Improve Material Inputs into Mechanistic Design for Reclaimed HMA & Recycled Concrete Aggregate (RCA) in Roadways

Revised Task 3 – Sensitivity Analyses

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1. PAVEMENT MECHANISTIC-EMPIRICAL DESIGN (PMED)

AASHTO (1993) and pavement mechanistic-empirical (PMED) are the two most commonly used design methods for flexible and rigid pavements (Edil 2011). *PMED method has been developed to take climate and traffic effects into account for pavement analyses since AASHTO methods do not consider these effects directly in pavement analyses*. In the PMED approach, pavement performance is evaluated based on mechanistically determined critical stresses, strains, temperatures, and moisture levels that are in turn the inputs to empirical prediction models for specific pavement distresses such as rutting, fatigue cracking, thermal cracking, and roughness for flexible pavements and cracking, faulting, and roughness for rigid pavements. Accurate characterization of the traffic, climate, and material input parameters is therefore important to ensure that the theoretical computation of pavement stresses, strains, temperatures, and moisture levels are accurate at the critical locations within the system (Schwartz et al. 2015).

Proper implementation of the PMED requires realistic values for the input parameters. The main inputs include general site and project information, allowable distress limits and associated reliability levels, traffic volumes and axle load distributions, pavement structure, material properties, groundwater depth, and climate. Pavement structures generally contain 3 layers: asphalt/Portland cement concrete (PCC) (often consisting of several sublayers or lifts), base/subbase, and subgrade. The layers beneath the asphalt/PCC usually consist of unbound materials, and their physical and engineering properties are very crucial for overall pavement performances and service life (Haider et al. 2014, Gopisetti et al. 2019, Hatipoglu et al. 2020, Gopisetti et al. 2020). Material properties are crucial parameters that must be considered during the design of pavements. Therefore, the properties of recycled asphalt pavement (RAP) and recycled concrete aggregate (RCA) materials should be well understood as they play an important role in pavement design as a base layer. To address this need, the research team created a large database summarizing the characteristics of RCA and RAP that had been used for such applications in pavements. Under this task (Task 3), the research team evaluated the impact of properties of these materials on pavement distress predictions via use of the AASHTOware Pavement ME software version 2.6.0. These analyses were conducted using, the lowest, the highest and the median value of different properties of RAP and RCA. The following sections provide detailed information about input parameters and performance distress evaluations.

2. INPUTS

To produce reliable and accurate results, the PMED relies on a high level of detailed information about input parameters for materials, traffic, and climate. Determining all these parameters requires extensive testing and data collection efforts, and it can be difficult to devote the resources to that if the information is not part of an already existing data set. As an alternative, the PMED software allows users to enter this information in a hierarchical fashion, meaning that the user has the option to provide different levels of detail, then the program adjusts these inputs accordingly. Level 1 input needs more precise information from field and laboratories which should lead to the most accurate pavement distress analyses while level 3 input provides the least precise pavement distress predictions.

For instance, traffic data in its simplest form could simply be an estimate of vehicle traffic volumes. Since the PMED process relies on traffic data to calculate pavement loads, the software would need to convert this into a load factor by assuming a typical distribution of vehicle types. However, if you had actual traffic counts for a project site, including vehicle class information, this would allow an additional level of input in the hierarchy. Assumptions would still need to be made about the spectrum of actual loads based on equivalency factors (ESALs or Equivalent Single Axle Loads). At the top of the hierarchy, vehicle weight data near the site to determine the actual load distribution, in addition to monitoring vehicle counts. This can be achieved by detailed analyses of Weigh-In-Motion (WIM) data. This is the one example of the most comprehensive data and increases the reliability of the design assumptions. However, the PMED process can still function at lower levels of detail.

During PMED analyses in this study, the design inputs of pavement surface layers and subgrade layers are kept constant to be able to investigate impact of the properties of RCA and RAP base layers on predicted pavement distresses. All analyses were conducted at 90% reliability level. Table 1 summarizes the general inputs used for PMED analyses.

Table 1. General inputs

Input	Value
Design Period	20 years
SM_r of Subgrade	15000 psi
Subgrade Gradation	A-1-b
Groundwater Depth (ft)	10
Flexible Pavement Input	
Binder Grade	Super Pave PG 58-34
Base Poisson's Ratio	0.35
HMA Poisson's Ratio	0.35
Rigid Pavement Input	
PCC Unit Weight (pcf)	150
PCC Poisson's Ratio	0.15

Notes: SM_r=Summary resilient modulus, SM_r is calculated at 208 kPa bulk stress and 48.6 kPa octahedral stress, HMA= Hot mix asphalt, PCC= Portland cement concrete.

Three different traffic volumes were considered for pavement design analyses (e.g. low, medium, and high traffic). Table 2 shows the traffic data used in Pavement ME analyses along with surface layer and base layer thicknesses which were selected per recommendations of Schwartz et al. (2011).

Table 2. Traffic inputs

Inputs	Low Traffic	Medium Traffic	High Traffic
AADTT	1000	7500	25000
Number of Lanes in Design Direction	2	3	3
Percent of Trucks in Design Direction (%)	50	50	50
Percent of Trucks in Design Lane (%)	75	55	50
Operational Speed (mph)	50	50	50
Asphalt Thickness in flexible pavement (in)	2	3	4
Base Thickness in flexible pavement (in)	8	10	12
PCC Thickness for rigid pavement (in)	8	9	11
Base Thickness in rigid pavement (in)	4	6	8

Notes: AADTT= Average Annual Daily Truck Traffic, PCC=Portland cement concrete.

In order to investigate the effects of RAP and RCA properties on pavement distress predictions when used as base layer materials, the lowest, the highest and median values of summary resilient modulus (SM_r), gradation, hydraulic conductivity, optimum moisture content (OMC) and maximum dry unit weight (γ_{dmax}) of these materials were collected from the database developed in Task 2. A summary of these input is also shown in Appendix A. The highest and the lowest values are obtained from the database for each property shown in Tables 3-12 while the median values are calculated from all the available data for each property in the database. For instance, the lowest SM_r of RAP was reported to be 24,366 psi by Edil et al. (2012a) thus other inputs shown in Table 3 were chosen from that paper accordingly. On the other hand, the highest SM_r of RAPs was 58,015 psi from Attia and Abdelrahman (2010a) and other inputs were collected from the same paper as well.

Table 3. Base inputs investigating SM_r effect of RAP

Data Value	Varied Parameter (SM_r, psi)	Gravel Percent (%)	Sand Percent (%)	Fines Content (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)
Lowest*	24366	49.3	50.4	0.4	138	5.2	2.73
Median	37927	45	54	1	126	6.1	0.71
Highest**	58015	51	48.6	0.4	134	5.5	-

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Edil et al. (2012a), **Attia and Abdelrahman (2010a)

The lowest SM_r of RCA was reported to be 17,898 psi by Cetin et al. (2020) thus other inputs shown in Table 4 are chosen from that report accordingly. The highest SM_r of RCAs was 53,664 psi from Diagne et al. (2015) and other inputs were collected from the same paper as well.

Table 4. Base inputs investigating SM_r effect of RCA

Data Value	Varied Parameter (SM_r, psi)	Gravel Percent (%)	Sand Percent (%)	Fines Content (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)
Lowest*	17898	38.3	54.6	7.1	123	11.1	0.06
Median	26542	50.8	45.5	3	127	10.8	0.2
Highest**	53664	47.2	48.6	1.8	134	6.1	0.35

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Cetin et al. (2020), **Diagne et al. (2015)

The lowest fines content of RAP was reported to be 0% by Alam et al. (2010) thus other inputs shown in Table 5 are chosen from that report accordingly. The highest fines content of RAPs was 11% from Camargo et al. (2013) and other inputs were collected from the same paper as well.

Table 5. Base inputs investigating fines content effect of RAP

Data Value	Varied Parameter (Fines content, %)	Gravel Percent (%)	Sand Percent (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)	SM_r (psi)
Lowest*	0	3	97	-	-	-	39349
Median	1	45	54	126	6.1	0.71	37927
Highest**	11	46	43	136	7.5	-	44962

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Alam et al. (2010), **Camargo et al. (2013)

The lowest fines content of RCA was reported to be 0.1% by Mahedi and Cetin (2020) thus other inputs shown in Table 6 are chosen from that report accordingly. The highest fines content of RCAs was 15% from Chen et al. (2013) and other inputs were collected from the same paper as well.

Table 6. Base inputs investigating fines content effect of RCA

Data Value	Varied Parameter (Fines content, %)	Gravel Percent (%)	Sand Percent (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)	SM_r (psi)
Lowest*	0.1	68.8	31.1	127	14.4	-	-
Median	3	50.8	45.5	127	10.8	0.2	26542
Highest**	15	41	44	121	11.9	-	27412

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Mahedi and Cetin (2020), **Chen et al. (2013)

The lowest gravel content of RAP was reported to be 3% by Alam et al. (2010) thus other inputs shown in Table 7 are chosen from that report accordingly. The highest gravel content of RAPs was 68.1% from Garg and Thompson (1996) and other inputs were collected from the same paper as well.

Table 7. Base inputs investigating gravel content effect of RAP

Data Value	Varied Parameter (Gravel Percent, %)	Sand Percent (%)	Fines content (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)	SM_r (psi)
Lowest*	3	97	0	-	-	-	39349
Median	45	54	1	126	6.1	0.71	37927
Highest**	68.1	28.1	3.8	135	6	-	31702

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Alam et al. (2010), **Garg and Thompson (1996)

The lowest gravel content of RCA was reported to be 31.8% by Edil et al. (2012a) thus other inputs shown in Table 8 are chosen from that report accordingly. The highest gravel content of RCAs was 94.1% from Mahedi and Cetin (2020) and other inputs were collected from the same paper as well.

Table 8. Base inputs investigating gravel content effect of RCA

Data Value	Varied Parameter (Gravel Percent, %)	Sand Percent (%)	Fines content (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)	SM_r (psi)
Lowest*	31.8	64.9	3.3	125	11.2	-	27412
Median	50.8	45.5	3	127	10.8	0.2008	26542
Highest**	94.1	4.9	1	118	12.6	-	-

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Edil et al. (2012a), **Mahedi and Cetin (2020)

The lowest sand content of RAP was reported to be 28.1% by Garg and Thompson (1996) thus other inputs shown in Table 9 are chosen from that report accordingly. The highest sand content of RAPs was 97% from Alam et al. (2010) and other inputs were collected from the same paper as well.

