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Low Temperature Performance Characteristics of Reclaimed Asphalt Pavement (RAP) Mortars with Virgin and Aged Soft Binders

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Abstract: Reclaimed asphalt pavement (RAP) has many advantages and is utilized to improve the high temperature properties of asphalt mixtures. Low temperature cracking is a predominant distress in asphalt pavements containing RAP materials. Thus, the evaluation of fracture resistance for asphalt mixtures containing RAP is of interest. The objective of this research is to explore the low temperature performance characteristics of RAP mortars containing sieved RAP and soft binders at three aged states. The stiffness values and m-values from bending beam rheometer (BBR) tests at three test temperatures of −18 °C, −12 °C and −6 °C were obtained to conduct the minimum low temperature grades. RAP mortar with a higher aged binder content had a higher minimum low temperature regardless of RAP source. In addition, RAP mortars with virgin soft binder had the best low temperature resistance followed by the RAP mortars with rolling thin film oven (RTFO) and pressure-aged vessel (PAV) binders.

Keywords: reclaimed asphalt pavement; mortar; stiffness; m-value; low temperature determination

1. Introduction

Reclaimed asphalt pavement (RAP) is being broadly used as a component of asphalt mixture for new highway pavement. Many research studies indicate that there are plenty benefits of using RAP for the new asphalt mixture, including reduction of total cost in pavement construction, natural resource conservation, environment protection, and rutting resistance improvement [1–4].

In the U.S., the National Asphalt Pavement Association (NAPA) has tracked the use of RAP through annual industry surveys since 2009 and found that the utilization of RAP materials was clearly increasing [5]. In 2012, contractors in 12 states used less than 15% of their total tonnage to produce the new asphalt mixture for paving purposes [6]. This represents a total tonnage increase of 22% with respect to asphalt mixtures in terms of RAP applications from 2009 to 2012 in the U.S. (from 56 to 68.3 million tons) [5].

Hong et al. [7] indicated that the resistance to rutting of hot mix asphalt (HMA) with 35% RAP was better compared to only virgin asphalt due to the incorporation of aged binder. Daniel et al. [8] found that the high-temperature performance grade remains the same or increases only one grade for the various RAP percentages. Attia and Abdelrahman [9] found that the effect of moisture on RAP is similar to the effect of moisture on granular material. Dynamic Shear Rheometer (DSR) testing was used to evaluate recycled RAP and virgin asphalt and indicated that the shear modulus (G*) and the G*/sin δ increased with the increasing percentage of RAP at both the high and intermediate test temperatures [10]. In addition, it also could be found that RAP sources were vital factors to determine the shear moduli and other DSR parameters [11].

Low-temperature cracking is predominant result of distress in asphalt pavements because of the thermal stress that builds up in pavements in extreme climates [12]. These low temperature cracks result in transverse cracks and other distresses along the pavement and ultimately accelerate the deterioration of the asphalt pavement structure. Some research studies indicated that the involvement of RAP material in new asphalt pavement might result in noticeable damage of pavement surface [13–15]. Therefore, the evaluation of fracture resistance for asphalt mixtures containing RAP is of interest to owners and agencies seeking better performing pavements in cold climates [12,16].

Some articles reported that low temperature bending beam rheometer (BBR) stiffness increased with increasing RAP, the m-value decreased with the increasing percentage of RAP, and the magnitude of the changes were dependent on the RAP source [17]. In addition, it was reported that the critical low performance grade (PG) temperature increased with the increased RAP materials [10,11,18,19].

Mogawer et al. [3] found that the RAP mixtures performed similarly to their respective control mixture for all low-temperature cracking tests. These data suggest that plant-produced mixtures with up to 30% RAP may not be more susceptible to low temperature failures. Swiertz et al. [2] reported that when using RAP, the low-temperature PG grade depended on fresh binder grade and source. Testing also showed that RAP source was not a significant factor for dynamic modulus at low temperatures, although it significantly affected the dynamic modulus at high temperatures. The addition of 40% RAP also significantly decreased the low-temperature fracture resistance [16].

However, the conventional methods of classifying aged asphalt binders from RAP materials requires initial extraction of the asphalt binder from the RAP, which involves the use of harmful chemical solvents such as trichloroethylene. In recent years, a new testing procedure has been developed to estimate the low temperature properties of the RAP binder without extraction or chemical treatments [20]. This project provides a possibility to evaluate the properties of RAP binders by testing the RAP mortars (fresh binders blended with fine RAP materials) without extracting the RAP binders from them. With the respect to testing procedure, the modified bending beam rheometer test is employed with minor modifications to the equipment which do not alter the test method and general settings. The properties of the binder in RAP are then estimated from the mortar properties. Many initial trials of the materials and equipment involved were performed before conducting the testing procedures to determine the low temperature properties of the aged binders in RAP materials [17,21].

The objective of this study is to explore the low temperature performance characteristics of six RAP mortars blended with the soft binders at three aged states. The main properties of stiffness values and m-values from BBR tests at three test temperatures of −18 °C, −12 °C and −6 °C were obtained to conduct the minimum low temperature grade of these RAP mortars.

2. Materials, Test Methods and Analysis Methods

In this study, one soft binder PG 58-28 was used for blending with RAP mortars. The rheological properties are shown in Table 1. In addition, six RAP types including 2 high-stiffness RAPs, 2 medium-stiffness RAPs and 2 low-stiffness RAPs which were denoted as A through F were selected to yield the modified asphalt mortars. The extracted aged binders from six RAPs were tested in BBR first and categorized as high-, medium- and low-stiffness RAPs. These values were based on the stiffness values of these extracted aged binders.

These RAP materials were initially sieved to a size which passed through a #50 (0.3-mm) sieve and was retained on a #100 (0.15-mm) sieve, and then were mixed with base binders at various aged states accordingly. The aged binder contents of the total binder in these RAP materials were obtained by using an ignition oven to burn all the asphalt for each RAP source. These aged binder contents of the total binder in the RAP mortar are 6.07%, 7.10%, 6.50%, 5.86%, 5.25%, and 8.3% for RAP sources

A–F, respectively. These aged binder percentages were defined the ratio of burned aged binder to the total RAP before burning (in mass). It should be noted that the tested samples were produced with pure binder (PG 58-22 binder) and fine RAP mortar (filler and aged binder) in this study.

Table 1. Rheological properties of performance grade (PG) 58-28 binder.

Base Binder	Unaged			RTFO	PAV		
	Viscosity (135 °C)	**Failure temp.**	**G*/sin δ (58 °C)**	**G*/sin δ (58 °C)**	**G*/sin δ (19 °C)**	**Stiffness (−18 °C)**	**m-Value (−18 °C)**
	(cP)	**(°C)**	**(kPa)**	**(kPa)**	**(kPa)**	**(MPa)**	
PG 58-28	315	60.2	1.38	3.88	3595	249	0.281

Notes: G*: shear modulus; RTFO: rolling thin film oven; PAV: pressure-aged vessel.

In this research study, the base binders (virgin, rolling thin film oven (RTFO), and pressure-aged vessel (PAV)) blended with various sieved RAPs were used to produce RAP mortars, which were employed to fabricate the BBR beams. The trial and error procedures were performed to obtain the proper percentage of RAP (in terms of aged binder percentage). A percentage over 15% of aged binders was very stiff and could not be poured at a high temperature of over 165 °C. Therefore, in this study, a percentage of up to 15% aged binder (i.e., sieved RAP including 15% aged binder) was used to produce the modified mortar. The value of 15% was the ratio of the aged binder from RAP to the total binders (aged binder with pure soft binder). In addition, two more concentrations (5% and 10%) were utilized to help explore the performance characteristics of these mortars in this study.

The BBR test generally provides a low temperature measure of the stiffness and relaxation properties of an asphalt binder. The obtained results are typically used to provide an indication of an asphalt binder's ability to resist low temperature cracking. The creep stiffness of asphalt binder from the BBR test is usually as a function of time, which is a measure of the thermal stresses in the asphalt binder resulting from thermal contraction. A higher creep stiffness value indicates higher thermal stresses. Originally, the crucial values included creep stiffness values at 60 sand the slope of the master curve at 60 s, commonly defined the "m-value" in Superpave system.

