Laboratory Tests and Numerical Simulation of Mixing Superheated Virgin Aggregate with RAP Materials

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Outline

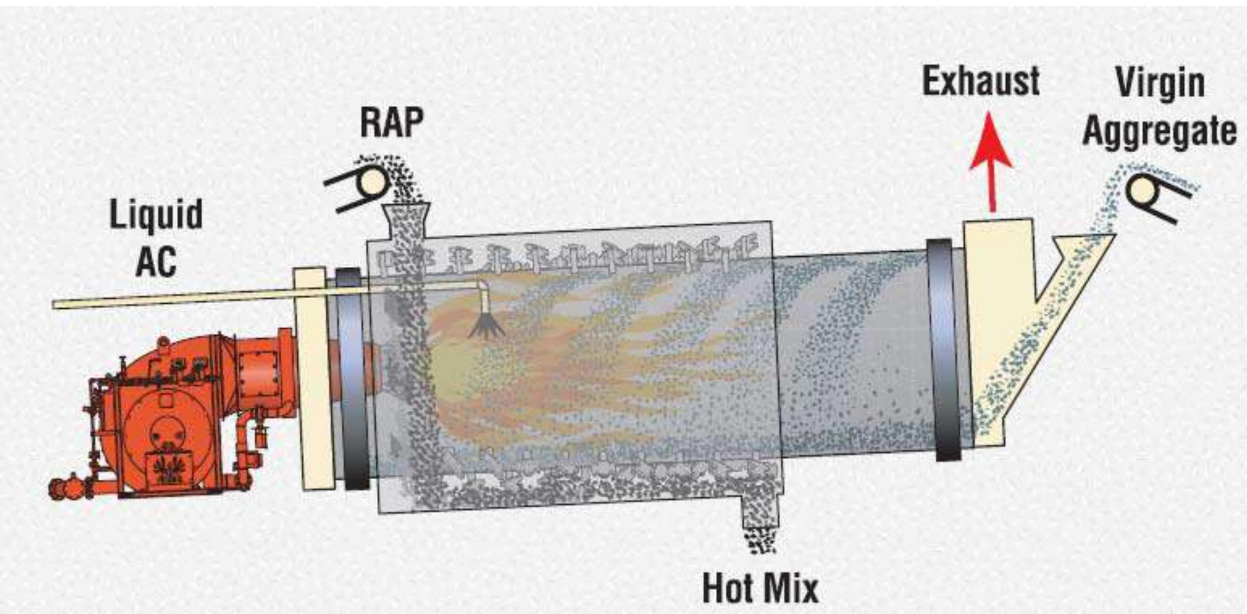
- Introduction
- Laboratory Test & Simulation Method
- Results & Discussion
- Conclusions

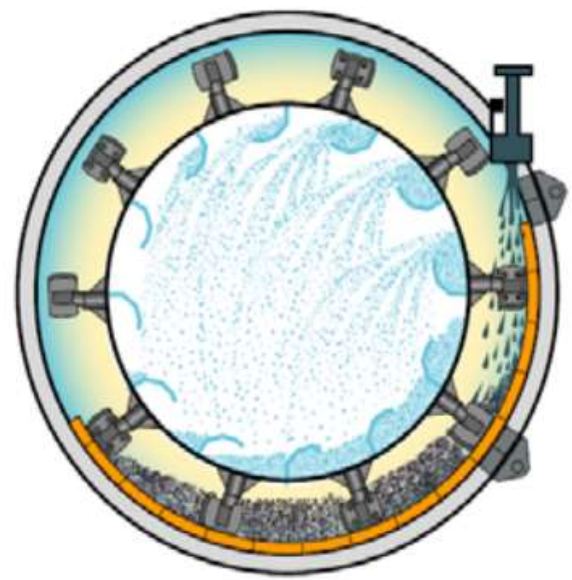
Introduction

- Findings on effects of RAP on performance of mixes from previous studies are mixed, such as effect of RAP on fatigue cracking
  - Based on only end product of mixes produced in lab or plant without looking into production process
- Plant production condition affects the performance of RAP mixes. (Mogawer et al. 2012)
  - Plant type, RAP percentage, RAP moisture, RAP binder properties, mixing time, production temperature, discharge temperature, storage temperature, et.al.

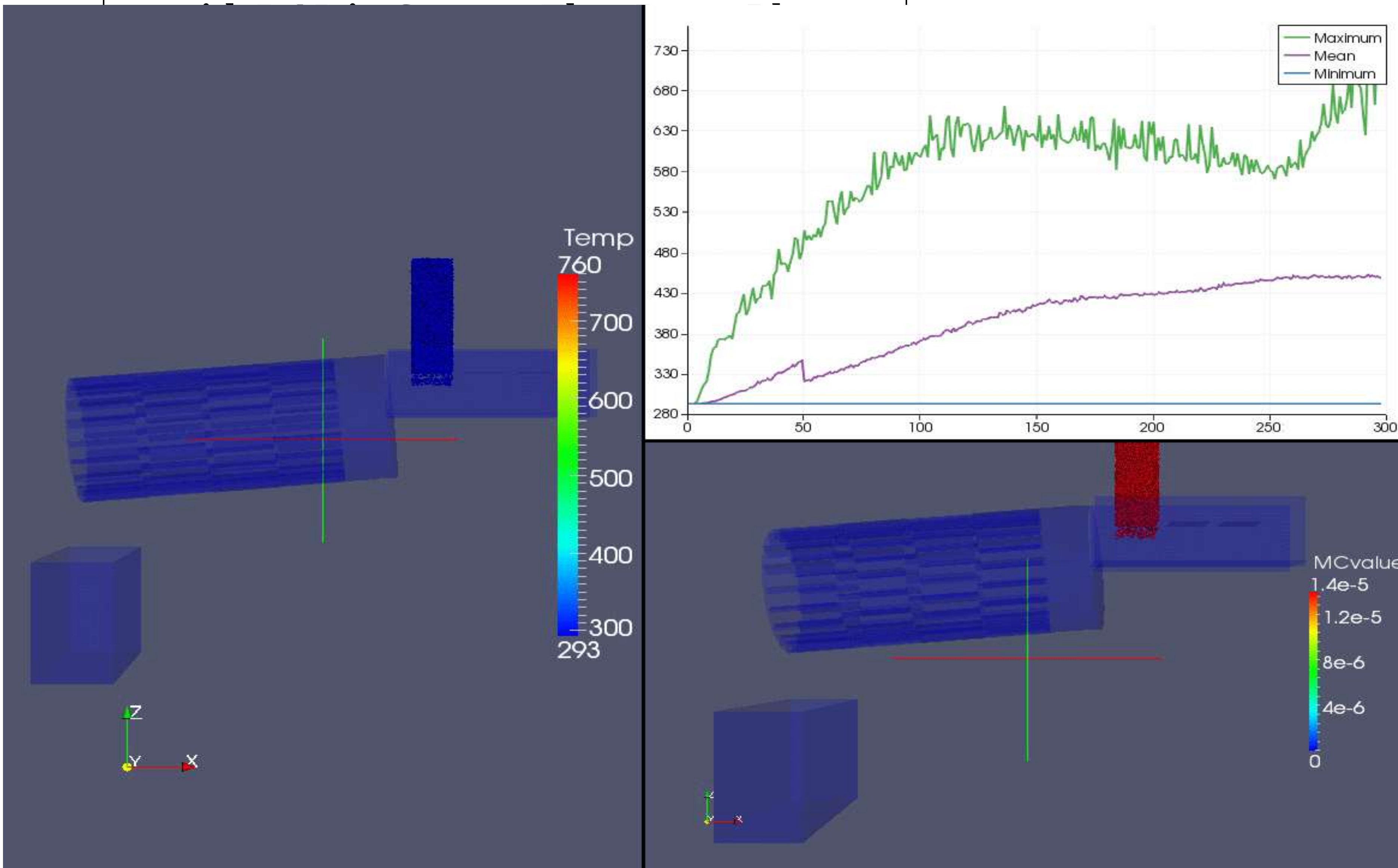
Introduction

- Example of production process: Astec Drum Plant (http://www.astecinc.com/products/drying-mixing/sequential-mixing.html)





