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Estimation of Low Temperature Properties of RAP Binder without Extraction

FINAL REPORT

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In recent years, the use of reclaimed asphalt pavement (RAP) as a component of asphalt mixtures has become a common practice. For many years, researchers and DOT officials have questioned the adverse effects, if any, of using solvents to extract and recover the binder. Therefore, researchers have been investigating new methods, without extraction techniques, of estimating the RAP binder properties, especially with respect to the low-temperature characteristics of binders and the mixtures. The major goal of this research project was to determine if the low-temperature properties of the aged asphalt binder in RAP could be obtained by using the fines (-#50 to +#100) generated from sieved RAP materials rather than from the binder extracted from the RAP. In addition, the low-temperature characteristics of several mixtures containing RAP were studied and evaluated for any correlation with the binder properties. Several samples were made with different RAP sources, different percentages of RAP content, various low temperatures (i.e., 0, -6, -12, and -18 °C), and at many states (i.e., virgin, RTFO, and PAV). In addition, some of the RAP sources were obtained after one year and BBR testing was conducted. Other testing procedures and specifications such as indirect tensile strength and semi-circle bending (SCB) were used and evaluated.</td></tr>
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Disclaimer

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1 Introduction

1.1 Problem Statement

In recent years, the use of reclaimed asphalt pavement (RAP) as a component of asphalt mixtures has become a common practice. Research has shown that in general, there are several benefits of using RAP in new mixtures, including expected reduction in the total cost of pavement construction, conservation of natural resources, and protecting the environment through reduced landfilling of RAP materials. However, there are many challenges related to estimating the properties of the aged binder in RAP since several changes have occurred over the years. The South Carolina Department of Transportation (SCDOT), among many other Department of Transportations (DOTs), uses extraction and recovery of the RAP binder to determine the aged binder's properties. For many years, researchers and DOT officials have questioned the adverse effects, if any, of using solvents to extract and recover the binder. Therefore, researchers have been investigating new methods of estimating the RAP binder properties, especially with respect to the low-temperature characteristics of binders and the mixtures.

In general, the type, extent and rate of fracture will affect the pavement's life span, rideability, and the need for maintenance treatments that might be very costly. There are several forms of fracture that are observed in flexible pavements including the following: thermal cracking (transverse to the direction of traffic), longitudinal surface cracking (otherwise referred to as "top-down" cracking), and reflective cracking. Reflective cracking, in general, is the result of an asphalt overlay placed on an existing jointed concrete pavement or a cracked pavement. Several researchers have been investigating the potential of developing testing and analysis methods that can be used to study the mechanisms of crack initiation and propagation in an asphalt pavement.

The original Superpave mix design procedures did not include the procedures to conduct a recycled HMA mix design. However, many state DOTs around the country, including SCDOT, used previously-developed procedures in late 1980s to conduct mix designs for mixtures containing RAP. In addition, the FHWA's Superpave Expert Task Group (ETG) has developed guidelines for the PG grade changes in the mix. These guidelines were followed by many state DOTs to conduct mix designs. These procedures were evaluated in a research project, NCHRP Project 9-12, and the results indicated that the guidelines are helpful in developing a proper mix design. However, there is a major problem with this system since for some mixtures, the procedure does not consider the age of the binder and considers only the amount of binder in the mix.

In this research project, several testing procedures for binders, mortars, and mixtures were utilized to determine the low-temperature characteristics of mixtures containing aged binders and RAP materials from various sources. These testing procedures included: modified BBR for RAP mortar testing; Semi-Circular Bending (SCB); and Indirect Tensile Strength (ITS) testing at different temperatures.

1.2 Modified Bending Beam Rheometer (BBR)

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. In this newly-developed testing procedure, the bending beam rheometer (BBR) is used with minor modifications to the equipment, and RAP mortar (fresh binder mixed with fine RAP materials) is tested instead of asphalt binder alone. The RAP mortar is tested with the modified BBR, and properties of the binder in RAP are then estimated from the mortar properties. There were many initial trials of the materials and equipment involved before establishing the developed testing procedures to determine the low-temperature properties of the aged binder in RAP materials.

1.3 Semi-Circular Bending (SCB)

In addition to disk shaped compact tension (DC(T)) testing procedures, the Semi-Circular Bending (SCB) test is used to determine the fracture toughness and fracture energy of an asphalt mixture. For this test, a load is applied vertically at the top of the semi-circular specimen using a pressure valve, and the load line displacement (LLD) is measured using a vertically-mounted extensometer. This load is controlled by the constant crack mouth opening displacement measured at the notch at the bottom of the specimen. The fracture toughness is calculated from the peak load. In addition, the fracture energy is determined from the area under load-LLD curve.

1.4 Indirect Tensile Strength (ITS) and Modified ITS

Many DOTs around the country are also using some form of the Indirect Tensile Strength (ITS) test to determine the low temperature characteristics of asphalt mixtures. Even though SCDOT does not use modified ITS testing procedures at this point, it is recommended for this proposed research project to test the mixtures containing RAP under these conditions. The modified ITS testing procedures will include testing the mixtures at 10 ºC and 0 ºC temperatures.

The Superpave specifications used by the Department are based on the linear viscoelastic analysis of creep and strength data at low temperatures for both asphalt binders and mixtures. Even though this was a major step forward compared to the previous procedures, this approach cannot provide the tools to predict the evolution of cracks and it does not allow taking into consideration the effects of traffic loading. In addition, it does not consider the variable aging through various asphalt layers and of the pavement system on the thermal behavior of the pavement.

1.5 Summary

In summary, the use of RAP is important to the asphalt industry in order to keep asphalt mix competitive in the market. Some of the benefits of using RAP in new mixtures are a shared cost savings to the consumer, higher strength and rutting resistance, and the environmental impact of re-using in lieu of landfilling the RAP materials. However, there are concerns when using too much RAP, such as producing mixtures that are too stiff or hard to produce and coat in fresh asphalt binder, achieving field compaction requirements, and resistance to cold weather cracking. The conventional method of classifying the aged asphalt binder from RAP materials requires initial extraction of the asphalt binder from the RAP, which is very time consuming and involves the use of harmful chemicals such as trichloroethylene. This project will examine the feasibility of a potential new method of analyzing the properties of RAP binder by using the fine particles of the RAP materials without extracting the RAP binder from them. These fine RAP particles contain the majority of the asphalt binder in the RAP and could possibly be blended directly with un-aged asphalt binder and tested for low-temperature properties. In addition, some of the low-temperature properties of asphalt mixtures containing RAP will be evaluated through various testing procedures.

2 Scope of the Research Project

2.1 Research Objectives

The major goal of this research project was to determine if the low-temperature properties of the aged asphalt binder in recycled asphalt pavement (RAP) could be obtained by using the fines (-#50 to +#100) generated from sieved RAP materials rather than from the binder extracted from the RAP. In addition, the low-temperature characteristics of several mixtures containing RAP were studied and evaluated for any correlation with the binder properties. The specific objectives of this research included the following:

1. Conduct an extensive literature review on the following topics (this objective will be performed concurrently with the objectives involving testing):
    a. The use of various techniques for determining the low-temperature properties of aged asphalt binder in RAP, including the modified Bending Beam Rheometer (BBR) test using fine (-#50 to +#100) RAP materials
    b. The use of various tests to determine the low-temperature properties of RAP mixtures;
2. Evaluate the low-temperature and other properties of several mortars containing RAP fines (with different stiffness values) using the modified BBR apparatus, and Dynamic Shear Rheometer (DSR),
3. Evaluate the low-temperature and other properties of several mortars containing RAP fines (with different stiffness values) using the modified BBR apparatus and DSR after Rolling Thin Film Oven (RTFO) conditioning;
4. Evaluate the low-temperature and other properties of several mortars containing RAP fines (with different stiffness values) using the modified BBR apparatus and DSR after Pressure Aging Vessel (PAV) conditioning;
5. Evaluate the low-temperature and other properties of several blended mortars containing virgin binders and fine aggregate from RAP (obtained from ignition oven burned RAP materials) using the modified BBR apparatus and DSR;
6. Evaluate the low-temperature and other properties of several blended mortars containing RTFO-aged binders and fine aggregate from RAP (obtained from ignition oven burned RAP materials) using the modified BBR apparatus and DSR;
7. Evaluate the low-temperature and other properties of several blended mortars containing PAV-aged binders and fine aggregate from RAP (obtained from ignition oven burned RAP materials) using the modified BBR apparatus and DSR;
8. Evaluate the low-temperature and other properties of several RAP mortars and blended mortars made from RAP materials re-collected from the original

source locations after one year to determine the effect of time on RAP source properties;

9. Evaluate the low-temperature properties of various asphalt mixtures using different laboratory testing procedures such as Indirect Tensile Strength (ITS),, Semi-Circular Bending (SCB) and modified ITS;
10. Develop a proposed laboratory procedure for the Department for determining the low-temperature properties of aged asphalt binder from RAP using RAP mortar materials;
11. Develop a proposed laboratory procedure for the Department for determining the low-temperature properties of asphalt mixtures containing RAP;
12. Validate the recommended testing procedures by testing laboratory-prepared binders and samples and comparing the results with previously-known values; and
13. Evaluate the cost averages and availability of various binder grades.

2.2 Organization of the Report

The contents of this report have been divided into several sections (chapters). Chapter 3 contains the literature review for many topics studied in this research project. Chapter 4 describes the materials and experimental design used for this work. Chapters 5 and 6 contain the results of the research activities. Chapter 7 contains the conclusions and the recommendations for this research study. Several appendices contain the laboratory or field testing results. The report also includes a partial list of references studied during this investigation.

3 Literature Review

A comprehensive literature review was conducted to investigate the utilization of RAP in asphalt mixtures. In addition, several methodologies were investigated to determine the feasibility of utilizing these techniques in this research program and by the SC DOT.

3.1 Reclaimed Asphalt Pavement

The use of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) applications is not a new concept. The origin of recycling asphaltic pavement surfaces dates back to 1915 (NCHRP 1978). However, it was not until the oil embargo of the 1970s that limited oil supplies significantly and increased the price of crude oil so that HMA recycling was given serious attention. Sullivan (1996) provided an executive summary of the state of the practice of recycled HMA in 1996. The report reveals that about 45 million tons of RAP is generated each year and 80% of it is reused in highway applications. This makes RAP the most recycled product in the United States, both in tonnage and in percentage of materials being recycled.

The actual amount of blending that happens in an asphalt mixture depends on many factors, including the stiffness of the RAP binder, the compatibility of the virgin and RAP binders, and specifics of the hot-mix plant, such as plant type (batch or drum), type and amount of mixing (pugmill or drum), mixing temperature, mix handling (live bottom trucks vs. dump trucks and shuttle buggies vs. windrow and pickup vs. dumping straight into the paver hopper), and perhaps more. In addition, laboratory-produced mixtures may not reflect the effects of all these factors, so testing of plant-produced mixtures would be more realistic. Thus, the degree of mixing of aged and virgin binders, particularly in relation to the effects of RAP on low-temperature properties, warrants further research (Shah et al. 2007).

McDaniel presented information on a study that focused on evaluating plant-produced mixes with up to 40% RAP and two virgin binder grades (McDaniel 2008). Asphalt binder properties (determined through extraction, recovery and PG binder tests) and mixture properties (determined through dynamic modulus, indirect tensile strength, and shear modulus) were all evaluated. The research indicated that the RAP did not have as much of an impact on the mixture properties as expected and that the higher RAP contents were not significantly stiffer than the virgin mix. Extraction, recovery, and PG grading indicated that the asphalt binder did not stiffen linearly with increasing RAP content, which is generally assumed in blending charts. Similar dynamic modulus results were found by Daniel and Lachance (Daniel and Lachance 2005).

Watson et al. (2008) considered that up to 20% RAP may generally be used without having a significant effect on fatigue life. The only exception was for the RAP blend in which the RAP contributed to a high proportion of the final binder content. Additionally, increasing RAP content did typically result in a lower number of cycles to failure, especially at high strain levels and at high RAP proportions (Xiao et al. 2011). Samples with 30% RAP had only about half the fatigue life of control samples without RAP. At those high RAP proportions, use of a softer virgin binder would likely be needed to improve fatigue results.

Li et al. (2008) found that both testing temperature and percentage of RAP in the mixtures significantly affects the fracture resistance. Fracture testing results indicated that the control mixtures have the highest fracture energy, and 20% RAP-modified mixtures exhibit similar fracture resistance abilities to the control mixtures.

Watson et al. (2008) indicated that the proportion of RAP has little effect on changes in the Los Angeles (LA) abrasion and flat and elongated (F&E) particle shape values for the combined blend. It was expected that RAP aggregate may actually be of benefit because some of the rough, irregular edges would have been broken off during previous handling, placement, and later milling of materials. The virgin aggregate source was found to be the most significant factor in controlling the LA abrasion loss and F&E properties. In addition, an increase in RAP content resulted in higher indirect tensile strengths (both conditioned and unconditioned).

Watson et al. (2008) found that the use of fine-graded RAP reduces the virgin binder requirements because of its high asphalt content, which translates into increased economic benefits. However, mixes that contain fine-graded graded RAP are stiffer because they have higher aged-to-virgin binder ratios and are more susceptible to fatigue cracking. Additionally, fine-graded RAP contains more material passing the No. 200 sieve, which must be accounted for during mix design.

Coarse-graded RAP has lower asphalt content, which indicates that mixtures containing this material would have a lower amount of aged binder and should exhibit a smaller increase in stiffness and have less potential for cold-temperature cracking. In Watson's study, the use of coarse-graded RAP also allowed for the reduction of the No. 7 stone requirement without affecting performance of the mixes. This may be beneficial if quarries become faced with a stone shortage due to the high demand for this material (Watson et al. 2008). The results also showed that adding RAP up to 30% has little effect on the low-temperature performance grade properties. The low-temperature grade of the combined binder blends was raised by one grade on only one of the cases. This may indicate that the grade of virgin binder does not have to be adjusted to provide the desired low-temperature properties (Watson et al. 2008).

At the April 2009 meeting of FHWA's Expert Task Group on Recycled Asphalt Pavement (RAP), the number one need in regard to the future use of higher RAP contents in asphalt mixtures was "Identify/develop performance tests for evaluating RAP mixes" (West 2009). With the dynamic modulus test showing sensitivity to the inclusion of RAP, the possible implementation of innovative analysis techniques using dynamic modulus data could fulfill this need.

Hong et al. (2010) observed that, in regard to transverse cracking, the relatively soft binders in these sections led to good crack-resistant capacity. HMA with 35% RAP deteriorated faster than that with only virgin material. In addition to using virgin binder, the use of 3% latex in the virgin sections possibly contributed to its cracking less than RAP sections did. It was further found that with all other factors equal, a pavement with 35% RAP is 0.47 times as effective as that with only virgin binder in regard to the capacity to resist transverse cracking.

Hong et al. (2010) indicated that for rutting, HMA with 35% RAP deteriorates more slowly than that with only virgin asphalt. In addition, it was discovered that with all other factors equal, a pavement with 35% RAP more slowly deteriorates at a rate of 0.70 times of that with only virgin material. Moreover, concerning the ride quality, tests indicated that there is no statistical difference between RAP mixtures and virgin mixture on roughness (IRI) change at a 95%-confidence level.

Daniel et al. (2010) found that the high-temperature performance grade remains the same or increases only one grade for the various RAP percentages. The low-temperature performance grades all remained the same or increased only one grade from the virgin mixture. The low-end failure temperatures and critical cracking temperatures changed by only a few degrees as the RAP percentages increased. In addition, some plants showed a slight decrease in these values with increasing RAP contents, while others showed a slight increase. The change in failure temperature as a function of percent binder replacement for both high and low temperatures was widely scattered, but it showed the expected decreasing trend with increasing percentages of RAP binder in the mix.

Daniel et al. (2010) indicated that the critical cracking temperature shows improvement with increasing percentages of RAP binder in the mixtures. More testing and analysis of various mixtures with replicate samples is needed to confirm this trend. In addition, the percent binder replacement calculation is recommended for normalizing different mixtures with respect to the asphalt content of the RAP and the asphalt content of the mixture.

Attia and Abdelrahman (2010) found that the effect of moisture on RAP is similar to the effect of moisture on granular material. More work is needed to develop a database for the impact of moisture on different RAP sources. The effect of moisture on RAP can be described by using the current models for granular material with one precaution: the upper ratio between the maximum modulus of resilience (MR) and the MR at optimum moisture content (OMC) should be based on a large database to avoid overestimation of the MR in a dry condition.

The survey by Hansen and Newcomb (2011) indicated that the asphalt industry remains the country's number one recycler. About 96% of the contractors/ branches reported using RAP. The amount of RAP used in HMA/WMA was 56.0 million tons in 2009 and 62.1 million tons in 2010. Assuming 5 percent asphalt binder in RAP, this represents over 3 million tons (19 million barrels) of asphalt binder conserved. Less than 1% of RAP was sent to landfills (Table 3-1).

Table 3-1: Summary of RAP Data from the NAPA Survey (Hansen and Newcomb 2011)

	Reported Tons Million		Total Estimated Tons Million	
	2009	2010	2009	2010
Companies/branches Reporting Using RAP	189	189		
Tons Accepted	23.2	24.0	67.2	73.5
Tons Used in HMA/WMA	20.1	21.6	56.1	62.1
Tons Used in Aggregate	1.5	1.6	6.2	7.3
Tons Used in Cold Mix	0.4	0.4	1.5	1.6
Tons Used in Other	0.1	0.07	0.7	0.8
Tons Landfilled	0.06	0.001	0.1	0.004
Avg. % for DOT mixes	12.5%	13.2%		
Avg. % for Other Agency mixes	14.0%	15.2%		
Avg. % for Commercial & Residential	17.5%	18.0%		
National Average All Mixes Based on % Reported For Different Sectors	15.6%	17.2%		
National Average All Mixes Based on RAP Tons Used In HMA/WMA	16.2%	18.0%		

3.2 <u>Low Temperature Properties of RAP Materials</u>

Low-temperature cracking is a predominant distress in asphalt pavements constructed in the northern United States and Canada because of the thermal stress that builds up in pavements in those extreme climates. These thermal cracks will result in the formation of transverse cracks along the pavement and ultimately accelerate the deterioration of the structure. 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 (Li et al. 2004).

Loria et al. (2011) found that the HMA mixtures with 50% RAP had an acceptable resistance to moisture damage and a better resistance with PG 52-34 asphalt binder. The mixtures with 50% RAP exhibited an acceptable resistance to thermal cracking as measured with the TSRST. It is hoped that the difference between the TSRST fracture temperatures and the critical low temperatures of the recovered asphalt binders from the 50% RAP mixes will be explained.

Mogawer et al. (2012) 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.

West et al. (2009) indicated that recovered binders from the RAP and control mixtures graded slightly better than the predicted high and low critical temperatures from the Superpave mix design procedure. Despite low air voids and high VFA for a few mixes, the RAP test sections have performed well on the NCAT test track under heavy loading. All sections have performed well for rutting. The section with 20% RAP and a PG 67-22 virgin binder has the most rutting, with 8.6 mm of rutting after 9.4 million ESALs. In addition, APA rutting tests on lab-molded cylindrical specimens from the RAP mixes also exhibited the influence of binder stiffness on rut test results. Except for the virgin control mix, the APA test results ranked the mixes in a way similar to the test track results.

West et al. (2009) found that on the basis of the field performance data available to date and the results of a variety of laboratory tests, there does not appear to be a strong case to support the approach of using a softer-grade virgin binder for high RAP mixes. Field performance of the mixtures was monitored through December 2008, at which time the test sections had carried 10 million ESALs. Additional laboratory work is under way to further analyze the issue of virgin binder effects and to include other tests for characterizing the mixtures for rutting and cracking.

Swiertz et al (2011) reported that when using RAP, the low-temperature PG grade depended on fresh binder grade and source. Similarly, two binder sources with the same low-temperature PG were shown to react differently with the same RAP source. Moreover, the results demonstrated that RAP sources may differ in total aging and composition, both of which may affect low-temperature properties of asphalt pavement; thus, RAP sources cannot be classified together. Swiertz et al (2011) also reported that a linear combination existed between the RAS-alone and RAP-alone blends, which allowed the effect on low-temperature PG of any RAP-RAS blend to be estimated.

Alternatively, Watson et al. (2008) found that adding RAP up to 30% had little effect on the low-temperature performance grade properties. The low-temperature grade of the combined binder blends was raised by one grade in only one of the cases. This may indicate that the grade of virgin binder does not always have to be adjusted to provide the desired low-temperature properties.

The dynamic modulus of asphalt mixtures is related to the major distress modes, such as permanent deformation, fatigue, and low-temperature cracking (Kandhal et al. 1995). An updated Mechanistic–Empirical Pavement Design Guide (MEPDG) proposed the dynamic modulus of asphalt mixtures as the key parameter in flexible pavement design that controls the permanent deformation and fatigue cracking resistance of asphalt pavements (Li et al. 2004).

Li et al. (2008) found that most mixes containing 20% RAP had higher dynamic modulus values than did mixes with 40% RAP at low temperatures or high frequencies, but both types of mixes (20% and 40% RAP) exhibited similar dynamic modulus values at higher temperatures. 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. Li et al. (2008)

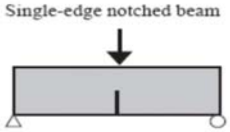
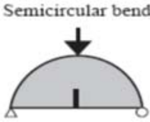
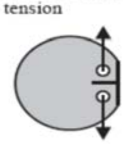
indicated that the RAP source does not significantly affect the fracture resistance for asphalt mixtures at low temperatures. No significant statistical relationship between dynamic modulus and fracture energy was found.

3.3 Main Test Methodologies for RAP Materials

The new MEPDG simulates thermal cracking by performing the indirect tensile creep (ITC) test and the indirect tensile strength (ITS) test. However, this approach does not directly address the crack propagation and the post-peak behavior of the tested materials as a result of a non-representative fracture test. It has been demonstrated that tensile strength values from the ITS test are not sensitive to parameters such as aggregate type and polymer modification type and level (Soleymani et al. 1999). As an accelerated performance test developed during the Strategic Highway Research Program (SHRP), the thermal stress restrained specimen test (TSRST) was initially used to test for low-temperature cracking. However, recently, the semi-circular bend (SCB) test and the disc-shaped compact tension test (DC(T)) have been more widely applied to simulate low-temperature cracking of asphalt concrete (Kandhal and Foo, 1997, Huang 1993, ARA 2004, Wagoner et al. 2005).

The SCB specimen has been successfully applied to measure the fracture resistance of HMA (Li et al. 2004, Hofman et al. 2003). The DC(T) specimen, which has been standardized in the ASTM E399 "Standard Test Method for Plane–Strain Fracture Toughness of Metallic Materials," also satisfies the requirements (ASTM E399). The advantages and disadvantages of the main low-temperature test methodologies are shown in Table 3-2.

Table 3-2: Potential Fracture Specimen Geometries with Advantages, Disadvantages, and Potential Fracture Surface Area (Wagoner et al. 2005)

Test Configuration	Advantages	Disadvantages	Potential Fracture Surface Area (mm^2)
Single-edge notched beam 	Pure Mode I loading Simple loading configuration Flexibility to investigate other areas (mix-mode fracture, specimen size effect, etc.)	Difficult to obtain field specimens	7500
Semicircular bending 	Easily obtained field specimens Simple three-point bending load	Complex stress state (arch effect arrests long cracks) Specimen size	3750*
Disk-shape compact tension 	Easily obtained field specimens Standard fracture test configuration	Application to HMA concrete unknown Crack deviation	5500*

*A specimen thickness of 50 mm was used in this calculation.

All these effects are best taken into consideration utilizing fracture mechanics. A recently-completed pooled fund study on asphalt mixtures' low-temperature properties showed that the semicircular bend (SCB) fracture test method, which has received considerable attention in asphalt mixture fracture testing because of its simplicity in specimen preparation and loading setup, is relatively sensitive to material properties and testing conditions (Li et al. 2007). The SCB fracture test was therefore employed in this research to measure the low-temperature fracture resistance of asphalt mixtures.

The SCB test was originally used to characterize rocks in the framework of fracture mechanics (Chong and Kuruppu 1984, Lim et al. 1994, Adamson et al. 1996, Ayatollahi and Aliha 2006). This test has gained significant popularity in evaluating asphalt mixtures since it was introduced in the international forum by the European and South African scholars in late 1990s and early 2000s. Considerable research was then conducted to apply the SCB test to asphalt mixtures, and at the same time, to assess the suitability of the test for characterizing asphalt mixtures. In addition to fracture properties, the SCB test was also used to evaluate the regular tensile strength of asphalt mixtures, explore fatigue properties of asphalt mixtures, estimate the tensile strength of asphalt mixtures, and investigate the fracture resistance of asphalt mixtures through J-integral on notched specimens.

In addition, Li et al. (2004, 2008) measured low-temperature fracture resistance of asphalt mixtures using the SCB test. Huang et al. (2005) also performed an in-depth study on this test for HMA mixtures and derived an equation to calculate the tensile strength at the middle point of the lower surface of the specimen. Furthermore, the SCB test was compared to the IDT test, and the results showed that the two tests were fully comparable and convertible.

Research to date has indicated that the SCB test possesses several advantages over the ITS and indirect tensile creep tests in determining the tensile strength of asphalt mixtures. In fact, the test setup is simple, and virtually any laboratory loading frame can be modified for the test. The test specimen can be easily prepared by cutting cylindrically-shaped samples fabricated in the laboratory or cored in the field. The permanent deformation under the loading strip in the standard ITS test can be reduced as the SCB test requires less force to break the specimen (Huang et al. 2005). In spite of its promise, it is still a developing method, and many aspects of the test need to be clarified.

To date, solvent extraction and recovery is the only method that physically separates the RAP binder from the RAP aggregate for characterization. Solvent extraction and recovery has long been criticized for altering binder properties and for posing difficulties in conducting tests (Swiertz Et al. 2011). Studies have demonstrated that after solvent extraction, RAP binder remains on the aggregate, sometimes to a considerable extent. Round robin testing indicated that regardless of the extraction procedure and solvent used, binder always remained on the aggregate (Cipione, et al. 1991). Binder hardening is another often-cited result of solvent extraction (Kondrath 2009, Burr et al. 1991). SHRP research demonstrated that hardening appears to occur with all commonly-used solvents and is even present when low-temperature extraction processes are used (Stroup-Gardiner and Nelson 2000).