Table 9. Base inputs investigating sand content effect of RAP

Data Value	Varied Parameter (Sand Percent, %)	Gravel Percent (%)	Fines content (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)	SM_r (psi)
Lowest*	28.1	68.1	3.8	135	6	-	31702
Median	54	45	1	126	6.1	0.71	37927
Highest**	97	3	0	-	-	-	39349

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Garg and Thompson (1996), **Alam et al. (2010)

The lowest sand content of RCA was reported to be 4.9% by Mahedi and Cetin (2020) thus other inputs shown in Table 10 are chosen from that report accordingly. The highest sand content of RCAs was 64.9% from Edil et al. (2017) and other inputs were collected from the same paper as well.

Table 10. Base inputs investigating sand content effect of RCA

Data Value	Varied Parameter (Sand Percent, %)	Gravel Percent (%)	Fines content (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)	SM_r (psi)
Lowest*	4.9	94.1	1	118	12.6	-	-
Median	45.5	50.8	3	127	10.8	0.2	26542
Highest**	64.9	31.8	3.5	125	11.2	-	27412

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Mahedi and Cetin (2020), **Edil et al. (2017)

The lowest D_{60} of RAP was reported to be 2.3 mm by Edil et al. (2012a) in a RAP sample from Minnesota thus other inputs shown in Table 11 are chosen from that report accordingly. The highest D_{60} of RAPs was 10.4 mm from Wu et al. (2012) and other inputs were collected from the same paper as well.

Table 11. Base inputs investigating D_{60} effect of RAP

Data Value	Varied Parameter (D_{60}, in)	Gravel Percent (%)	Sand Percent (%)	Fines content (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)	SM_r (psi)
Lowest*	0.090	26.3	71.2	2.5	134	6.7	0.013	26107
Median	0.19	45	54	1	126	6.05	0.71	37927
Highest**	0.409	67	32	1	-	-	-	29008

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Edil et al. (2012a), **Wu et al. (2012)

The lowest D_{60} of RCA was reported to be 1.7 mm by Edil et al. (2012a) thus other inputs shown in Table 12 are chosen from that report accordingly. The highest D_{60} of RCAs was 16.3 mm from Edil et al. (2012a) and other inputs were collected from the same paper as well.

Table 12. Base inputs investigating D_{60} effect of RCA

Data Value	Varied Parameter (D_{60}, in)	Gravel Percent (%)	Sand Percent (%)	Fines content (%)	MDU (pcf)	OMC (%)	Hydraulic conductivity (ft/hr)	SM_r (psi)
Lowest*	0.067	31.8	31.8	3.3	125	11.2	-	27412
Median	0.268	50.8	45.5	3	127	10.8	0.2	26542
Highest*	0.642	76.3	21.6	2.1	127	9.2	-	23786

Notes: SM_r=Summary resilient modulus, MDU= Maximum dry unit weight, OMC= Optimum moisture content. *Edil et al. (2012a)

3. DISTRESSES

The following pavement distresses were analyzed via PMED software: 1) for flexible pavements-International Roughness Index (IRI), rutting, and fatigue distresses, 2) for rigid pavements-IRI, joint faulting, transverse cracking.

Target failure values at a reliability level of 90% for different pavement distresses for flexible pavements are summarized in Table 13. IRI values greater than 170 in/mile were marked as a failure in this study per suggestions of Elbheiry et al. (2011) and this value was determined as the terminal IRI. 0.75 inches was determined as a target value for failure for total rutting (Ceylan et al. 2015). Table 14 represents the target values of distresses for rigid pavements. Terminal IRI and joint faulting distresses for rigid pavements were chosen as 172 in/mile and 0.12 inches, respectively.

Table 13. Pavement distress types and target values for flexible pavement

Parameter	Target value	Reliability (%)
Terminal IRI (in/mile)	170	90
Total Pavement Rutting (in)	0.75	90

Notes: IRI= International Roughness Index

Table 14. Pavement distress types and target values for rigid pavement

Parameter	Target value	Reliability (%)
Terminal IRI (in/mile)	172	90
Mean Joint Faulting (in)	0.12	90

Notes: IRI= International Roughness Index

In this section, distress analysis is done using the inputs indicated in Section 2 focusing on two distresses which might be affected by the base properties, IRI and total pavement deformation.

3.1. International Roughness Index (IRI) for Flexible Pavements

The international roughness index (IRI) is a standard measure of pavement smoothness and ride quality (Izevbekhai and Akkari 2011). The terminal IRI value was defined to be 170 in/mile (Elbheiry et al. 2011). The initial IRI value was determined to be 63 in/mile which was in accordance with the suggestions provided by Izevbekhai and Akkari (2011) and Ceylan et al. (2015).

3.1.1. Impact of Summary Resilient Modulus (SM_r) on IRI

The predicted IRI values using the inputs mentioned in Table 3 and Table 4 are shown in Figure 1 for RAP and Figure 2 for RCA in flexible pavements. Both Figure 1 and Figure 2 show that higher traffic and base layers with lower SM_r yield higher IRI in flexible pavements indicating that stiffness of the base layers have an impact on IRI. However, it does not seem to cause high differences in terms of IRI performance and none of the results exceeded the terminal IRI values. Thus, acceptable RAP/RCA pavement performance in terms of IRI was obtained while using different SM_r values presented in database.

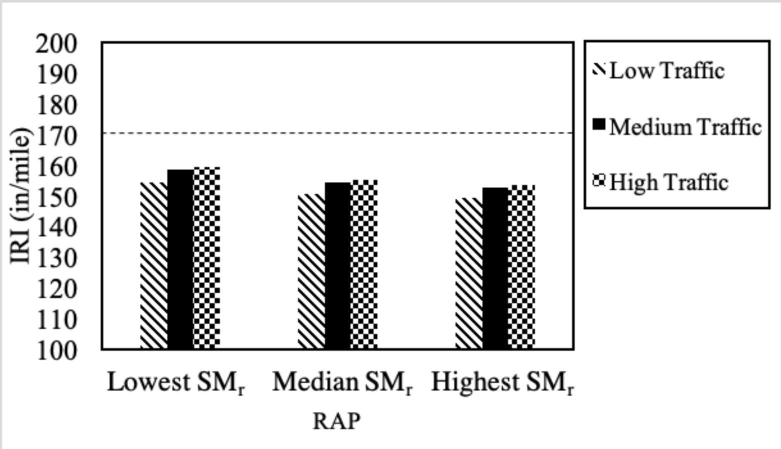

Figure 1. IRI versus different SM_r of RAP

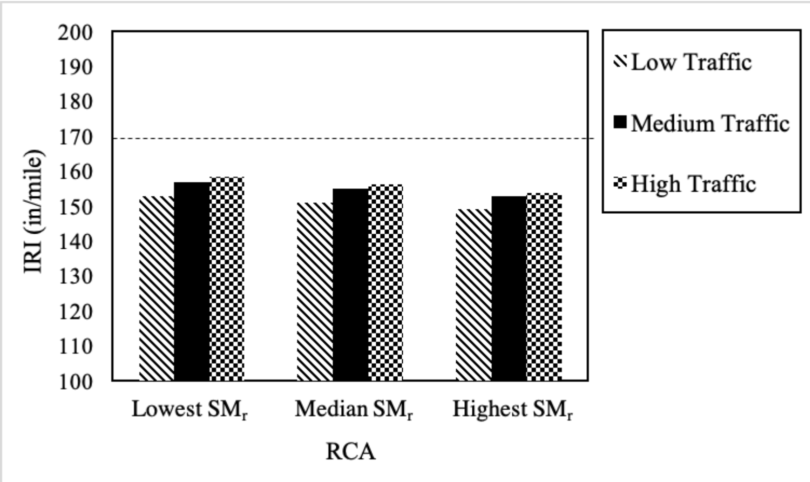

Figure 2. IRI versus different SM_r of RCA

3.1.2. Impact of Fines Content on IRI

The predicted IRI values using the inputs mentioned in Table 5 and Table 6 are shown in Figure 3 for RAP and Figure 4 for RCA in flexible pavements. Results showed that higher fines contents in RAP (ranging between 0%-11%) and RCA (ranging between 0.1%-15%) used as a base course material had higher IRI values in flexible pavements (Figure 3 and Figure 4). However, none of the results exceeded the terminal IRI values indicating that acceptable RAP/RCA pavement performance in terms of IRI was obtained while using different fines content values presented in database. In addition, higher volume of traffic yielded higher IRI values regardless of fines content of RAP and RCA materials.

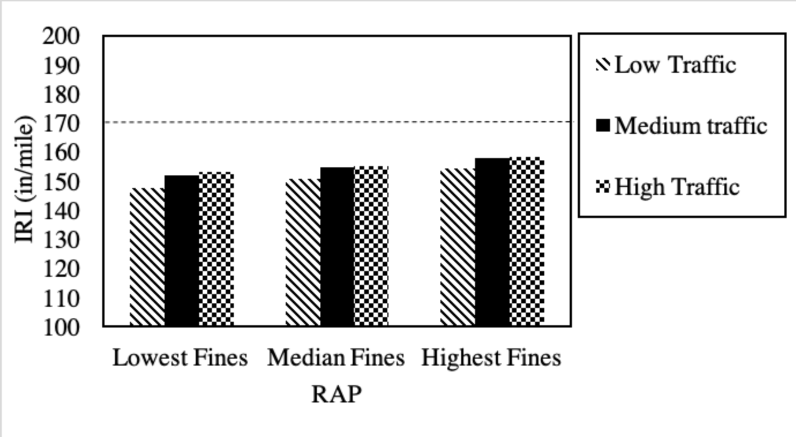

Figure 3. IRI versus different fines content of RAP in flexible pavement

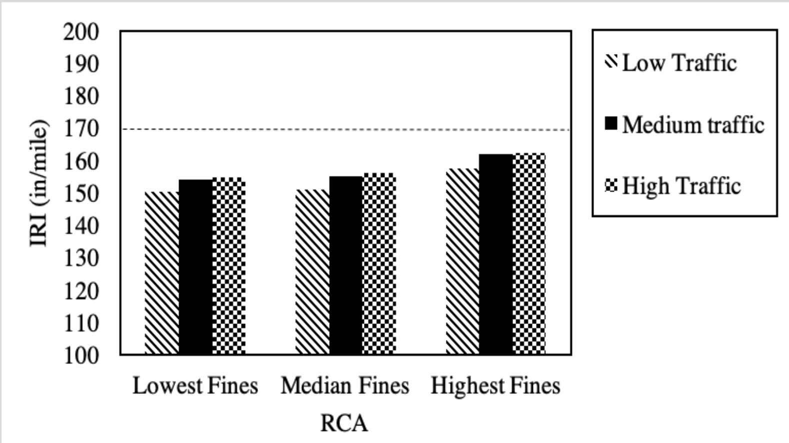

Figure 4. IRI versus different fines content of RCA in flexible pavement

3.1.3. Impact of Gravel Content on IRI

The predicted IRI values using the inputs mentioned in Table 7 and Table 8 are shown in Figure 5 for RAP and Figure 6 for RCA in flexible pavements. Results showed that higher gravel content in RAP (ranging between 3%-68.1%) and RCA (ranging between 31.8%-94.1%) materials seemed to increase IRI values slightly (almost negligible). As expected, higher traffic volume resulted in higher IRI values. Moreover, none of the results exceeded the terminal IRI values indicating that acceptable RAP/RCA pavement performance in terms of IRI was obtained while using different gravel content values presented in database.