In this study, three test temperatures of −18 °C, −12 °C, and −6 °C were utilized to test the stiffness/deflection values of various RAP mortars in terms of soft binder aging states. These stiffness values and m-values were used to determine the minimum low temperatures of these asphalt RAP mortars.

The virgin binder PG 58-28 was blended with RAP mortars concluding three aged binders (5%, 10% and 15%) from six RAP sources (A–F). The fabricated BBR samples were tested at three temperatures (−6 °C, −12 °C and −18 °C).

The Superpave criteria for characterizing low temperature cracking of an asphalt binder are based on the definition of a critical cracking temperature, which is the maximum temperature below which cracking occurs as a result of a single cooling cycle. Therefore, cracking would happen when an asphalt binder reached a critical stiffness value. This critical temperature is typically defined the limiting stiffness temperature.

The Superpave binder specification uses BBR to measure the stiffness of asphalt binder at specified temperatures. The temperature at which the stiffness value of an asphalt binder exceeds 300 MPa is called the limiting stiffness temperature. Meanwhile, to address various cooling rates, the slope of the creep curve (denoted as m) is also included in the binder specification. The temperature at which the m value drops below 0.30 is a factor in determining the limiting stiffness. For most asphalt binders the m-value is a controlling value for defining the limiting stiffness temperature.

3. Results and Discussions

3.1. RAP Mortars with Virgin Soft Binder

3.1.1. Stiffness Values and m-Values

Figure 1 showed the main stiffness values and m-values results at −6 °C. As shown in Figure 1, it can be found that, as expected, the stiffness values of RAP mortars with virgin binder generally decrease while m-values increase when the loading duration increases with logarithmic trends regardless of RAP source. In addition, the stiffness values and m-values of the RAP mortars, which were blended from virgin binder and RAP mortar, cannot be achieved when using 5% aged binder because these RAP mortars are too soft at the testing temperature of −6 °C.

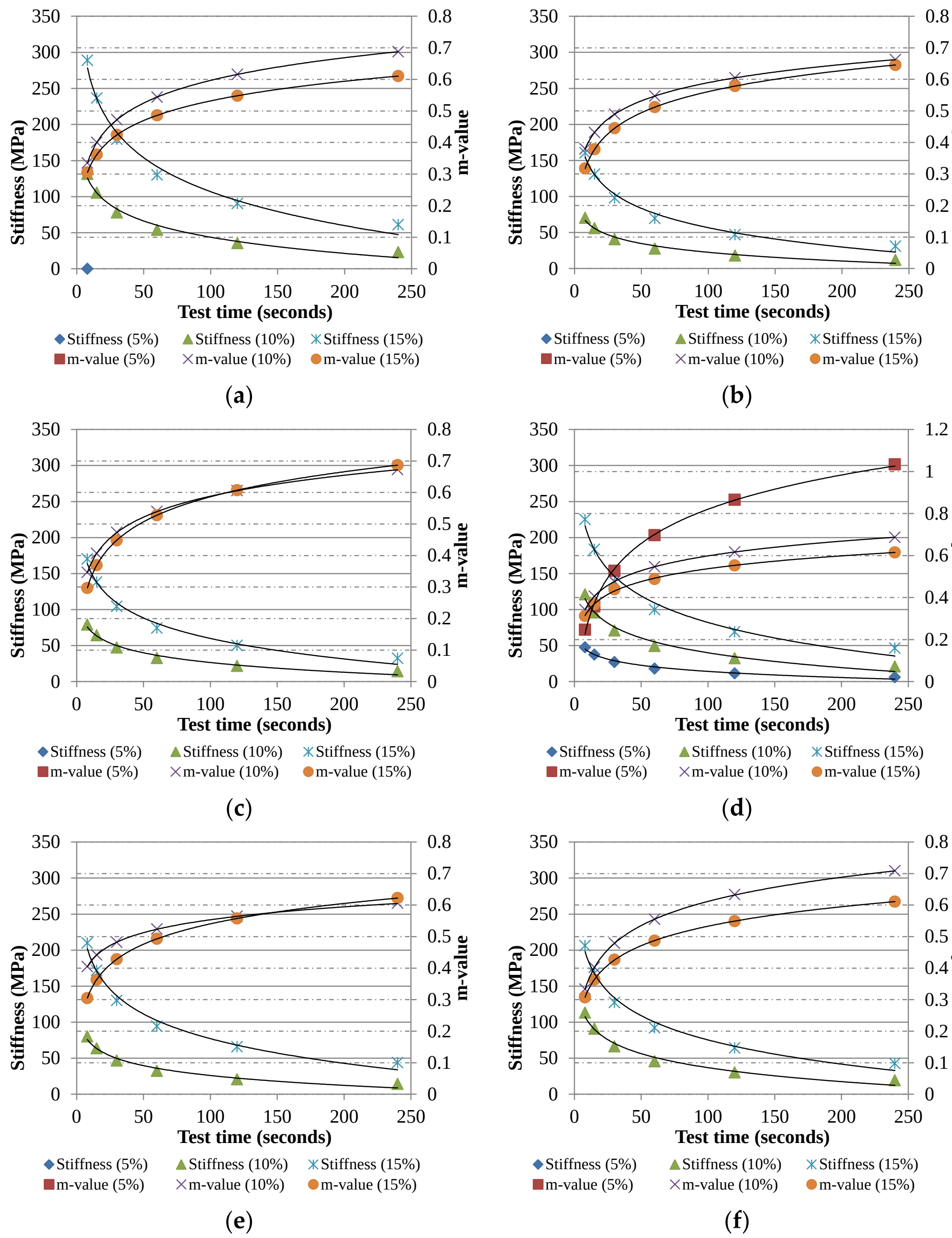


Figure 1. Stiffness values and m-values of reclaimed asphalt pavement (RAP) sources A–F modified with virgin binder PG 58-28 at −6 °C, (**a**–**f**) RAP sources A–F. A–F the names of RAP source in this study.

A higher percentage of aged binder results in a higher stiffness value and a lower m-value regardless of test duration and RAP source in Figure 1. Meanwhile, in terms of the stiffness values and m-values of RAP mortars A–F, it is noted that these values are significantly different at a same test time. The reason is that the aged binders from all RAP sources vary.

Other stiffness values and m-values of RAP mortars (A–F) and virgin binder at −12 °C and −18 °C are not shown in this paper due to the limitation of paper length. Generally similar trends can be found regardless of RAP source and test temperature in this study.

3.1.2. Low Temperature Determinations of RAP Mortars

Figure 2 shows the minimum low temperatures at a stiffness value of 300 MPa in terms of various RAP mortars blended with virgin binder PG 58-22. It can be found that an increased test temperature reduces the stiffness value of RAP mortars. In addition, a higher involved aged binder significantly results in a greater stiffness value regardless of test temperature and RAP source. Meanwhile, it can be seen that, irrespectively of RAP source, the RAP mortars containing 5% aged binder have stiffness values less than 300 MPa at the lowest temperature of −18 °C in this study. Therefore, these minimum low temperatures are definitely less than −18 °C.