Example Production Process of HMA/WMA



Asphalt mixture with RAP

Introduction

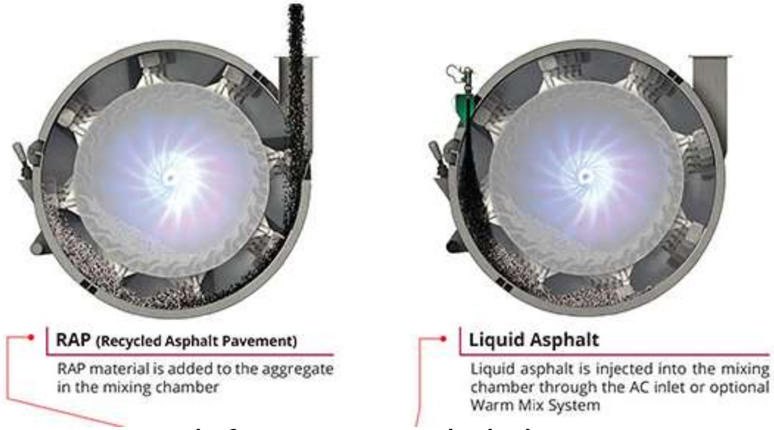
- RAP content and RAP moisture could affect production condition

RAP Content (%)	RAP Moisture Content (%)	Superheat Temperature Required (°C)			
		116 °C Mix	127 °C Mix	138 °C Mix	149 °C Mix
10	0	132	144	156	168
	1	134	147	159	171
	2	137	149	162	174
	3	140	152	164	177
	4	143	155	167	179
	5	146	158	170	182
20	0	144	158	172	186
	1	151	164	178	192
	2	157	171	184	198
	3	163	177	191	204
	4	169	183	197	211
	5	175	189	203	217
30	0	162	178	166	209
	1	173	188	315	219
	2	183	199	214	230
	3	194	209	225	241
	4	204	220	236	251
	5	215	231	246	262
40	0	186	203	221	239
	1	218	219	237	256
	2	234	235	253	272
	3	250	251	269	288
	4	266	267	286	304
	5	282	283	302	320
50	0	216	238	260	282
	1	240	262	284	309
	2	264	287	309	331
	3	289	311	333	356
	4	313	336	358	380
	5	338	360	382	404

(After Brock and Richmond 2005)

Introduction

- Three fundamental blending mechanisms between RAP binder and virgin binder according to *production process*
  - *RAP binder mobilization and transfer to virgin aggregate（step2）*
  - *Mechanical blending between RAP binder and virgin binder by mixing paddle (Step3)*
  - Diffusion between RAP binder and virgin binder(step3+long term effect)

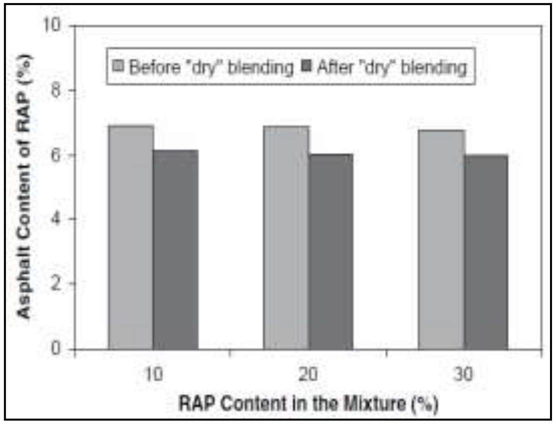


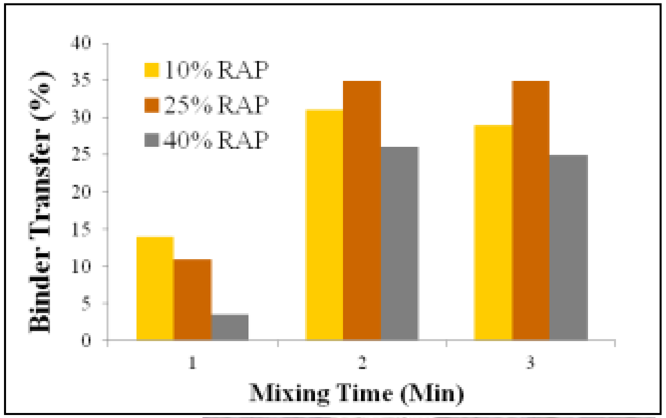
(After Astec Website)


(After Rad 2013)

Introduction

- Previous laboratory study for RAP binder transfer
  - Huang et.al (2005)
    - Superheated aggregate of 190ºC
    - Mixing coarse virgin aggregate with fine RAP
    - RAP binder content reduced from 6.8% to 6.0%
    - 11% of RAP binder transferred
  - Mehta et.al (2012)
    - Superheated aggregate of 177ºC
    - RAP: 10%, 25% and 40%
    - Mixing time: 1 min, 2 min, and 3 min
  - Johnson et.al (2013)
    - 30s for batch plant
    - Laboratory drum mixer could not duplicate plant mixing





Introduction

- Study Objectives
  - Effect of RAP content, RAP moisture, mixing time, and virgin aggregate temperature on temperature evolution of RAP and superheated aggregate, and the evolution of RAP binder transfer during production
  - Comingling of RAP and virgin binder

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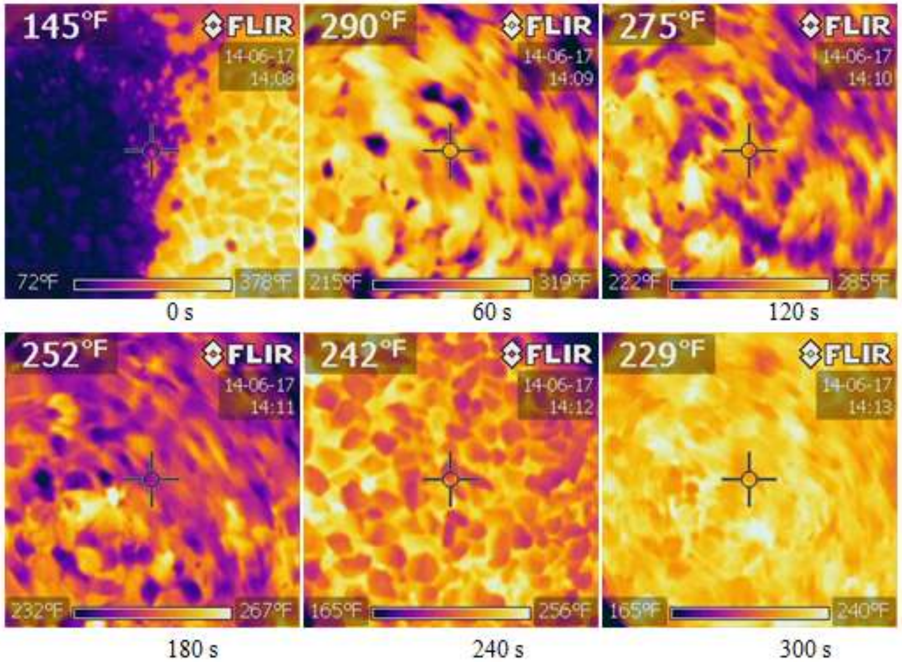
Laboratory Experiment & Simulation Method