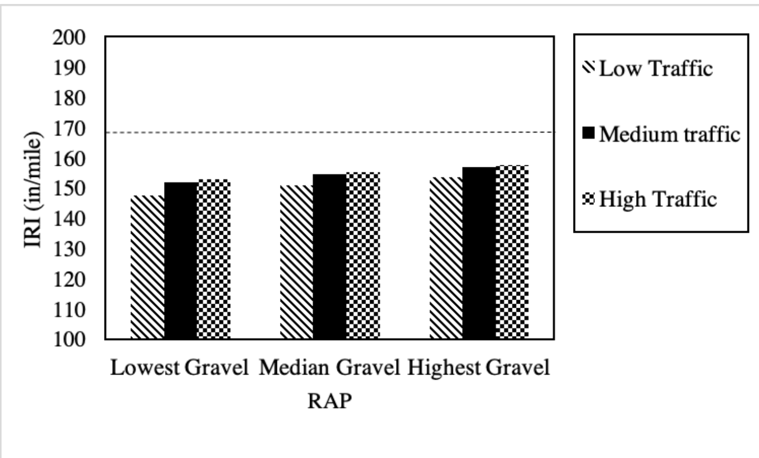

Figure 5. IRI versus different gravel content of RAP in flexible pavement

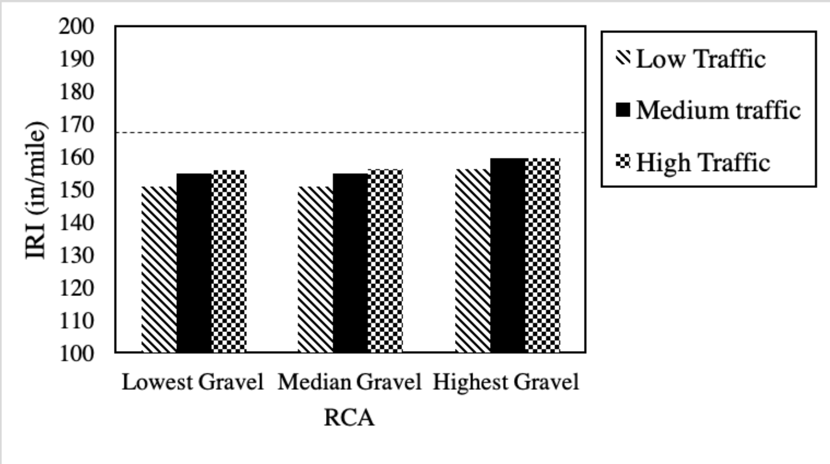

Figure 6. IRI versus different gravel content of RCA in flexible pavement

3.1.4. Impact of Sand Content on IRI

The predicted IRI values using the inputs mentioned in Table 9 and Table 10 are shown in Figure 7 for RAP and Figure 8 for RCA in flexible pavements. Figure 7 and Figure 8 show that there is a small decrease in IRI values when RAP (ranging between 28.1%-97%) and RCA (ranging between 4.9%-64.9%) base materials have relatively higher sand contents. However, this change was very small and can be assumed negligible. Moreover, none of the results exceeded the terminal IRI values indicating that acceptable RAP/RCA pavement performance in terms of IRI was obtained while using different sand content values presented in database.

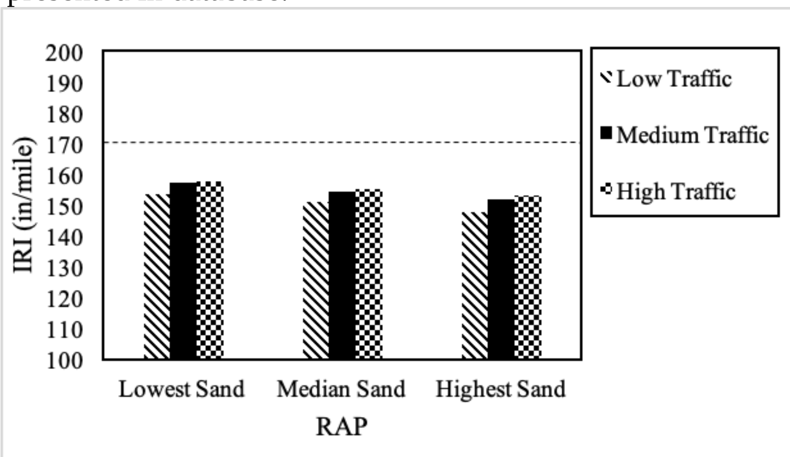

Figure 7. IRI versus different sand content of RAP in flexible pavement

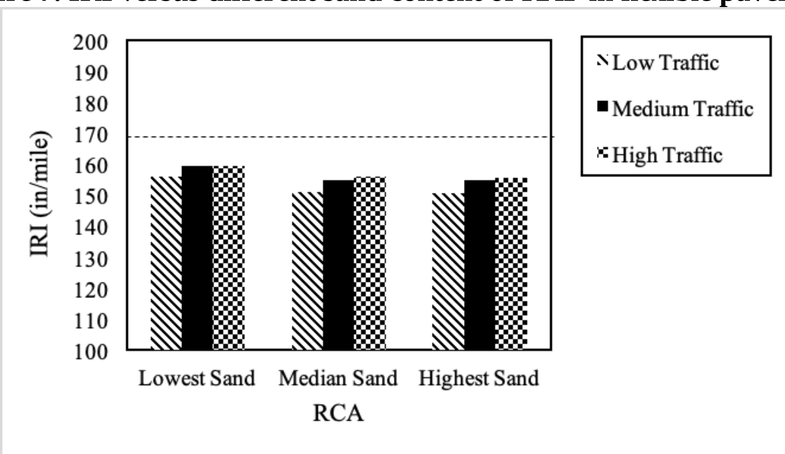

Figure 8. IRI versus different sand content of RCA in flexible pavement

3.1.5. Impact of D_{60} on IRI

The predicted IRI values using the inputs mentioned in Table 11 and Table 12 are shown in Figure 9 for RAP and Figure 10 for RCA in flexible pavements. Impacts of D_{60} of the RAP and RCA materials were also investigated to determine whether there was a relationship between D_{60} of these materials and predicted IRI. As shown in Figures 9 and 10, no trend is observed between D_{60} and IRI values while higher traffic volume causes higher IRI values as expected.

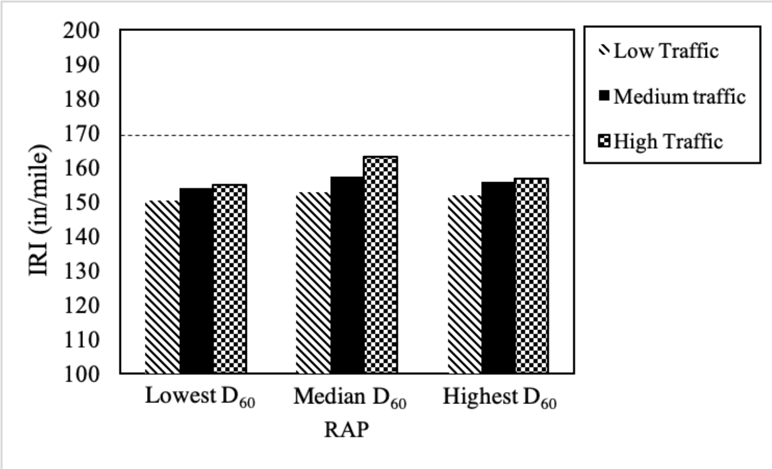

Figure 9. IRI versus different D_{60} of RAP in flexible pavement

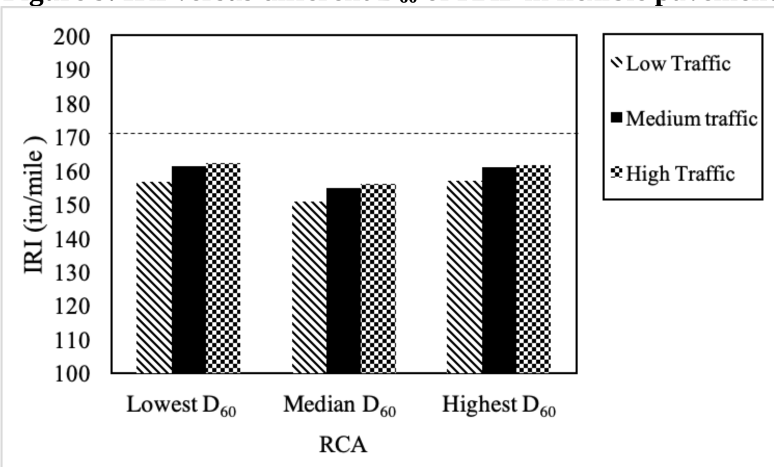

Figure 10. IRI versus different D_{60} of RCA in flexible pavement

3.2. International Roughness Index (IRI) for Rigid Pavements

3.2.1. Impact of SM_r on IRI

The predicted IRI values using the inputs mentioned in Table 3 and Table 4 are shown in Figure 11 for RAP and Figure 12 for RCA in rigid pavements. Results showed that traffic volume had a significant impact on IRI of rigid pavements while SM_r of the RAP and RCA materials did not seem to impact the rigid pavements IRI performances.

