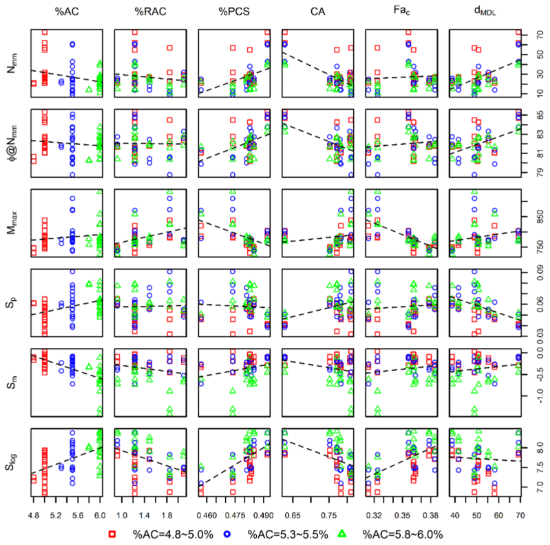
Case Study – Characterize the Compactability of MnROAD Mixtures

- 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 characterizing gyratory compaction data are developed to evaluate the compactability of mixtures

- Using gyratory compaction data of real mixtures, correlations between compactability and material properties, such as binder content and gradation, were analyzed, which are of great importance for designing more compactable mixtures.

- The proposed mechanisms shed light on the modeling of compaction process.

Current Progress

Modeling the gyratory compaction process based on the mesoscopic mechanisms

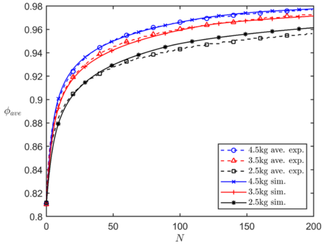
- Nonlocalilty of jamming

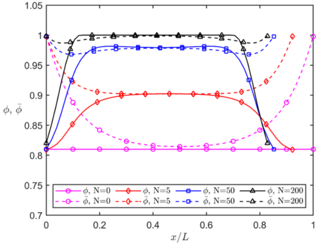
$$\bar{\phi}(x,t) = \int_{-\infty}^{\infty} \alpha(x - x')\,\phi(x',t)\,dx'$$

- Rate of densification derived based on the frequency of evolution of the jammed states

$$\frac{\partial \dot{x}}{\partial x} = -C_1 \exp\left(-C_2(\bar{\phi} - \phi_0)^k\right)$$

- Benefits
  - Simulate the shape of compaction curve
  - Simulate the density profile
  - Simulate the size effect





Yan, Marasteanu, and Le, *One-Dimensional Nonlocal Model for Gyratory Compaction of Hot Asphalt Mixtures*, in progress

Thank you!