After the binder has been extracted, it must be recovered from the solvent solution for characterization. Concerns that arise about the recovery method include the presence of residual solvent after recovery, the aging of binder by high temperature, and the labor intensity of the method used (Kondrath 2009). Research has indicated that even 0.5% residual solvent can cause a 50% decrease in viscosity (Peterson et al. 2000). To address the need for non-solvent-based binder characterization, procedures were developed for low-temperature characterization of RAP binder properties through the use of mix designs and back-calculation of binder properties.

The current method of testing the aged binder properties in the RAP is the extraction and recovery of asphalt binder with solvents method as specified in the AASHTO T164 and ASTM D2172 procedures. However, research studies (Stroup-Gardiner and Nelson 2000, Carey and Paul 1982) have consistently shown that this method is not accurate and has the following disadvantages Ma et al. (2010):

- Asphalt content in the RAP cannot be accurately estimated, because the binder extraction from the aggregates process might not be complete.
- Test results are sensitive to any residuals in the recovered binder; 1% residual filler or 0.5% solvent by weight of binder can lead to significant influences on the binder properties.
- Reaction of asphalt while in solution, sometimes called solvent aging, can alter properties during both extraction and recovery.

Ma et al. (2010) reported that estimating the effect of RAP materials on the performance of HMA requires accurate evaluation of the RAP materials. As mentioned, the extraction and recovery method poses a high variability as well as sensitivity to variables. Also, the general guidelines that are based on quantities of RAP used in practice are too simplistic and could result in inferior low-temperature performance. Therefore, a new procedure for more accurate evaluation of the properties of RAP binder is needed, particularly for the stiffness and creep rate m-values that are good indicators of cracking resistance. Ma et al. (2010) introduced a procedure to estimate these low-temperature properties of RAP binder using the standard bending beam rheometer (BBR) with minor modifications.

Ma et al. (2010) found that the BBR with only minor modifications can be used to test RAP mortars produced by mixing selected sizes of RAP with fresh binder. In addition, based on extensive testing, it was found that certain sizes of RAP can be separated and used in producing mortars that can be easily mixed, cast in standard BBR molds, and aged in the PAV. The selected size of RAP in this study was passing the #50 sieve and retained on the #100 sieve. Simple binder–mortar relationships, as well as widely-used linear blending charts, were found sufficient to obtain very good estimates of the binder properties in the RAP.

Ma et al. (2010) also reported that from the concept of blending charts and a linear relationship between the mortar and binder properties, the stiffness and m-value of RAP binder can be estimated. Test results were verified by testing the same RAP material with two fresh binders. Sample preparation and test repeatability were also verified. The test procedure developed proved capable of capturing the RAP binder low-temperature properties with very good repeatability. In addition, more work is needed to try other RAP sources and fresh binders. A spreadsheet has been developed to automate the calculations and determine amount of RAP that can be mixed without exceeding PG limits for S(60) and m(60).

To test the mortar using the BBR, the standard BBR mold and preparation procedure had to be modified Ma et al. (2010). The modified mold produced samples with end cross-sectional dimensions of 12.7 mm (breadth) × 9.35 mm (height) instead of 12.7 mm (breadth) × 6.35 mm (height). The new thickness is more than four times the maximum aggregate size (passing sieve # 8 ≤ 2.36 mm) of the RAP mortar. Thus, it is believed that maximum aggregate size has no interference with response measured. From the elementary bending theory (Al-Qadi et al. 2005), the shear effect due to the increased thickness contributes to only 2% of the center deflection, which is deemed acceptable. On the basis of many trials, it was found that the plastic strips commonly used in the BBR should be replaced by Teflon tape. Also, the use of screws for assembly of the end pieces instead of O-rings is necessary to allow pressure to be applied during molding while keeping thickness of specimen constant. This modification eases the molding, trimming, and demolding processes.

4 Materials and Experimental Design

4.1 Materials

The laboratory experimental design included the utilizations of 3 asphalt binders (PG 58-28 (I), PG 64-22 (II), and PG 76-22 (III)) from 2 sources (referred to as 1 and 2), which are commonly used for various types of surfaces in South Carolina. The rheological properties of these binders at three aging states are shown in Table 4-1.

Table 4-1: Rheological Properties of Three Base Binders

Binder type	Source	Aging states						
		Unaged			RTFO	PAV		
		Viscosity (135°C)	Failure temp.	G*/sinδ (64°C)	G*/sinδ (64°C)	G*sinδ (25°C)	Stiffness (-12°C)	m-values (-12°C)
		(cP)	(°C)	(kPa)	(kPa)	(kPa)	(MPa)	
PG 58-28 (I)	2	315	60.2	1.38 (58°C)	3.88 (58°C)	3595 (19°C)	249 (-18°C)	0.281 (-18°C)
PG 64-22 (II)	1	465	65.6	1.23	3.70	3529	178	0.306
PG 76-22 (III)	2	1735	81.15	1613.1 (76°C)	3625.3 (76°C)	2807	129.5	0.258

Six reclaimed asphalt pavement (RAP) sources (denoted as A through F) were selected to yield the modified asphalt mortars according to the recommendations from steering committee of this project. These RAPs were sieved to the size of passing #50 sieve and retaining on #100 sieve, and then were mixed with various aged states base binders accordingly. In addition, portions of these sieved RAPs were burned in an ignition oven to get rid of all aged binder to obtain the fine aggregate to produce the modified mortars. The typical images from these sieved RAPs are shown in Figure 4-1.

(A) (B)

Figure 4-1: Typical images, (A) sieved RAP (-#50 to #100); (B) burned RAP

These sieved RAPs were burned to investigate the binder contents. Two hundred grams were used to conduct the testing. The calculated aged binders are shown in Table 4-2. It can be noted that all aged binder percentages are in the range of 5.0% to

8.5%. The highest and lowest aged binder concentrations are from RAP sources F and E, respectively.

Table 4-2: Binder contents (%) of various RAP mortars

-50 RAP retained on #100 sieve	A			B			C		
Sample #	1	2	**Mean**	1	2	**Mean**	1	2	**Mean**
Original (g)	200	200	**200**	200	200	**200**	200	200	**200**
loss (g)	12.2	12.1	**12.2**	14.2	14.2	**14.2**	12.9	13.1	**13.0**
AC (%)	6.1	6.05	**6.07**	7.1	7.1	**7.10**	6.45	6.55	**6.50**
-50 RAP retained on #100 sieve	D			E			F		
	1	2	**Mean**	1	2	**Mean**	1	2	**Mean**
Original (g)	250	250	**250**	200	200	**200**	200	200	**200**
loss (g)	14.7	14.6	**14.7**	11.2	9.8	**10.5**	16.3	16.9	**16.6**
AC (%)	5.88	5.84	**5.86**	5.6	4.9	**5.25**	8.15	8.45	**8.3**

Three aggregate sources (designated as A, B and C) commonly used in South Carolina for interstate projects were utilized in this research. The engineering properties of the aggregate sources are shown in Table 4-3. Aggregate source “a” is composed predominantly of quartz and potassium feldspar while Aggregate “b” is a metamorphic rock. Aggregate “a” has a higher LA abrasion loss, specific gravity values, soundness percentage loss, and sand equivalent values. These properties may affect the performance of mixtures. In addition, two various amounts of reclaimed asphalt pavement (RAP) (15 and 30% aged binder) and tree RAP sources (high stiffness, medium stiffness, and low stiffness RAPs) were selected to produce the mixtures in this study. There were a total of 6 Superpave mix designs, which were conducted based on the utilizations of 1% hydrated lime.

Table 4-3: Physical properties of aggregates

Coarse Aggregate	LA Loss (%)	Absorption (%)	Specific Gravity			Soundness % Loss at 5 Cycles		Sand Equivalent	Hardness
			BSG	BSG SSD	ASG	3/4 to 3/8	3/8 to #4		
A	51	0.80	2.660	2.660	2.700	1.20	2.00	61	-
B	36	0.90	2.570	2.600	2.640	0.50	0.60	38	5
C	58	0.69	2.630	2.650	2.680	0.08	0.13	75	-
Fine Aggregate	**Fineness Modulus**	**Absorption (%)**		**BSG SSD**		**Soundness % Loss**			
A	2.82	0.40		2.590		4.5			
B	2.88	0.40		2.640		1.0			
C	2.82	0.30		2.680		1.3			

Notes: a, b, c = aggregate source; LA = Los Angeles; BSG = bulk specific gravity; SSD = saturated surface dry; ASG: Apparent specific gravity

4.2 Mortar Sample Fabrication and Testing

In this research study, the fabricated mortars, mixed with based binders and various fine RAPs, were used to produce BBR samples. A trial and error process was performed to determine the suitable percentage of RAP (aged binder percentage). It was found that if over 15% aged binder was used (with fine aggregate) in the mortar, regardless of RAP source, the mixed mortar was very stiff and could not be poured at a high temperature of over 165 °C (Figure 4-2). In addition, it was also observed that the stiffness values of these mortars were very high (over 1000 MPa) and even though no deflections could be found at a test temperature of -12 °C after a 240-second loading. Therefore, in this study, a percentage of up to 15% aged binder was used to produce the modified mortar. In addition, two more concentrations (5% and 10%) were utilized to help explore the performance characteristics of these mortars for this study, instead of the proposed two percentage of 15% and 30% aged binders.

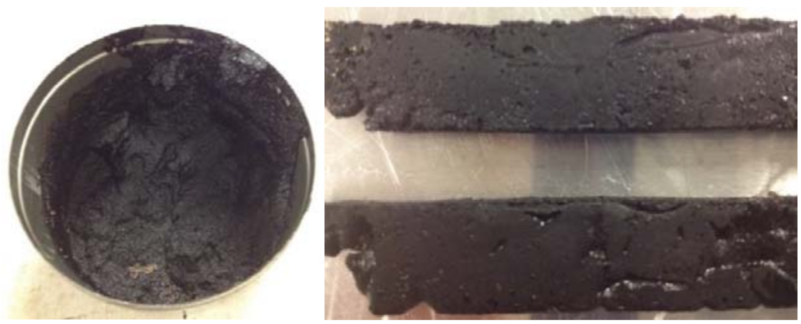
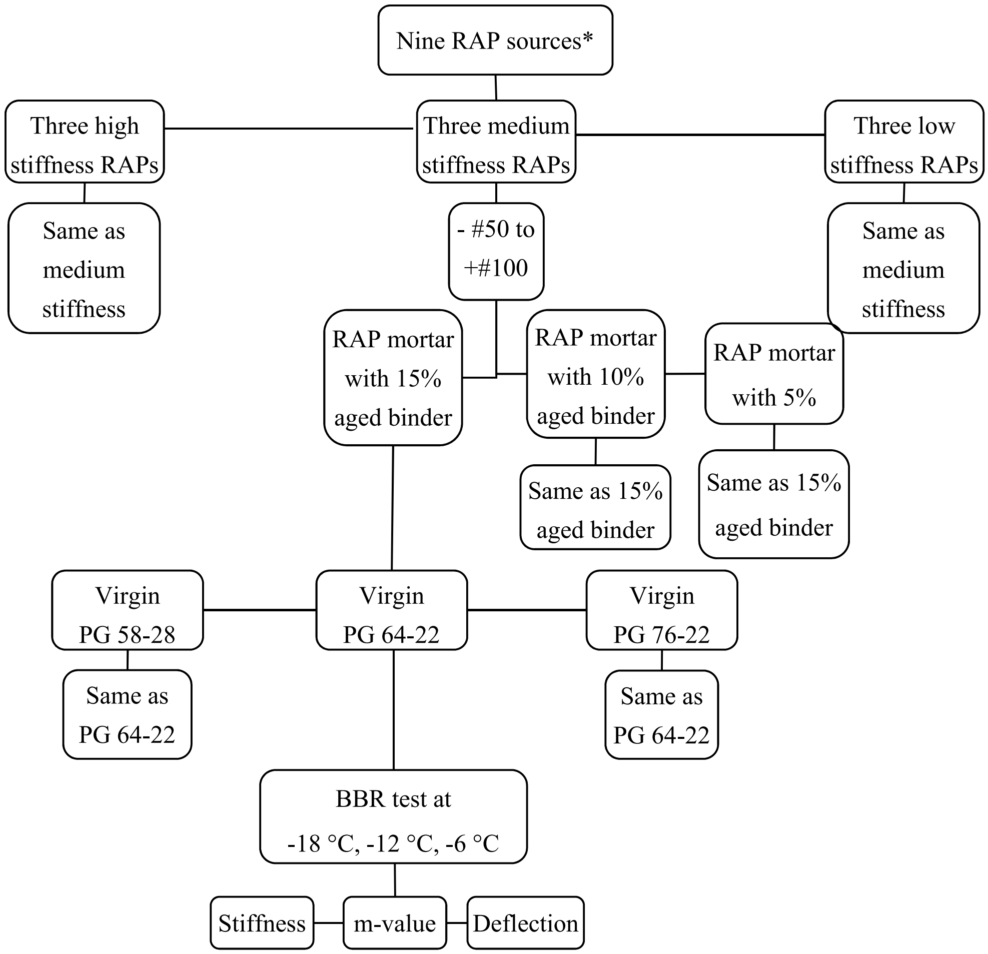


Figure 4-2: Stiff mortar samples and beams (15%RAP mortar with virgin binder PG76-22) after poured at 180 °C

The base test method to explore the low temperature characteristics of various modified mortars used in this study was bending beam rheometer (BBR). In this study, three temperatures of -18 °C, -12 °C, and -6 °C were employed to test the stiffness/deflection of various RAP binders. These stiffness values and m-values were used to determine the failure temperature of an asphalt RAP mortar.

4.2.1 Low-Temperature Characteristics of Virgin Binders Mixed with RAP Mortars

The laboratory experimental design shown in Figure 4-3 outlines the testing used to determine the low-temperature characteristics of mortar made from fine material from six RAP sources (2 with high stiffness, 2 with medium stiffness, and 2 with low stiffness) mixed with virgin asphalt binders. One size fractions of fine RAP materials (-#50 to +#100) and three asphalt binder grades (PG 58-28, PG 64-22, and PG 76-22) were utilized. In addition, three aged binder contents (5%, 10%, and 15%) were used. These RAP mortar mixtures were used in testing of low-temperature properties using the BBR apparatus.   The low-temperature grade was determined if the tested values for the mortars fell within the SHRP Performance Grade limits.



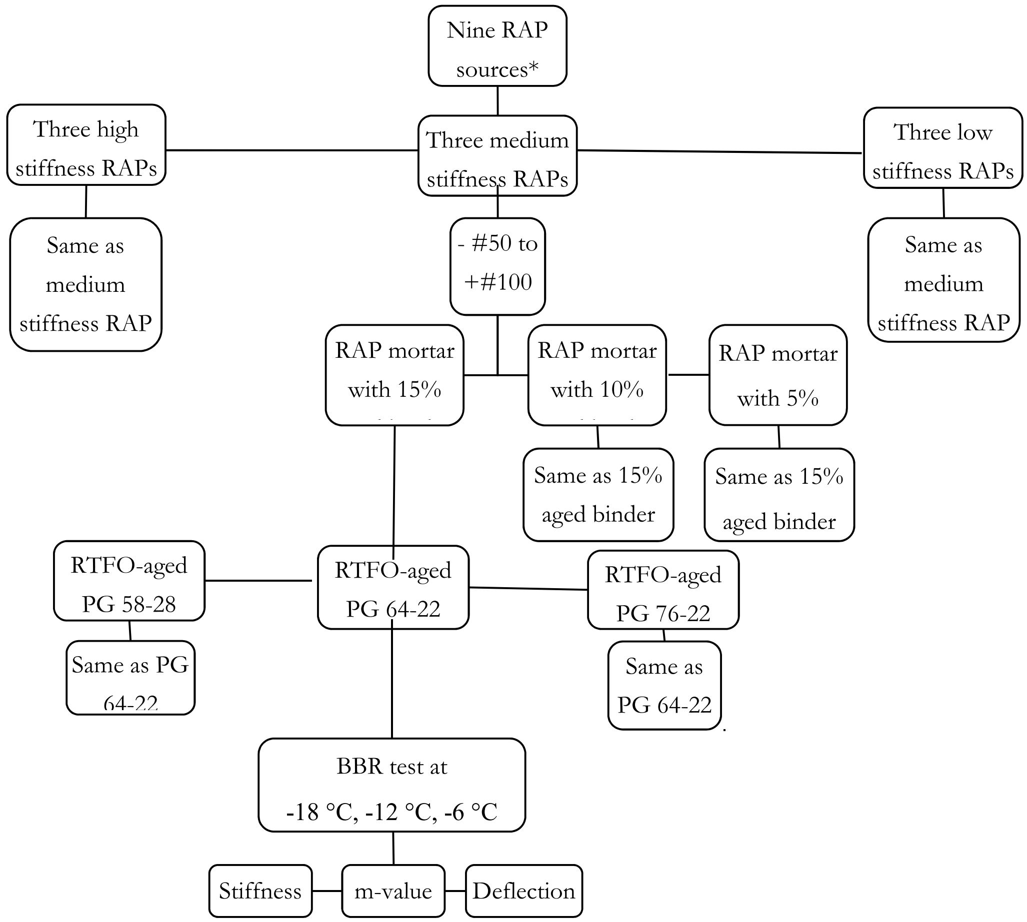
Notes:

* Six RAPs (two RAPs for each stiffness type) will be used in the first year; three RAPs (one of each stiffness type) will be utilized in the second year.

Figure 4-3: Low-Temperature Performance Tests of RAP Mortars with Original (Virgin) Binders

4.2.2 Low-Temperature Characteristics of RTFO-Aged Binders Mixed with RAP Mortars

The laboratory experimental design shown in Figure 4-4 outlines the proposed testing to determine the low-temperature characteristics of mortars made from fine material from the same six RAP sources mixed with RTFO-aged binders. The same size fraction of fine RAP materials (-#50 to +#100), the same three asphalt binder grades (PG 58-28, PG 64-22, and PG 76-22), and the same three aged binder contents (5%, 10% and 15%) were utilized. These RAP mortar mixtures were used to test for low-temperature properties using the BBR apparatus. The results of this objective were used to determine the effects of short-term aging of the binders.

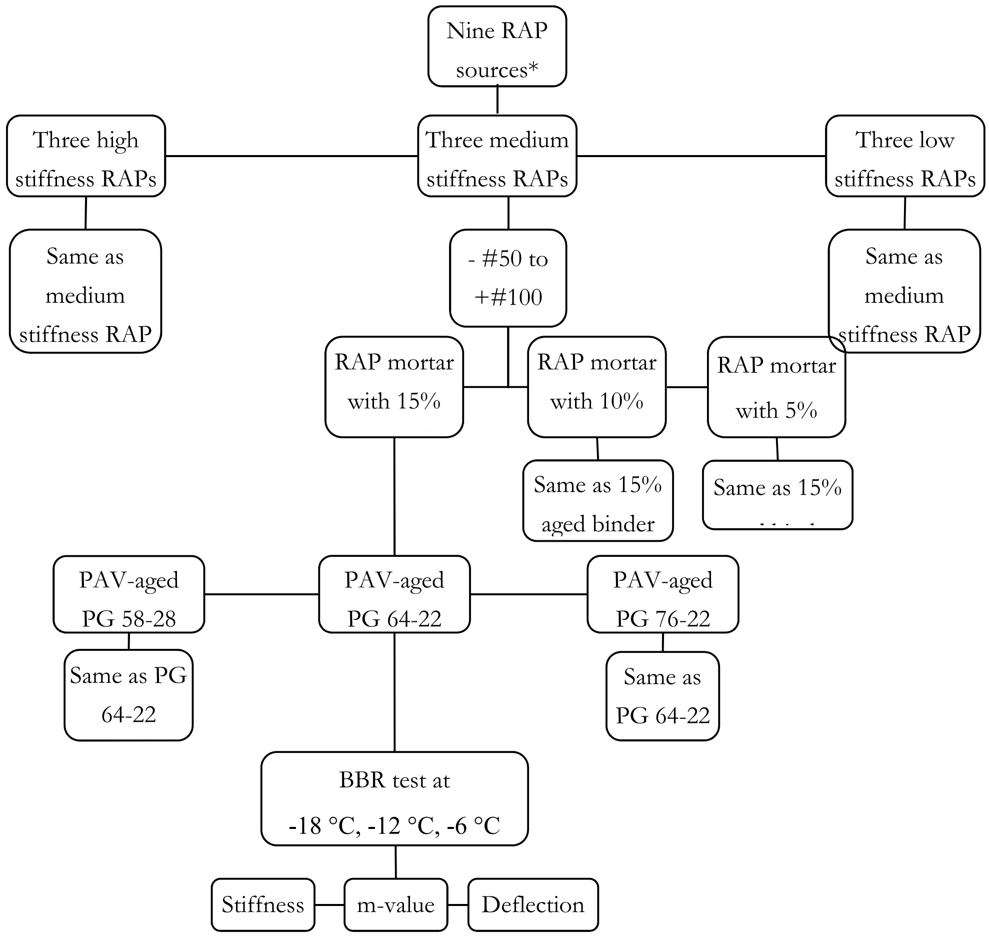


Notes:
* Six RAPs (two RAPs for each stiffness type) will be used in the first year; three RAPs (one of each stiffness type) will be utilized in the second year.

Figure 4-4: Low-Temperature Performance Tests of RAP Mortars with RTFO-Aged Binders

4.2.3 Low-Temperature Characteristics of PAV-Aged Binders Mixed with RAP Mortars

The laboratory experimental design shown in Figure 4-5 was followed to determine the low-temperature characteristics of mortar made from fine material from the same six RAP sources mixed with PAV-aged binders. The same size fraction of fine RAP materials (-#50 to +#100), the same three asphalt binder grades (PG 58-28, PG 64-22, and PG 76-22), and the same three aged binder contents (5%, 10% and 15%) were utilized. These RAP mortar mixtures were used to test for low-temperature properties using the BBR apparatus. The results of this objective were used to determine the effects of long-term aging of binders.

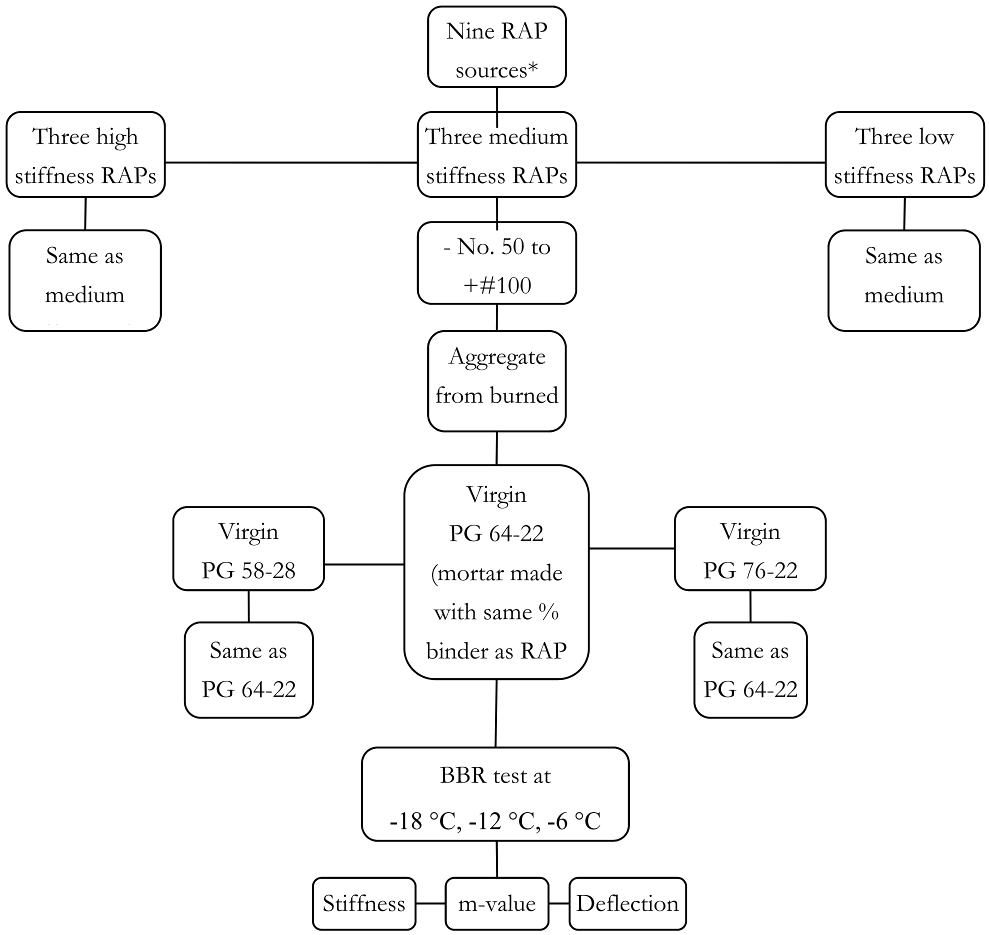


Six RAPs (two RAPs for each stiffness type) will be used in the first year; three RAPs (one of each stiffness type) will be utilized in the second year.

Figure 4-5: Low-Temperature Performance Tests of RAP Mortars with PAV-Aged Binders

4.2.4 Low-Temperature Characteristics of Virgin Binders Mixed with Fines Obtained from Ignition Oven Burn of RAP Materials

The laboratory experimental design shown in Figure 4-6 was followed to determine the low-temperature characteristics of blended mortars made from virgin binders blended with fine aggregate obtained from burning RAP materials in the ignition oven. The same six RAP sources were burned using the ignition oven to produce the fine aggregate for this portion of the study. The same total binder content and the same size fraction of fine RAP materials (-#50 to +#100) that were used in the RAP mortar samples, described above, was used for this portion of the study. The fine aggregates from the burned RAP materials were mixed with virgin asphalt binders (PG 58-28, PG 64-22, and PG 76-22) and tested. These blended mortars were tested for low-temperature properties using the BBR apparatus. The results of this objective were used as a control for the “blended mortar” portion of the experimental design. However, the results of this objective were also compared to the results from the “virgin binder mixed with RAP mortar” portion of the experimental design in order to evaluate the effect of the aged binder contained in the RAP mortars.