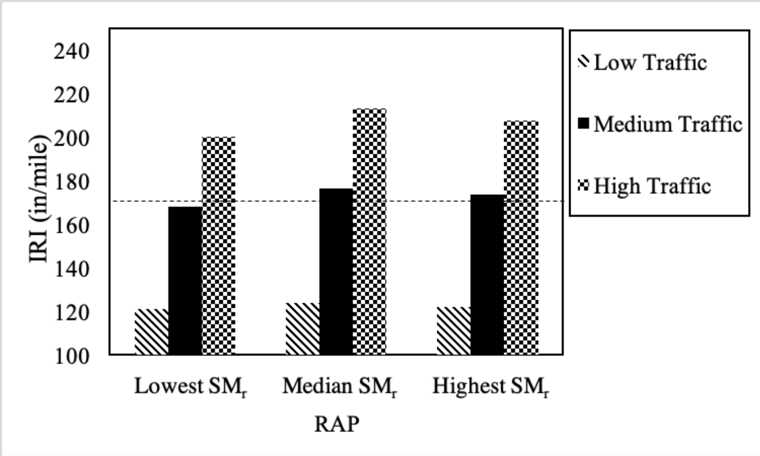

Figure 11. IRI versus different SM_r of RAP in rigid pavement

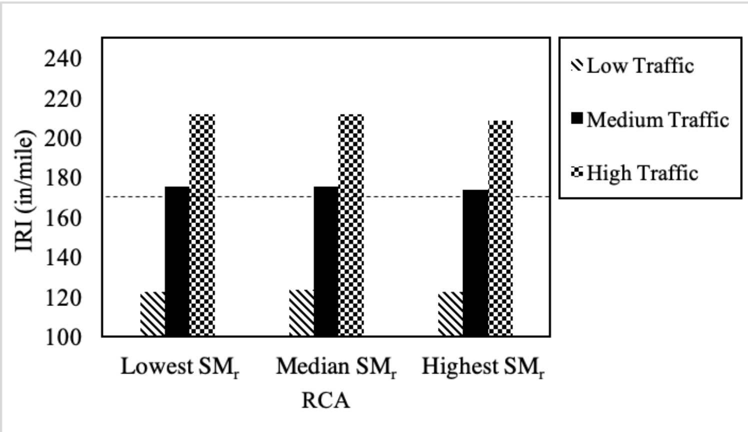

Figure 12. IRI versus different SM_r of RCA in rigid pavement

3.2.2. Impact of Fines Content on IRI

The predicted IRI values using the inputs mentioned in Table 5 and Table 6 are shown in Figure 13 for RAP and Figure 14 for RCA in rigid pavements. Figure 13 shows that an increase in fines content in RAP material (ranging between 0%-11%) caused a slight decrease in IRI values for rigid pavements. On the other hand, an opposite trend was observed for RCA material as an increase in fines content (ranging between 0.1%-15%) resulted in higher IRI values. Moreover, Figures 13 and 14 show that all IRI values exceeded the terminal IRI value for RAP except the ones subjected to lower traffic volume while RCA IRI values satisfied this threshold performance for medium traffic level as well.

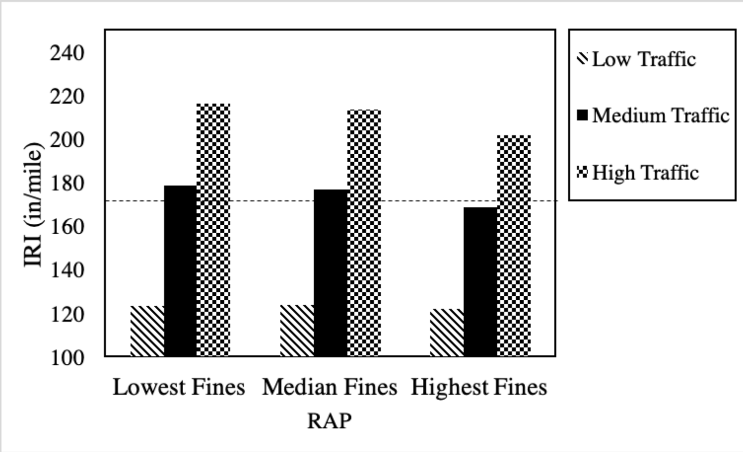

Figure 13. IRI versus different fines content of RAP in rigid pavement

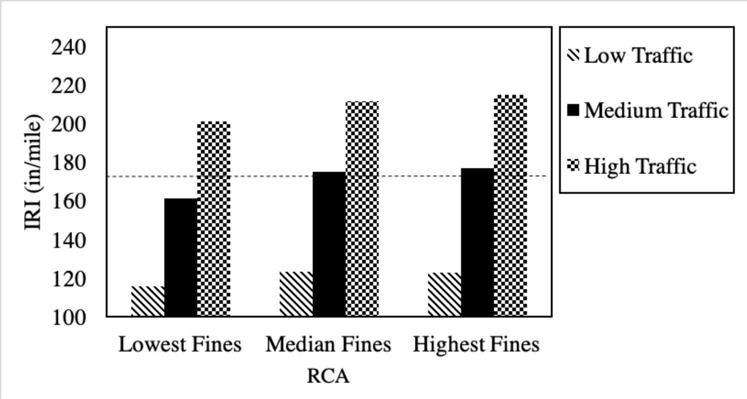

Figure 14. IRI versus different fines content of RCA in rigid pavement

3.2.3. Impact of Gravel Content on IRI

The predicted IRI values using the inputs mentioned in Table 7 and Table 8 are shown in Figure 15 for RAP and Figure 16 for RCA in rigid pavements. Figures 15 and 16 show that IRI values decrease when RAP (ranging between 3%-68.1%) and RCA (ranging between 31.8%-94.1%) with higher gravel contents are used as base materials. In addition, it was observed that terminal IRI values were exceeded when the lowest and median gravel contents were used under high and medium level traffic volumes. This suggests determining the gravel content of RAP and RCA materials before their use as a base material for rigid pavement design.

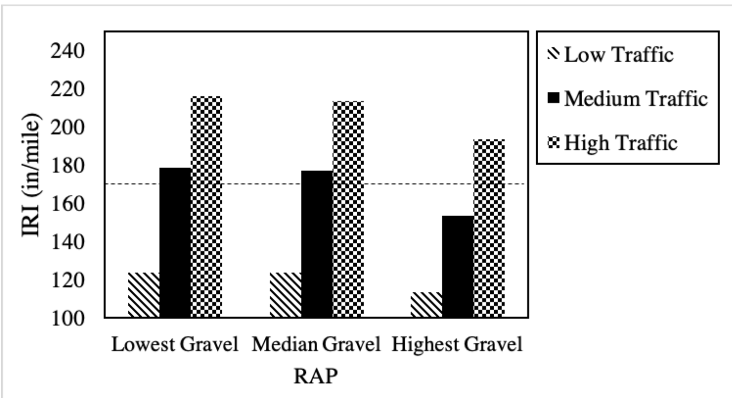

Figure 15. IRI versus different gravel content of RAP in rigid pavement

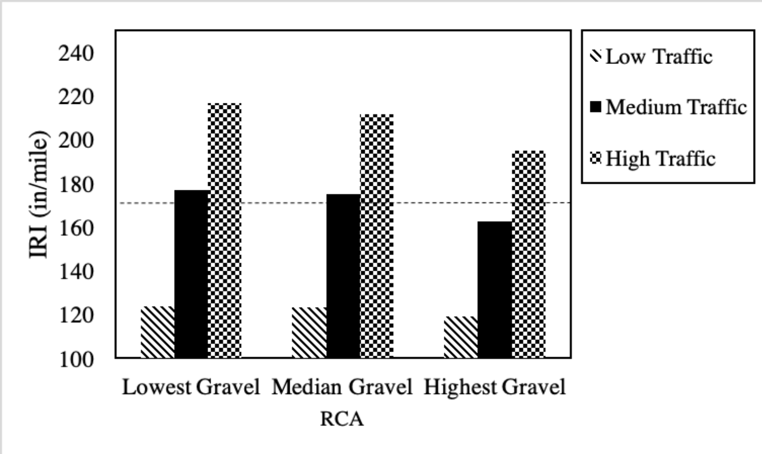

Figure 16. IRI versus different gravel content of RCA in rigid pavement

3.2.4. Impact of Sand Content on IRI

The predicted IRI values using the inputs mentioned in Table 9 and Table 10 are shown in Figure 17 for RAP and Figure 18 for RCA in rigid pavements. *Figure 17 and 18 show that IRI values of RAP and RCA increase significantly when sand contents change from the lowest (28.1% for RAP and 4.9% for RCA) to median values. On the other hand, no solid trends were observed between IRI values when changing sand contents from median to highest values for both RAP and RCA.* These results suggest that *sand contents of RAP bases could be a critical parameter to be checked before conducting rigid pavement design*.

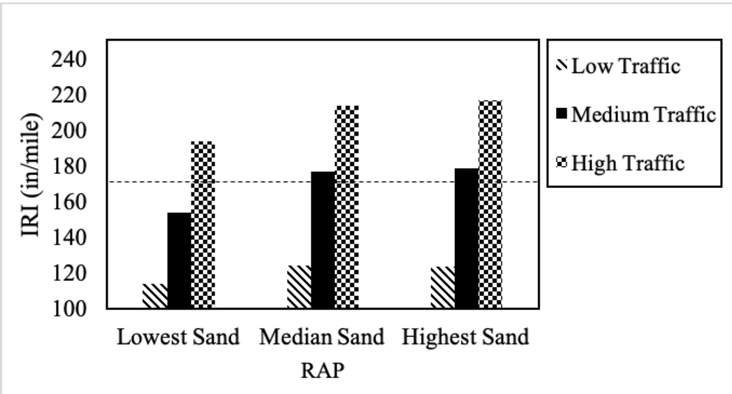

Figure 17. IRI versus different sand content of RAP in rigid pavement

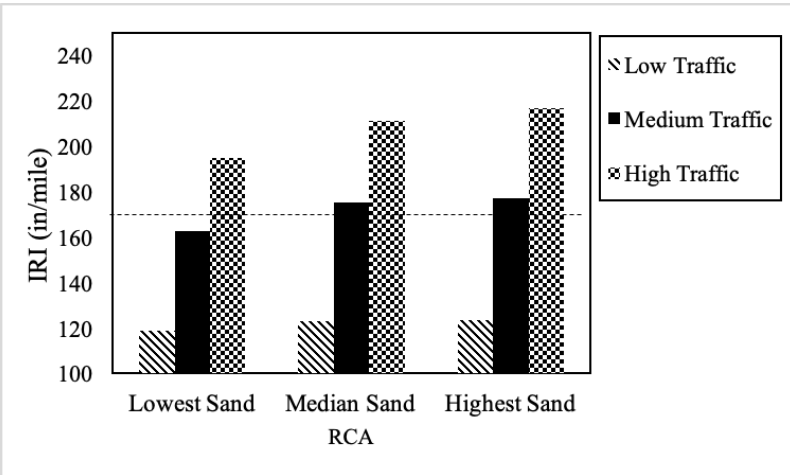

Figure 18. IRI versus different sand content of RCA in rigid pavement

3.2.5. Impact of D_{60} on IRI

The predicted IRI values using the inputs mentioned in Table 11 and Table 12 are shown in Figure 19 for RAP and Figure 20 for RCA in rigid pavements. Results for both RAP and RCA showed that an increase in D_{60} from the lowest (0.090 inch in RAP and 0.067 inch in RCA) to median value (0.19 inch in RAP and 0.268 inch in RCA) did not seem to impact the IRI performance of rigid pavements while it was improved significantly when D_{60} was the highest value presented in the database. *The results suggest using D_{60} values higher than the lowest values recorded in the database which is 0.09 inch for RAP and 0.067 inch for RCA materials.*