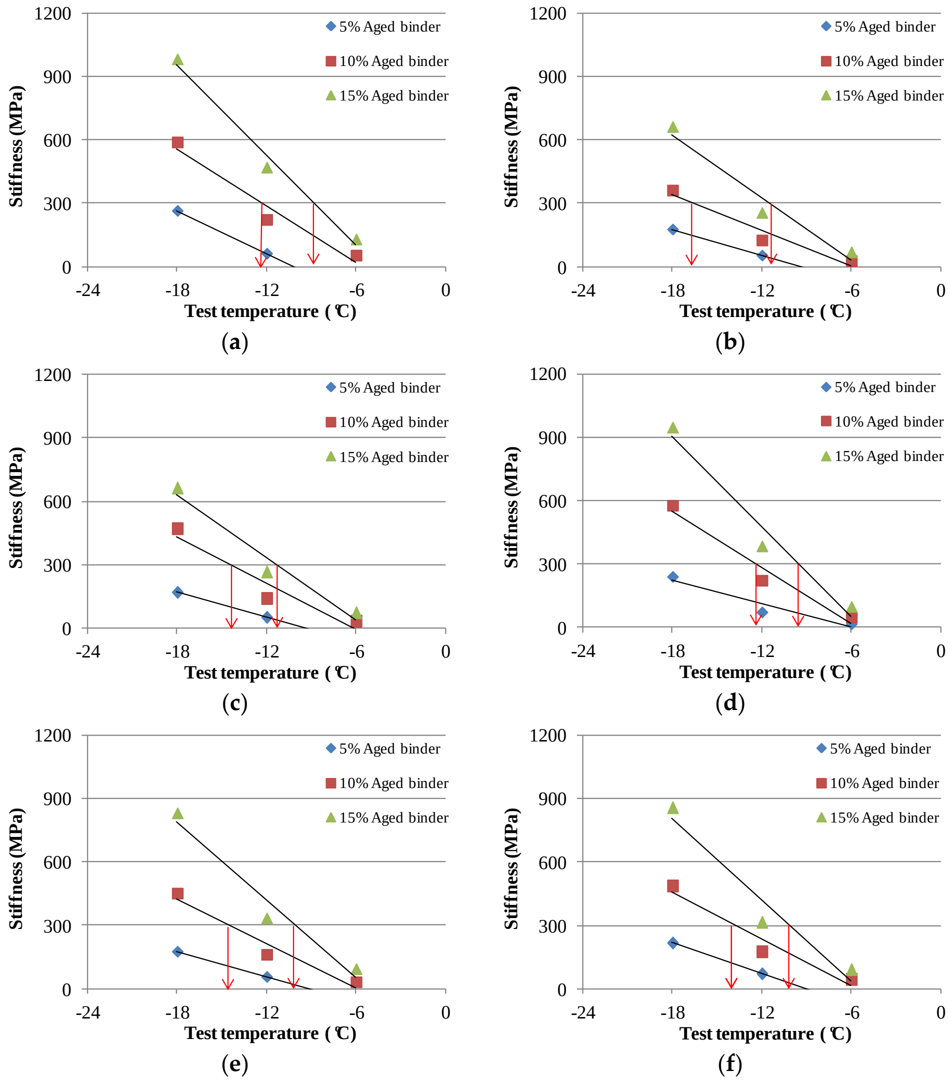


Figure 2. Low temperature determinations of RAP sources A–F with virgin binder PG 58-22 in terms of stiffness, (**a**–**f**) RAP sources A–F.

Additionally, Figure 2 indicates that, when the RAP mortars with 10% aged binder generally have a stiffness value of 300 MPa, their corresponding low temperatures are typically less than −12 °C. However, when the used aged binder is greater than 15%, the minimum low temperature is usually greater than −12 °C.

The minimum low temperature determinations of the RAP mortars with PG 58-28 with respect to m-values are shown in Figure 3. It can be observed that the m-values are greater than 0.300 at a temperature greater than −18 °C regardless of RAP source and aged binder content because the virgin binder PG 58-28 is generally quite soft. Therefore, the low temperatures of these RAP mortars were mainly determined by the stiffness values of these binders.

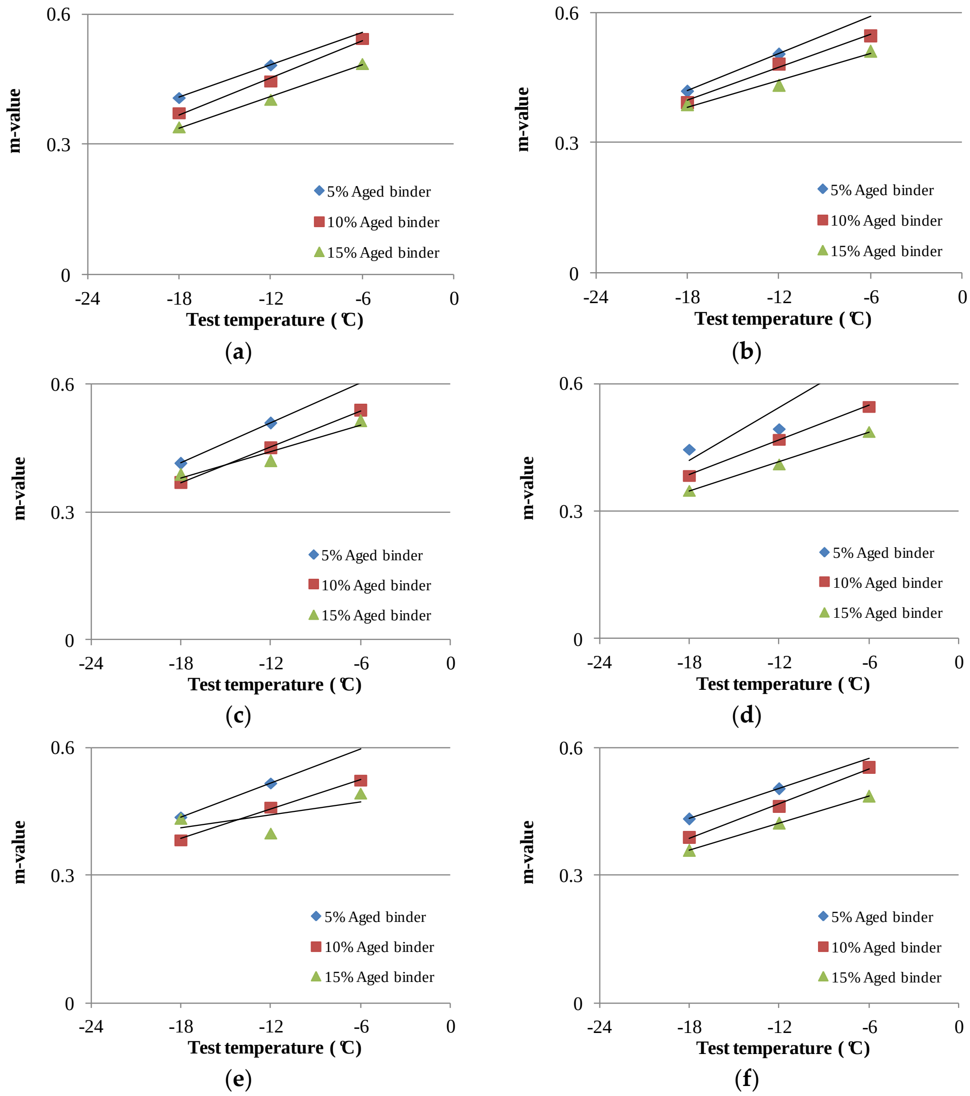


Figure 3. Low temperature determinations of RAP sources A–F with virgin binder PG 58-28 in terms of m-value, (**a**–**f**) RAP sources A–F.

In order to obtain the minimum low temperatures of various RAP mortars from various RAP sources and aged binder contents, Table 2 presents the minimum low temperatures based on those determined values from the stiffness values and m-values, derived from the conducted regression analysis. A higher temperature was selected as a minimum low temperature in this study because this would be able to satisfy the demand of the asphalt binder to resist the pavement cracking at a low performance temperature.

Table 2. Minimum low temperatures of RAP sources A–F with virgin binder PG 58-28.

Min. Temp (°C)	Stiffness			m-Value			Low Temperature Determination		
	Aged Binder Percentage			Aged Binder Percentage			Aged Binder Percentage		
	5%	10%	15%	5%	10%	15%	5%	10%	15%
A	−21	−12.2	−8.8	<−24	−22.7	−20.8	**−21**	**−12.2**	**−8.8**
B	<−24	−16.5	−11.7	<−24	<−24	<−24	**<−24**	**−16.5**	**−11.7**
C	<−24	−14.2	−11.3	<−24	−22.5	<−24	**<−24**	**−14.2**	**−11.3**
D	−21.3	−12.2	−9.7	−23.4	<−24	−21.9	**−21.3**	**−12.2**	**−9.7**
E	<−24	−14.1	−10	<−24	<−24	<−24	**<−24**	**−14.1**	**−10**
F	−21.8	−13.7	−10.1	<−24	<−24	−23.8	**−21.8**	**−13.7**	**−10.1**

As shown in Table 2, it can be seen that the minimum low temperatures are generally close to −12 °C for all RAP mortars when using 5% aged binder. However, these minimum low temperatures rise to approximately −6 °C when 15% aged binder was utilized to produce the BBR samples. Obviously, the increase of aged binder results in the remarkable increase of minimum low temperatures of these RAP mortars. Additionally, the RAP source only has a slight impact on the minimum low temperatures when using a higher aged binder content, but had a medium influence as lower aged binders were employed.