- Mixing behavior between virgin aggregate and RAP
  - Video camera

Laboratory Experiment & Simulation Method

- Temperature evolution
  - Infrared camera
- RAP binder transfer
  - Binder content of virgin aggregate after mixing
  - AASHTO T164



Simulation Method & Laboratory Experiment

- Simulation set up

Particle density (kg/m^3) for virgin aggregate and RAP materials	2200
Particle diameter of virgin aggregate (mm)	10
Particle diameter of RAP (mm)	4.8
RAP percentage (%)	**10, 30, 50**
RAP binder content (%)	4.5
Particle Young's modulus (N/m^2)	1.38e7*
Particle Poisson's ratio	0.25*
Coefficient of restitution	0.40
Coefficient of sliding friction	0.80
Coefficient of rolling friction	0.70
Particle specific thermal capacity (J/kg·K)	800
Particle thermal conductivity (J/K·s·m)	7
Initial virgin aggregate temperature (F)	**320, 356, 374**
Initial RAP particle temperature (F)	**68**
DEM time step (s)	0.00003
Drum rotational speed (RPM)	50
Total simulation time (s)	**300**

Laboratory Experiment & Simulation Method

- Discrete element method (DEM)
  - Simulate mixing process
  - Newton's second law

$$m_i \frac{dv_i}{dt} = \sum_j F_{ij}^n + \sum_j F_{ij}^t + F_i^g \qquad \text{Translation}$$

$$I_i \frac{d\omega_i}{dt} = r_i \times \sum_j F_{ij}^t + T_i \qquad \text{Rotation}$$

  - Platform is based on open source software "LIGGGHTS"

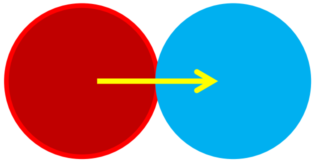
Laboratory Experiment & Simulation Method

- Heat conduction theory
  - Studying temperature evolution between superheated virgin aggregate and RAP aggregate

Temperature difference

$$\dot{Q}_{pi-pj} = h_{c,i-j} \Delta T_{pi-pj}$$

$$h_{c,i-j} = \frac{4K_{pi}K_{pj}}{K_{pi} + K_{pj}} \sqrt{(A_{contant\ ,i-j})}$$



$$m_p c_p \frac{dT_{p,i}}{dt} = \sum \dot{Q}_{pi-pj}$$

Heat conduction flux

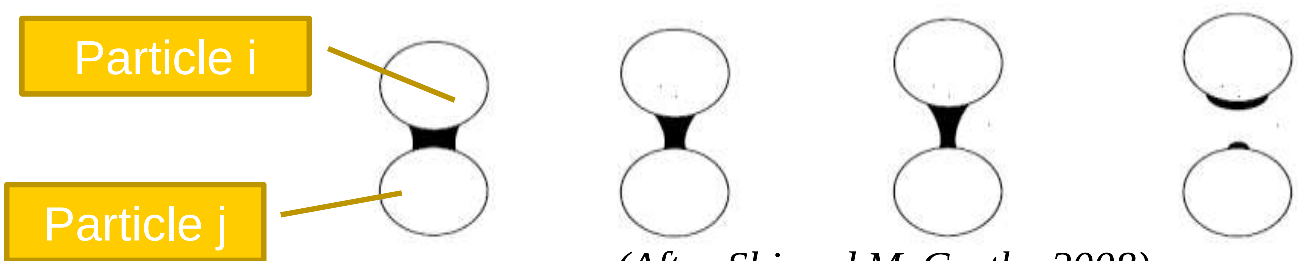
Laboratory Experiment & Simulation Method

- Modified liquid bridge theory (*Shi and McCarthy 2008*)
  - Define minimum transfer activation temperature
  - Assume to equal critical high temperature PG, 80.6ºC for the RAP in this study

$$bm_i = \frac{m_i}{2} \times (1 - \sqrt{1 - \frac{R_j^2}{(R_i + R_j)^2}})$$ Liquid bridge mass from i

$$bm_j = \frac{m_j}{2} \times (1 - \sqrt{1 - \frac{R_i^2}{(R_i + R_j)^2}})$$ Liquid bridge mass from j

$$bm = bm_i + bm_j$$ Total liquid bridge mass



(*After Shi and McCarthy 2008*)