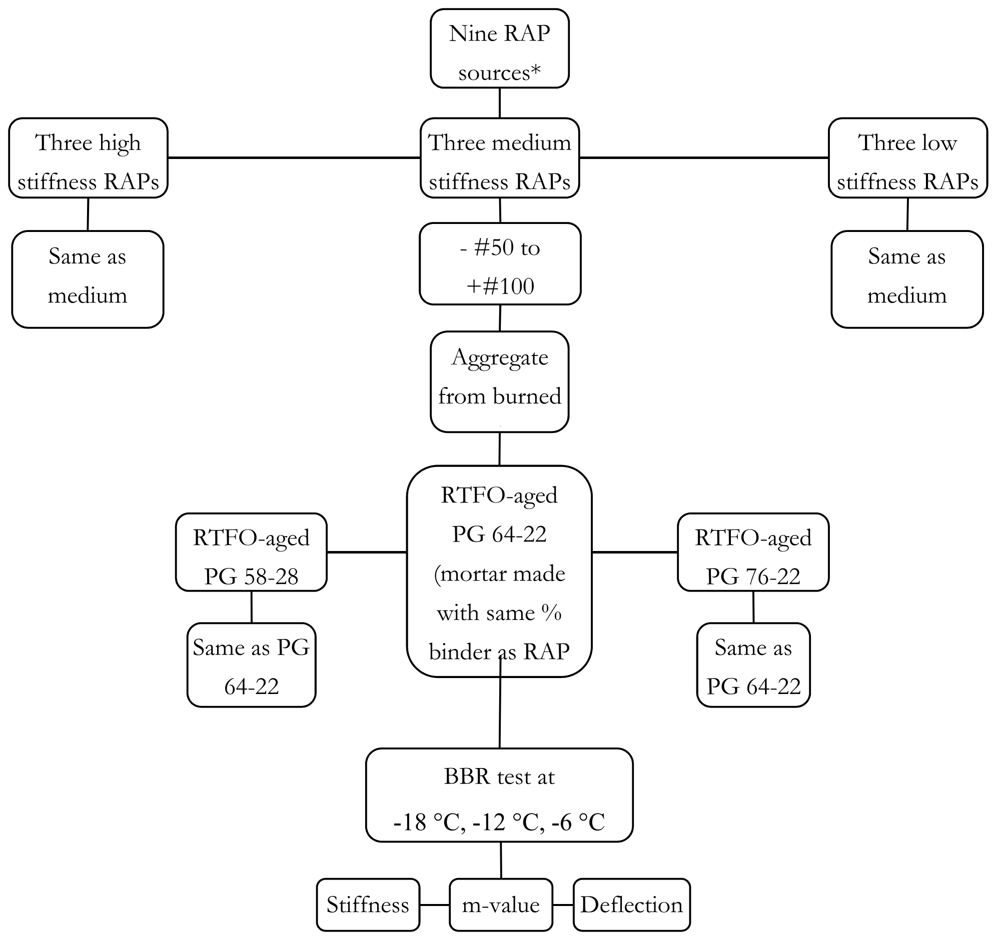
Notes:

* Six RAPs (two RAPs for each stiffness type) will be used in the first year; three RAPs (one of each stiffness type) will be utilized in the second year.

Figure 4-6: Low-Temperature Performance Tests of Mortar Made with Fine Aggregates from Ignition Oven-Burned RAP and Original (Virgin) Binders

4.2.5 Low-Temperature Characteristics of RTFO-Aged Binders Mixed with Fines Obtained from Ignition Oven Burn

The laboratory experimental design shown in Figure 4-7 was used to determine the low-temperature characteristics of blended mortars made from RTFO-aged binders blended with fine aggregate obtained from burning RAP materials in the ignition oven. The fine aggregates from the burned RAP materials will be mixed with RTFO-aged asphalt binders (PG 58-28, PG 64-22, and PG 76-22) and tested. The objective of this portion of the research project was to determine the effects of short-term aging of binders. Additionally, the results of this objective were compared to the results from the "RTFO-aged binder mixed with RAP mortar" portion of the experimental design in order to evaluate the effect of the aged binder contained in the RAP mortars.



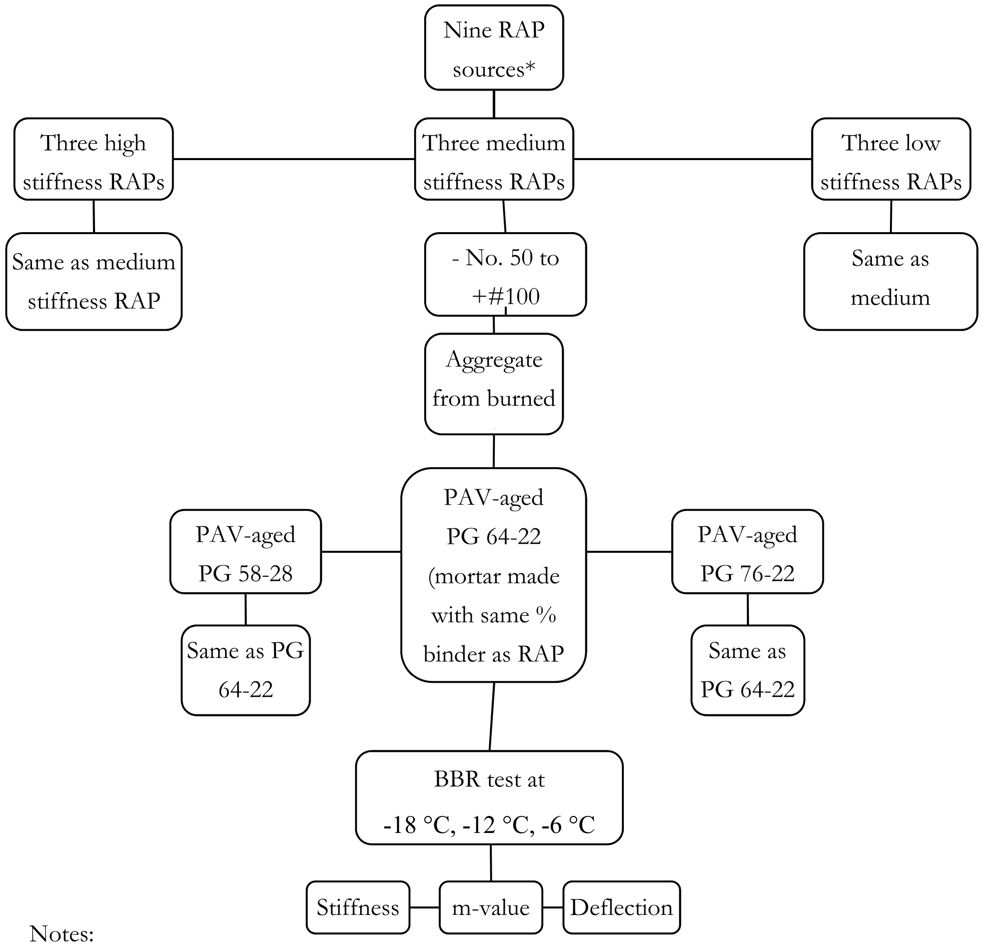
Notes:

* Six RAPs (two RAPs for each stiffness type) will be used in the first year; three RAPs (one of each stiffness type) will be utilized in the second year.

Figure 4-7: Low-Temperature Performance Tests of Mortar Made with Fine Aggregates from Ignition Oven-Burned RAP and RTFO-Aged Binders

4.2.6 Low-Temperature Characteristics of PAV-Aged Binders Mixed with Fines Obtained from Ignition Oven Burn

Figure 4-8 shows the laboratory experimental design used to determine the low-temperature characteristics of blended mortars made from PAV-aged binders blended with fine aggregate obtained from burning RAP materials in the ignition oven. The fine aggregates from the burned RAP materials were mixed with PAV-aged asphalt binders (PG 58-28, PG 64-22, and PG 76-22) and tested. The results of this phase of the project were compared to other results obtained from other objectives to determine the effects of long-term aging of binders. Additionally, the results of this objective were also compared to the results from the "PAV-aged binder mixed with RAP mortar" portion of the project in order to evaluate the effect of the aged binder contained in the RAP mortars.



Notes:

* Six RAPs (two RAPs for each stiffness type) will be used in the first year; three RAPs (one of each stiffness type) will be utilized in the second year.

Figure 4-8: Low-Temperature Performance Tests of Mortar Made with Fine Aggregates from Ignition Oven-Burned RAP and PAV-Aged Binders

4.2.7 Low-Temperature Properties of RAP Sources after One Year

All of the above-mentioned binders were used to test six RAP sources (two with high stiffness, two with medium stiffness, and two with low stiffness) after one year of the initiation of testing. The same testing procedures described above were used for this portion of testing. However, for this phase of the work only three of the original RAP sources (one of the high stiffness, one of the medium stiffness, and one of the low stiffness sources) were collected again after one year from the commencement of the research work from the same stockpile. This phase of the research work investigated the effects of time (one year) on the low-temperature properties of RAP obtained from the same source.

4.2.8 Low-Temperature Properties of Extracted Binders from Six RAP Sources

In addition, conventional extracted binders from six RAP sources were blended with three virgin binders (PG 58-28, PG 64-22, and PG 76-22) in this study, as shown in Figure 4-9. The extraction process followed the specification of SC T-95: *Standard Method of Test for Recovery of Asphalt Binder from Hot Mix Asphalt by Means of the Rotavapor Apparatus.* All of the above-mentioned testing procedures and binders were used to test six RAP sources (2 with high stiffness, 2 with medium stiffness, and 2 with low stiffness). The percentages of aged binders used were 15% and 30% in this portion of the study, which represented an approximately maximum content of aged binder and typical content of aged binder used in South Carolina. DSR tests were performed to explore the rheological properties of these modified binders at high, medium, and low temperatures.

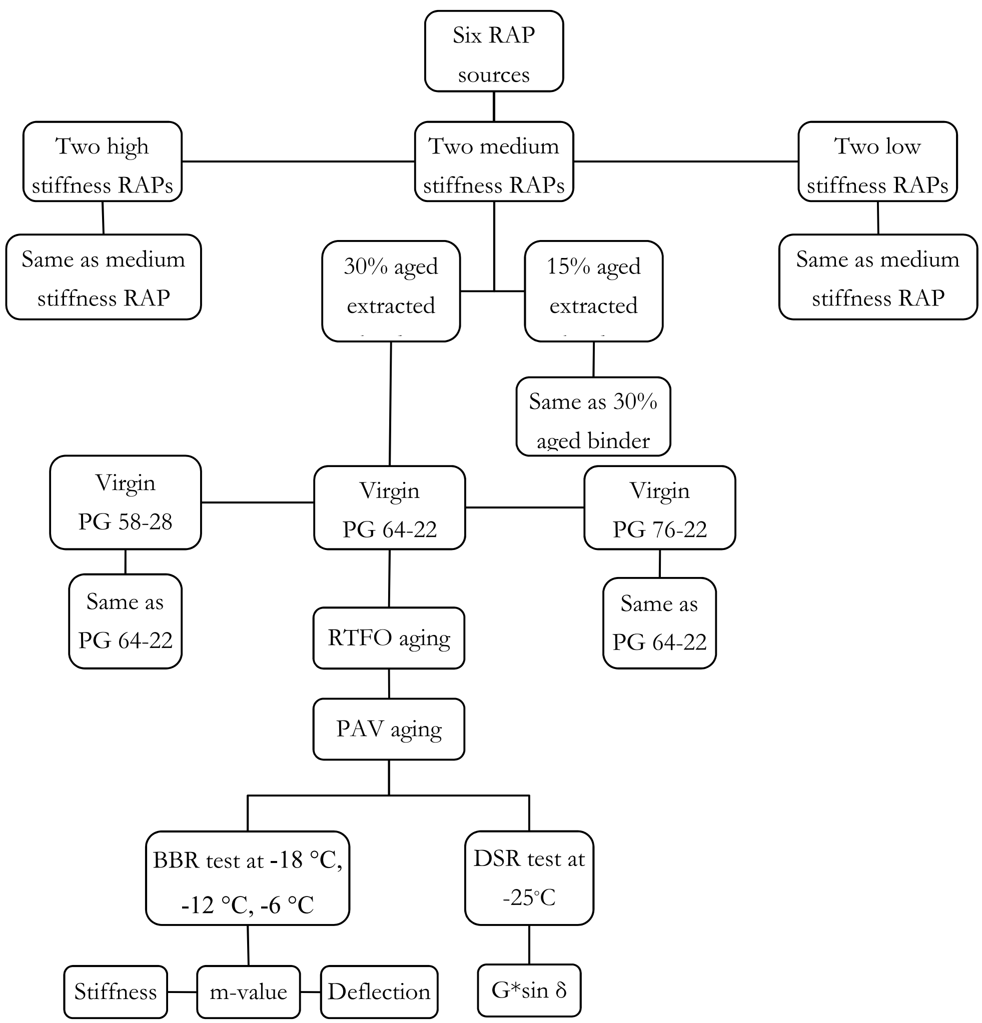


Figure 4-9: Low-Temperature Performance Tests of Extracted Aged Binders from RAP Mixed with Virgin Binders after Short-Term and Long-Term Aged Procedures

4.2.9 Low-Temperature Properties of Various Asphalt Mixtures Containing RAP

In this phase of the project, asphalt mixtures containing RAP were tested for low-temperature characteristics (Figure 4-10). Several existing and newly-developed testing procedures were used. The proposed testing procedures included Indirect Tensile Strength (ITS), Semi-Circular Bending (SCB) and modified ITS. The testing procedure were discussed and approved by the Steering Committee members.

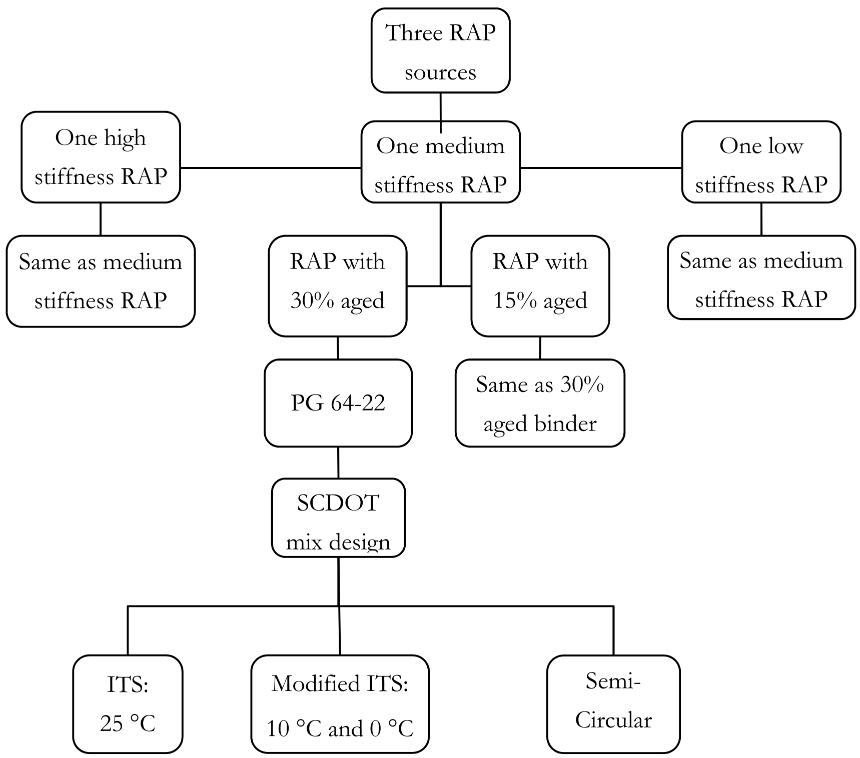


Figure 4-10: Low-Temperature Performance Tests of Mixtures with RAP

4.3 <u>Mix Design, ITS and SCB Sample Fabrications and Tests</u>

The mix design was a 12.5 mm mixture that satisfied the specifications set forth by the South Carolina Department of Transportation (SCDOT)) for a surface Type B mixture (N_{design} = 75). The design aggregate gradations for each mixture from various RAP sources are presented in Figure 4-11.

In this study, the optimum binder content (OBC) was defined as the amount of binder required to achieve 4.0% air voids. The optimized mix designs for these RAP mixtures are shown in Table 2. After the mix designs were completed, for each aggregate and RAP combination, four Superpave gyratory compacted specimens, 150mm in diameter and 95mm in height, were prepared with 7 ± 1% air voids and then the samples were tested at 25 °C (77°F) to determine the indirect tensile strengths. Two of the samples were tested in dry condition and the other two in wet condition as per the SCDOT procedure for determining the moisture susceptibility (SC T 70).

In addition, one set of ITS sample were conditioned at 10 °C for 24 hours and then were stored at a room temperature of 25 °C for another 4 hours. These conditioned samples were put into a hot water tank at 60 °C for 24 hours, and then 2 hours conditioning at water tank of 25 °C before testing. Similar procedures were followed to condition another set of samples at 0 °C. A total of 72 ITS samples were tested to obtain the ITS and TSR values at three conditions.

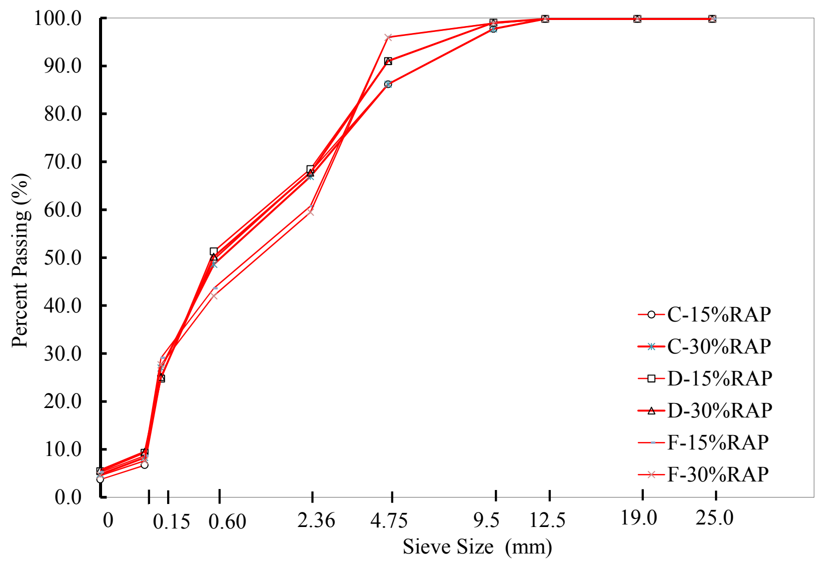


Figure 4-11: Gradations of Various Mixtures

Additionally, the semicircular bending (SCB) test method was used to determine the fracture energy of various mixtures. This test takes advantage of the simple specimen preparation from Superpave Gyratory compacted (SGC) cylinders and the simple loading setup. Three SGC specimens with 7 ± 1% air void were prepared according to AASHTO T 312. From the center of each 115 ± 5 mm tall specimen, a cylindrical slice that is 25 mm ± 2 mm thick is obtained. The slice was cut in two identical "halves" and then a notch was cut along the axis of symmetry of each half that was 15 ± 0.5 mm in length and no wider than 1.5 mm. A schematic of the test set-up is shown in Figure 4-12. The detailed process can be found from AASHTO Provisional standard: Determining the Fracture Energy of Asphalt Mixtures Using the Semi Circular Bend Geometry (SCB).

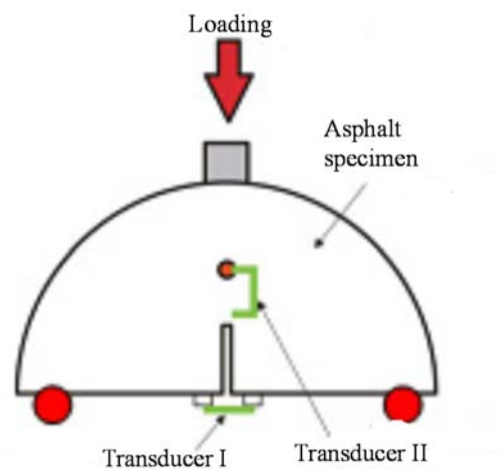


Figure 4-12: SCB Test Schematic

5 BBR Results for Unburned and Burned RAP

5.1 The Modified Binder of RAP Mortar Mixed with Virgin Binder

5.1.1 Stiffness Values and M-Values of the Modified Binders

The Bending Beam Rheometer (BBR) test offers a measure of low temperature stiffness and relaxation properties of an asphalt binder. The tested parameters can provide an indication of an asphalt binder's ability to resist low temperature cracking. The BBR test is typically used to determine an asphalt binder's creep stiffness as a function of time, which is a measure of the thermal stresses in the asphalt binder resulting from thermal contraction. If these stresses are too great, cracking will occur in asphalt pavement. A higher creep stiffness value indicates higher thermal stresses. The key reporting values are creep stiffness values at 60 seconds and the slope of the master stiffness curve at 60 seconds, commonly referred to as the "m-value".

Three virgin binders (PG 58-28, PG 64-22, and PG 76-22) were blended with three percentages of 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). Most of the test results are shown in the following figures.

As shown in Figure 5-1, at -6 °C, it can be observed that, as expected, the stiffness values of virgin binders with RAP mortars 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 modified binders blended from virgin PG 58-28 binders and RAP mortar could not be obtained because these binders were too soft at the testing temperature of -6 °C. As shown in Figure 5-1, it can be found that a higher percentage of aged binder results in a higher stiffness value and a lower m-value regardless of test time and RAP source. Meanwhile, when comparing the stiffness values and m-values of RAP sources A-F, it is noted that these values are significantly different at a same test time. Obviously, the reason is that the aged binders from all RAP sources vary to some extent.

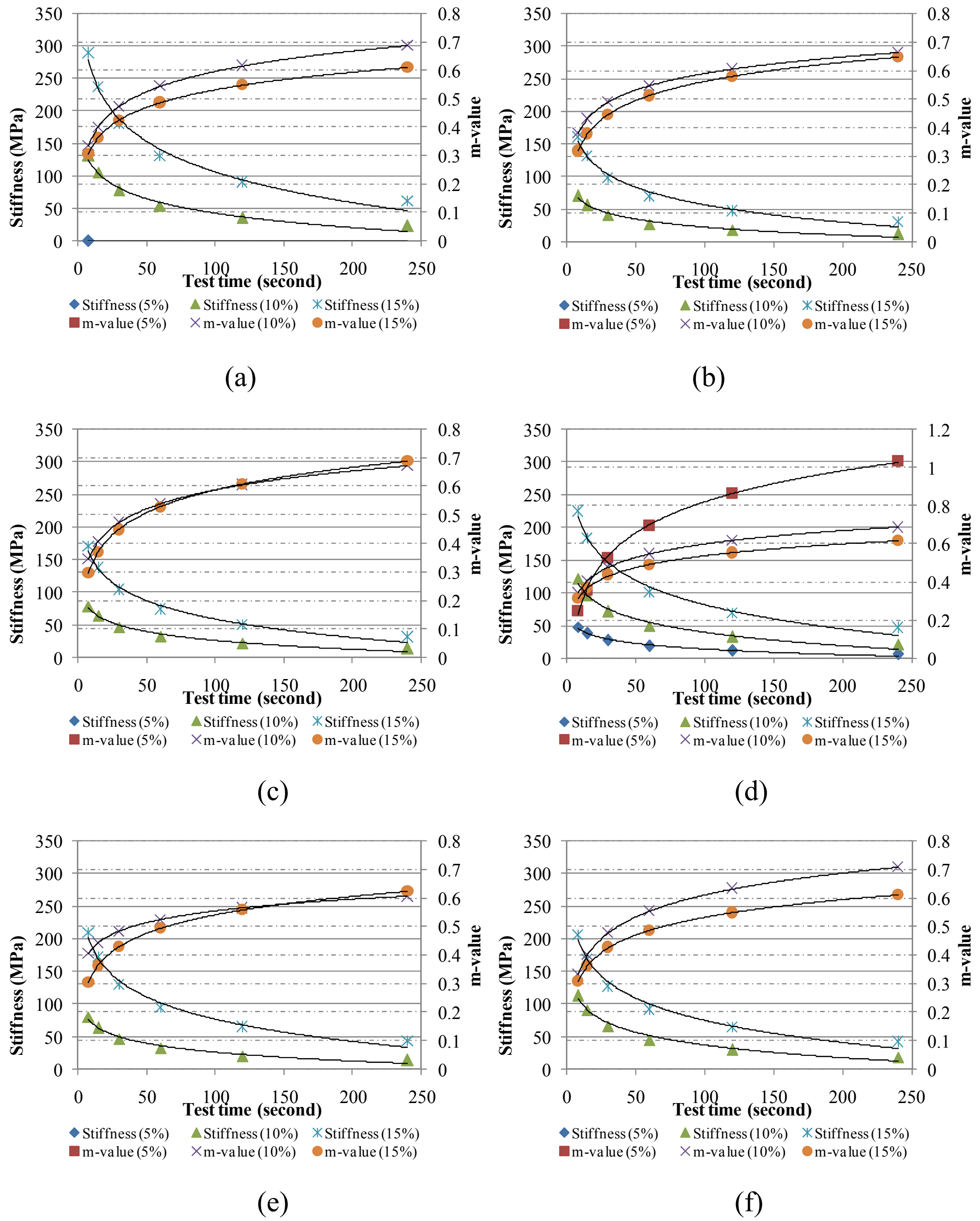


Figure 5-1: Stiffness and m-values of RAP sources A-F modified with virgin binder PG 58-28 at -6 ºC

The stiffness and m-values of the modified binders blended with PG 64-22 virgin binders and aged binders are shown in Figure 5-2. Similar to Figure 5-1, stiffness and m-values of the modified binders are following logarithmic trends regardless of RAP source. Similarly, the stiffness values reduced and m-values increased when the test time increased. Apart from the materials used shown in Figure 5-1, all modified binders are stiff enough to be tested in BBR. In addition, these stiffness values are generally greater than those values from the modified binders blended with PG 58-28.