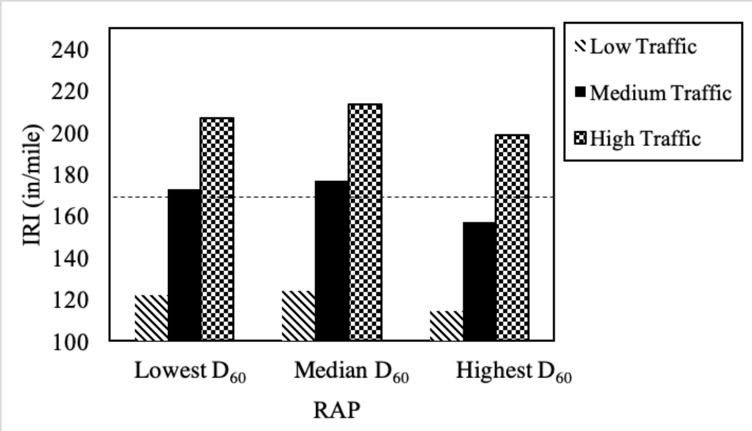

Figure 19. IRI versus different D_{60} of RAP in rigid pavement

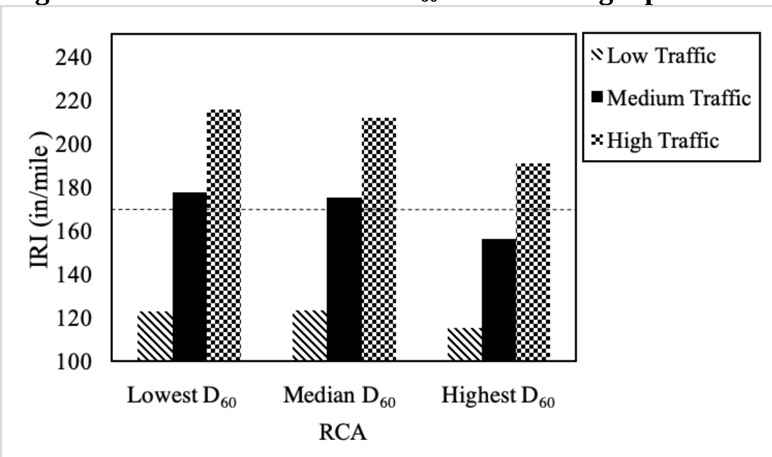

Figure 20. IRI versus different D_{60} of RCA in rigid pavement

3.3. Total Rutting on Flexible Pavements

3.3.1. Impact of SM_r on Total Rutting

Figure 21 and Figure 22 show that the summary resilient modulus (SM_r) of RCA and RAP has an impact on the total rutting of the pavement system. It was observed that changes in SM_r of both RAP (ranging between 24366 psi-58015 psi) and RCA (ranging between 17898 psi-53664 psi) had a similar rate of decrease in total rutting distress predictions.

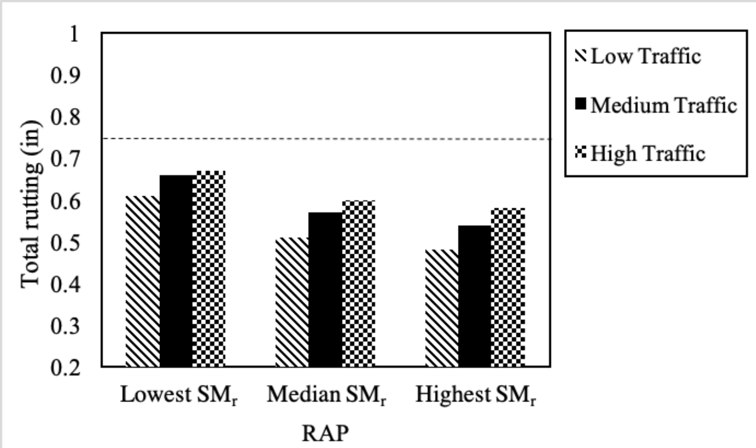

Figure 21. Total rutting versus different SM$_r$ of RAP

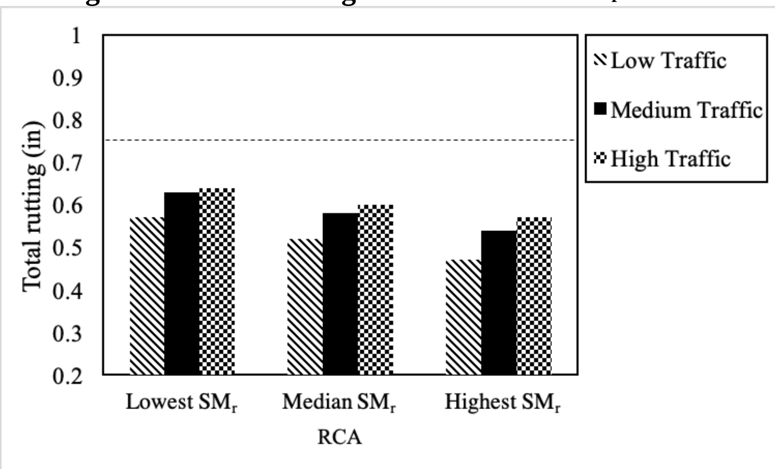

Figure 22. Total rutting versus different SM$_r$ of RCA

3.3.2. Impact of Fines Content on Total Rutting

According to Figure 23 and Figure 24, total rutting of pavements (running Pavement ME with input shown in Tables 5 and 6) increase significantly with an increase in fines contents of both RAP (ranging between 0%-11%) and RCA (ranging between 0.1%-15%) materials. This indicates that extra attention should be paid for fines content of these materials even though none of the cases exceeded the terminal total rutting thresholds.

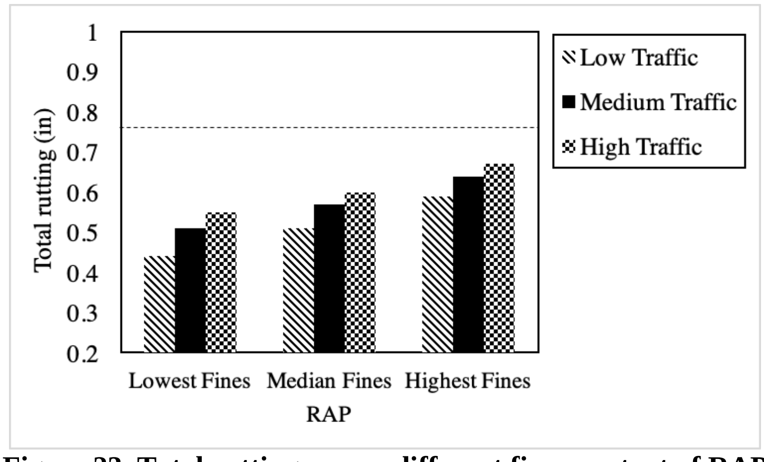

Figure 23. Total rutting versus different fines content of RAP

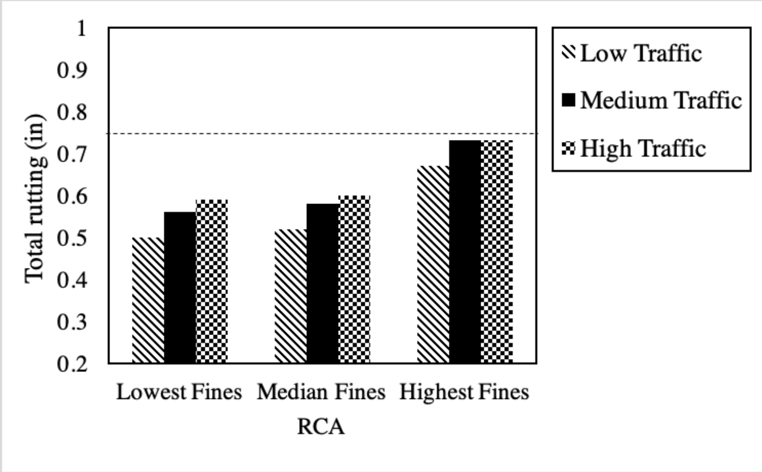

Figure 24. Total rutting versus different fines content of RCA

3.3.3. Impact of Gravel Content on Total Rutting

Figures 25 and 26 show that RCAs and RAPs with higher gravel content resulted in higher total rutting distresses in both RAP (ranging between 3%-68.1%) and RCA (ranging between 31.8%-94.1%). However, all the cases were below the total rutting criteria of 0.75 in (input data used for Pavement ME is shown in Tables 7 and 8).

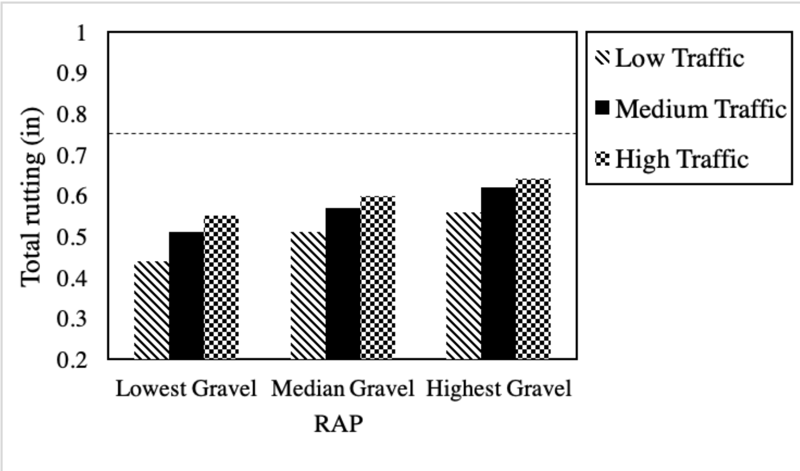

Figure 25. Total rutting versus different gravel content of RAP

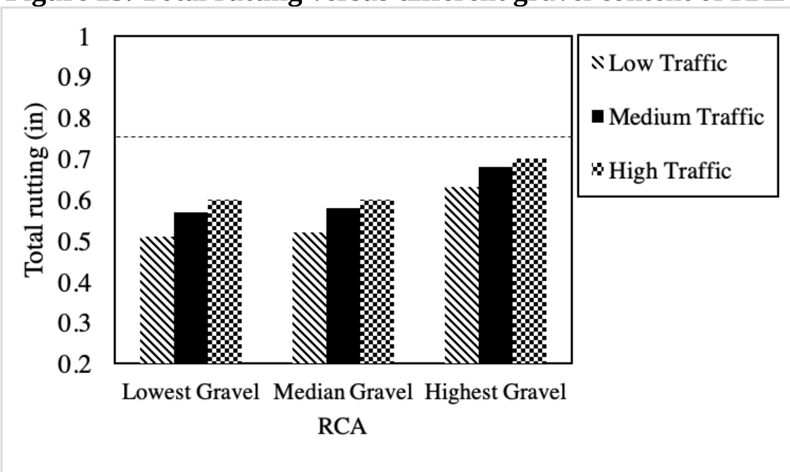

Figure 26. Total rutting versus different gravel content of RCA

3.3.4. Impact of Sand Content on Total Rutting

Unlike gravel and fines content, both RAPs (ranging between 28.1%-97%) and RCAs (ranging between 4.9%-64.9%) with higher sand content yielded lower total rutting distresses (Figure 27 and Figure 28). In addition, all cases were below the rutting failure criteria for these analyses (input data used for Pavement ME is shown in Tables 9 and 10).