3.2. RAP Mortars Mixed with RTFO Binder

3.2.1. Stiffness Values and m-Values of RAP Mortars

This section presents the test results of the RAP mortars mixed with various RAP sources and a short-term aged (RTFO) binder of PG 58-28. The fabricated BBR samples were tested at three temperatures (−6 °C, −12 °C, and −18 °C). The main test results are shown in Figure 4.

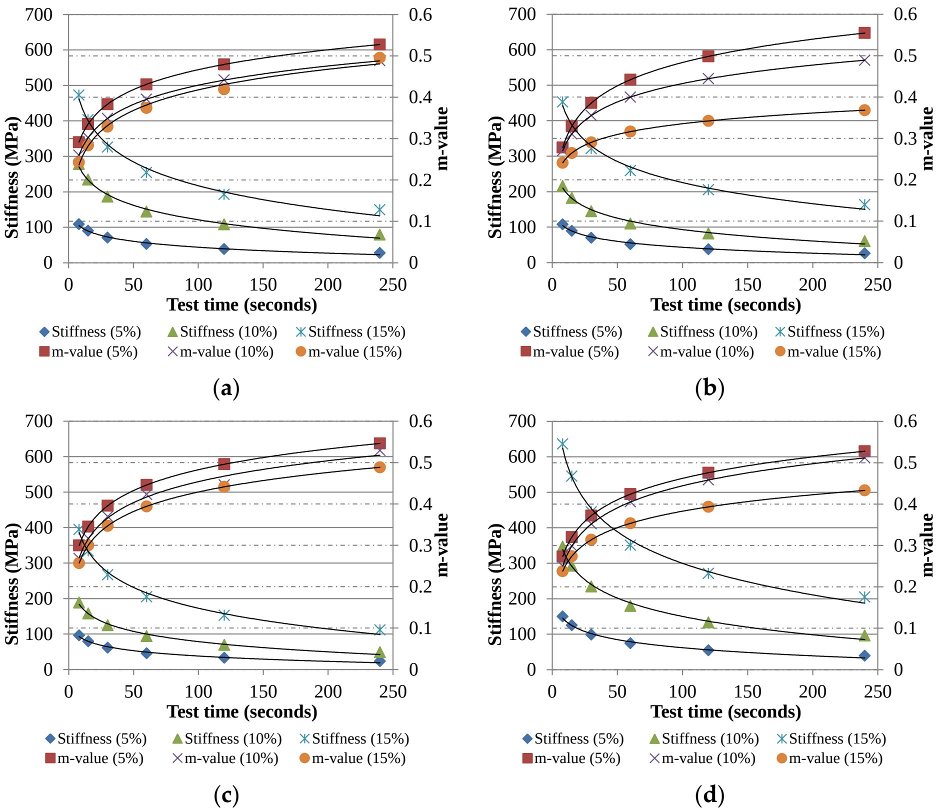


Figure 4. *Cont.*

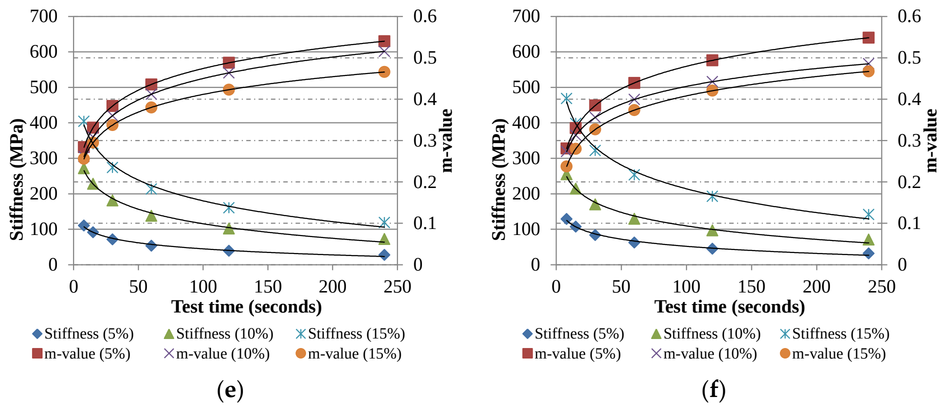


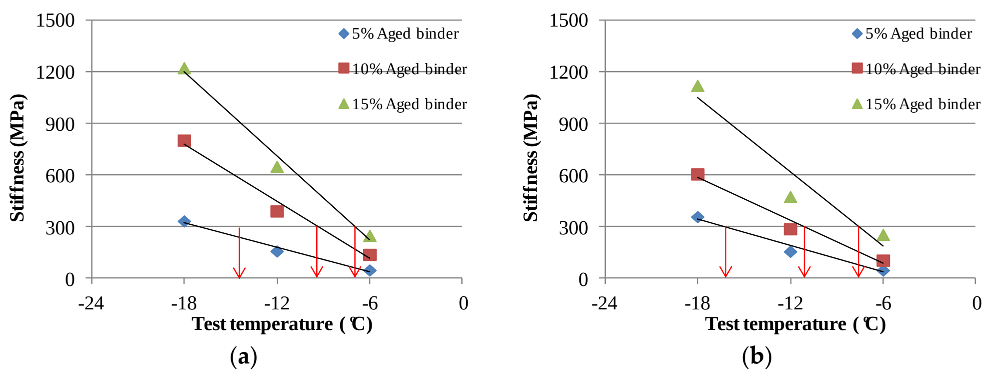
Figure 4. Stiffness values and m-values of RAP sources A–F modified with reclaimed asphalt pavement (RTFO) binder PG 58-28 at −6 °C, (**a**–**f**) RAP sources A–F.

As shown in Figure 4, it can be found that, at −6 °C, all RAP mortars mixed with sieved RAP and RTFO aged PG 58-28 binder showed increased m-values and the decreased stiffness values during a loading process. It is also noted that, as expected, RAP mortars with a higher aged binder content containing the aged soft binder have a higher stiffness and a lower m-value, following logarithmic trends regardless of RAP source and test time. In addition, different from the RAP mortars mixed with virgin binder PG 58-28, the RAP mortar with a 5% aged binder mixed with RTFO binder can show stiffness values and m-values during a loading procedure. Moreover, these stiffness values are significantly higher compared to those values of the modified binders mixed with virgin binder due to the RTFO aged binders.

3.2.2. Low Temperature Determinations of RAP Mortar

The previous data indicated that the cracking resistance at a low temperature of a modified binder is based on the stiffness and m-values at various test temperatures. In this section, the minimum low temperature determinations of the RAP mortars mixed with RAPs (A–F) and RTFO binders are summarized.

In Figure 5, it can be found that the RAP mortar with a higher aged binder content has a higher low temperature when its stiffness value is 300 MPa. In other words, the aged binder results in a higher stiffness regardless of RAP type. However, various RAP mortars generally have different low temperature values, dependent on RAP type.