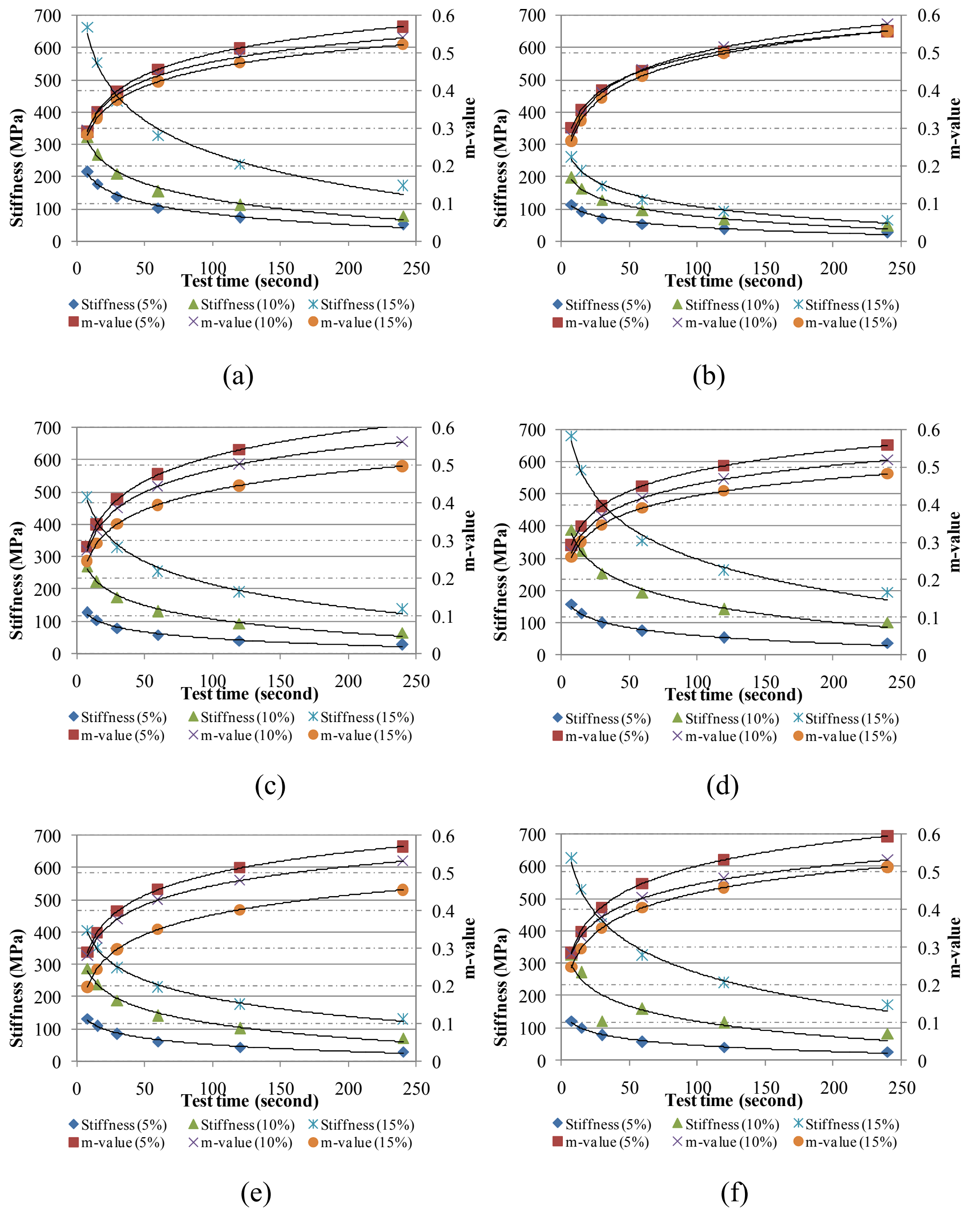


Figure 5-2 Stiffness and m-values of RAP sources A-F modified with virgin binder PG 64-22 at -6 °C

Figure 5-3 shows the stiffness and m-values of the modified binders blended with PG 76-22 virgin binders and aged binders. Similar to Figure 5-1, stiffness and m-values of the modified binders are following logarithmic trends regardless of RAP source. Also, the stiffness values reduce and m-values increase when the test time increases.

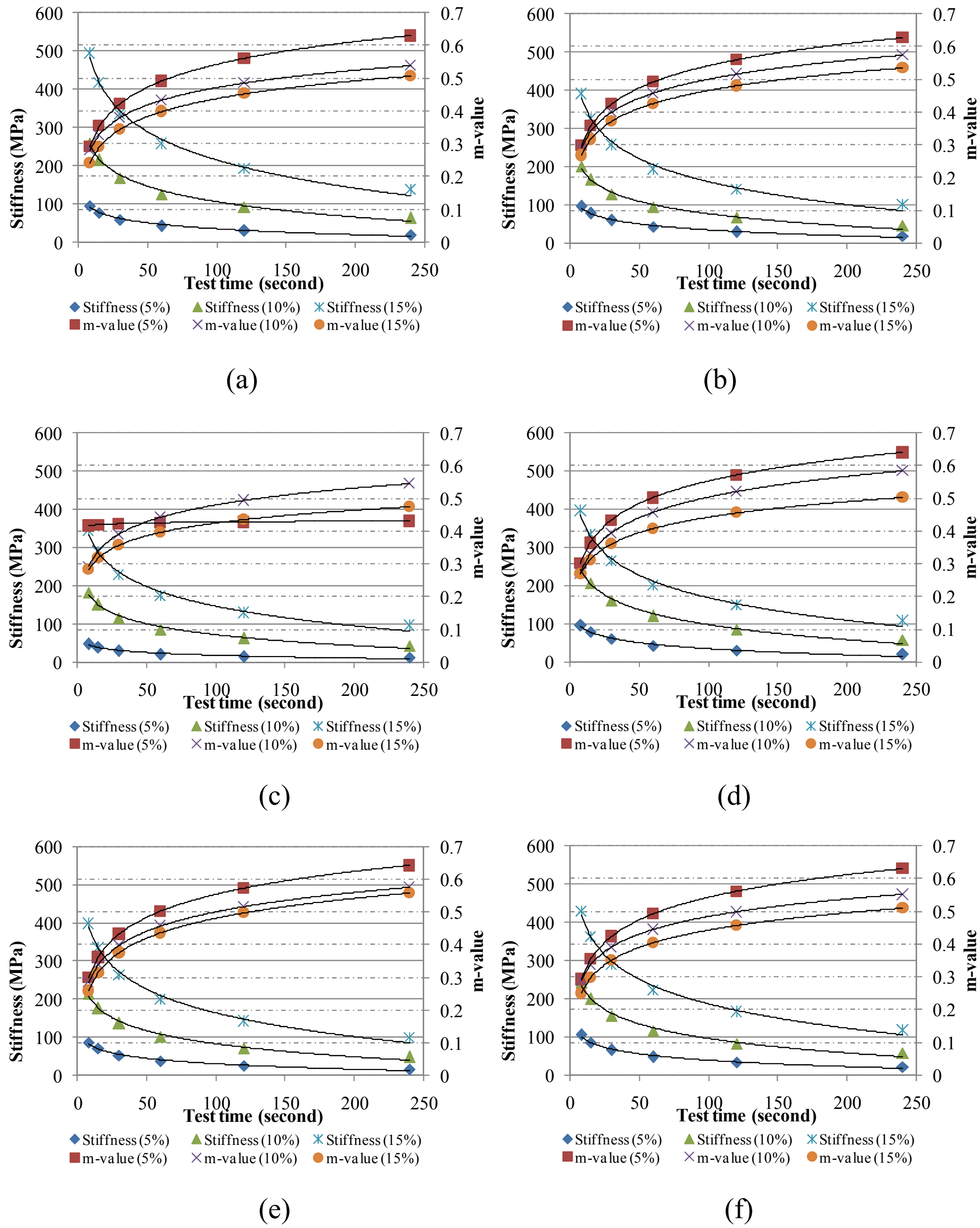


Figure 5-3 Stiffness and m-values of RAP sources A-F modified with virgin binder PG 76-22 at -6 °C

Other stiffness and m-values of the modified binders mixed with RAP mortars (A-F) and virgin binders (PG 58-22, PG 64-22, and PG 76-22) at -12 °C and -18 °C are presented in Appendix A. Generally, similar trends can be found regardless of RAP source, binder grade, and test temperatures used in this study.

5.1.2 Low Temperature Determinations of the Modified Binders Based on Stiffness and M-Values

The Superpave requirement for low temperature cracking of asphalt binder is based on the concept of a critical cracking temperature, which is that temperature below that cracking will occur as a result of a single cooling cycle. Therefore, when the asphalt binder reaches a critical stiffness value, cracking should occur. This temperature is called the limiting stiffness temperature.

The Superpave Binder Specification uses BBR to measure the stiffness of an asphalt binder at specified temperatures. The temperature at which the binder's stiffness exceeds 300 MPa is defined as the limiting stiffness temperature. In addition, to address varying 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 the controlling value for determining the limiting stiffness temperature. Determining the limiting stiffness of the binder has been made easy with the use of BBR.

Figure 5-4 shows the minimum low temperatures at a certain stiffness, 300 MPa, of various modified binders mixed with RAP mortar and virgin binder PG 58-22. It can be noted that an increase in test temperature reduces the stiffness value of modified binders. In addition, a higher aged binder significantly has a greater stiffness value regardless of test temperature and RAP source. Meanwhile, it can be seen that, regardless of RAP source, the modified binders containing 5% aged binder have stiffness values less than 300 MPa at the lowest temperature of -18 °C used in this study. Therefore, it could be concluded that the low temperature susceptibility of these binders are definitely less than -18 °C. Based on the Superpave binder specification, the low temperature grade should be less than -28 °C.

Additionally, Figure 5-4 indicates that, generally, when the binders were modified with 10% aged binder and they have a stiffness value of 300 MPa, their corresponding low temperatures are typically less than -12 °C. However, when the used aged binder was greater than 15%, the low temperature was usually greater than -12 °C.

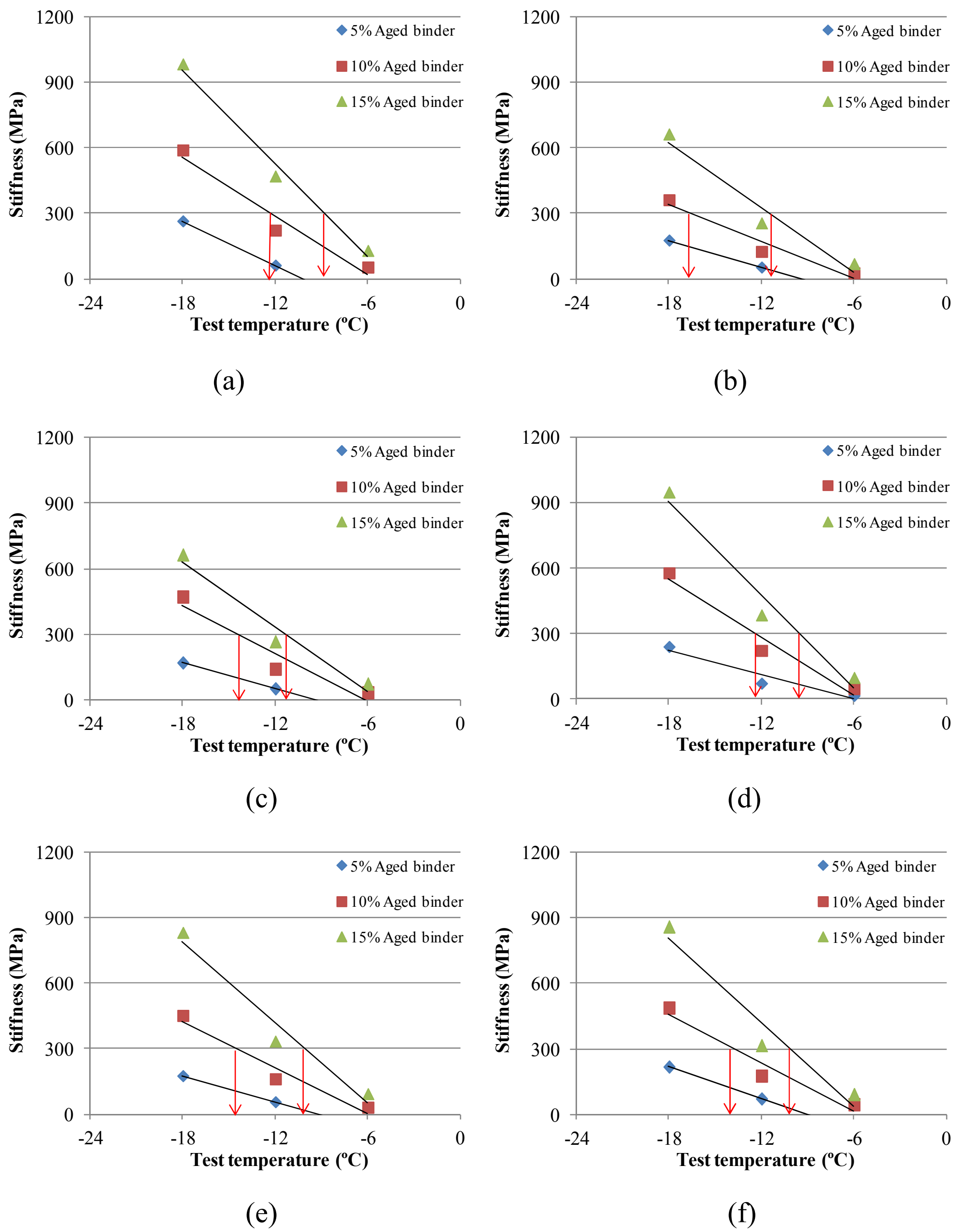


Figure 5-4: Low temperature determinations of RAP sources A-F with virgin binder PG 58-22 in terms of stiffness

The minimum low temperatures at a stiffness equaling to 300 MPa of various modified binder mixed with virgin binder PG 64-22 and different RAP sources are shown in Figure 5-5. Similar to Figure 5-4, a higher temperature results in a higher stiffness value. In addition, a higher aged binder content also leads to a higher stiffness regardless of RAP source and test temperature. However, it can be noted that the modified binders with 5% aged binders generally have a low temperature greater than -18 °C, with a stiffness equaling 300 MPa.

In addition, Figure 5-5 shows that the modified binders mixed with 10% aged binder and PG 64-22 binder generally have the low temperatures greater than -12 °C, which is higher than those modified binders mixed with PG 58-22 binder containing same percentage of aged binder. Moreover, when the modified binders blended with 15% aged binder, their low temperatures are close to -6 °C. This significantly affects the application scopes of these modified binders due to a high risk to low temperature cracking.

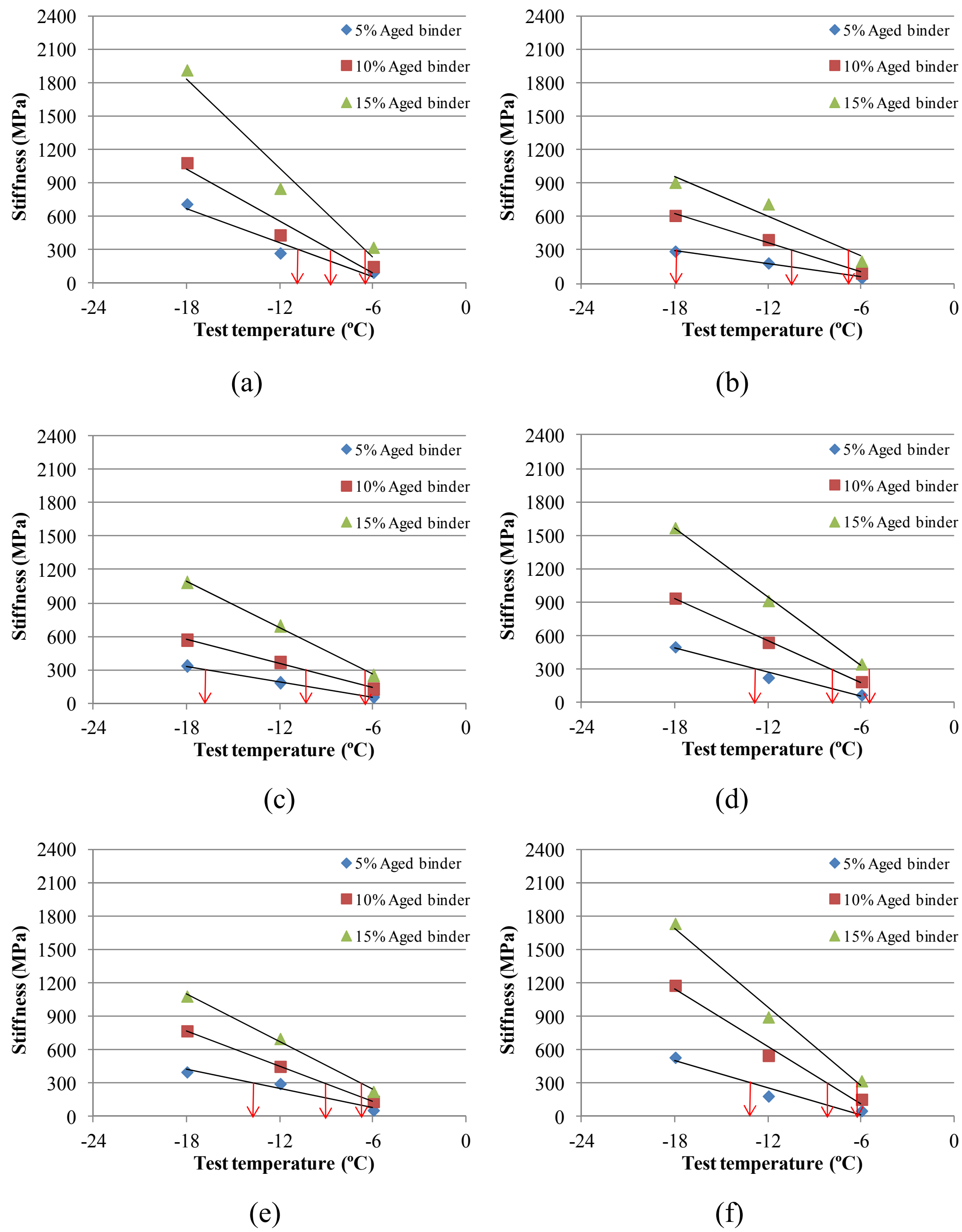


Figure 5-5: Low temperature determinations of RAP sources A-F with virgin binder PG 64-22 in terms of stiffness

The stiffness values of modified binders mixed with aged binder and PG 76-22 virgin binder at different test temperatures are shown in Figure 5-6. Similar to Figure 5-4 and Figure 5-5, an increased in test temperature results in a reduction of stiffness, but an increased aged binder content leads to an increase of stiffness regardless of RAP source.

From these stiffness values, it can be observed that the minimum low temperatures at a stiffness of 300 MPa of various modified binders generally are higher than -18 °C when 5% aged binder was used. All the modified binders containing 10% aged binders typically had temperatures greater than -12° C. Additionally, the low temperatures are higher than -18 °C but less than -18 °C when the blended modified binders included 15% aged binder.

The low temperature determination of the modified binders mixed with various RAP sources and PG 58-28 with respect to m-values are shown in Figure 5-7. It can be observed that the m-values are greater than 0.300 at temperatures greater than -18 °C regardless of RAP source and aged binder content because the virgin binder PG 58-28 is generally quite soft.

As shown in Figure 5-8, the modified binders mixed with various RAP sources and PG 64-22 with respect to m-values have m-values greater than 0.300 when the aged binder percentage is less than 5%, while in most cases the modified binders have m-values less than 0.300 if the aged binder is higher than 10%, and the minimum low temperatures are generally in the range of -12 °C to -18 °C.

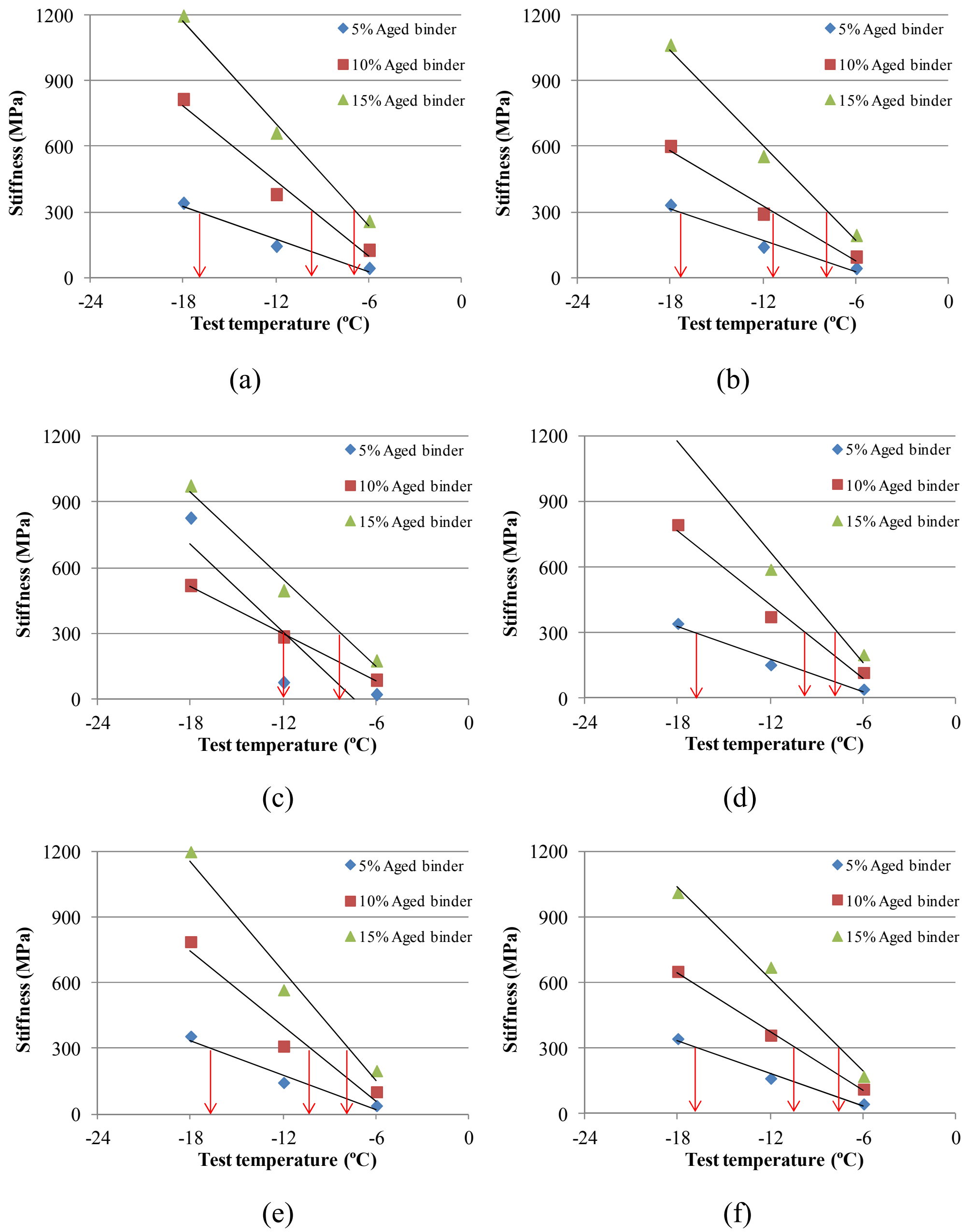
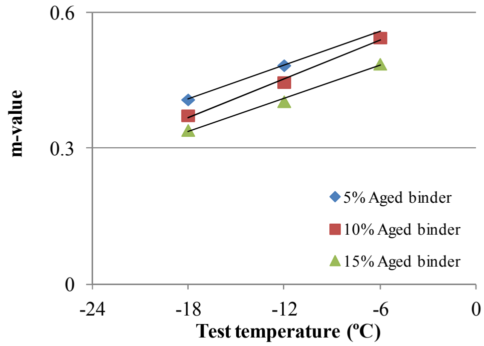
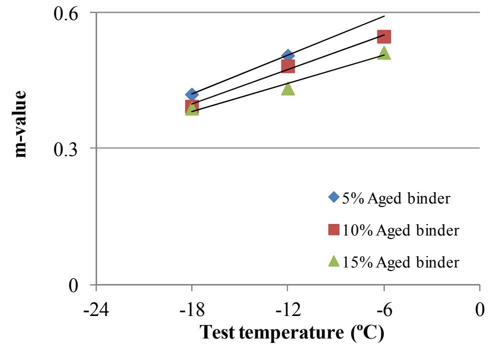


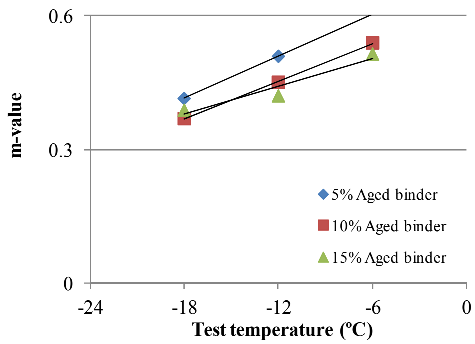
Figure 5-6: Low temperature determinations of RAP sources A-F with virgin binder PG 76-22 in terms of stiffness



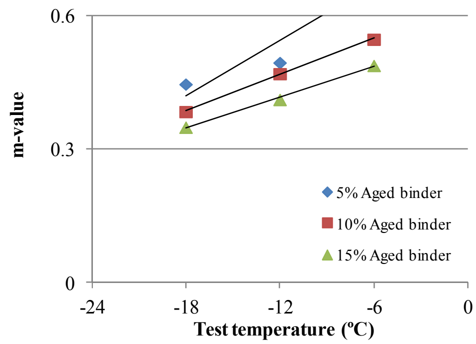
(a)



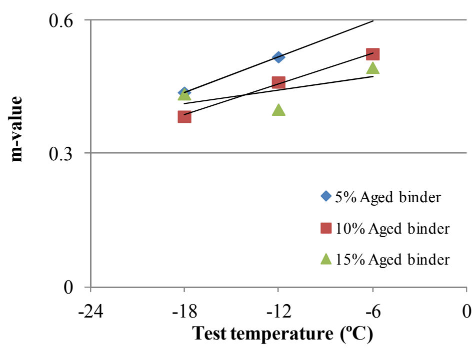
(b)



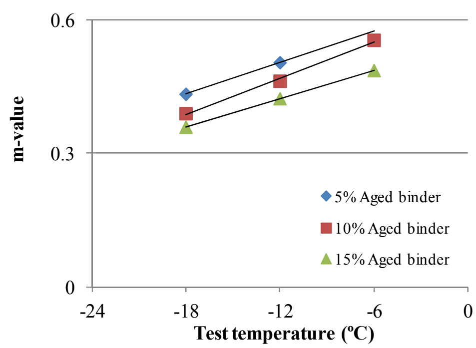
(c)



(d)



(e)



(f)

Figure 5-7: Low temperature determinations of RAP sources A-F with virgin binder PG 58-28 in terms of m-value

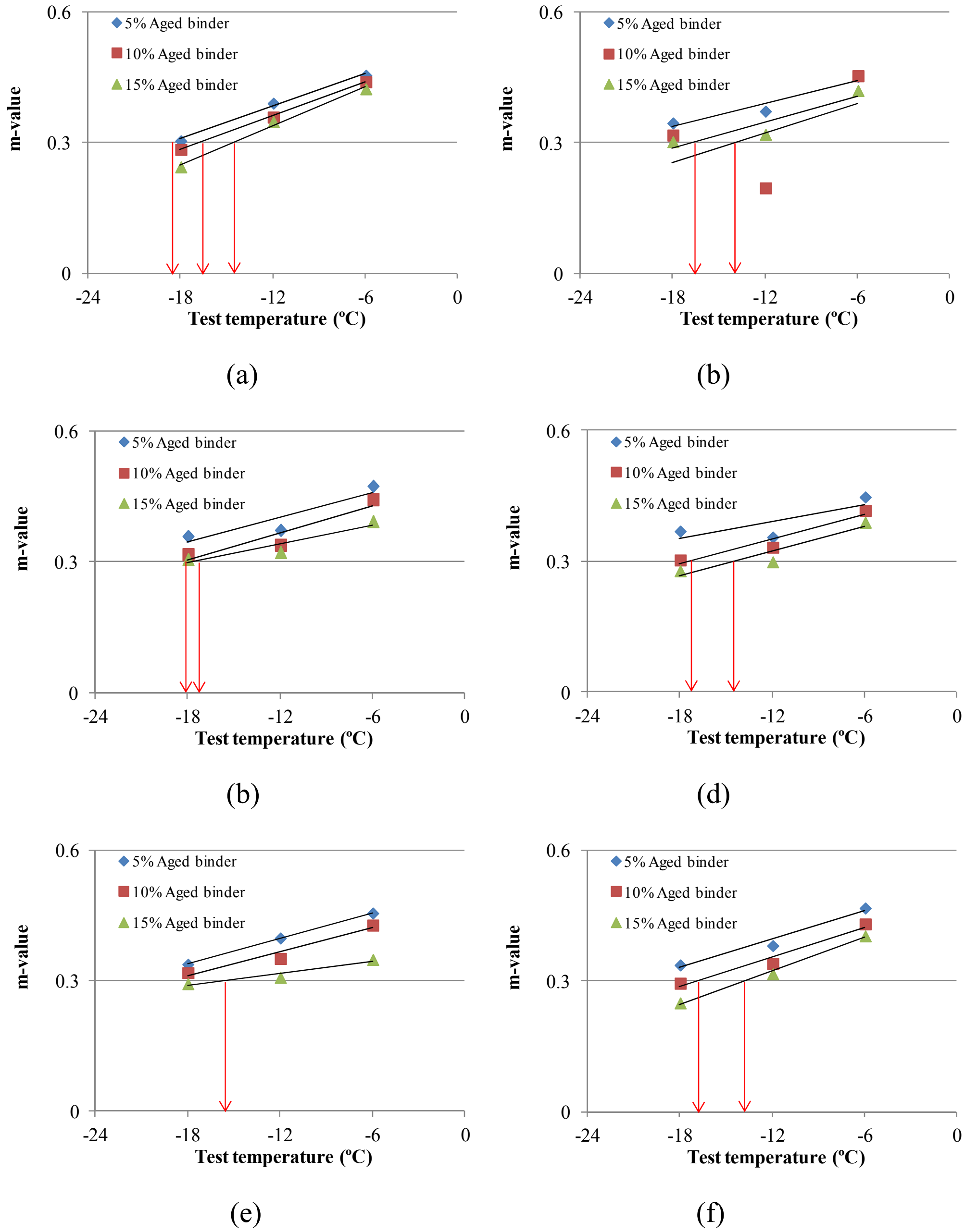


Figure 5-8: Low temperature determinations of RAP sources A-F with virgin binder PG 64-22 in terms of m-value

In Figure 5-9, it can be noted that m-values of the modified binders mixed with various RAP sources and PG 76-22 are generally greater than 0.300 at -18 °C when the aged binder percentage is less than 15%. All minimum low temperatures are less than -12 °C regardless of aged binder contents and RAP sources used in this study.