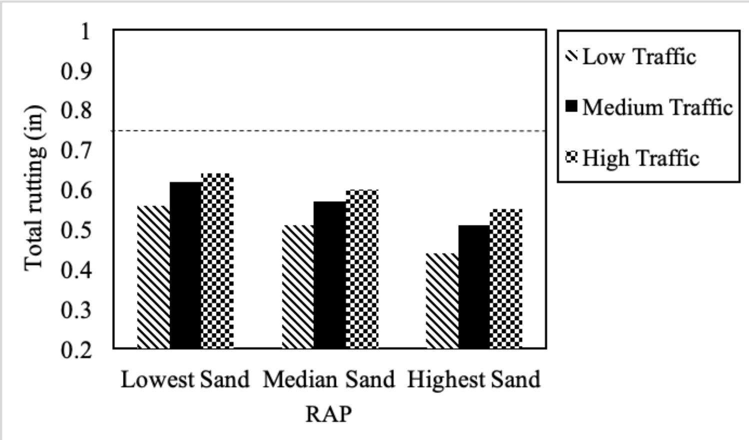

Figure 27. Total rutting versus different sand content of RAP

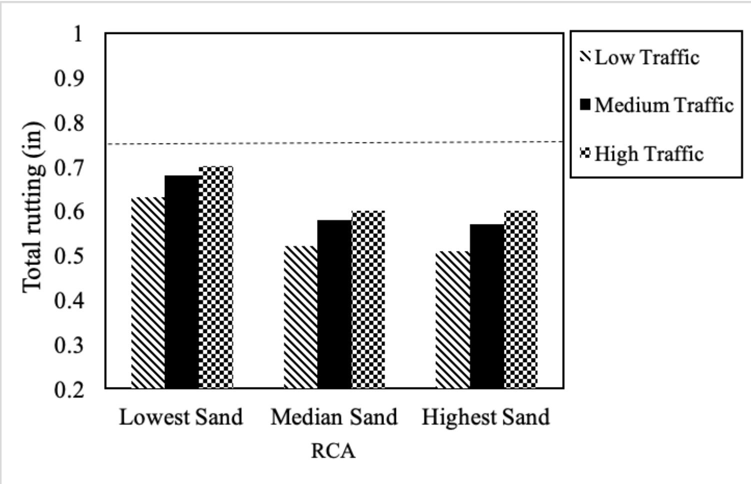

Figure 28. Total rutting versus different sand content of RCA

3.3.5. Impact of D_{60} on Total Rutting

Figure 29 shows that higher D_{60} for RAP materials tend to slightly increase total rutting of pavements (input data used for Pavement ME is shown in Table 11). On the other hand, the median D_{60} value presented in the database yielded to the lower total rutting distress predictions for RCA material (Figure 30) (input data used for Pavement ME is shown in Table 12). Overall, both Figures 29 and 30 show that any data used from the database in the analyses resulted in total rutting values lower than that of total rutting failure criteria.

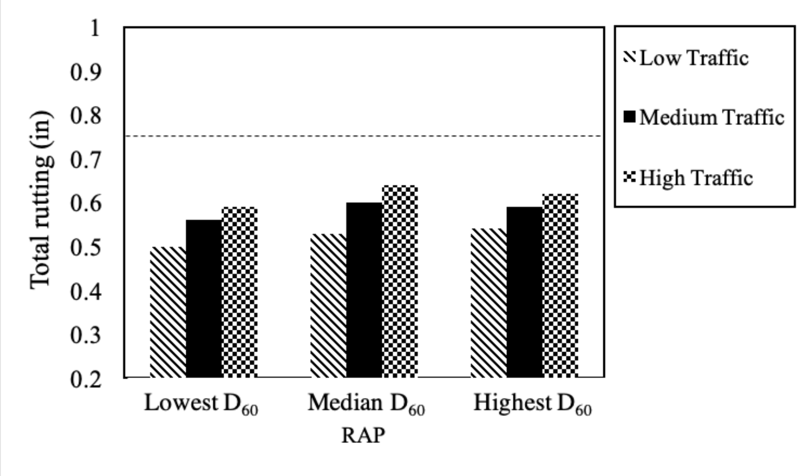

Figure 29. Total rutting versus different D_{60} of RAP

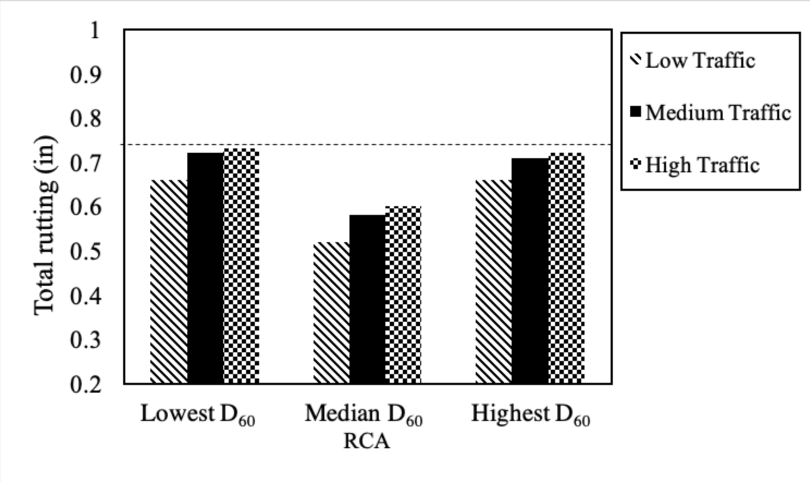

Figure 30. Total rutting versus different D_{60} of RCA

3.4. MEAN JOINT FAULTING

Transverse joint faulting is one of the main types of distresses in rigid pavements affecting its serviceability. Joint faulting is defined as the difference in elevation between adjacent joints at a transverse joint and it is developed due to a combination of repeated heavy axle loads, insufficient load transfer between the adjacent slabs, free moisture in the pavement structure, and erodible base or subgrade material. When there is an excess moisture in a pavement with an erodible base or underlying fine-grained subgrade material, repeated vehicle loadings will cause the mixture of water and fines materials to be removed from beneath the leave slab corner and ejected to the surface through the transverse joint or along the shoulder. This process is called pumping which will eventually cause a void below the leave slab corner. Additionally, some of the fines that are not ejected will be deposited under the approach slab corner, making the approach slab to rise. This material building up beneath the approach corner and losing support due to a void under the leave corner can result in significant faulting at the joint (especially for rigid pavement without dowels). As mentioned above it is clear that properties of base materials may have a great impact on joint faulting distresses of rigid pavements. Therefore, sensitivity analyses were conducted to determine whether the values collected in the database provide results that are under threshold limits for joint faulting distress (0.12 inches) for rigid pavement design analyses.

3.4.1. Impact of SM_r on Mean Joint Faulting

Figures 31 and 32 show that SM_r of either RAP or RCA materials have minimal impact on joint faulting distress predictions for rigid pavements while they are directly impacted by an increase in traffic volumes. (input data used for Pavement ME is shown in Tables 3 and 4).

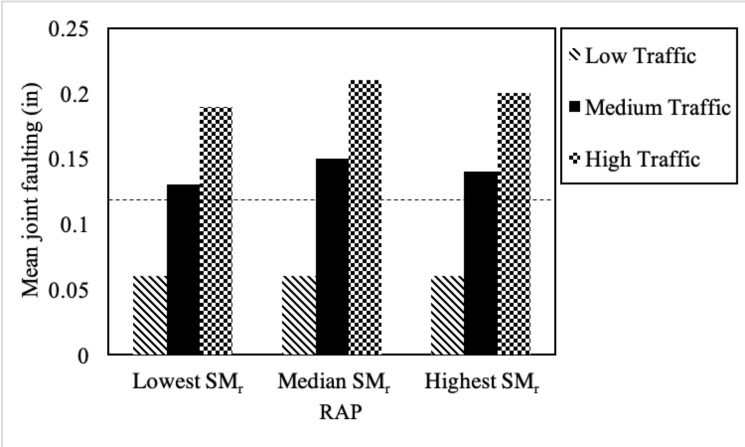

Figure 31. Mean joint faulting versus different SM_r of RAP

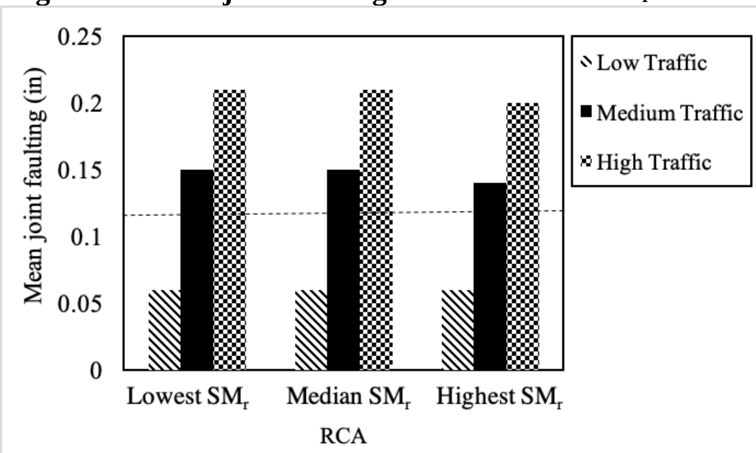

Figure 32. Mean joint faulting versus different SM_r of RCA

3.4.2. Impact of Fines Content on Mean Joint Faulting

Figure 33 shows that RAP material with the highest fines content (11%) resulted in a slight decrease in joint faulting distresses under medium and high traffic volumes. On the other hand, Figure 34 shows that joint faulting distresses increased slightly when fines content of RCA increased from the lowest (0.1%) fines content values to medium fines content (input data used for Pavement ME is shown in Tables 5 and 6).