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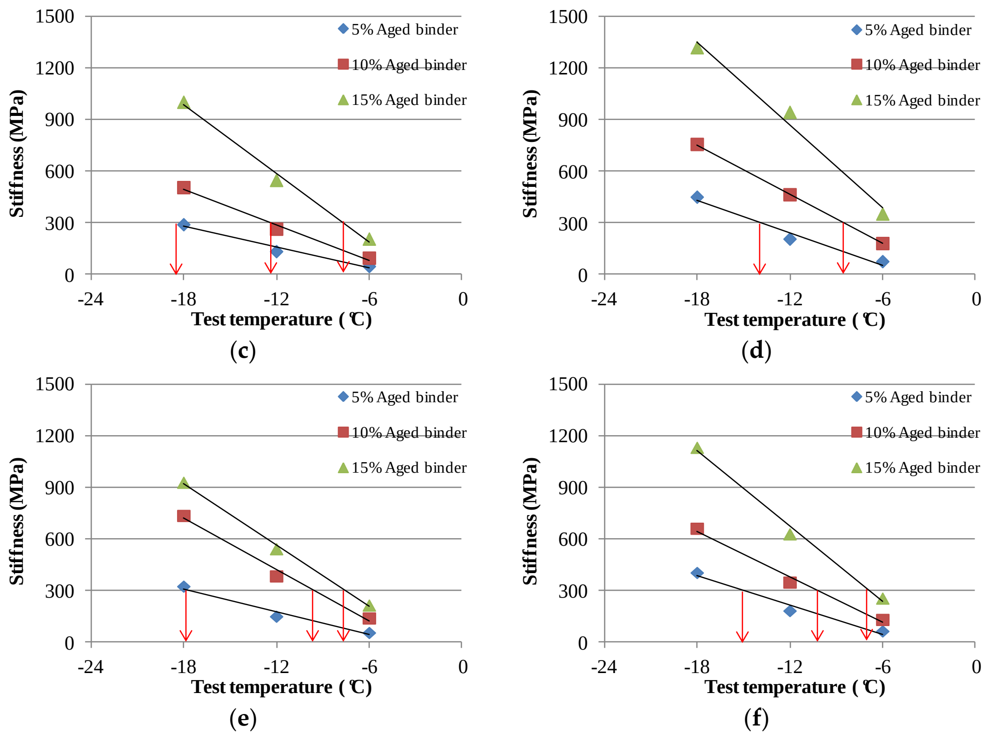
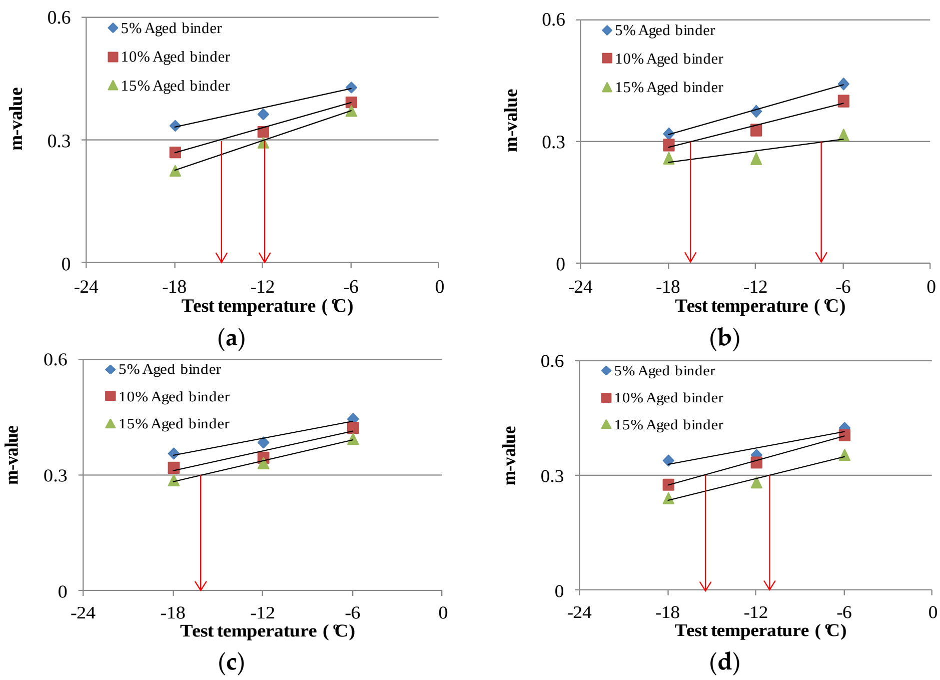


Figure 5. Low temperature determinations of RAP sources A–F with RTFO binder PG 58-22 in terms of stiffness, (**a**–**f**) RAP sources A–F.

In accordance with m-values of the RAP mortars, it can be noted that, in Figure 6, in some cases, m-values are greater than 0.300 when the test temperature is lower than −18 °C. Therefore, these RAP mortars can resist a low temperature of −18 °C or even lower. In addition, it can be noted that a higher aged binder content results in a higher low temperature regardless of RAP type.



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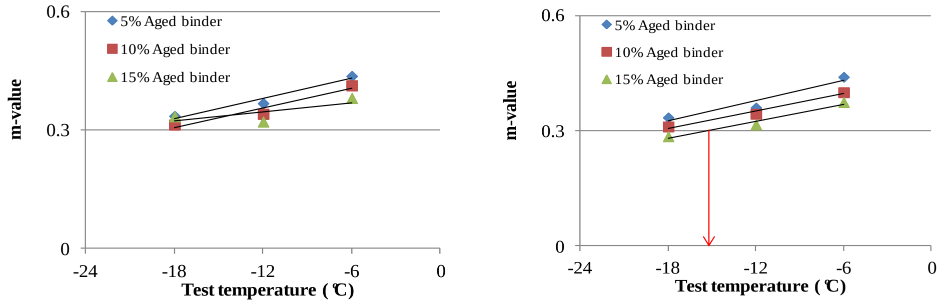


(**e**) (**f**)

Figure 6. Low temperature determinations of RAP sources A–F with RTFO binder PG 58-22 in terms of m-value, (**a**–**f**) RAP sources A–F.

The minimum low temperatures of various RAP mortars mixed with various RAP sources and aged binder contents are shown in Table 3. It can be observed that the low temperatures derived from the conducted regression analysis were summarized from stiffness values and m-values. As before, a higher temperature was selected as a minimum low temperature in this study because this could satisfy the demand of the asphalt binder to resist the pavement cracking.

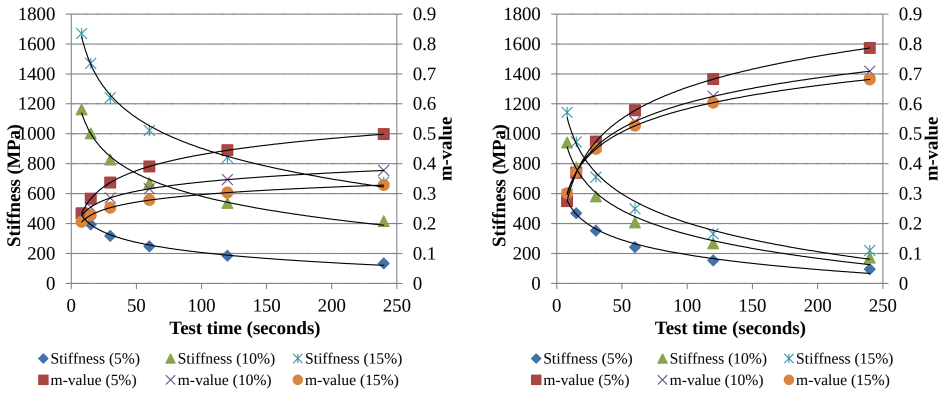
Table 3. Minimum low temperatures of RAP sources A–F with RTFO binder PG 58-28.

Min. Temp. (°C)	Stiffness			m-Value			Low Temperature Determination		
	Aged Binder Percentage			Aged Binder Percentage			Aged Binder Percentage		
	5%	10%	15%	5%	10%	15%	5%	10%	15%
A	−17	−9.4	−6.9	−21.4	−14.8	−11.9	**−17**	**−9.4**	**−6.9**
B	−16.2	−11.1	−7.8	−19.8	−16.4	−7.3	**−16.2**	**−11.1**	**−7.3**
C	−18.9	−12.2	−7.9	<−24	−19.2	−7.3	**−18.9**	**−12.2**	**−7.3**
D	−13.8	−8.7	−4.6	−21.8	−15.6	−12.1	**−13.8**	**−8.7**	**−4.6**
E	−17.7	−9.6	−7.8	−20.8	−18.5	<−24	**−17.7**	**−9.6**	**−7.8**
F	−15.2	−10.1	−6.9	−20.4	−19.1	−15.4	**−15.2**	**−10.1**	**−6.9**

3.3. RAP Mortar Mixed with PAV binder

3.3.1. Stiffness Values and m-Values of RAP Mortar

As shown before, the summarized figures present the stiffness values and m-values of the RAP mortars mixed with RAPs A–F and PAV aged binders. These values are shown in Figure 7, which presents the stiffness values and m-values of the RAP mortars with PAV PG 58-28. As described before, the aged binder concentration and RAP source affect the stiffness values and m-values of RAP mortars.