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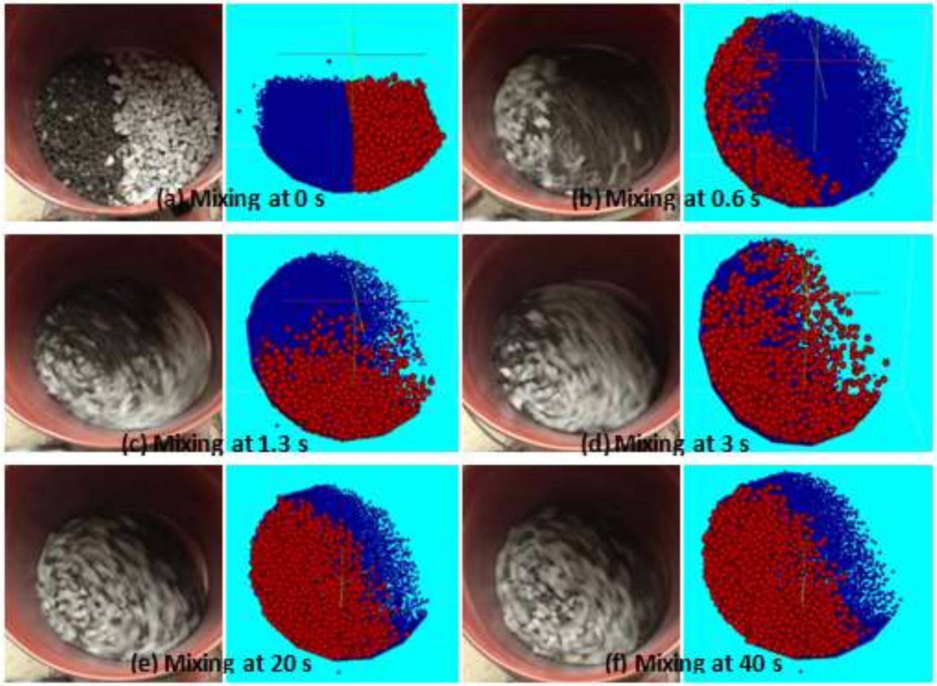
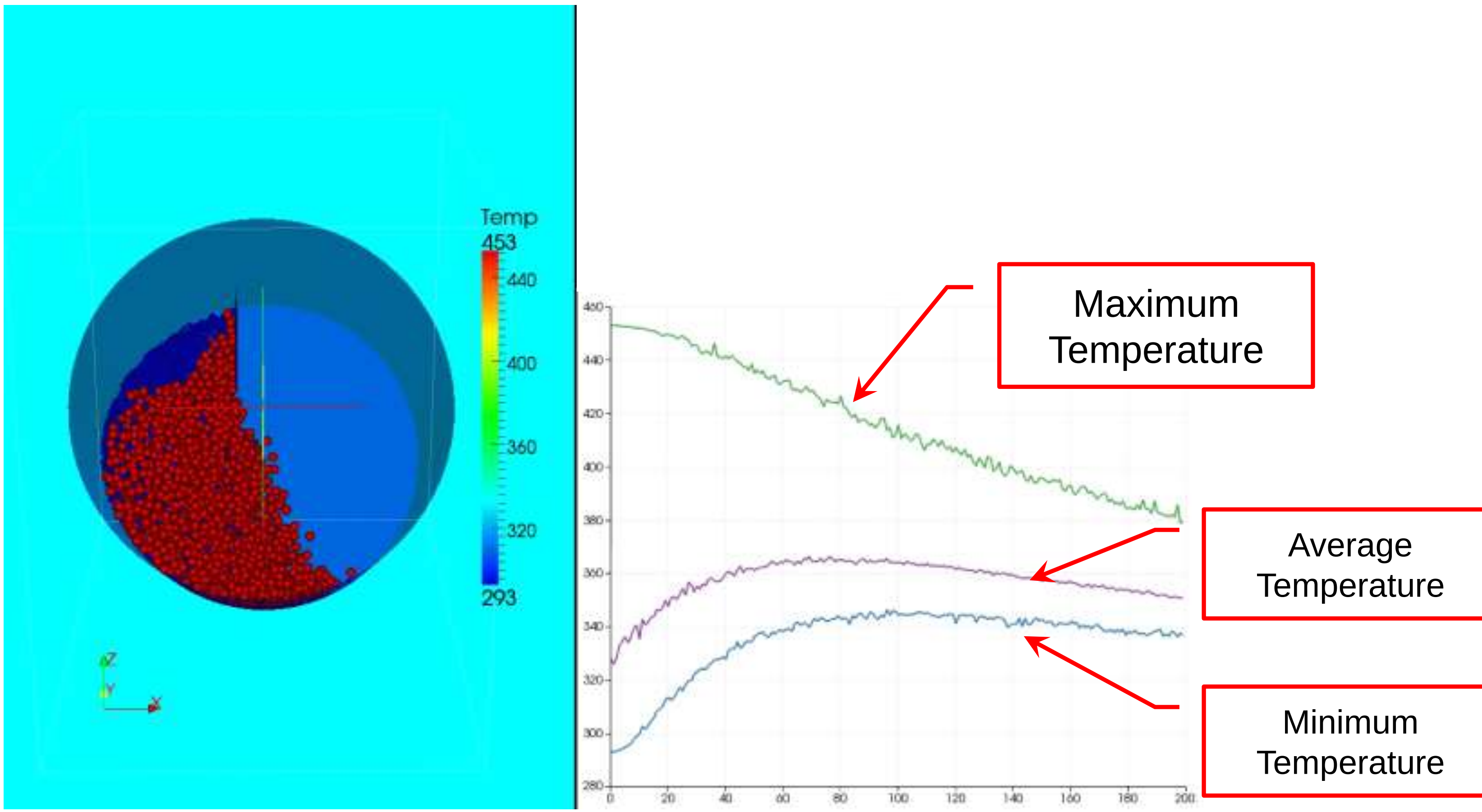
Results and Discussion

- Mixing behavior (Experiment and Simulation)
  - Similar mixing behavior of virgin aggregate and RAP between experiment and DEM simulation
  - Identify *segregation* of coarse virgin aggregate and fine RAP for both experiment and simulation without flights