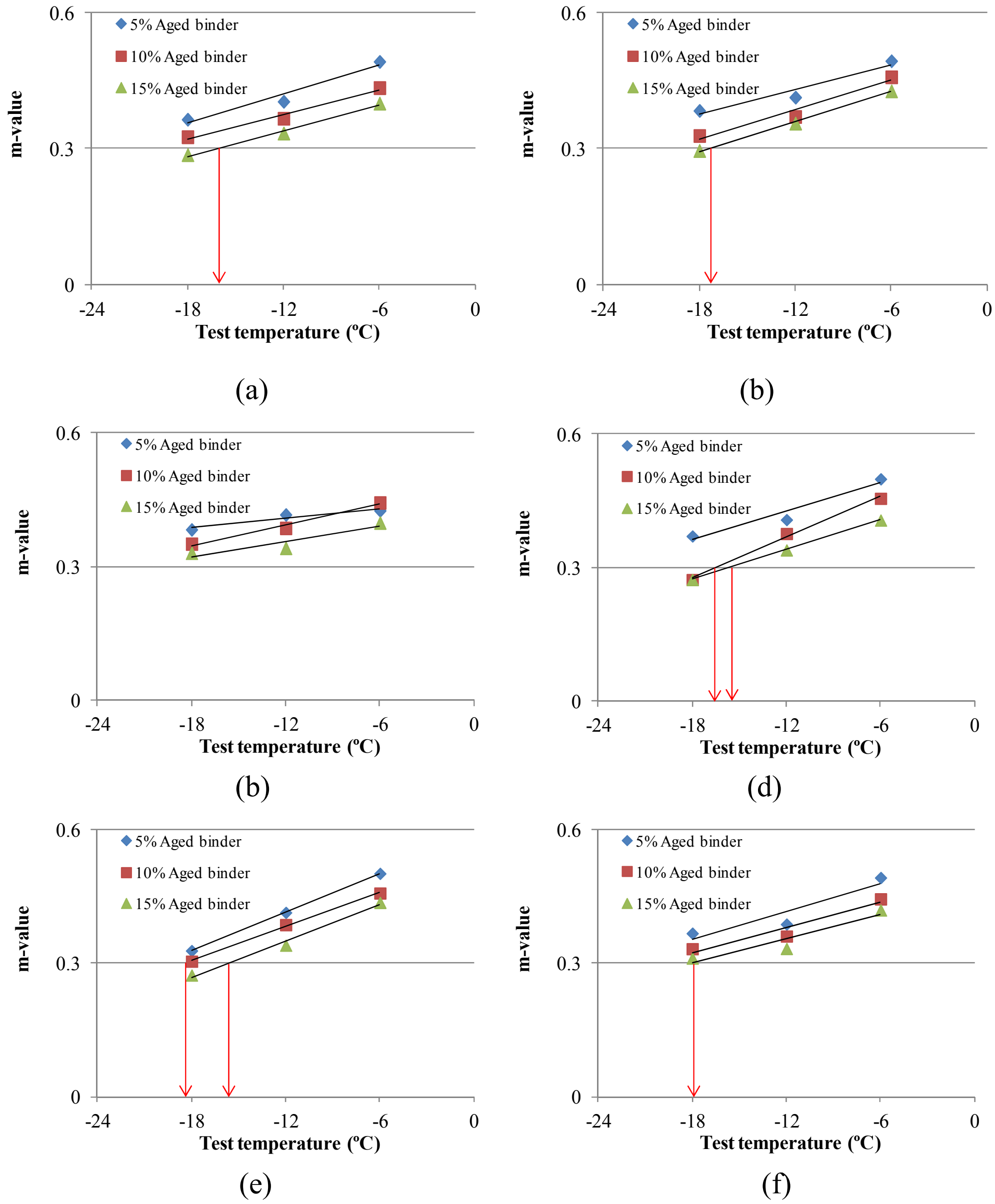


Figure 5-9: Low temperature determinations of RAP sources A-F with virgin binder PG 76-22 in terms of m-value

Table 5-1 to 5-3 show the minimum low temperature of various modified binders mixed with various RAP sources, aged binder contents, and virgin binder types. These values were obtained from stiffness and m value, derived from the conducted regression analysis. 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 5-1: Minimum low temperatures of RAP sources A-F mixed with virgin binder PG 58-28

RAP Source	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**

Table 5-2: Minimum low temperatures of RAP sources A-F mixed with virgin binder PG 64-22

RAP Source	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	-11.2	-8.8	-6.7	-18.4	-16.6	-14.5	**-11.2**	**-8.8**	**-6.7**
B	-17.9	-10.4	-6.9	-21.6	-14	-16.8	**-17.9**	**-10.4**	**-6.9**
C	-16.8	-10.3	-6.5	-21.9	-18.2	-17.5	**-16.8**	**-10.3**	**-6.5**
D	-13	-7.9	-5.6	<-24	-17.3	-14.6	**-13**	**-7.9**	**-5.6**
E	-13.8	-9.2	-6.8	-21.3	-19.2	-15.8	**-13.8**	**-9.2**	**-6.8**
F	-13.4	-8.2	-6.3	-20.7	-16.9	-13.8	**-13.4**	**-8.2**	**-6.3**

Table 5-3: Minimum low temperatures of RAP sources A-F mixed with virgin binder PG 76-22

RAP Source	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	-17.3	-9.7	-7.2	-23.4	-20.3	-16	**-17.3**	**-9.7**	**-7.2**
B	-17.6	-11.5	-7.9	<-24	-19.8	-17.4	**-17.6**	**-11.5**	**-7.9**
C	-11.8	-11.9	-8.3	<-24	-23.8	-21.3	**-11.8**	**-11.9**	**-8.3**
D	-16.9	-9.8	-7.8	-23.4	-16.6	-15.7	**-16.9**	**-9.8**	**-7.8**
E	-16.7	-10.2	-7.7	-19.7	-18.4	-15.8	**-16.7**	**-10.2**	**-7.7**
F	-16.6	-10.3	-7.5	-23.2	-20.1	-17.9	**-16.6**	**-10.3**	**-7.5**

5.2 The Modified Binder of RAP Mortar Mixed with RTFO Binder

5.2.1 Stiffness Values and M-Values of the Modified Binders during Test Duration

BBR test offers low temperature stiffness and m-value of an asphalt binder. The tested parameters have been described in previous section. This section presents the test results of the modified binders mixed with various RAP mortars and three short-term aged (RTFO) binders (PG 58-28, PG 64-22, and PG 76-22). The fabricated BBR samples were tested at three temperatures (-6 °C, -12 °C, and -18 °C). The main test results are shown in the following figures.

As shown in Figure 5-10, it can be observed that, at -6 °C, all modified binders mixed with RAP mortar and RTFO PG 58-28 binder show the increased m-values and the decreased stiffness values during a loading process. It is also noted that, as expected, RTFO binders with a higher aged binders from RAP mortar have a higher stiffness and a lower m-value followed logarithmic trends regardless of RAP source and test time. In addition, apart from the modified binders mixed with virgin binder PG 58-28, the modified binder with a 5% aged binder from RAP mortar mixed with RTFO binder can show a stiffness value and an m-value. Moreover, these stiffness values are significantly higher compared to those values of the modified binders mixed with virgin binder.

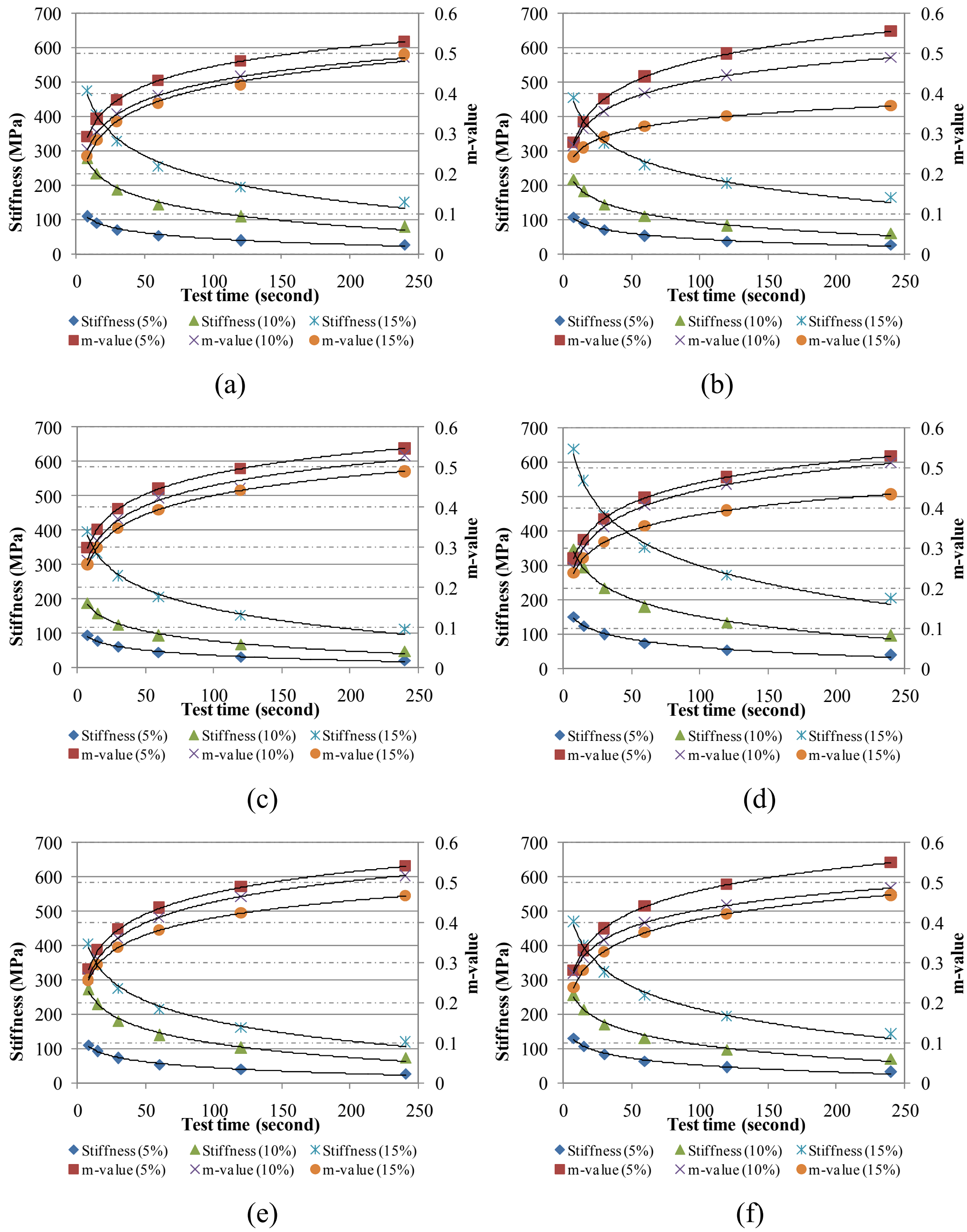


Figure 5-10: Stiffness and m-values of RAP sources A-F modified mixed with RTFO binder PG 58-28 at -6 ºC

Similar to Figure 5-10, Figure 5-11 indicates that all modified binders mixed with RAP mortar and RTFO PG 64-22 binder show the increased m-values and the decreased stiffness value, and these values are following logarithmic trends as well. Compared to the modified binders with RTFO PG 58-28 binders, these binders in Figure 5-11 show higher stiffness values and lower m-values since PG 64-22 generally has a higher stiffness value and a lower m-value at -6 °C after a short-term aging process.

Obviously, there are some differences in stiffness values and m-values between any two binders from various RAP mortars.

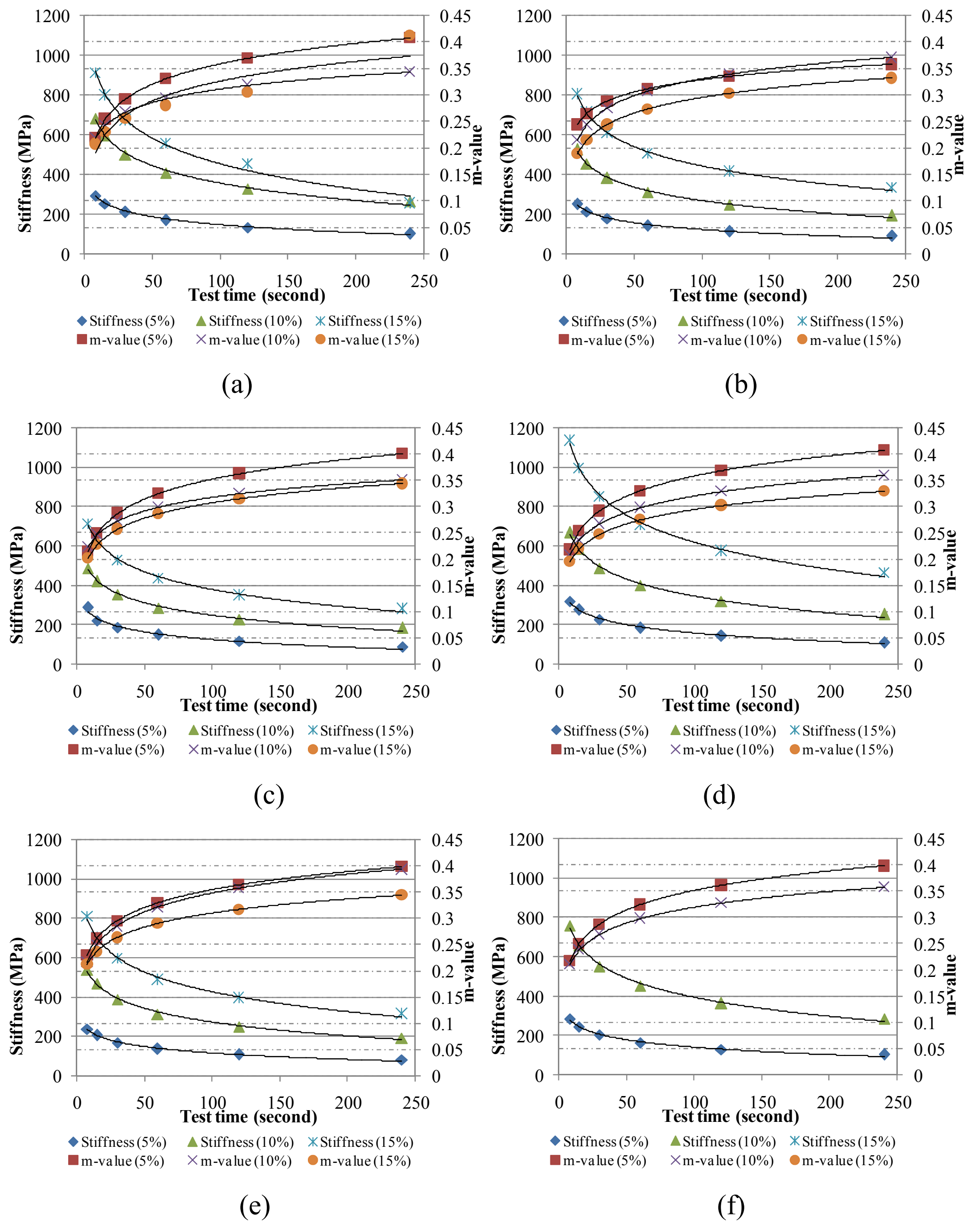


Figure 5-11: Stiffness and m-values of RAP sources A-F modified mixed with RTFO binder PG 64-22 at -6 °C

Figure 5-12 shows the stiffness and m-values of the modified binders blended with PG 76-22 RTFO binders and RAP mortars at -6 °C. Similar to Figure 5-11, stiffness and m-values of the modified binders are following logarithmic trends regardless of

RAP source. Also, the stiffness values were reduced and m-values increased when the test time increased. In addition, it can be noted that, compared to the stiffness values of the modified binders when mixed with RTFO aged PG 64-22 binders in Figure 5-11, some stiffness values are lower in Figure 5-12 even though RTFO aged PG 76-22 binders were used when compared to the same RAP source.

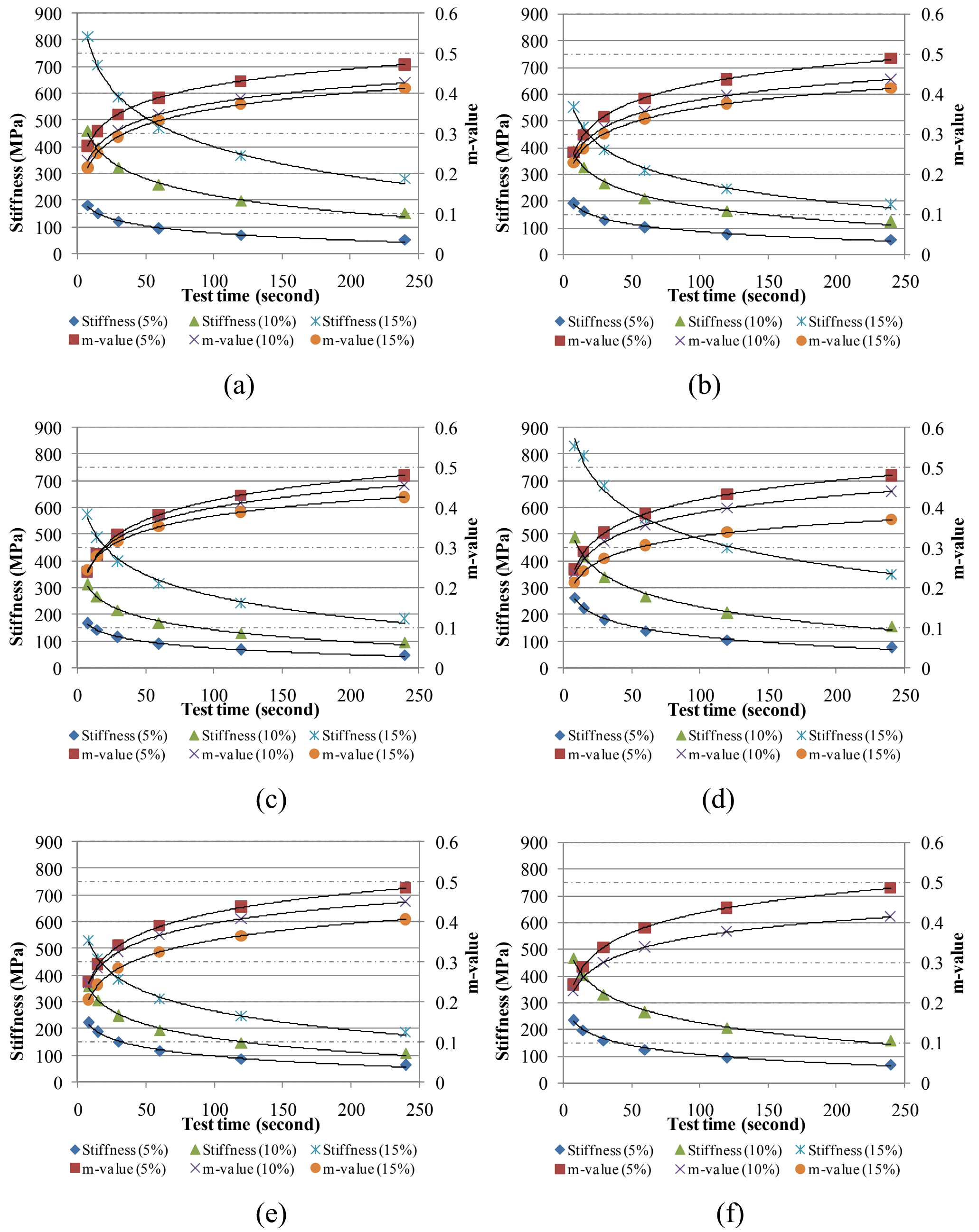


Figure 5-12: Stiffness and m-values of RAP sources A-F modified with RTFO binder PG 76-22 at -6 ºC

Other stiffness and m-values of the modified binders mixed with RAP mortars (A-F) and RTFO binders (PG 58-22, PG 64-22, and PG 76-22) at -12 °C and -18 °C are presented in Appendix B. In general, similar trends can be found regardless of RAP source, binder grade, and test temperature used in this study.

5.2.2 Low Temperature Determination of the Modified Binders Based on Stiffness and M-Values

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 low temperature determination of the modified binders mixed with various RAPs (A-F) and containing RTFO binders are summarized below.

In Figure 5-13, it can be found that the modified binders with a higher aged binder have a higher low temperature when their stiffness value is 300 MPa. In other words, the aged binder results in a higher stiffness regardless of RAP type. However, various modified binders generally have different low temperature values, depending on RAP type.

In addition, in terms of RTFO PG 64-22 binder, Figure 5-14 indicates that the modified binder with a lower percentage aged binder has a lower temperature when the stiffness value is 300 MPa. Similar to Figure 5-13, these low temperature determinations are dependent on RAP types. Compare to the modified binders with PG 58-22, these modified binders generally have higher stiffness values and thus some low temperature determinations are greater than -6 °C.