(**a**) (**b**)

Figure 7. *Cont.*

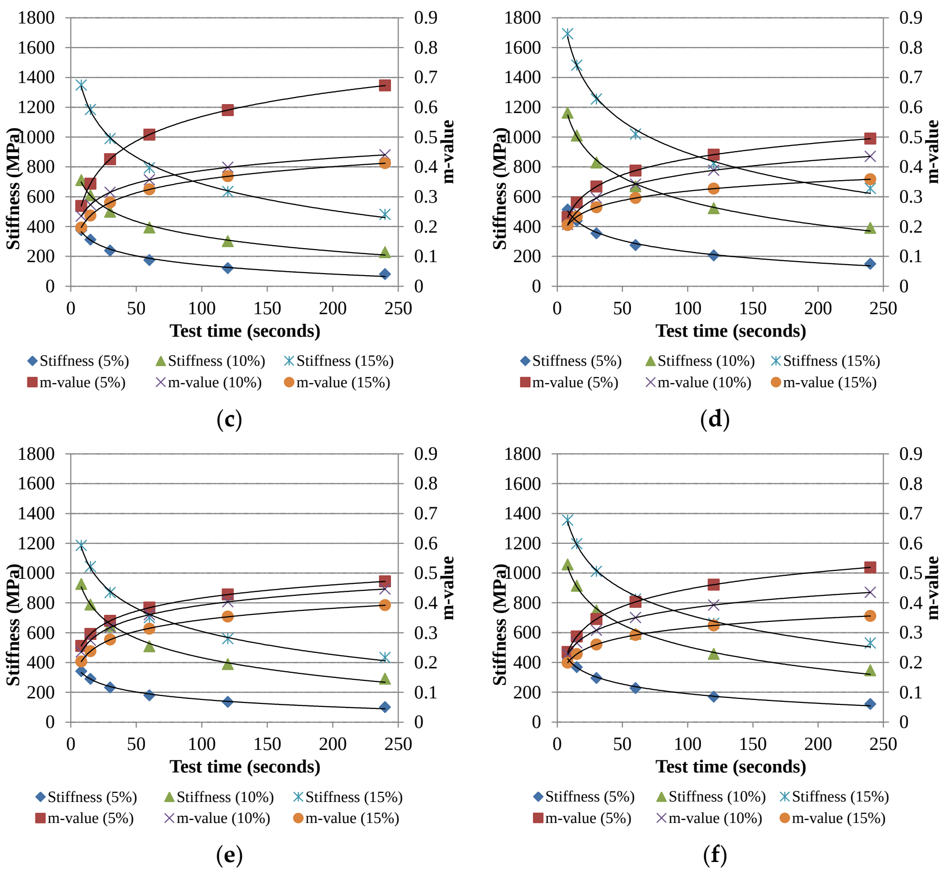
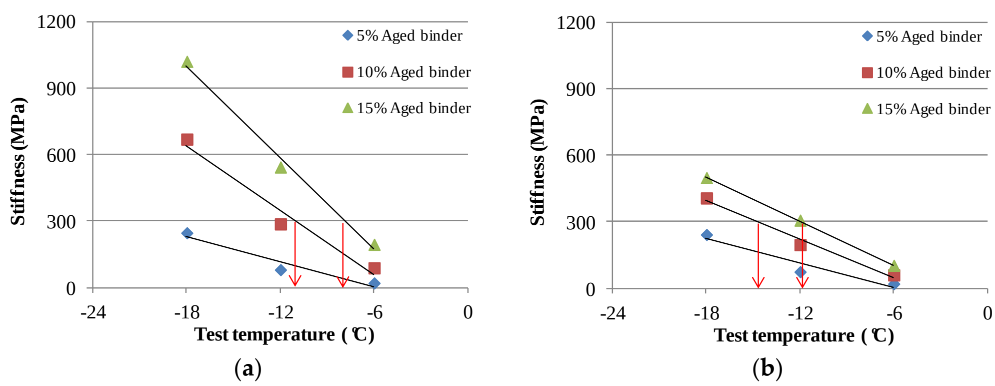


Figure 7. Stiffness and m-values of RAP sources A–F modified with PAV binder PG 58-22, (**a**–**f**) RAP sources A–F.

3.3.2. Low Temperature Determinations of Mortar

Similar to virgin and RTFO binders, the stiffness values and m-values of the RAP mortars mixed with PAV binder can determine the minimum low temperatures of various binders with a specified value of stiffness equaling to 300 MPa and a m-value of 0.300. These determined values can be found in Figure 8.



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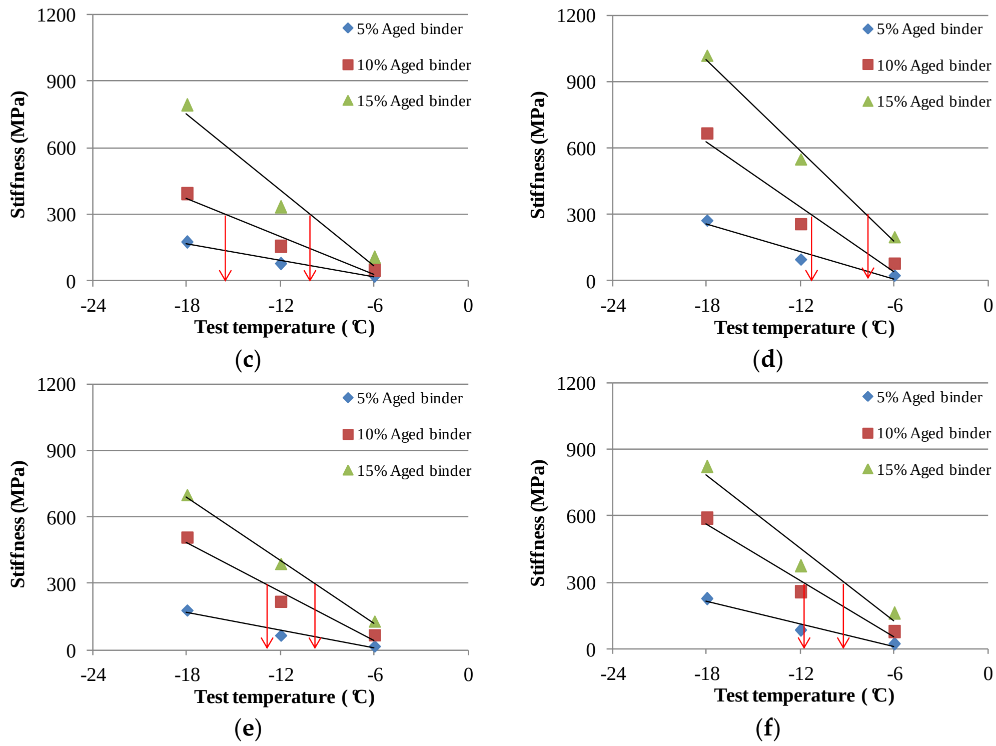

Figure 8. Minimum low temperature determinations of RAP sources A–F with PAV binder PG 58-28 in terms of stiffness, (**a**–**f**) RAP sources A–F.

In addition, these minimum low temperatures also can be determined by the m-values of these RAP mortars, based on the m-values greater than 0.300. As expected, Figure 9 indicates that the RAP mortars blended with PAV aged PG 58-28 binder and a lower aged binder have higher m-values. In addition, a higher test temperature results in a greater m-value.

Table 4 summarized the minimum low temperatures of various RAP mortars mixed with various RAP sources and aged binder contents, derived from the conducted regression analysis. As described before, a higher temperature was selected as a minimum low temperature in this study because this could satisfy the demand of the asphalt binder to resist the pavement cracking. Obviously, these minimum low temperatures from PAV binders are higher than those minimum low temperatures from RTFO binders, followed by those values from virgin binders.