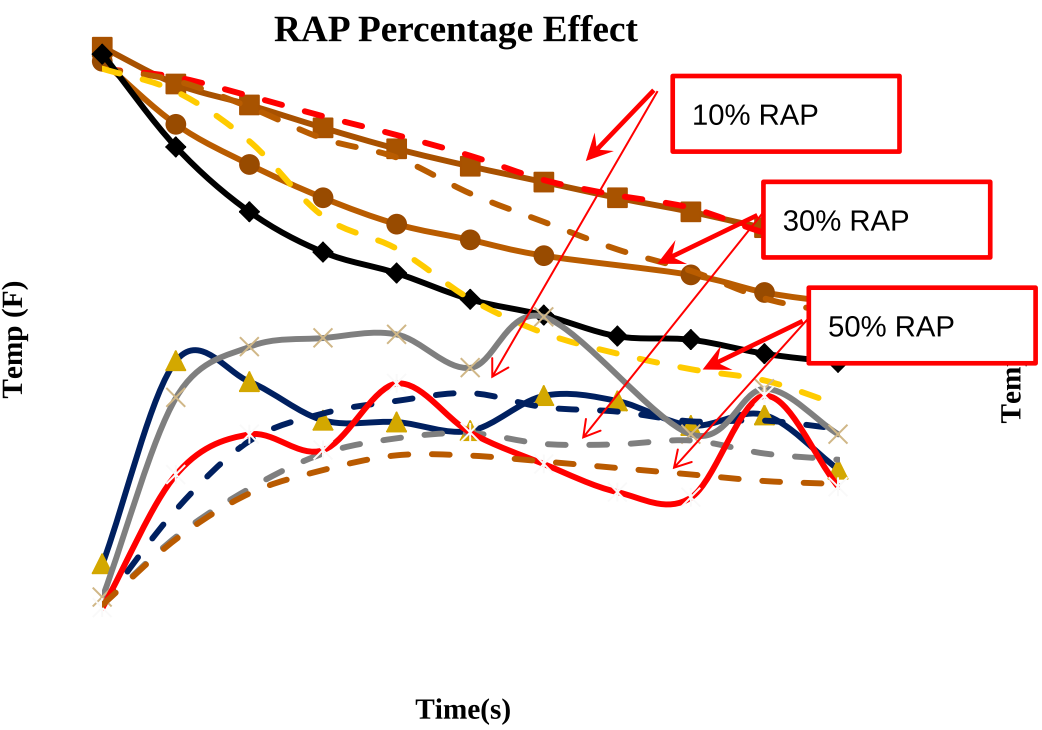
Results and Discussion

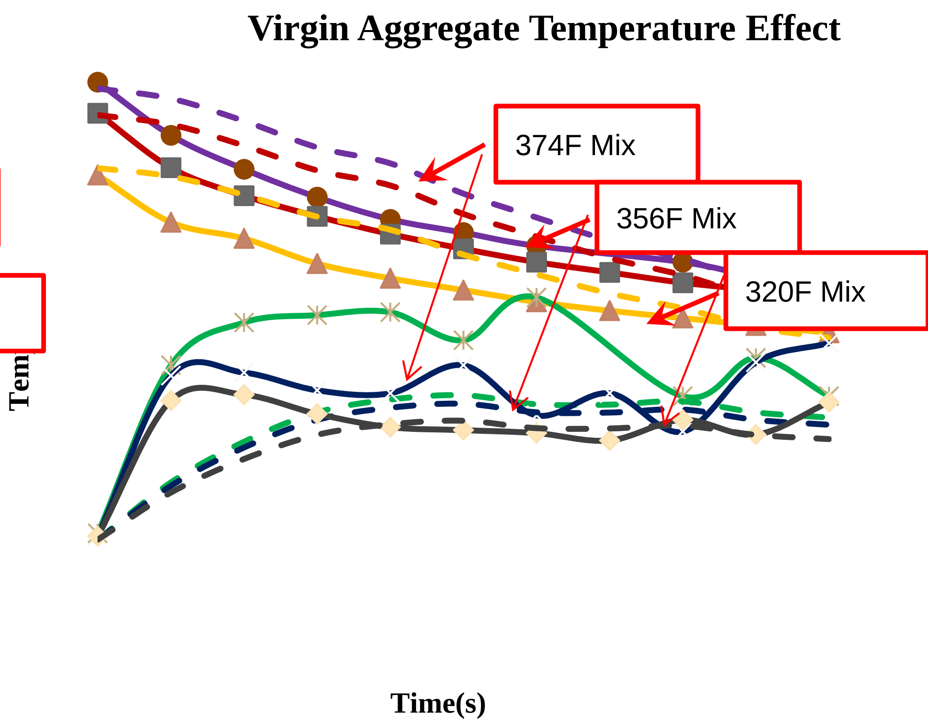
- Temperature evolution study (Simulation)



Results and Discussion

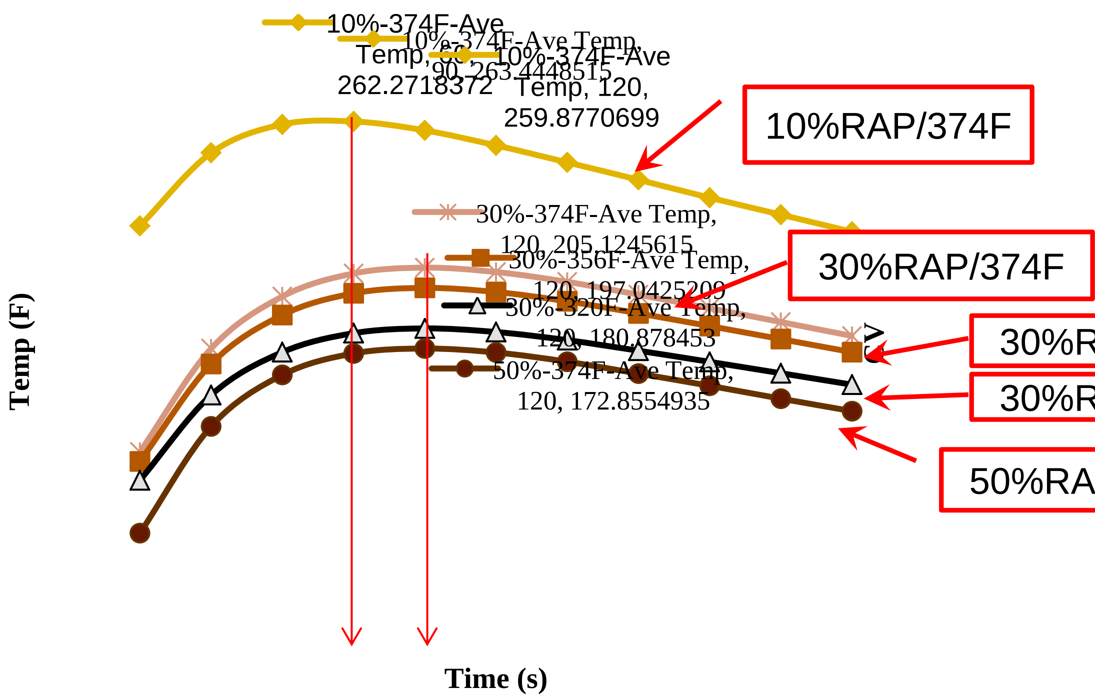
- Temperature evolution study (Experiment and Simulation)
  - Effects of RAP percentage and virgin aggregate temperature