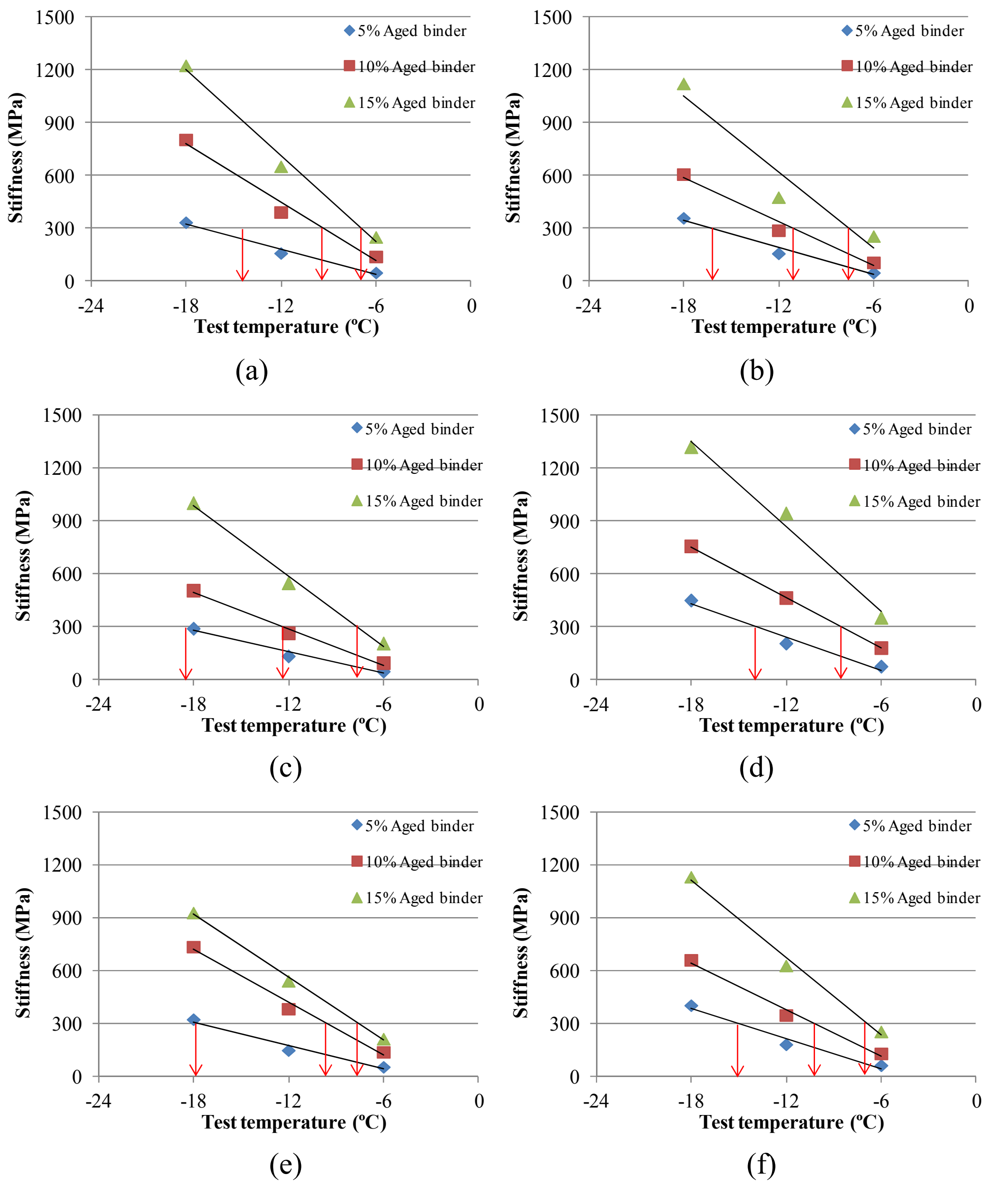


Figure 5-13: Low temperature determination of RAP sources A-F containing RTFO binder PG 58-22 in terms of stiffness

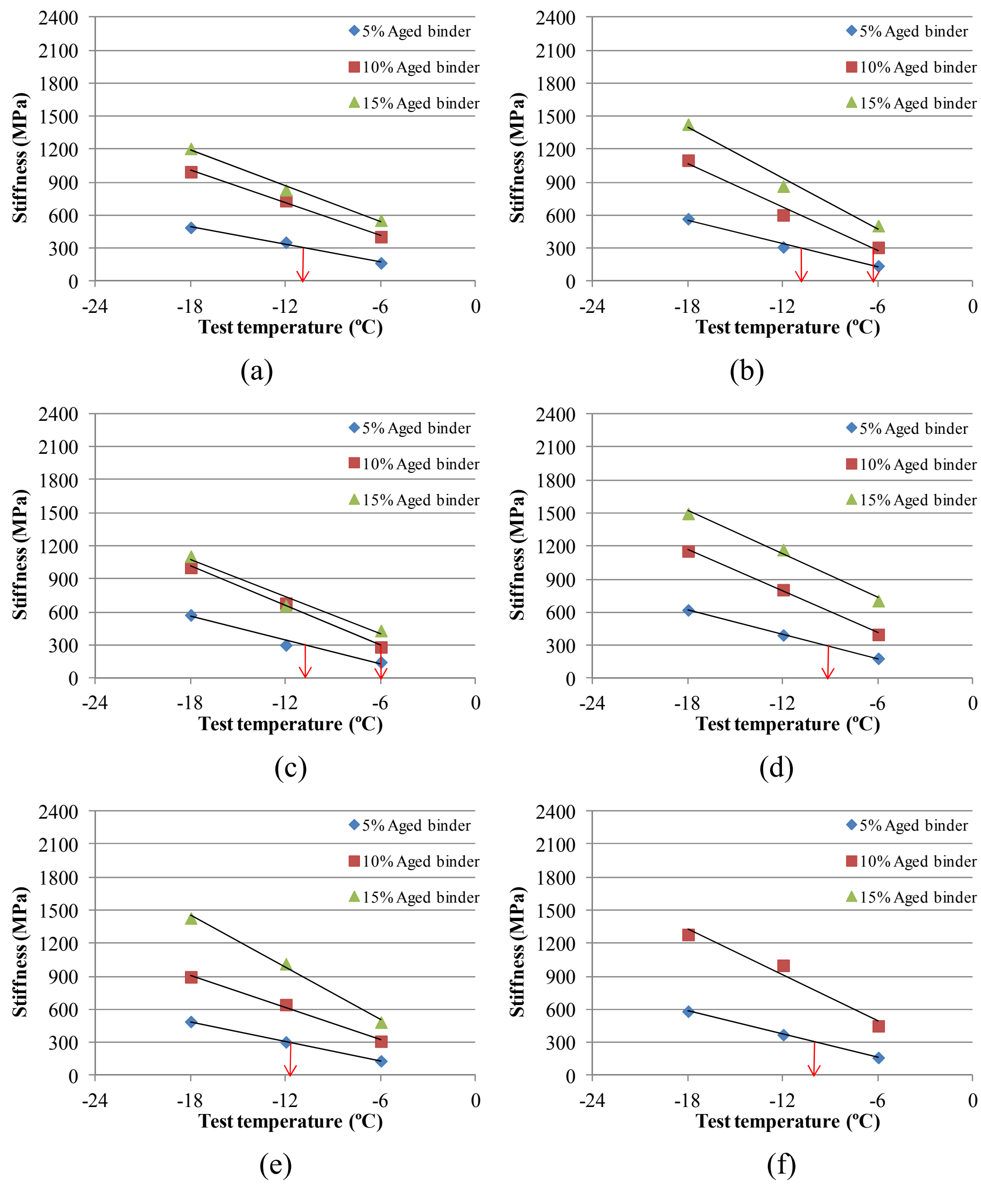


Figure 5-14: Low temperature determinations of RAP sources A-F mixed with RTFO binder PG 64-22 in terms of stiffness

Figure 5-15 shows that the modified binders mixed with RAP sources A-F mortar and mixed with RTFO PG 76-22 binders have similar trends as shown in Figure 5-13 and Figure 5-14. However, since PG 76-22 has a higher stiffness value compared to PG 58-28 and PG 64-22 binders, the modified binders containing RTFO PG 76-22 generally have higher stiffness values and result in higher low test temperatures (i.e., stiffness of 300 MPa).

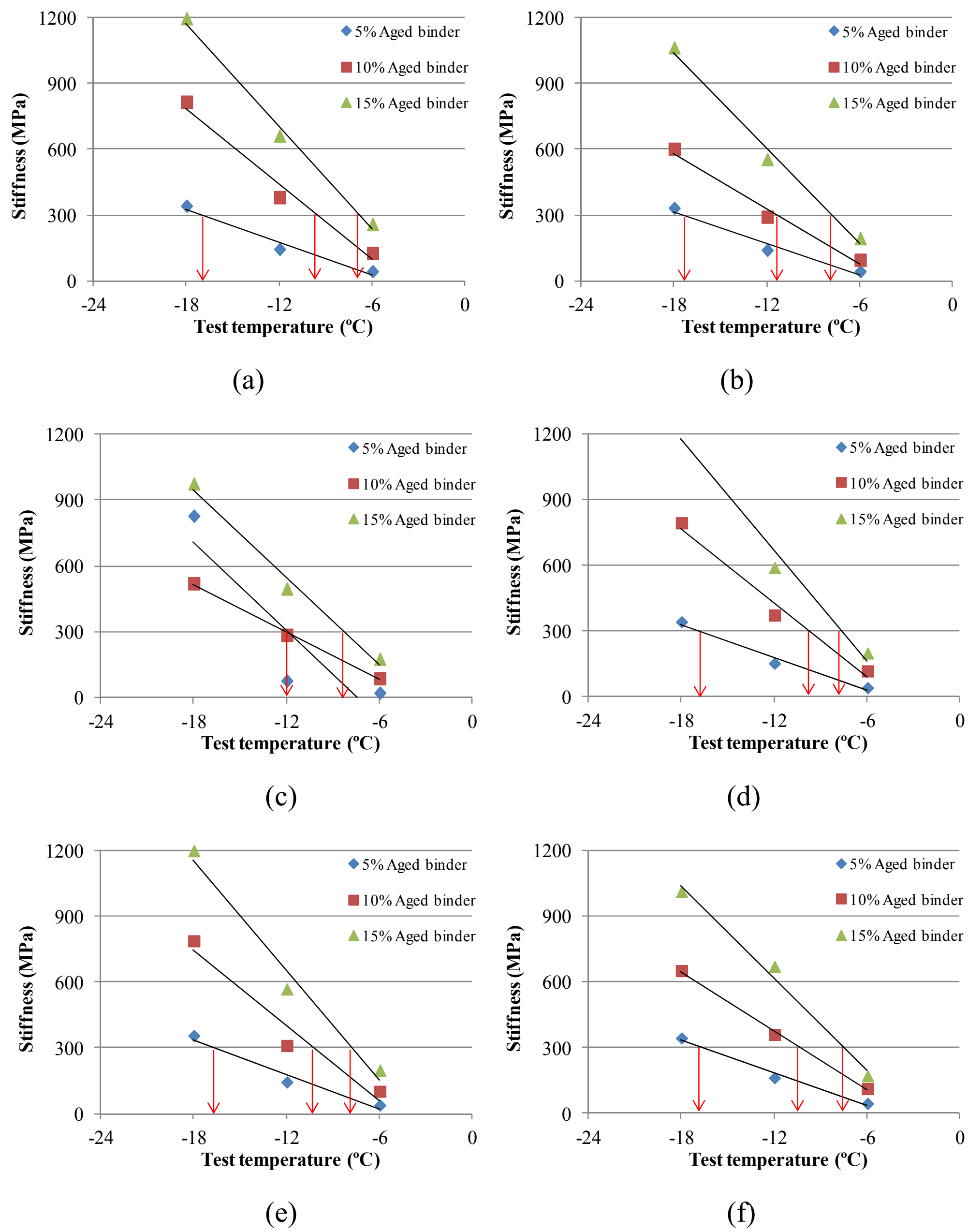


Figure 5-15: Low temperature determinations of RAP sources A-F with virgin binder PG 76-22 in terms of stiffness

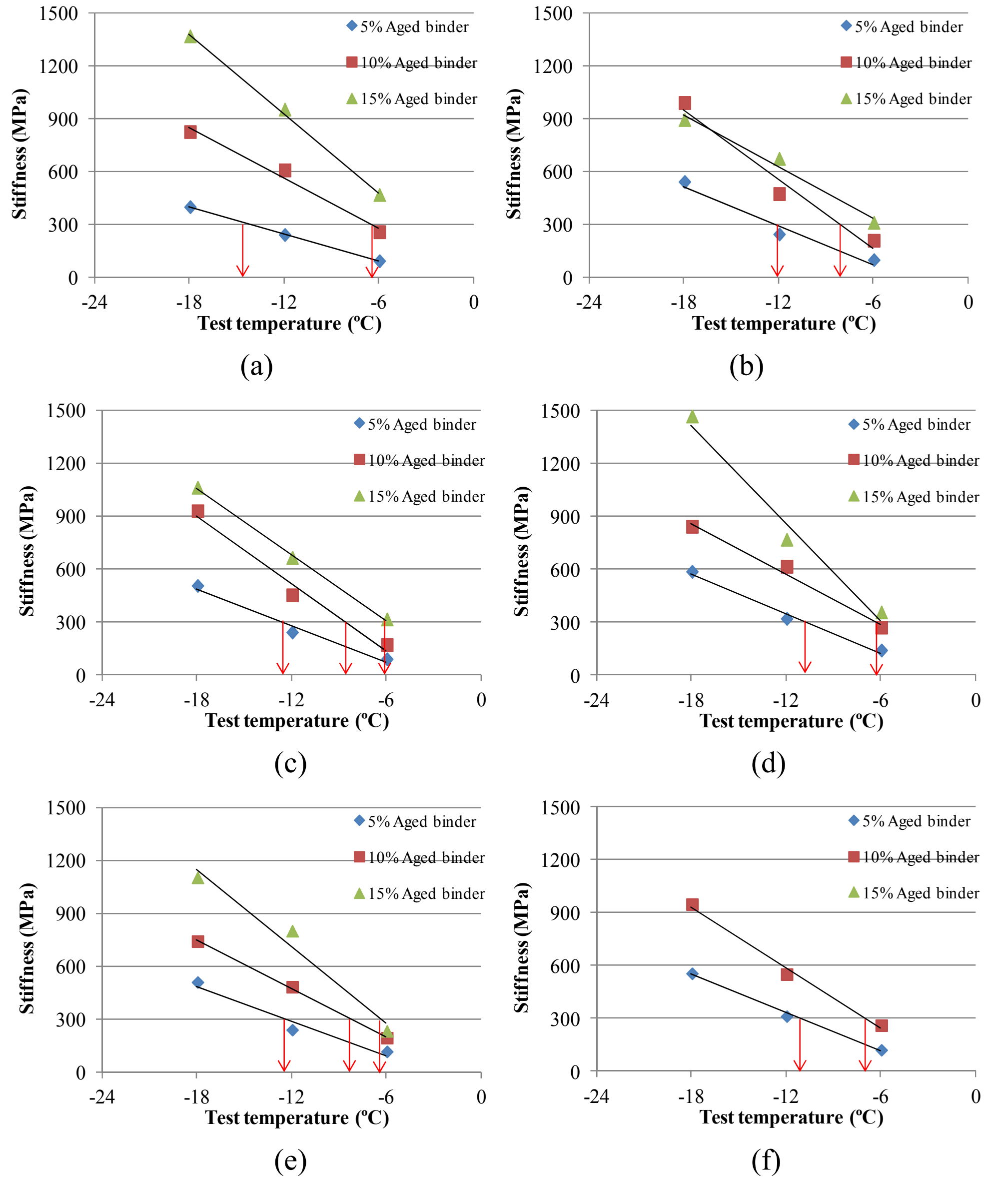


Figure 5-16: Low temperature determination of RAP sources A-F containing RTFO binder PG 64-22 in terms of stiffness

In accordance with m-values of the modified binders, it can be noted that, in Figure 5-17, in some cases, m-values are greater than 0.300 when the test temperature is lower than -18 °C. Therefore, these modified binders can resist a low temperature of -18 °C or even lower. In addition, it can be noted that, a higher aged binder results in a higher test temperature regardless of the RAP type. Similar trends can be found in Figure 5-18 and Figure 5-19, which included the modified binders mixed with RAP sources A-F and containing RTFO binders PG 64-22 and PG 76-22, respectively.

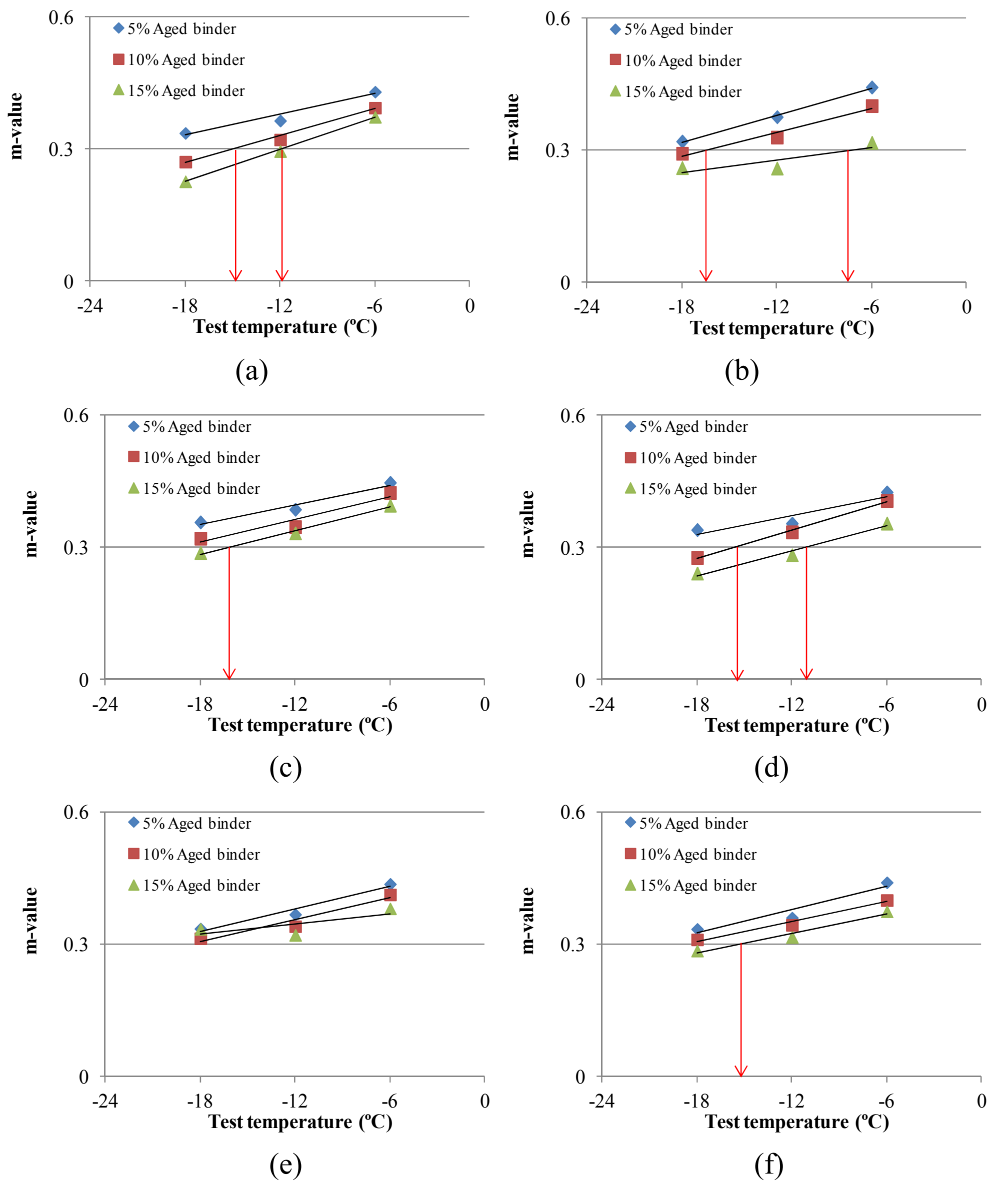


Figure 5-17: Low temperature determinations of RAP sources A-F with RTFO binder PG 58-22 in terms of m-value

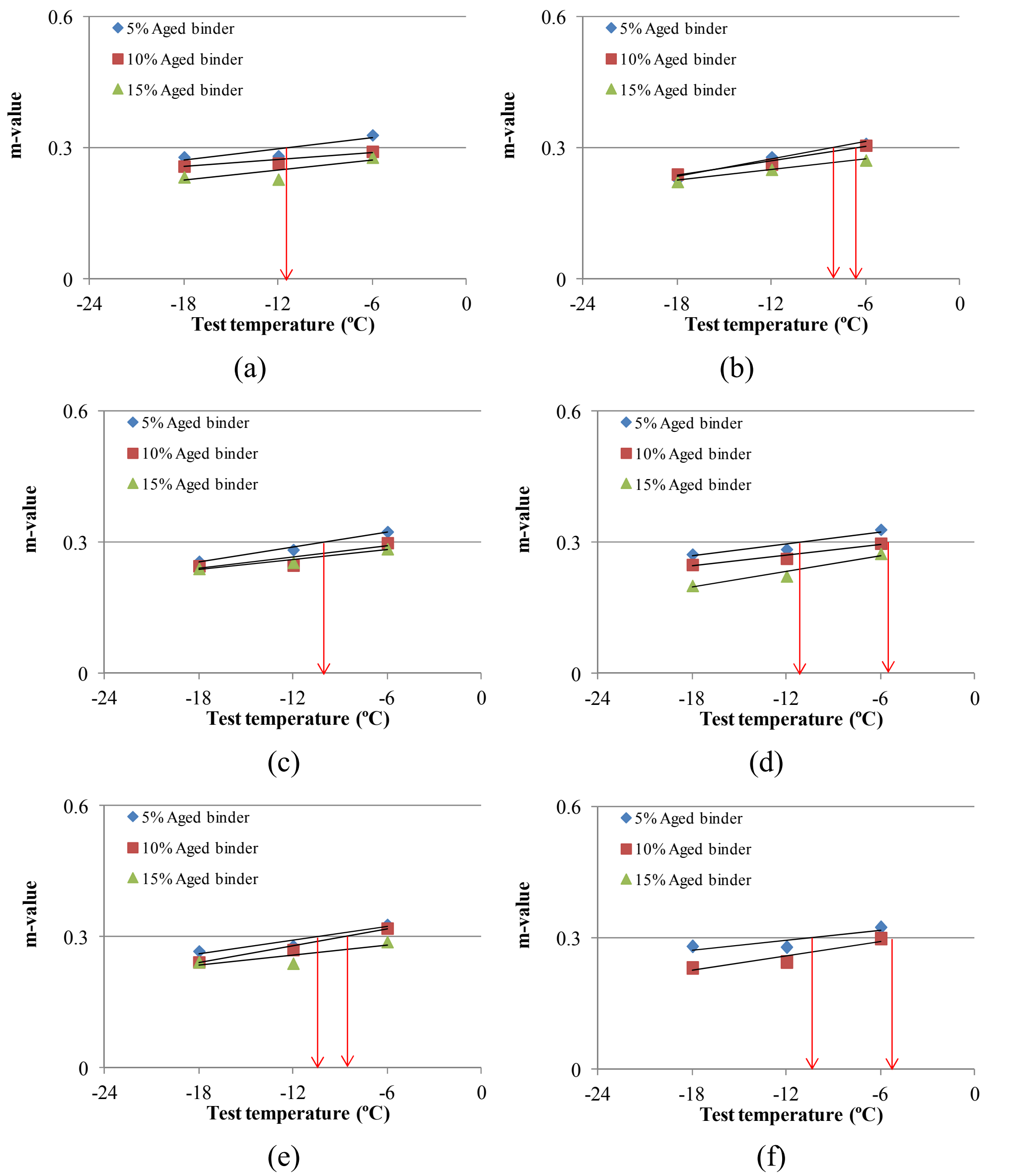


Figure 5-18: Failure temperature determination of RAP sources A-F containing RTFO PG 64-22 in terms of m-value

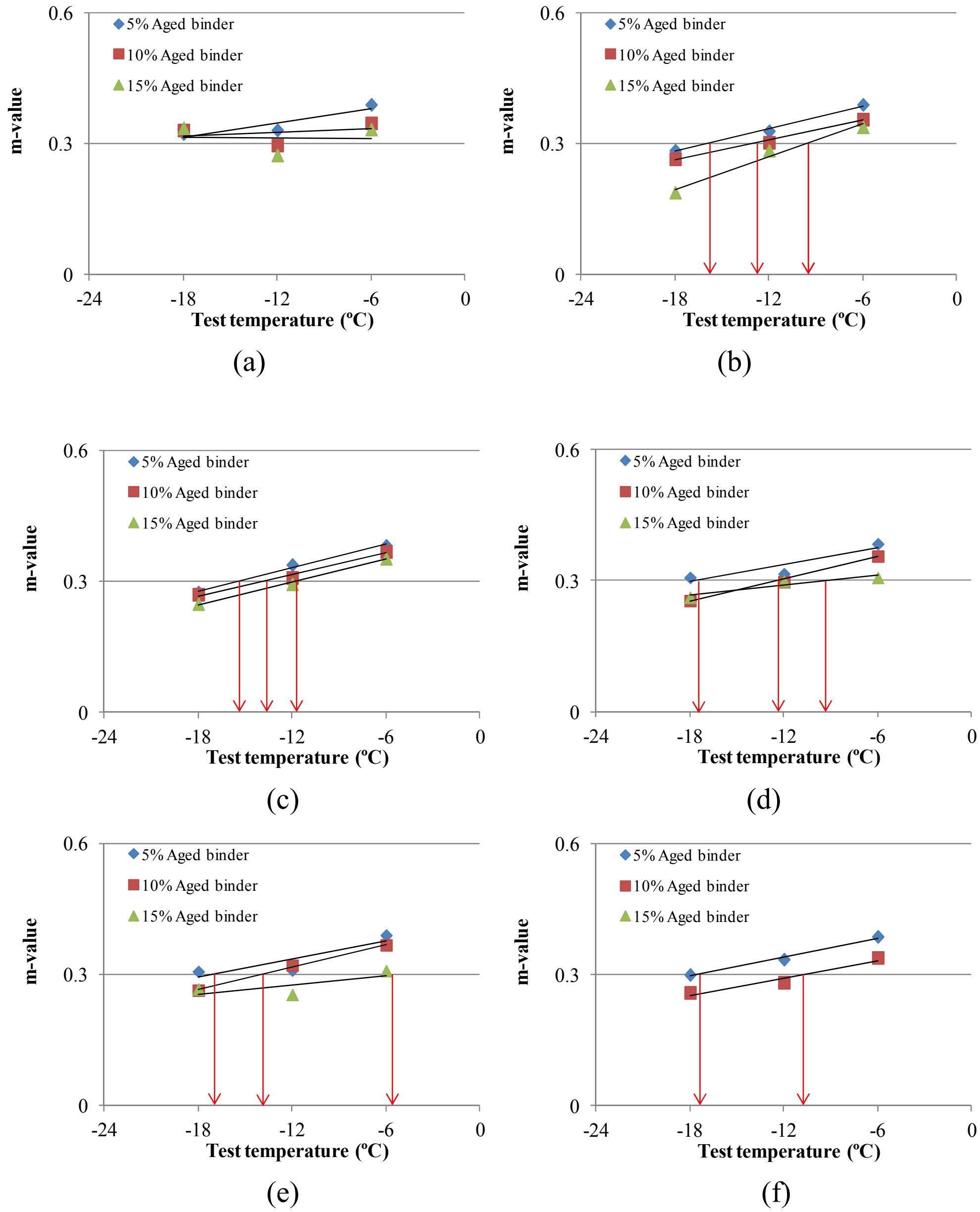


Figure 5-19: Failure temperature determinations of RAP sources A-F containing RTFO PG 76-22 in terms of m-value

The minimum low temperatures of various modified binders mixed with various RAP sources, aged binder contents, and RTFO binder types are shown in Table 5-4, Table 5-5 and Table 5-6, respectively. The low temperatures derived from the conducted regression analysis are summarized from stiffness 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 5-4: Minimum low temperatures of RAP sources A-F containing RTFO binder PG 58-28

RAP Source	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**

Table 5-5: Minimum low temperatures of RAP sources A-F containing RTFO binder PG 64-22

RAP Source	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	-10.9	-3.8	-1.7	-11.5	-3.7	1.2	**-10.9**	**-3.7**	**1.2**
B	-10.8	-6.3	-3.4	-8.1	-6.4	-0.3	**-8.1**	**-6.3**	**-0.3**
C	-10.9	-6	-4.2	-10.1	-4.5	-2.2	**-10.1**	**-4.5**	**-2.2**
D	-9.2	-4.1	0.6	-11.2	-5.7	-1.5	**-9.2**	**-4.1**	**0.6**
E	-11.8	-5.6	-3.5	-10.3	-8.5	-2	**-10.3**	**-5.6**	**-2**
F	-10.1	-3.2	-	-10.3	-5.4	-	**-10.1**	**-3.2**	**-**

Table 5-6: Minimum low temperatures of RAP sources A-F containing RTFO binder PG 76-22

RAP Source	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	-14.2	-6.4	-3.9	-20.1	<-24	<-24	**-14.2**	**-6.4**	**-3.9**
B	-12.1	-8.2	-5.3	-15.8	-12.9	-9.5	**-12.1**	**-8.2**	**-5.3**
C	-12.6	-8.7	-6.1	-15.4	-13.7	-11.8	**-12.6**	**-8.7**	**-6.1**
D	-10.9	-6.5	-5.8	-17.5	-12.4	-9.5	**-10.9**	**-6.5**	**-5.8**
E	-12.4	-8.3	-6.3	-17.2	-13.9	-5.8	**-12.4**	**-8.3**	**-5.8**
F	-11.3	-7.1	-	-17.6	-10.8	-	**-11.3**	**-7.1**	**-**

5.3 The Modified Binder of RAP Mortar Mixed with PAV Binder

5.3.1 Stiffness and M-Values of the Modified Binders during Test Duration

As shown before, the summarized figures present the stiffness and m-values of the modified binders mixed with RAP sources A-F and PAV aged binders. These values are shown in the following figures. Figure 5-20 shows the stiffness and m-values of the modified binders with PG 58-28. As mentioned before, the aged binder concentration and RAP sources affect the stiffness and m-values. In addition, Figure 5-21 shows the stiffness and m-values of the modified binders with PAV binder PG 62-22. The stiffness and m-values of the modified binders with RAP sources A-F and PAV binder PG 76-22 are shown in Figure 5-22.