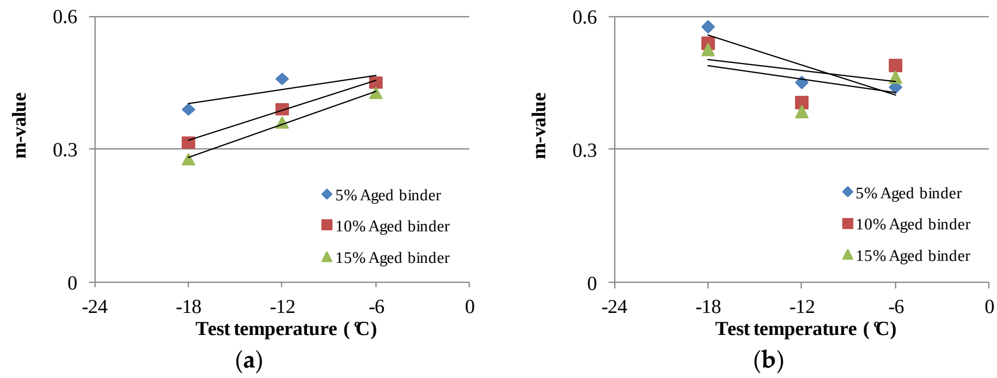

Figure 9. *Cont.*

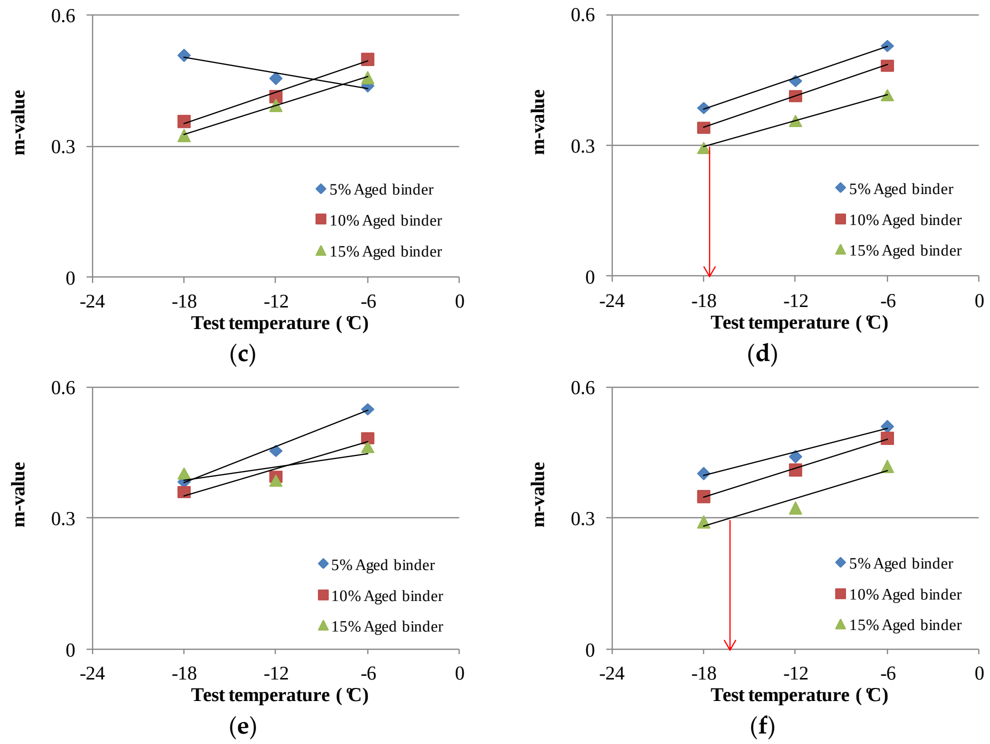

Figure 9. Minimum low temperature determinations of RAP sources A–F with PAV binder PG 58-28 in terms of m-value, (**a**–**f**) RAP sources A–F.

Table 4. Minimum low temperatures of RAP sources A–F containing PAV binder PG 58-28.

Min. Temp. (°C)	Stiffness			m-Value			Low Temperature Determination		
	Aged Binder Percentage			Aged Binder Percentage			Aged Binder Percentage		
	5%	10%	15%	5%	10%	15%	5%	10%	15%
A	−21.2	−11	−7.9	<−24	−20	−16.3	**−21.2**	**−11**	**−7.9**
B	−22.2	−14.8	−11.9	-	-	-	**−22.2**	**−14.8**	**−11.9**
C	<−24	−15.8	−10.1	-	−22.3	−19.8	**-**	**−15.8**	**−10.1**
D	−19.7	−11.3	−7.8	<−24	−21.7	−17.8	**−19.7**	**−11.3**	**−7.8**
E	<−24	−12.9	−9.8	−23.8	−22.7	<−24	**−23.8**	**−12.9**	**−9.8**
F	−22.5	−11.9	−9.3	<−24	−22.4	−16.2	**−22.5**	**−11.9**	**−9.3**

3.4. Minimum Low Temperature Comparisons

The minimum low temperature results of RAP mortars containing virgin binder, RTFO binder and PAV binder simulate the low temperature resistances of RAP mixture during and after construction and after long-term performance, respectively. As shown in Figure 10a, minimum low temperatures of RAP mortars with 5% aged binder and virgin soft binder are generally less than −18 °C, but these low temperatures are only less than −12 °C when blended with RTFO and PAV binders. Thus, as expected, the short- and long-term aging procedures can result in the increase of minimum low temperatures regardless of RAP type.

Similarly, as shown in Figure 10b,c, it can be noted that when using 10% and 15% aged binders, the RAP mortars with virgin soft binder have the best low temperature resistance, followed by the RAP mortars with RTFO and PAV binders. Therefore, it is necessary to use soft binder to modify the RAP mixture to achieve a better low temperature resistance.

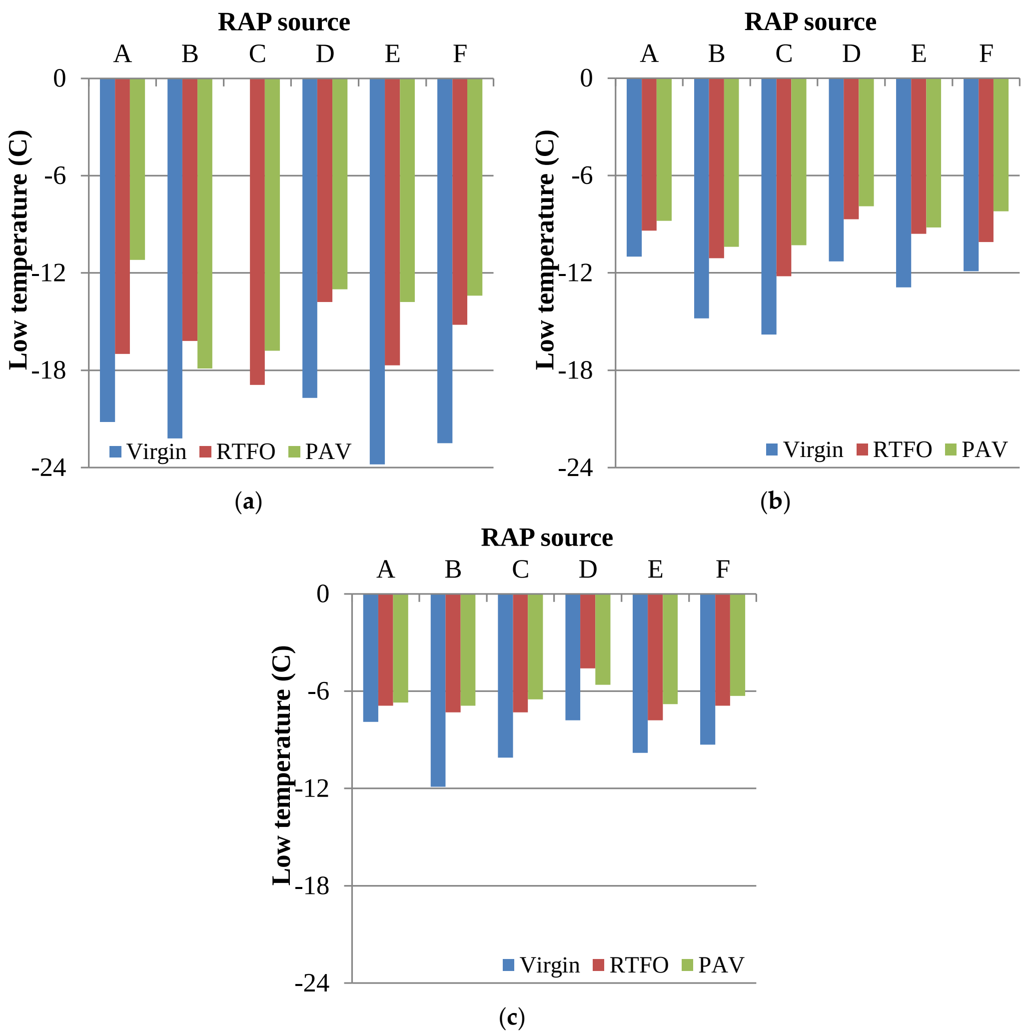

Figure 10. Minimum low temperatures of RAP mortars in terms of aged binder percentage and binder aged states, (**a**) 5% aged binder; (**b**) 10% aged binder; (**c**) 15% aged binder.