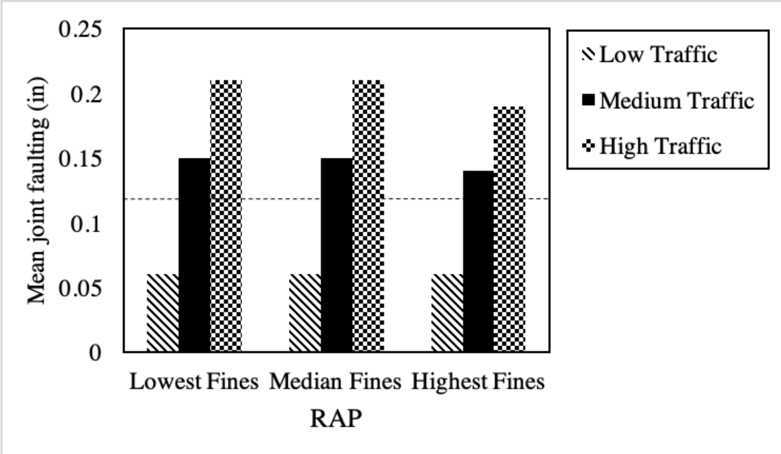

Figure 33. Mean joint faulting versus different fines content of RAP

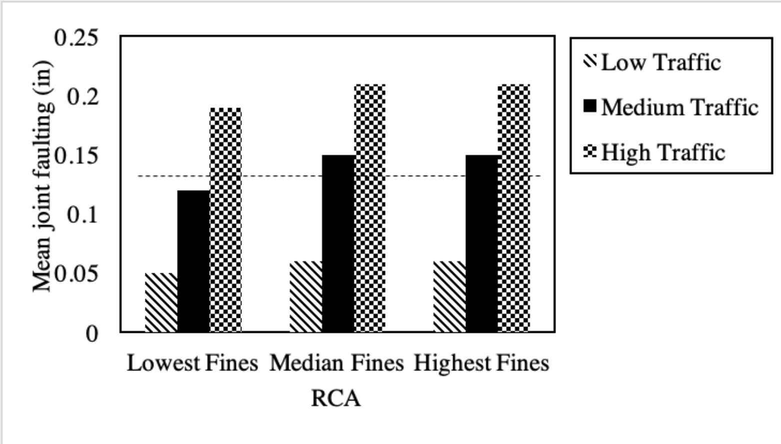

Figure 34. Mean joint faulting versus different fines content of RCA

3.4.3. Impact of Gravel Content on Mean Joint Faulting

Both Figures 35 and 36 show that using the highest gravel content for both RAP (68.1%) and RCA (94.1%) materials yielded a slight decrease in joint faulting distresses for rigid pavements under all traffic conditions (input data used for Pavement ME is shown in Tables 7 and 8).

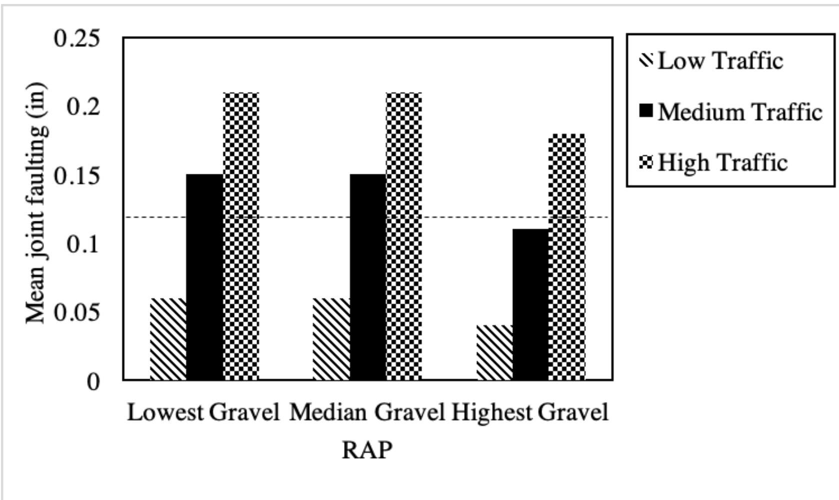

Figure 35. Mean joint faulting versus different gravel content of RAP

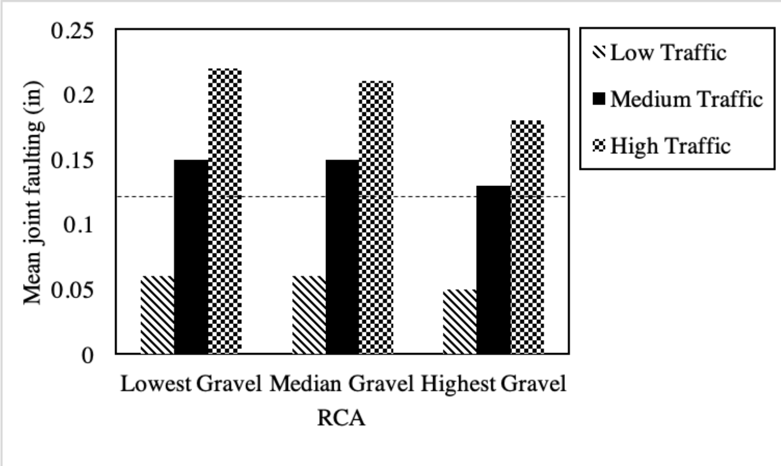

Figure 36. Mean joint faulting versus different gravel content of RCA

3.4.4. Impact of Sand Content on Mean Joint Faulting

For both RAP and RCA materials, it was observed that an increase in sand content (ranging between 28.1%-97.0% for RAP and 4.90%-64.9% for RCA) in these materials caused a consistent increase in joint faulting distresses under all traffic conditions (input data used for Pavement ME is shown in Tables 9 and 10). Figure 37 and 38 are derived from running Pavement ME using inputs from Table 9 and 10.

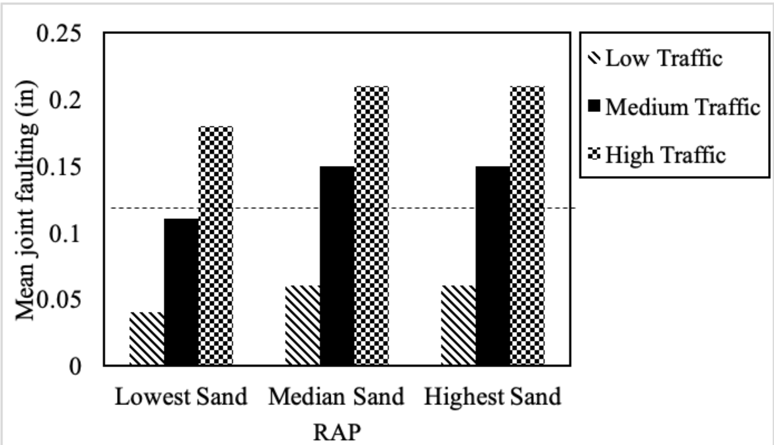

Figure 37. Mean joint faulting versus different sand content of RAP

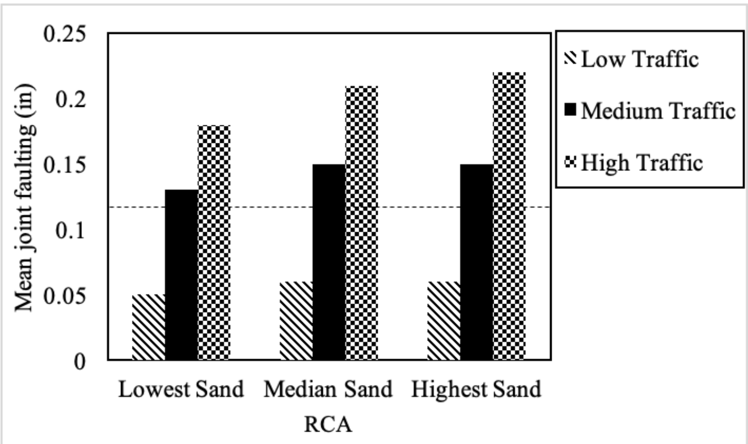

Figure 38. Mean joint faulting versus different sand content of RCA

3.4.5. Impact of D_{60} on Mean Joint Faulting

Both Figures 39 and 40 show that joint faulting distresses decrease slightly when the highest D_{60} values from the database are used for both RAP (0.409 inch) and RCA (0.642 inch) materials (input data used for Pavement ME is shown in Tables 11 and 12).

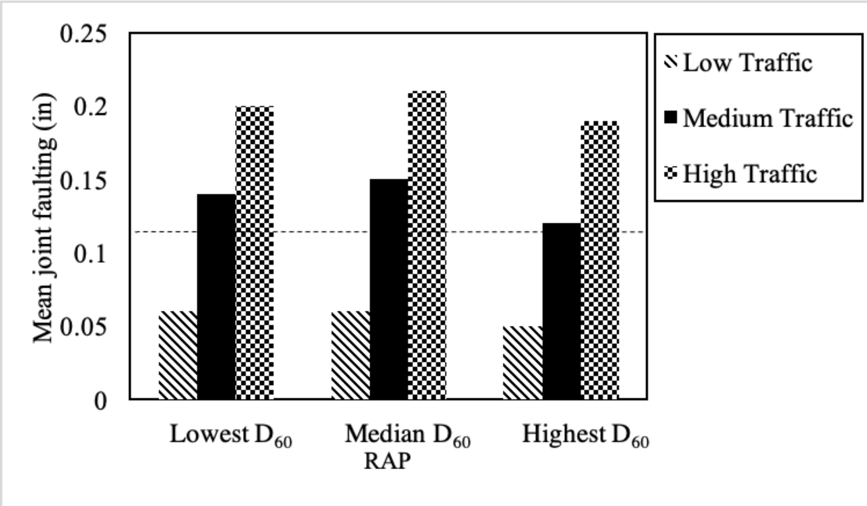

Figure 39. Mean joint faulting versus different D_{60} of RAP

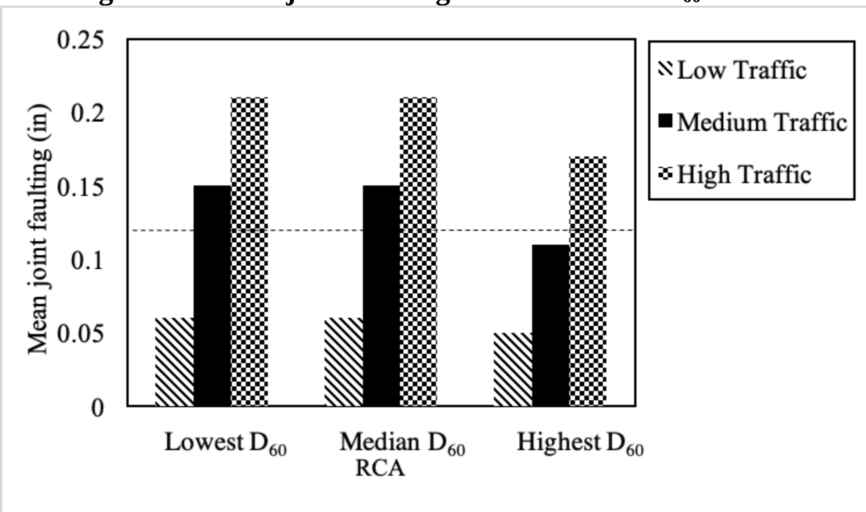

Figure 40. Mean joint faulting versus different D_{60} of RCA

4. CONCLUSIONS/RECOMMENDATIONS

An extensive database was established in Task 2 on properties of RAP and RCA materials used as base or subbase materials in pavement systems. In Task 3, sensitivity analysis was conducted to determine how these input properties of the 100% RAP and RCA could affect pavement distress predictions for both flexible and rigid pavement via using AASHTOware Pavement ME software. Based on the results of PMED analyses, the following conclusions can be drawn:

For Flexible Pavements:

- Summary resilient modulus (SM_r) of base has the highest influence on the pavement performance among other material inputs for base.