Other stiffness and m-values of the modified binders mixed with RAP mortars (A-F) and PAV binders (PG 58-22, PG 64-22, and PG 76-22) at -12 °C and -18 °C are presented in Appendix C. Generally similar trends can be found regardless of RAP source, binder grade, and test temperature used in this study.

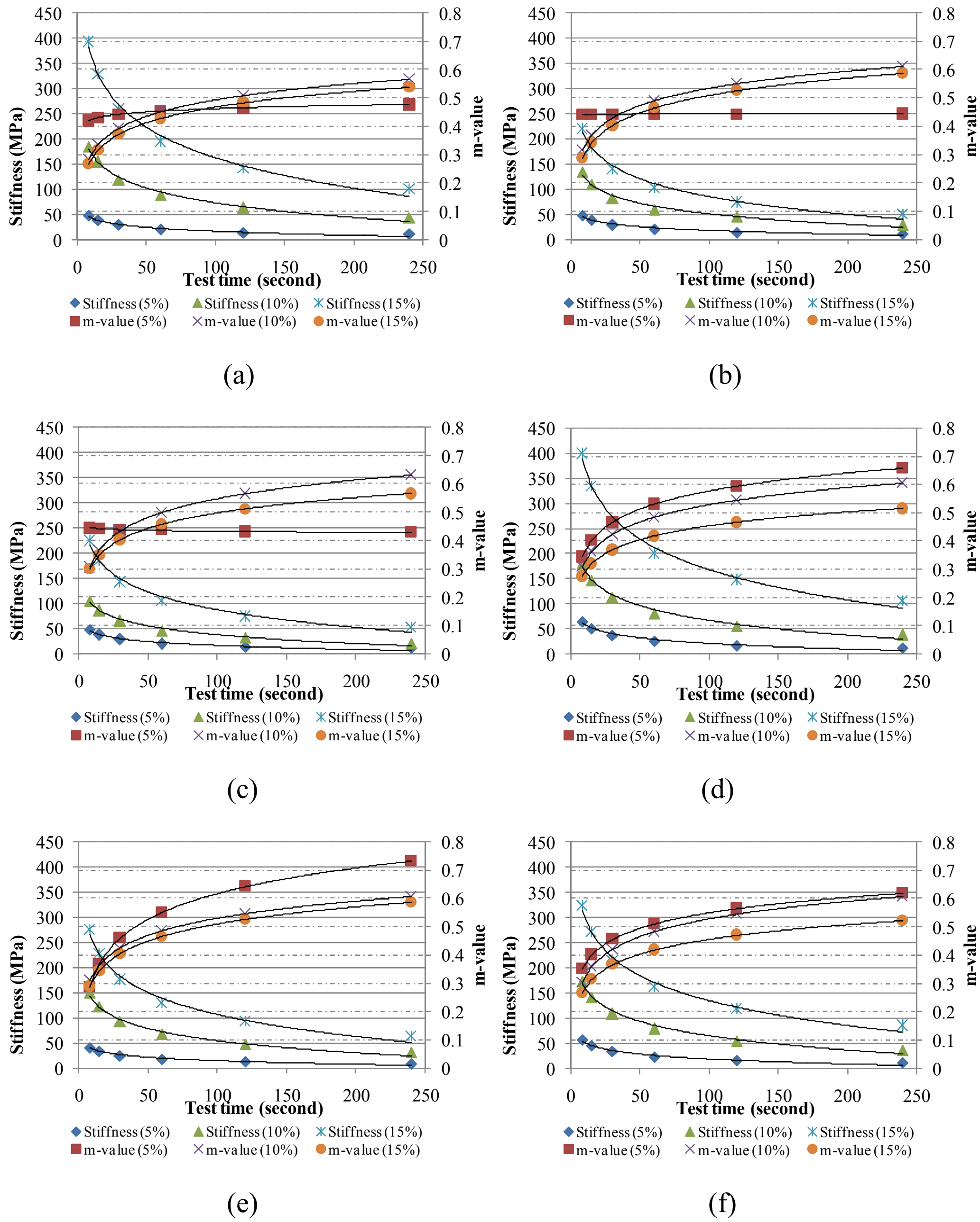


Figure 5-20: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 58-22

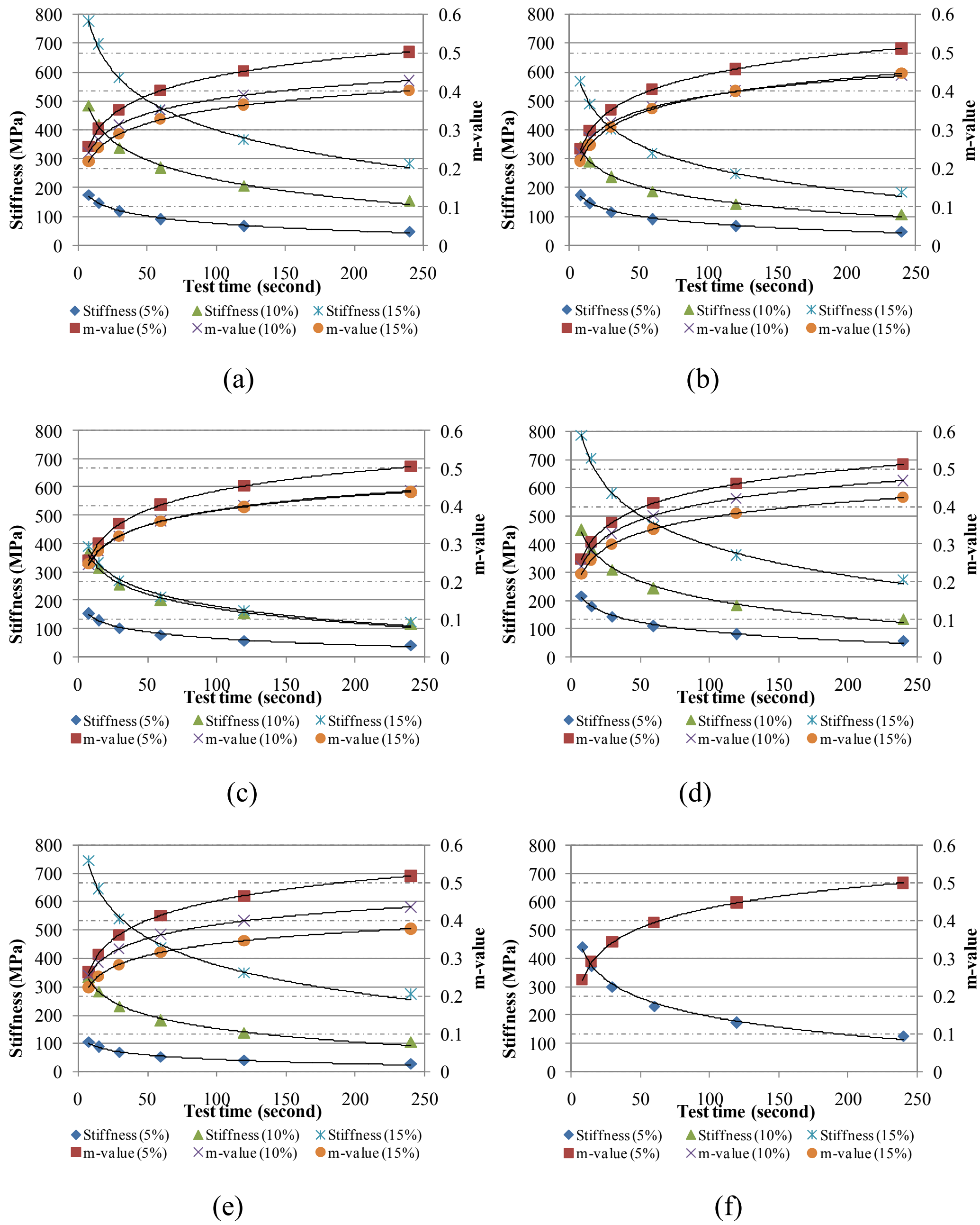


Figure 5-21: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 64-22

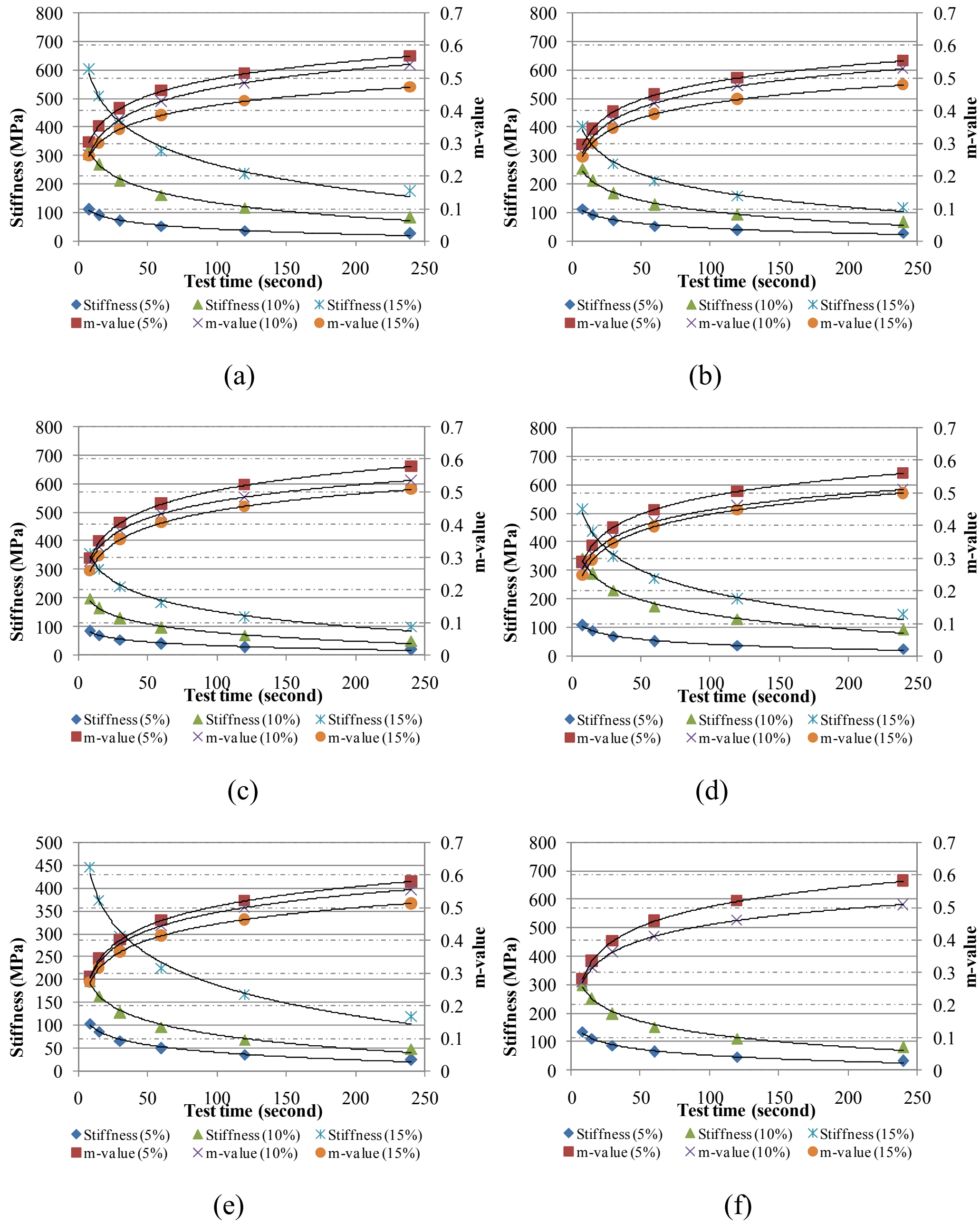


Figure 5-22: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 76-22

5.3.2 Low Temperature Determination of the Modified Binders Based on Stiffness and M-Values

Similar to virgin and RTFO binders, the stiffness and m-values of the modified binders mixed with PAV binders can determine the minimum low temperatures of various binders with a specified value of stiffness equaling to 300 MPa and an m-value of 0.300. These determined values can be found in the following figures.

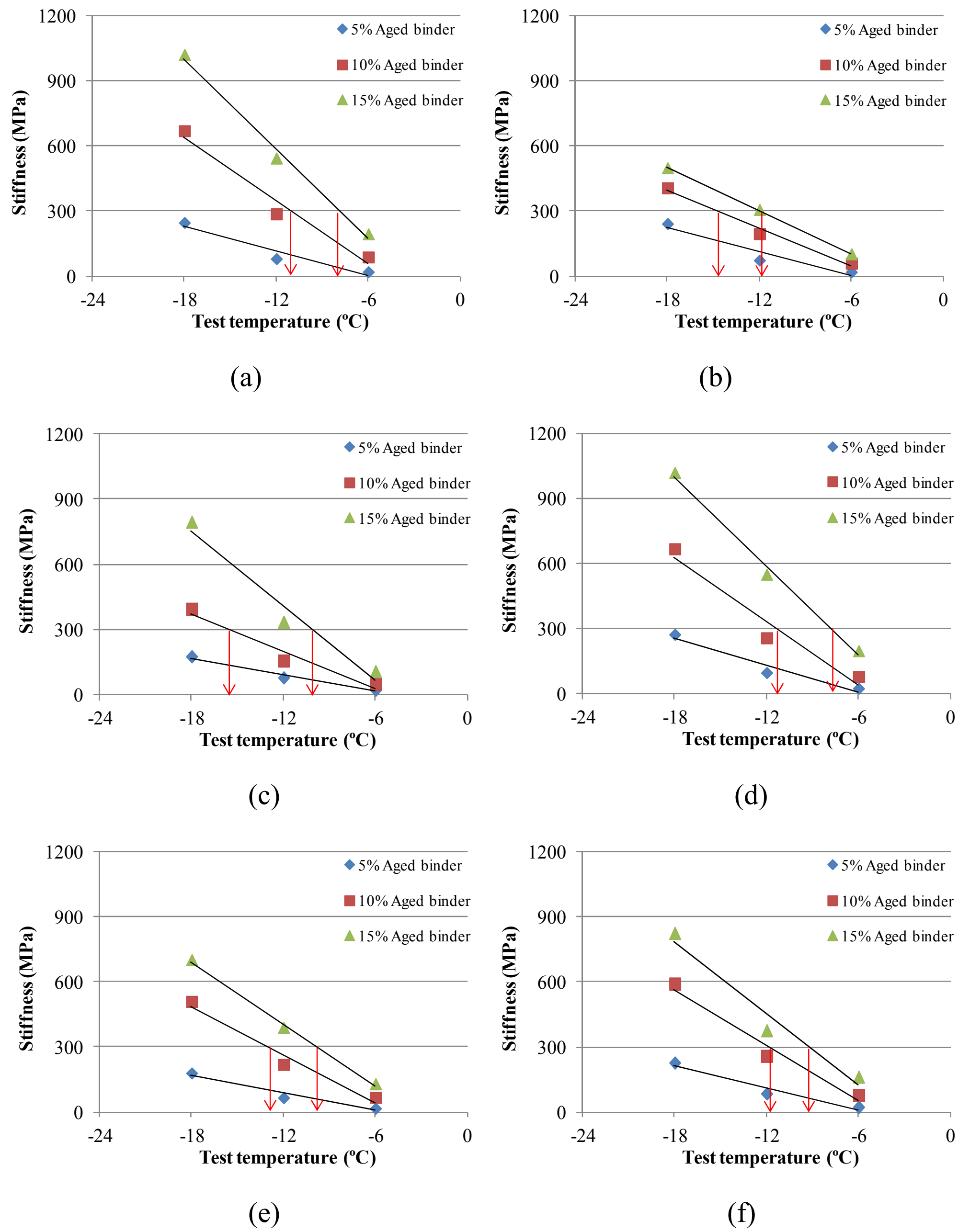


Figure 5-23: Minimum low temperature determination of RAP sources A-F containing PAV binder PG 58-28 in terms of stiffness

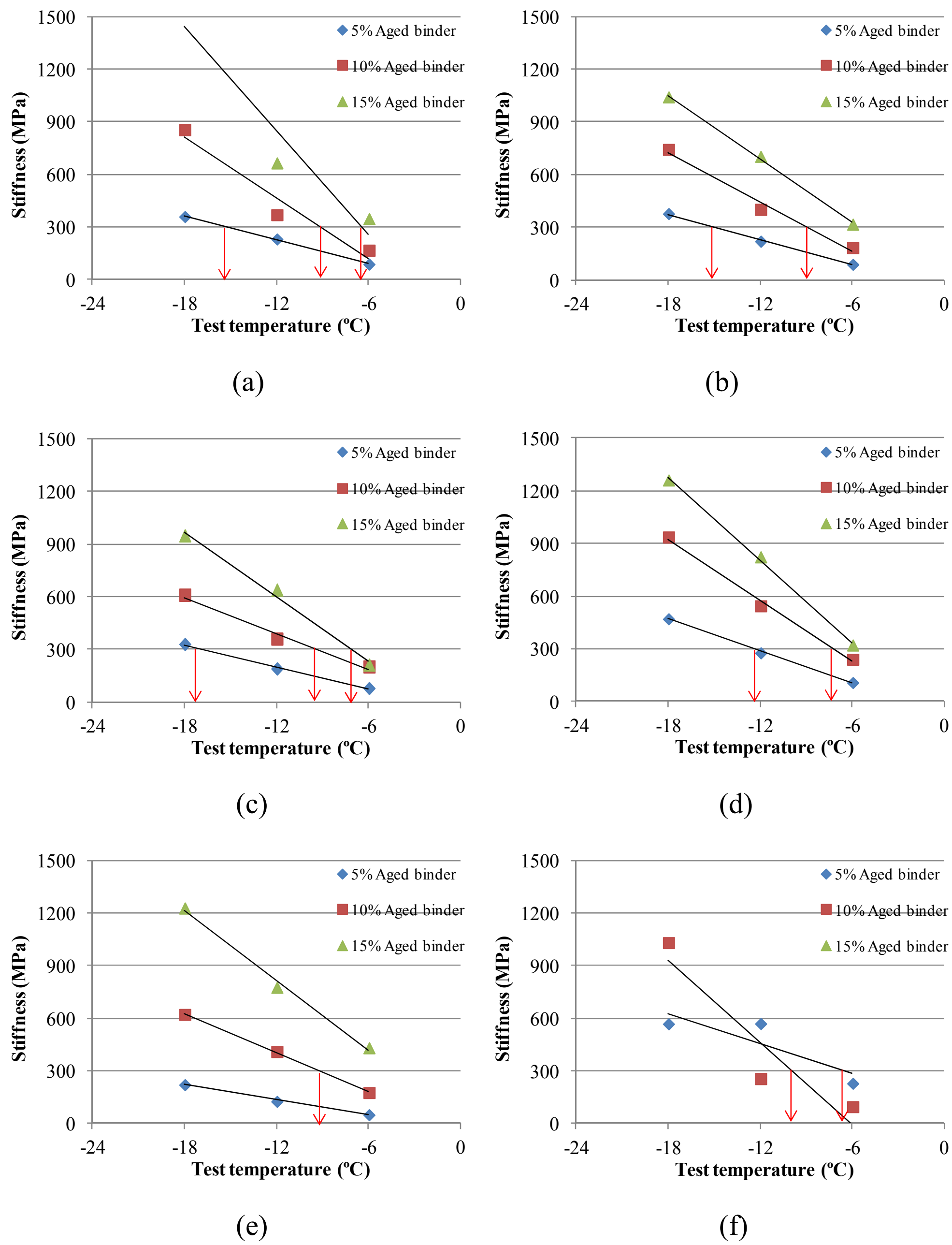


Figure 5-24: Minimum low temperature determination of RAP sources A-F containing PAV binder PG 64-22 in terms of stiffness

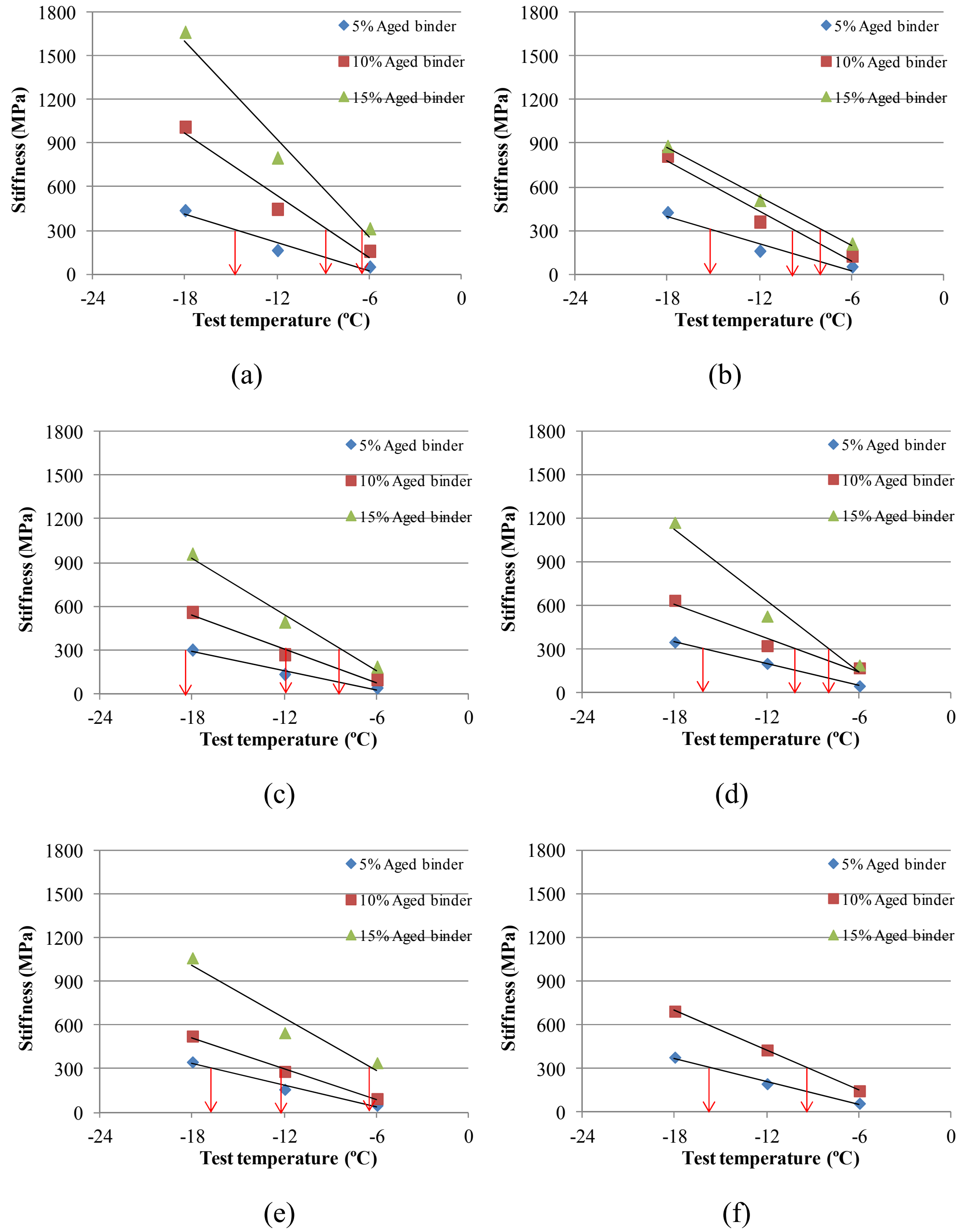


Figure 5-25: Minimum low temperature determinations of RAP sources A-F containing PAV binder PG 76-22 in terms of stiffness

In addition, these minimum low temperatures also can be determined by the m-values of these modified binders, based on the m-values greater than 0.300. As expected, the modified binders from PG 58-28 binder and with a lower aged binder have higher m-values. Figure 5-26 through Figure 5-28 show the m-values of the modified binders with PG 58-22, PG 64-22, and PG 76-22, respectively.