4. Conclusions

The RAP mortars containing six RAP sources blending one soft binder at three aging states were investigated with respect to their stiffness and m-values at three minimum test temperatures of −6 °C, −12 °C, and −18 °C. The following conclusions can be drawn:

1. For the sieved RAP containing a high percentage of aged binder over 15% it was generally not easy to conduct the BBR test, and thus it was recommended to use a low-aged binder of less than 15%.
2. The conducted BBR tests for RAP mortars were effective and no modifications were needed to test RAP mortars, which were combined with sieved fine RAP and asphalt binder.
3. The stiffness values and m-values at 60 s from BBR tests could be utilized to explore the minimum low temperatures based on the stiffness value of 300 MPa and m-value of 0.300.
4. RAP mortar with a higher aged binder content had a higher minimum low temperature regardless of RAP source. RAP mortars with virgin soft binder had the best low temperature resistance followed by the RAP mortars with RTFO and PAV binders.
5. The source of RAP did not play a crucial role in determining the low temperature performance characteristics of RAP mortars.

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References

1. Newcomb, D.E.; Brown, E.R.; Epps, J.A. *Designing HMA Mixtures with High RAP Content: A Practical Guide*; Quality Improvement Series 124; National Asphalt Pavement Association: Lanham, MD, USA, 2007.
2. Swiertz, D.; Mahmoud, E.; Bahia, H.U. Estimating the Effect of Recycled Asphalt Pavements and Asphalt Shingles on Fresh Binder, Low-Temperature Properties without Extraction and Recovery. *J. Transp. Res. Board* **2011**, *2208*, 48–55. [CrossRef]
3. Mogawer, W.S.; Austerman, A.J.; Bonaquist, R. Determining the Influence of Plant Type and Production Parameters on Performance of Plant-Produced Reclaimed Asphalt Pavement Mixtures. *J. Transp. Res. Board* **2012**, *2268*, 71–81. [CrossRef]
4. Xiao, F.; Hou, X.; Amirkhanian, S.; Kim, K. Superpave Evaluation of Higher RAP Contents Using WMA Technologies. *Constr. Build. Mater.* **2016**, *112*, 1080–1087. [CrossRef]
5. Hansen, K.; Copeland, A. *Annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage: 2009–2013*; Information Series 138; National Asphalt Pavement Association: Lanham, MD, USA, 2013; Available online: https://www.asphaltpavement.org/PDFs/IS138/IS138-2013_RAP-RAS-WMA_Survey_Final.pdf (accessed on 15 January 2017).
6. West, R.; Kvasnak, A.; Tran, N.; Powell, B.; Turner, P. Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixes Laboratory and Accelerated Field Performance Testing at the National Center for Asphalt Technology Test Track. *J. Transp. Res. Board* **2009**, *2126*, 100–108. [CrossRef]
7. Hong, F.; Chen, D.; Mikhail, M.M. Long-Term Performance Evaluation of Recycled Asphalt Pavement Results from Texas Pavement Studies Category 5 Sections from the Long-Term Pavement Performance Program. *Transp. Res. Rec. J. Transp. Res. Board* **2010**, *2180*, 58–66. [CrossRef]
8. Daniel, J.S.; Pochily, J.L.; Boisvert, D.M. Can More Reclaimed Asphalt Pavement Be Added? Study of Extracted Binder Properties from Plant-Produced Mixtures with up to 25% Reclaimed Asphalt Pavement. *Transp. Res. Rec. J. Transp. Res. Board* **2010**, *2180*, 19–29. [CrossRef]
9. Attia, M.; Abdelrahman, M. Modeling the Effect of Moisture on Resilient Modulus of Untreated Reclaimed Asphalt Pavement. *Transp. Res. Rec. J. Transp. Res. Board* **2010**, *2167*, 30–40. [CrossRef]
10. Roque, R.; Yan, Y.; Cocconcelli, C.; Lopp, G. *Perform an Investigation of the Effects of Increased Reclaimed Asphalt Pavement (RAP) Levels in Dense Graded Friction Courses*; University of Florida: Gainesville, FL, USA, 2015; Available online: http://www.dot.state.fl.us/research-center/completed_Proj/Summary_SMO/FDOT-BDU77-rpt.pdf (accessed on 16 January 2017).
11. National Cooperative Highway Research Program (NCHRP); Stroup-Gardiner, M. *Use of Reclaimed Asphalt Pavement and Recycled Asphalt Shingles in Asphalt Mixtures (No. Project 20-05, Topic 46-05)*; National Cooperative Highway Research Program: Washington, DC, USA, 2016.
12. Li, X.; Clyne, T.R.; Marasteanu, M.O. *Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality*; Report Mn/DOT 2005-02; Minnesota Department of Transportation: Maplewood, MN, USA, 2004.
13. National Cooperative Highway Research Program (NCHRP). *Synthesis of Highway Practice 54: Recycling Materials for Highways*; TRB, National Research Council: Washington, DC, USA, 1978; p. 1.
14. Xiao, F.; Amirkhanian, S.N.; Juang, H.C. Rutting Resistance of Rubberized Asphalt Concrete Pavement Containing Reclaimed Asphalt Pavement Mixtures. *J. Mater. Civ. Eng.* **2007**, *19*, 475–483. [CrossRef]
15. West, R.; Willis, J.R.; Marasteanu, M. *NCHRP Report 752: Improved Mix Design, Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content*; Transportation Research Board of the National Academies: Washington, DC, USA, 2013.
16. Li, X.; Marasteanu, M.O.; Williams, R.C.; Clyne, T.R. Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures. *Transp. Res. Rec. J. Transp. Res. Board* **2008**, *2051*, 90–97. [CrossRef]
17. Amirkhanian, S.; Xiao, F.; Corley, M. *Estimation of Low Temperature Properties of RAP Binder without Extraction*; Report No. FHWA-SC-16-01; Tri County Technical College: Pendleton, SC, USA, 2016.

18. Maupin, G.W.; Diefenderfer, S.D.; Gillespie, J.S. *Evaluation of Using Higher Percentages of Recycled Asphalt Pavement in Asphalt Mixes in Virginia*; Report No. VTRC 08-R22; Virginia Transportation Research Council: Charlottesville, VA, USA, 2008.
19. Scholz, T.V. *Preliminary Investigation of RAP and RAS in HMAC, Final Report SR 500-291, Kiewit Center for Infrastructure and Transportation*; School of Civil and Construction Engineering, Oregon State University: Corvallis, OR, USA, 2010.
20. Ma, T.; Mahmoud, E.; Bahia, H.U. Estimation of Reclaimed Asphalt Pavement Binder Low-Temperature Properties without Extraction. Development of Testing Procedure. *J. Transp. Res. Board* **2010**, *2179*, 58–65. [CrossRef]
21. Xiao, F.; Amirkhanian, S.N.; Wu, B. Fatigue and Stiffness Evaluations of Reclaimed Asphalt Pavement in Hot Mix Asphalt Mixtures. *J. Test. Eval.* **2011**, *39*, 50–58.