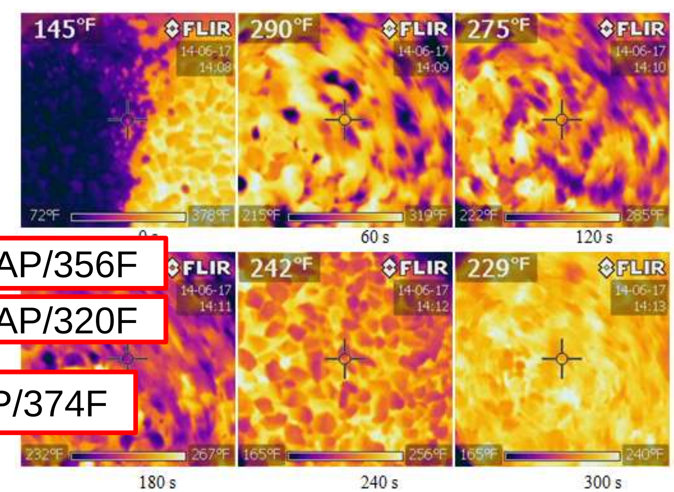




Results and Discussion

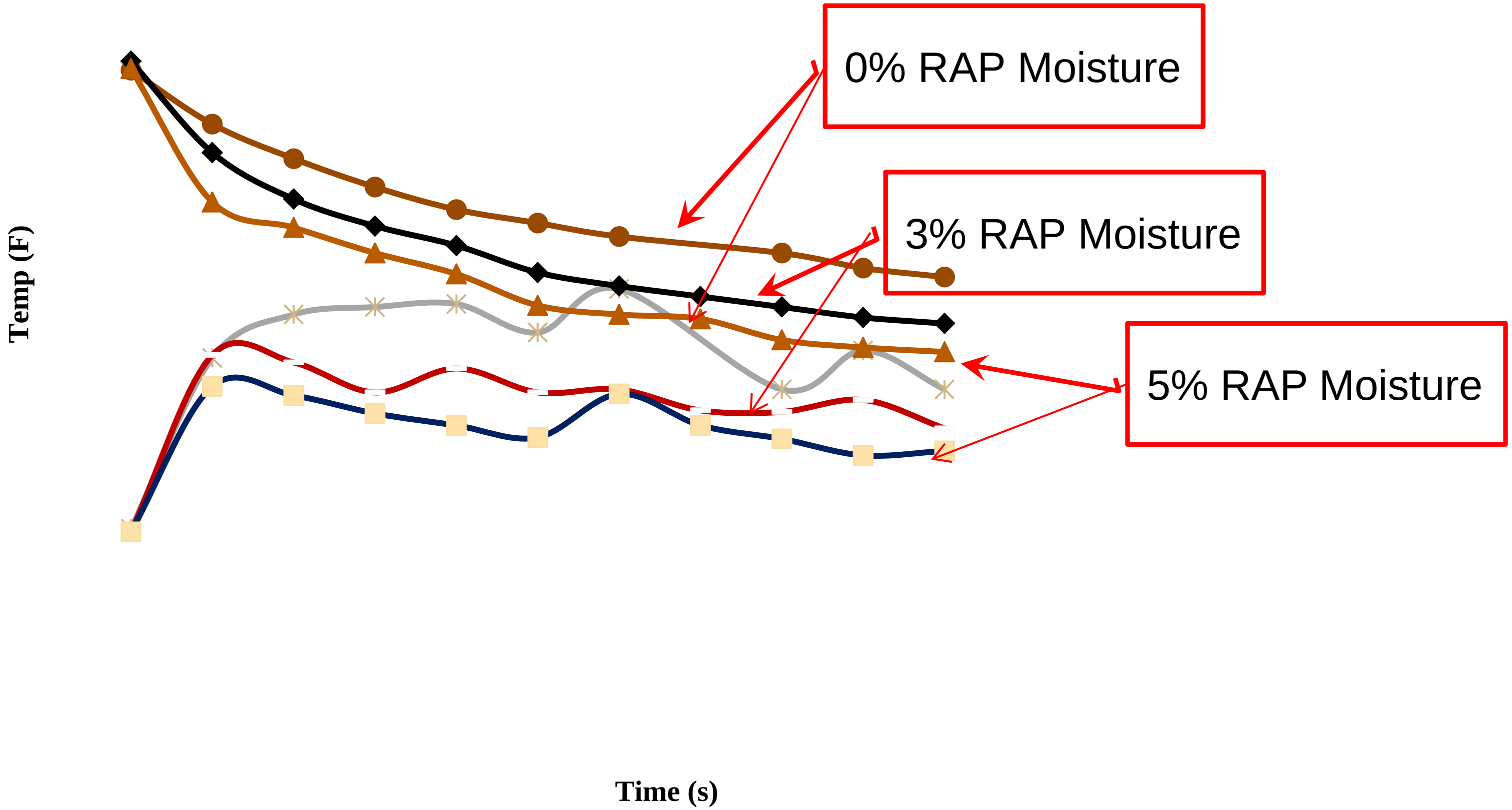
- Mixture temperature vs. mixing time based on DEM Simulation
  - Peak temperature during mixing, 90-120s for lab mixer
  - Uniformity of mixture: coefficient of variation (CV=μ/σ)





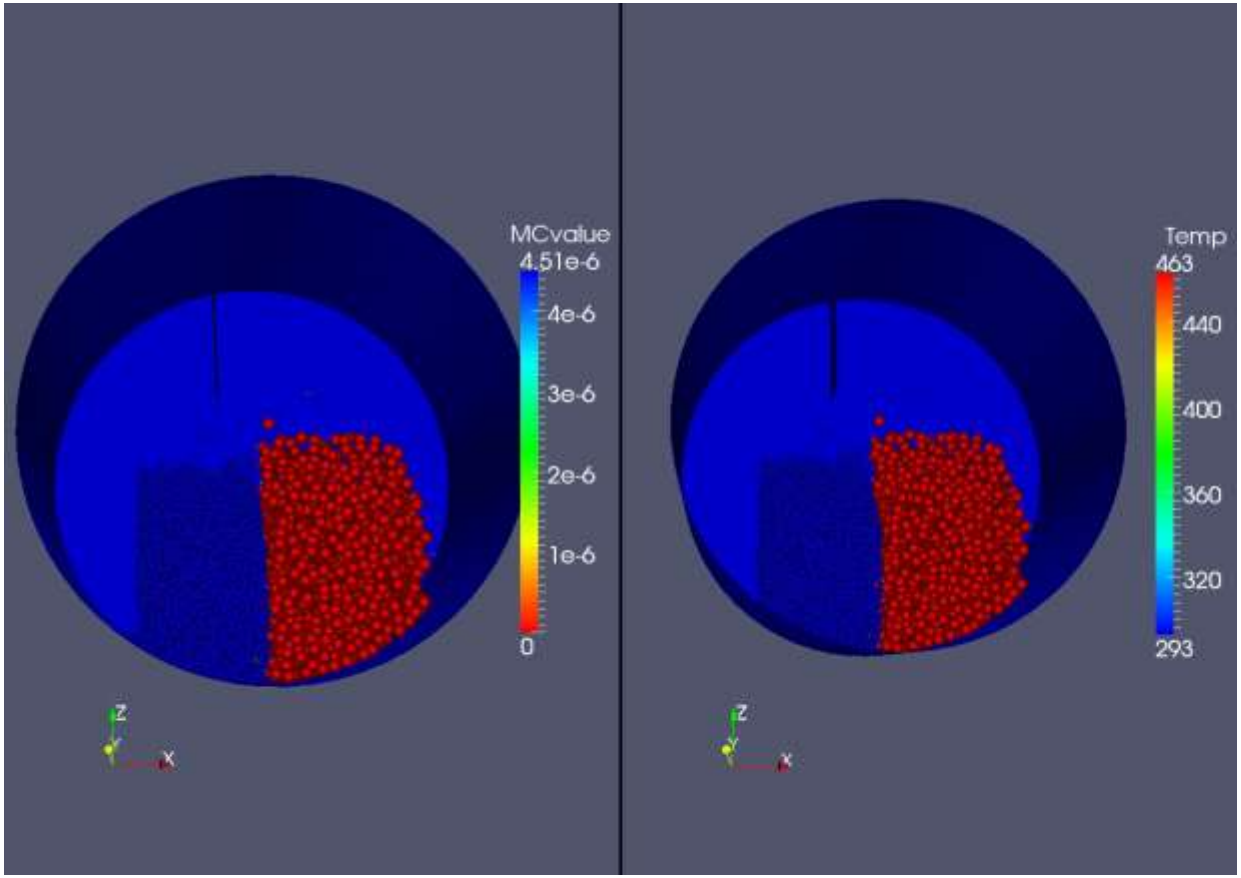
Results and Discussion

- Temperature Evolution Study (Experiment)
  - RAP moisture effect



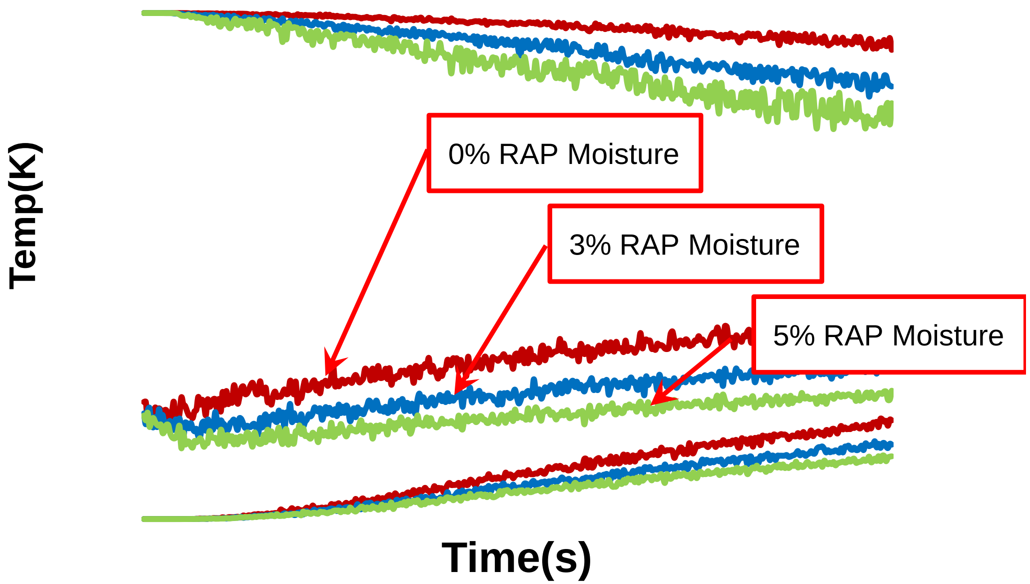
Preliminary simulation of RAP Moisture Effect