- While with higher traffic volume, higher base and asphalt layer or PCC thicknesses were applied, more damage was observed with higher AADTT values.
- There is an increasing trend in total rutting with higher fines contents in RAP and RCA.
- There is a decreasing trend in rutting with higher SM_r in both RAP and RCA.
- As sand content increases, the rutting of the pavement decreases in both RAP and RCA.
- While fines content gets higher, the IRI increases as well in both RCA and RAP in flexible pavements.
- No special trend was observed in different D_{60} values with total rutting.
- No trend was observed between D_{60} and IRI in RCA and RAP in both flexible and rigid pavements.
- All cases in flexible pavement pass the IRI and total rutting criteria. However, in some cases such as high fines content, low sand, and high gravel content for RCA in medium and high traffic areas, they come close to the target values defined.
- Overall, it can be suggested that flexible pavements with 20 years of design life can provide adequate performance under any type of traffic volumes. However, it is recommended to determine the gradation and resilient modulus of the base course materials as they have major effects on total rutting and IRI.

For Rigid Pavements:

- Mean joint faulting and IRI control the rigid pavement design located in high traffic and in some cases medium traffic volume as they always fail in all cases for both RAP and RCA.
- All cases with RAP and RCA as base course materials in low traffic volume satisfy the target value for IRI and mean joint faulting distresses.

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APPENDIX A. RAP DATABASE

Ref.	Loc.	Gravel (%)	Sand (%)	Fine (%)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	SM_r (MPa)	CBR	Density (kN/m^3)	OMC (%)	HC (m/s)
Edil et al. (2012a)	MN	26.3	71.2	2.5	0.3	0.7	2.3	180		20.8	6.7	0.0000011
	MI	49.3	50.4	0.4	0.4	1.7	6.5	168		21.5	5.2	0.000231
	CO	31.7	67.7	0.7	0.4	0.9	3.3	184		20.7	5.7	0.0000382
	CA	36.8	61.4	1.8	0.3	1.3	4.2	173		20.7	6.1	
	TX	41	44.9	1	0.7	2.5	7.9	198		20.3	8	0.0000318
	OH	32.1	66.2	1.7	0.5	1.6	3.8	197		19.8	8.8	0.0000503
	NJ	50.9	48.4	0.7	1	2.8	5.9	209		20.4	6.5	0.000369
	WI	30.9	68.5	0.5	0.6	1.4	3.6	266		20	7.3	0.0000519
Edil et al. (2012b)	WI	46	43	11				310		21.2	7.5	
Edil et al. (2012c)	MN	40	52	8				257	19	20.04	4.9	
Locander (2009)	CO	64	35.1	0.9				239.64		19.35	7.2	7.7x10-4
		59	40.1	0.9				211.8		19	10.7	0.00074
		59	40	1				181.13		18.8	8.8	0.00073
Bennert et al. (2000)	NJ, RAP	60	59	1	1	3.1	8	300.3		18.35	5	
Huang and Dong (2014)	TN	41	58	1				286.5		18.73	7.95	
Puppala et al. (2012)	TX	48	48	4				251		21.3	6	
Soleimanbeigi and Edil (2015)	WI	20	78	2				390		18.7	5	

Camargo et al. (2013)	WI	46	43	11				309	22	21.2	7.5	
Soleimanbeigi et al. (2015)	CO			0.7	0.35			255		20.7	5.7	
	TX			1	0.72			345		20.3	8.1	
	NJ			0.7	1			280		20.4	6.5	
Attia and Abdelrahman (2010a)	MN	51	48.6	0.4	0.6	2	7	380		20.82	5.5	
Attia and Abdelrahman (2010b)	MN	51	48.6	0.4	0.6	2	7	380		20.82	5.5	
Bennert and Maher (2005)	NJ	49	50.9	0.1	0.516	0.08	0.15	268	18			0.0000486 5
Wu et al. (2012)	WA	67	32	1	0.45	4.9	10.4	200				
Guthrie et al. (2007)	UT RAP 1	45	46.5	8.5	0.127	0.889	5.08		21	20.26	5.6	
	UT RAP 2	45	54	1	0.508	1.651	4.826		22	18.22	5.75	
Hasan et al. (2018)	NM	48	51.7	0.3	0.5	0.98	9					
Alam et al. (2010)	MN	3	97	0				271.3				
Cosentino et al. (2003)	FL	40	59.1	0.9	0.27	0.65	4.7	291.39	32	18.5	8.2	0.000002

Bejarano (2001)	CA	54	45	1				310		24.12	5.5	
Garg and Thompson (1996)	IL	68.1	28.1	3.8				218.58		21.04	6	
Mijic et al. (2019)	MD RAP 1	46.3	51.8	1.83						19.6	5.7	0.0000983
	MD RAP 2	37.8	61.3	0.93						18.5	6.8	0.000566
	MD RAP 3	45.7	54.1	0.13						17.2	6.3	0.00114
	MD RAP 4	40.7	59	0.33						18.7	6.8	0.000251
	MD RAP 5	44	54.8	1.19						19.2	7.5	0.0000689
	MD RAP 6	45.3	54.2	0.47						19.1	6.4	0.000201
	MD RAP 7	47.6	52	0.39						18.5	8.2	0.000527
Ullah and Tanyu (2019)	VA RAP 1	46	53	1	0.5	2	5.1					
	VA RAP 2	39	60	1	0.5	1.5	4.5					
	VA RAP 5	26	73	1	0.32	1.1	3					
	VA RAP 11	42	57	1	0.5	1.7	5					
Ullah et al. (2018)	VA RAP 1 as is	45	53.5	1.5						19	5.5	
	VA RAP 2 as is	40	57.8	2.2						19.47	5.5	
Edil et al. (2017)	MN	26.3	71.2	2.5								

Ba et al. 2012	TX RAP	54	45.01	0.99	0.8	2.5	8					
	CO RAP	31	68.31	0.69	0.4	0.9	3.1					
Cosentino et al. (2012)	APAC Melbourne Crushed	24.2	75.2	0.6	0.3	0.91	3.1		62.4	19.16	5	
	APAC Melbourne Milled	41.9	57.6	0.5	0.5	2	5		60	19.03	6.2	0.000031
	Whitehurst Gainesville Milled	54	45.6	0.4	0.4	1.5	4.8		60	19.08	4	0.0000013
	APAC Jacksonville Crushed	26.6	66.6	6.8	0.1	0.3	3		68	19.63	4.5	0.00000018
Kang et al. (2011)	MN							193		20.79	4	0.000022152
Abdelrahman and Noureldin (2014)	MN							330		20.82	5.5	
Attia and Abdelrahman (2011)	MN							400				

APPENDIX B. RCA DATABASE

Ref.	Loc.	Gravel (%)	Sand (%)	Fine (%)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	SM_r (MPa)	CBR	Density (kN/m^3)	OMC (%)	HC (m/s)
Edil et al. (2012a)	MN	31.8	31.8	3.3	0.1	0.4	1.7	189		19.5	11.2	
	MI	68.5	28.3	3.2	0.4	4.1	12.3	171		20.8	8.7	
	CO	40.9	46.3	12.8	0.1	0.6	4.9	175		18.9	11.9	
	CA	50.6	47.1	2.3	0.3	1.7	6.8	178		19.9	10.4	
	TX	76.3	21.6	2.1	0.4	6.5	16.3	164		19.7	9.2	
	OH	43.2	49.5	7.3	0.2	1.2	5.3	163		19.4	11.8	
	NJ	41.2	54.6	4.3	0.2	0.5	5.1	208		19.8	9.5	
Bennert et al. (2000)	NJ	60	56	4	0.18	1.5	11	297.6		19.45	7.5	
Soleimanbeigi et al. (2015)	Tx			2.1	0.43			188		19.7	9.2	
	Nj			4.3	0.18			160		19.8	9.5	
	CA			2.3						19.9	10.4	
	MI			3.2						20.8	8.7	
Kang et al. (2011)	MN RCM	48	51	1	0.4	0.8	7	164.8445312		19.02	9.4	0.00000010212
Bennert and Maher (2005)	NJ	71	26.2	2.8	0.29	0.2	0.6	272.9	169			0.00000105
Bestgen et al. (2016)	Eastern USA RCA 1	45	45	10	0.11	0.6	6.5	295	148	20.2	9.5	
	Eastern USA RCA 2	40	55	5	0.11	0.28	5	220	144	20.1	9.5	
Tutumluer et al. (2012)	IL	55	37	8	0.23	2.5	7.5	188	58	20	9.3	

Diagne et al. (2015)	WI	51	47.2	1.8	0.17	1.2	7	370		20.9	6.1	0.000 03
Cetin et al. (2020)	Coarse RCA	61.7	34.9	3.4				127.3 7707 52		19.31	11.3	2.67E -06
	Fine RCA	38.3	54.6	7.1				123.3 8589 25		19.1	11.1	4.85E -06
Mahedi and Cetin (2020)	TX RCA 1	93.4	5.8	0.8						19	10.9	
	TX RCA 2	68.8	31.1	0.1						19.7	14.4	
	IA RCA 1	48.8	51.1	0.1						19	14.8	
	IA RCA 2	82	17.8	0.2						18.4	14.3	
	MN RCA	94.1	4.9	1						18.3	12.6	
Natarajan et al. (2019)	MN RCA									19.5	11.2	
	MN RCA Passing	55	43	2	0.4	1.9	8			21.4	12	
	MN RCA Center line	37	61	2	0.35	0.8	4			21	11.7	
	MN RCA Driving	52	46	2	0.32	1.4	8			21.7	13.5	
Chen et al. (2013)	CA	50	47	3						19.8	10.9	0.000 019
	CO	41	44	15						18.9	11.9	0.000 016
	MI	69	28	3						20.8	8.7	0.000 026

	MN	32	64	4						19.5	11.2	0.000018
	TX	76	21	3						19.7	9.2	0.000008
	WI Fresh	48	50	2						19.4	10.8	0.0012
	WI Stockpile	65	32	3						19.9	9.9	0.00071
Edil et al. 2017	MN	31.8	64.9	3.3								