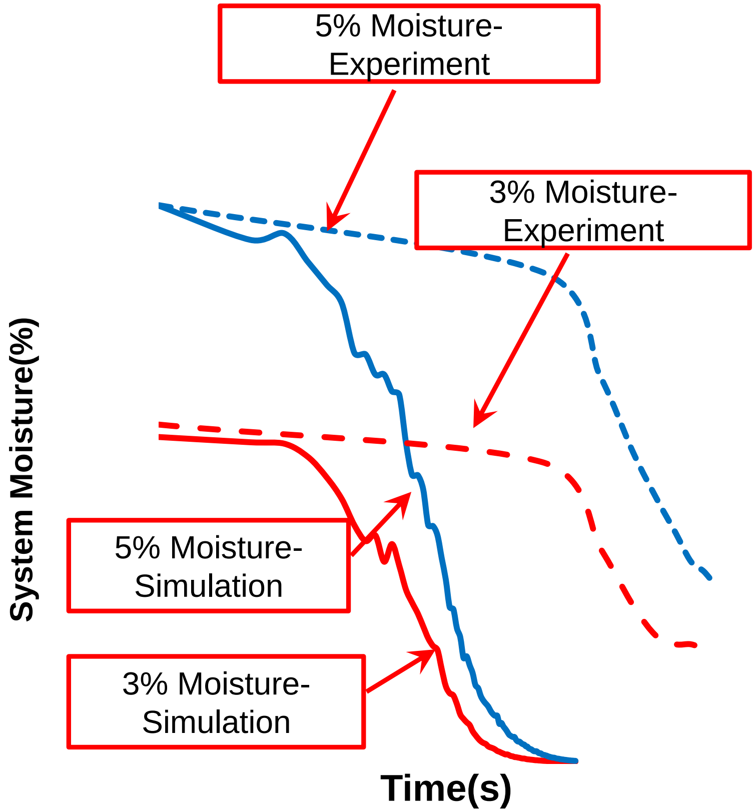
- Consider moisture transfer between particles
- Consider energy balance during evaporation



Simulation of RAP Moisture Effect

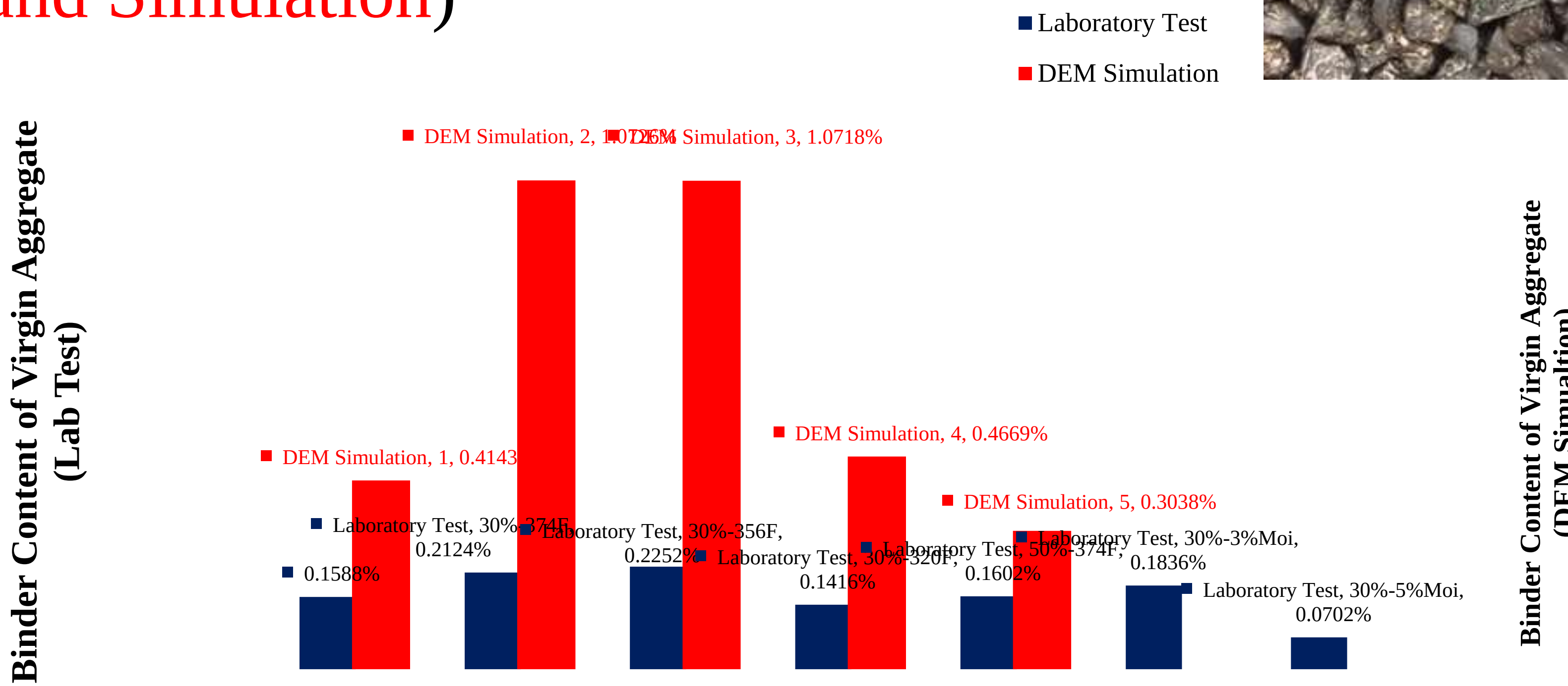
- RAP moisture effect on the temperature evolution
- Moisture evolution





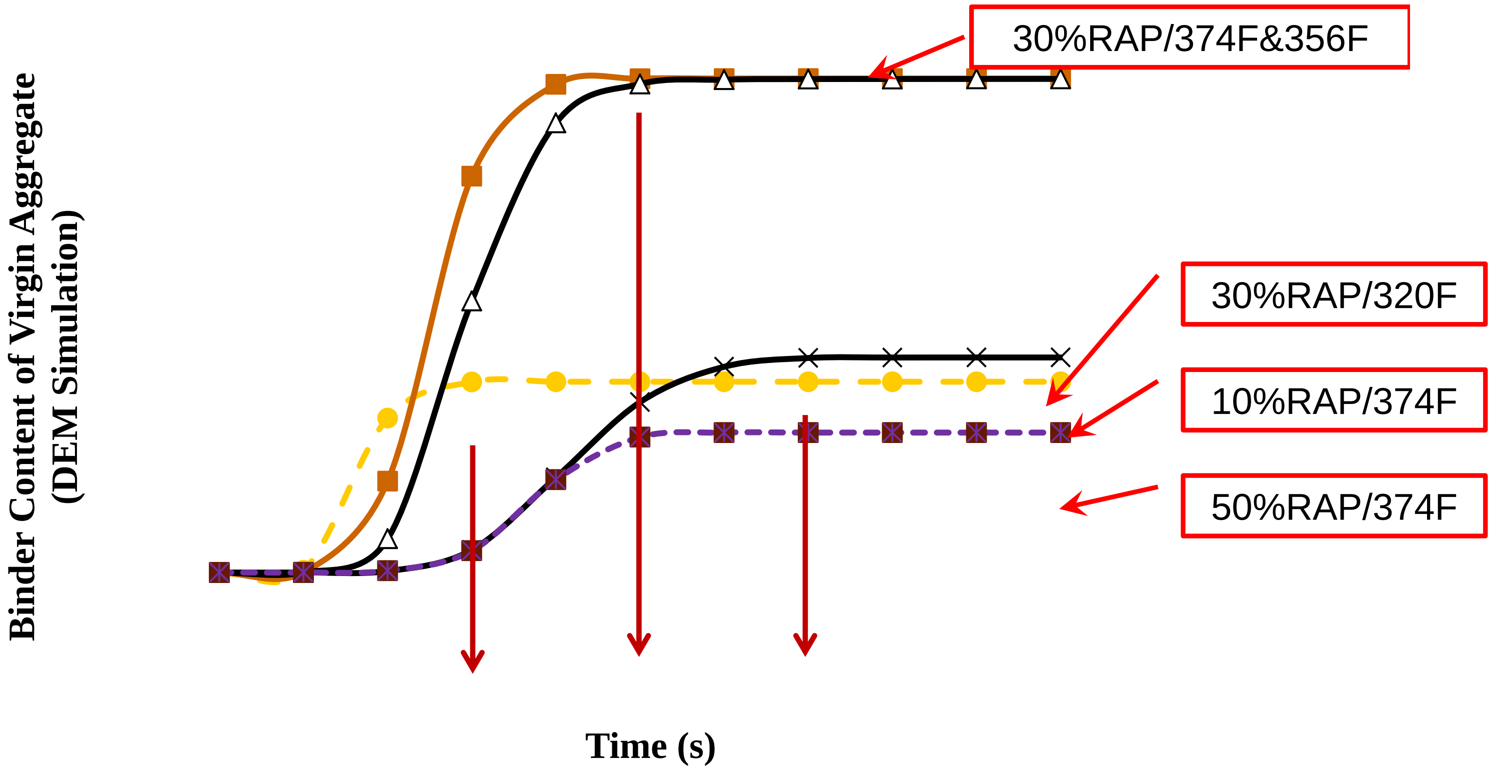
Results and Discussion

- RAP binder transfer study (Experiment and Simulation)



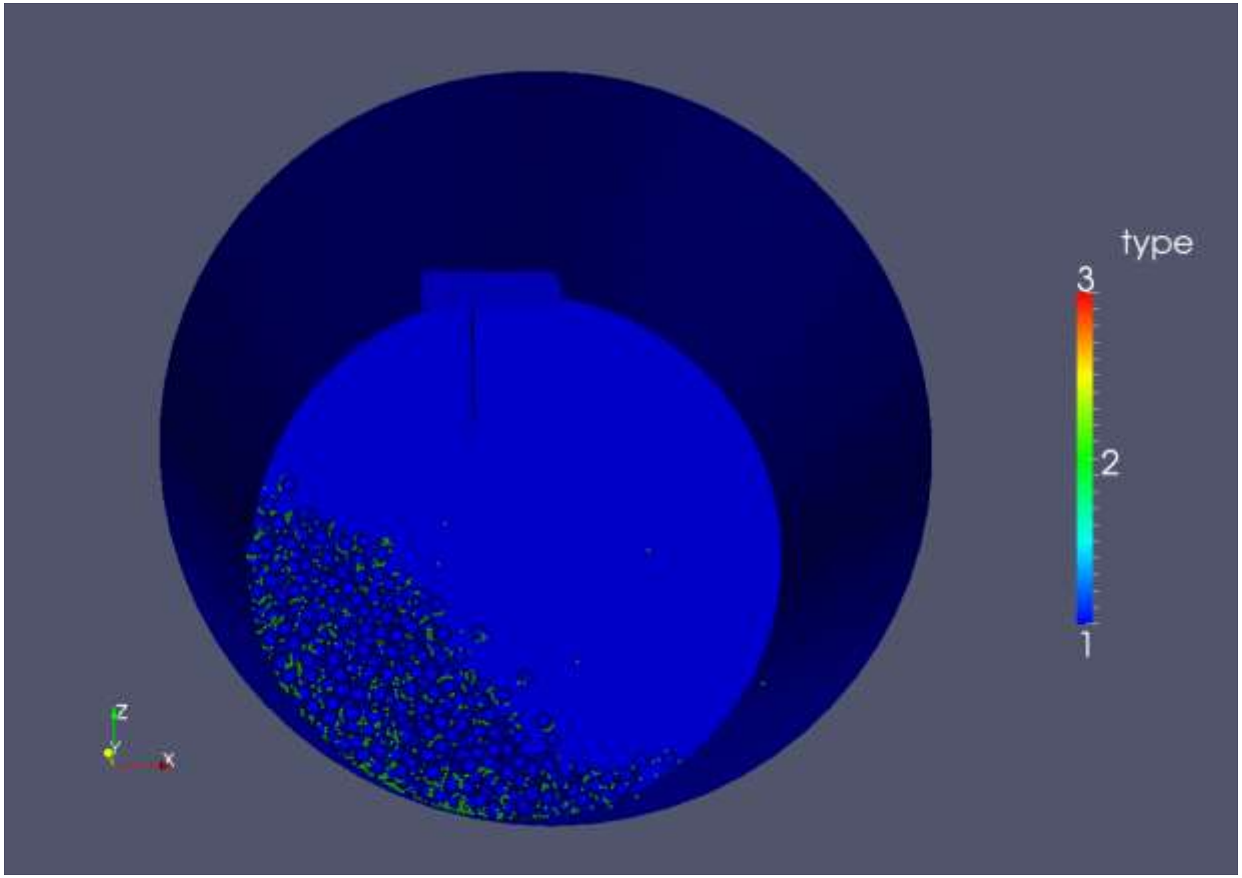
Results and Discussion

- RAP binder transfer vs. time from DEM Simulation
  - Consistent status of binder transfer



Preliminary Blending/Comingling Simulation

- Consider binder as droplet
- Include droplets of RAP binder and virgin binder
- Define different cohesive (binder-binder) and adhesive (binder-aggregate) force



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Conclusions

- DEM simulations constitute a promising approach to simulate the mixing process
  - Mixing behavior, temperature evolution, RAP binder transfer
- Temperature evolution study
  - High RAP percentage and high RAP moisture lead to fast drop of virgin aggregate temperature
  - High RAP moisture needs for higher virgin aggregate temperature
  - Longer mixing time is needed for high percentage RAP

Conclusions

- RAP binder transfer
  - RAP binder transfer increased as virgin aggregate temperature increased
  - RAP binder transfer decreased as RAP moisture increased
  - Longer mixing time is needed to reach binder transfer consistency when RAP percentage increased or virgin aggregate temperature decreased
- Production conditions greatly affect the temperature evolution and RAP binder transfer

Thank you!

Questions & Suggestions?