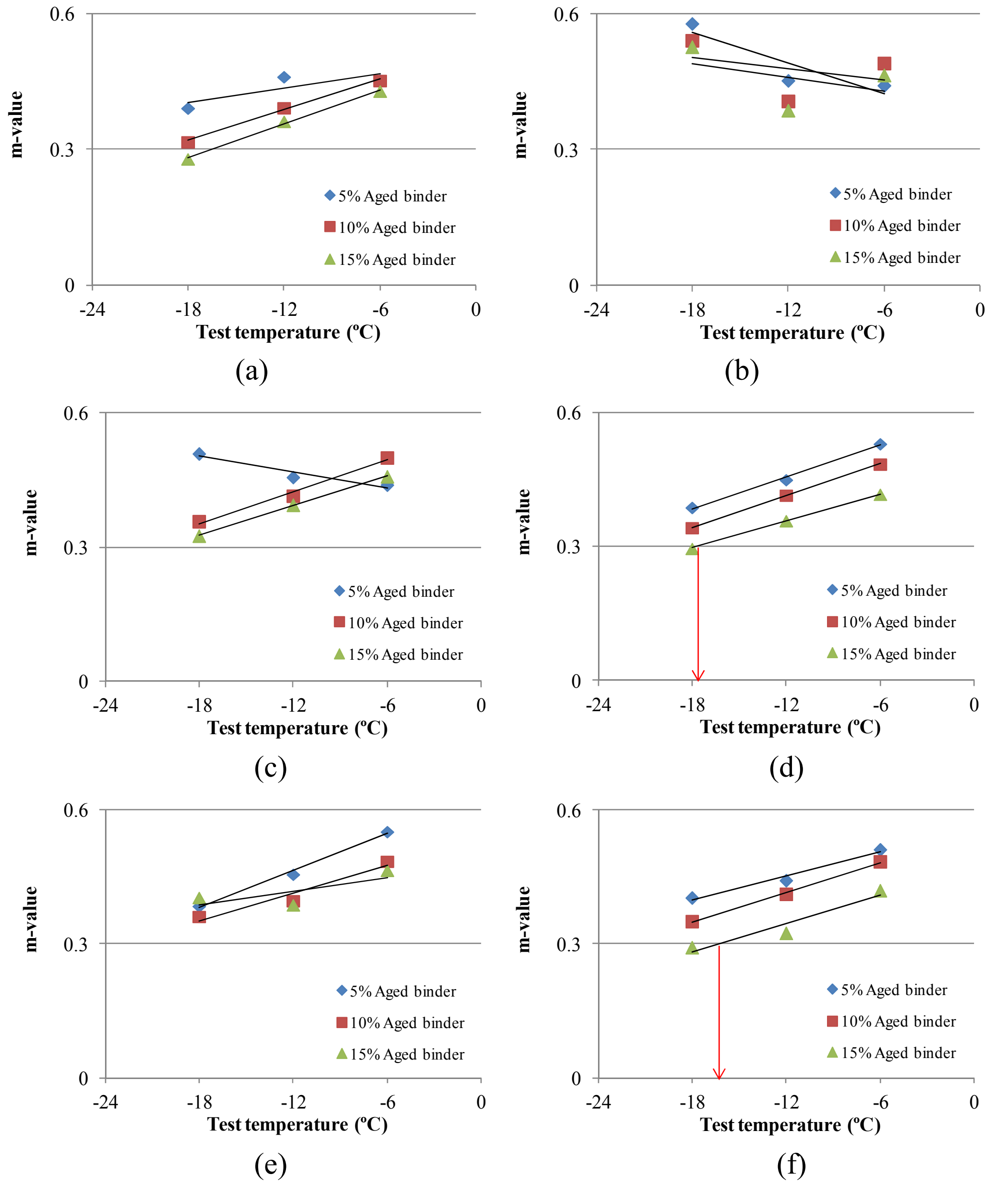


Figure 5-26: Minimum low temperature determination of RAP sources A-F containing PAV binder PG 58-28 in terms of m-value

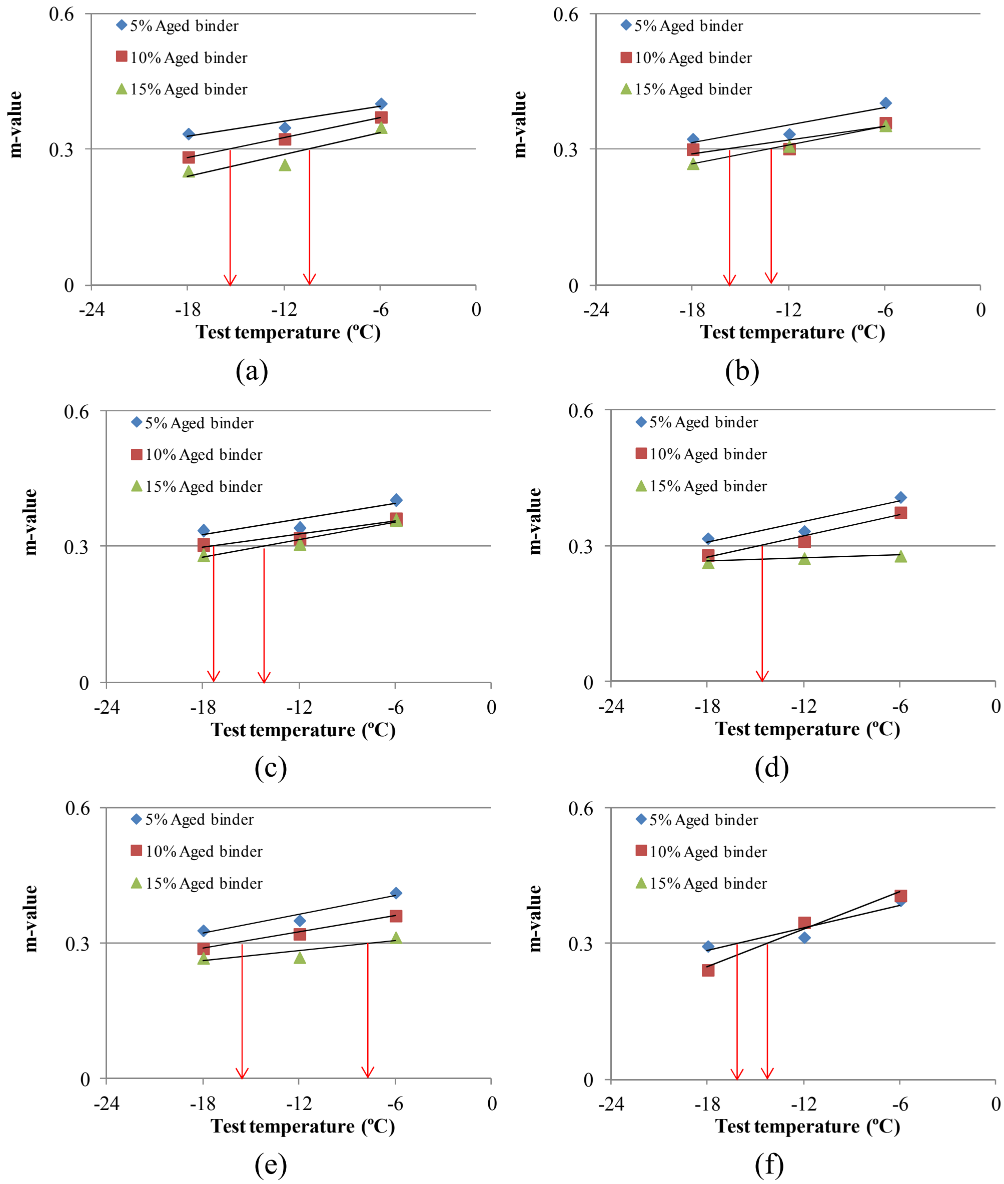


Figure 5-27: Minimum low temperature determination of RAP sources A-F containing PAV binder PG 64-22 in terms of m-value

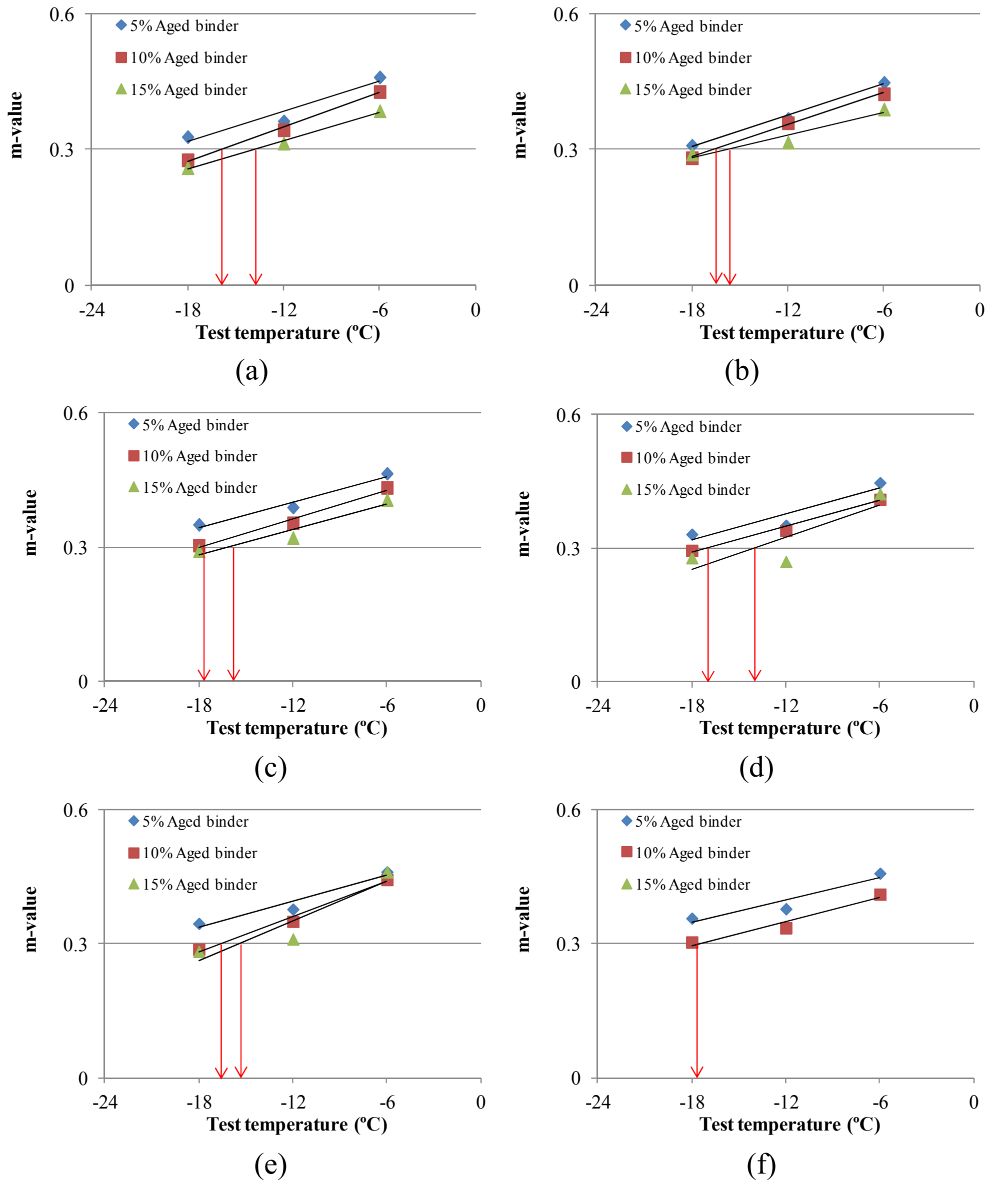


Figure 5-28: Minimum low temperature determination of RAP sources A-F containing PAV binder PG 76-22 in terms of m-value

Table 5-7 through Table 5-9 show the minimum low temperatures of various modified binders mixed with various RAP sources, aged binder contents, and PAV binder types, derived from the conducted regression analysis. As mentioned 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.

Table 5-7: Minimum low temperatures of RAP sources A-F containing PAV binder PG 58-28

RAP Source	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**

Table 5-8: Minimum low temperatures of RAP sources A-F containing PAV binder PG 64-22

RAP Source	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	-15.7	-9.2	-6.4	-22.4	-15.5	-10.4	**-15.7**	**-9.2**	**-6.4**
B	-15.4	-9.1	-6	-20.3	-15.7	-13.2	**-20.3**	**-9.1**	**-6**
C	-17.2	-9.6	-7.3	-22.3	-17.6	-14.2	**-17.2**	**-9.6**	**-7.3**
D	-12.7	-7.5	-5.6	-19.3	-14.8	3.8	**-12.7**	**-7.5**	**3.8**
E	-23	-9.2	-4.1	-20.3	-15.9	-7.8	**-20.3**	**-9.2**	**-4.1**
F	-6.2	-10.1	-	-16.2	-14.3	-	**-6.2**	**-10.1**	**-**

Table 5-9: Minimum low temperatures of RAP sources A-F containing PAV binder PG 76-22

RAP Source	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	-14.7	-8.6	-6.4	-19.8	-15.9	-13.8	**-14.7**	**-8.6**	**-6.4**
B	-15.3	-9.8	-7.9	-18.5	-16.6	-15.8	**-15.3**	**-9.8**	**-7.9**
C	-18.4	-12.1	-8.2	-22.3	-17.8	-15.9	**-18.4**	**-12.1**	**-8.2**
D	-16.3	-10.1	-7.9	-20.2	-17.1	-14	**-16.3**	**-10.1**	**-7.9**
E	-17	-11.8	-6.3	-21.9	-16.7	-15.4	**-17**	**-11.8**	**-6.3**
F	-15.8	-9.4	-	-23.7	-17.5	-	**-15.8**	**-9.4**	**-**

5.4 The Modified Binder of Burned RAP Mortar Mixed with Virgin Binder

5.4.1 Stiffness and M-Values of the Modified Binders during Various Test Durations

The fine RAPs were burned in the oven to remove the aged binder and then were mixed with the various binders. The stiffness and m-values of the modified binders would be based on the composites of various sands and binders. The ratios of sands to unaged binders are the same as those ratios of sands to the combinations of aged binders and unaged binders, which were tested before.

Three virgin binders (PG 58-28, PG 64-22, and PG 76-22) were blended with the sands from six burned RAP sources (A-F). The fabricated BBR samples were tested at three temperatures (-6 °C, -12 °C and -18 °C). The main test results are shown in the following figures.

As shown in Figure 5-29 through Figure 5-31, it can be observed that, as expected, the stiffness values of virgin binders with burned RAP mortars (sand) generally decrease while the m-values increase as the test duration increases.

Similarly, an increased sand content generally results in a higher stiffness and a lower m values regardless of burned RAP source and binder grade. In addition, a higher grade results in a higher stiffness value irrespectively of burned RAP source.

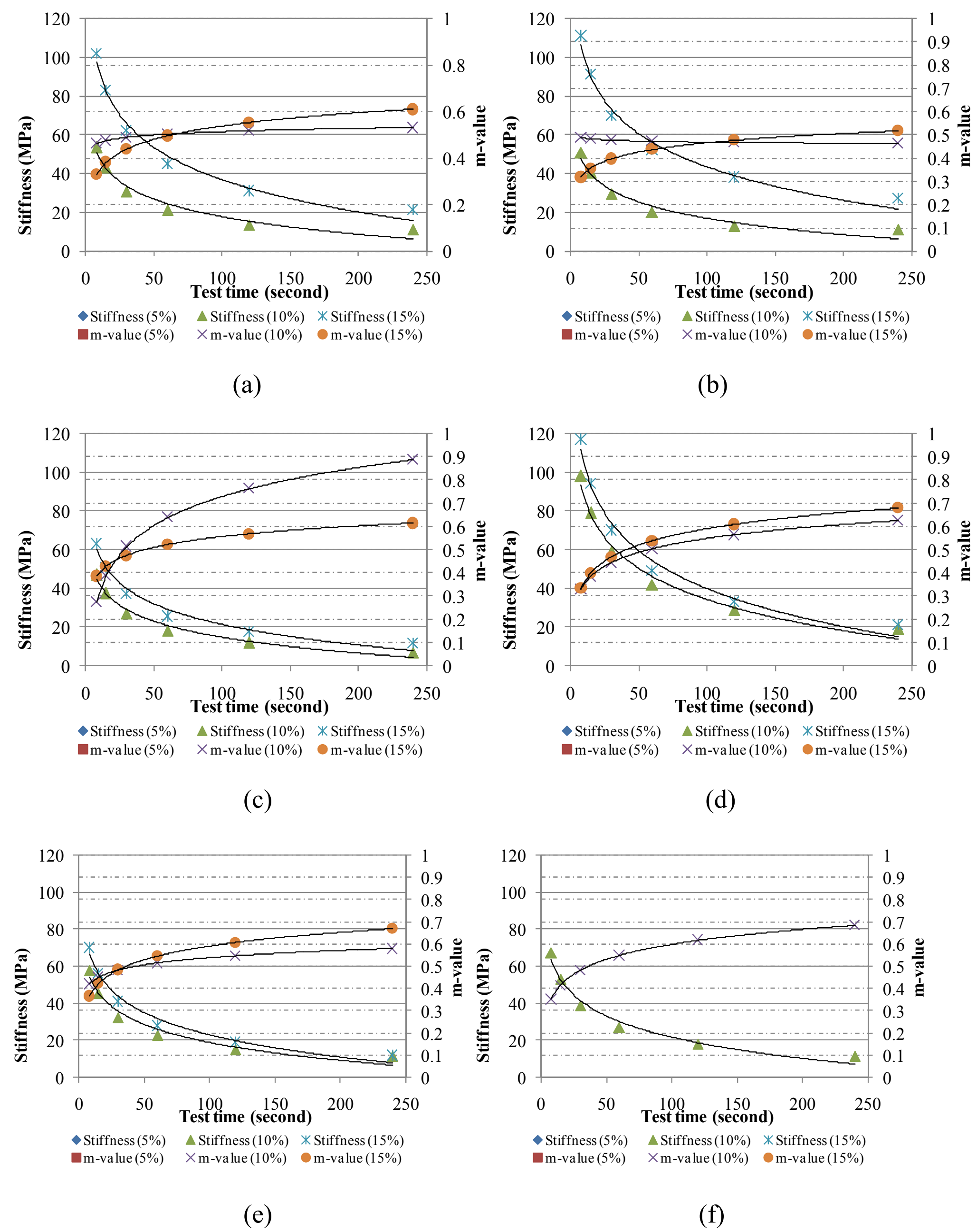


Figure 5-29: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 58-28

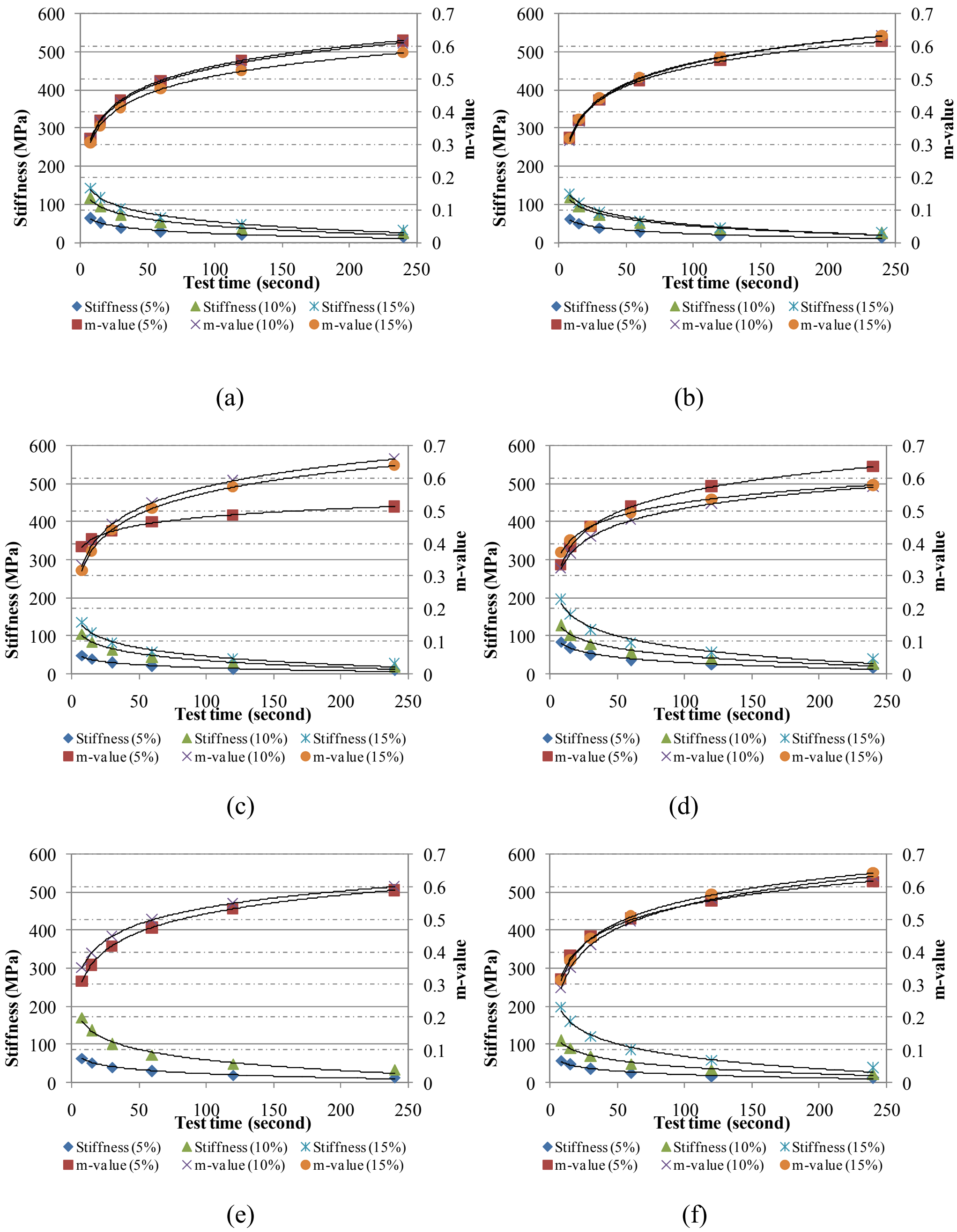


Figure 5-30: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 64-22

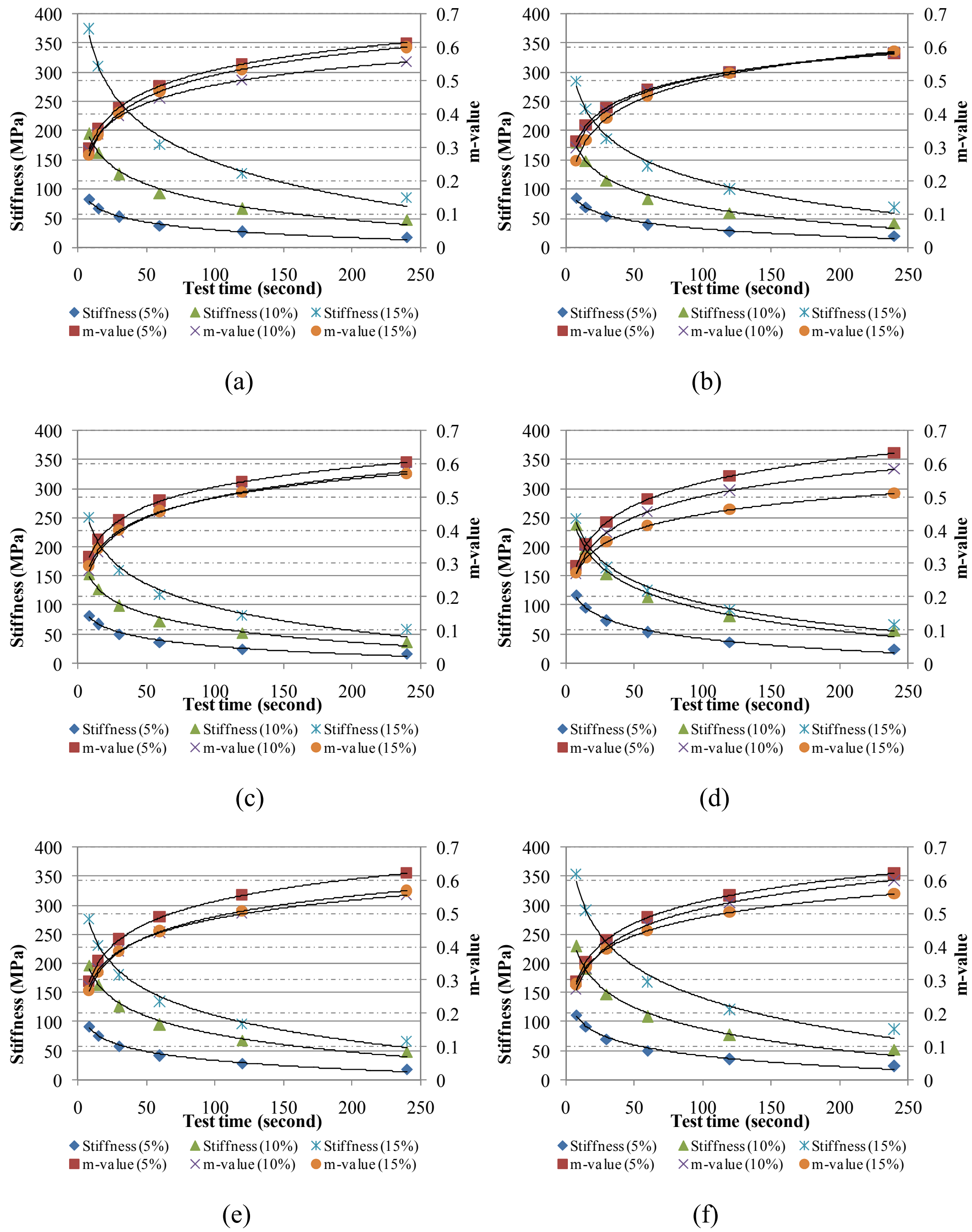


Figure 5-31: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 76-22

Other stiffness and m-values of the modified binders mixed with burned RAP mortars (A-F) and virgin binders (PG 58-22, PG 64-22, and PG 76-22) at -12 °C and -18 °C are presented in Appendix D. Generally, similar trends can be found regardless of RAP source, binder grade, and test temperatures used in this study.

5.4.2 Low Temperature Determinations of the Modified Binders Based on Stiffness and M-Values

The minimum low temperatures of the modified binders mixed burned RAPs and virgin binders can be determined from their stiffness and m-values. These stiffness and m-values are shown the following figures. Figure 5-32 through Figure 5-34 show the low temperature determinations of the burned RAPs (sands) with virgin PG 58-28, PG 64-22, and PG 76-22 binders in terms of the stiffness values.

In general, a higher percentage of burned RAP resulted in a higher temperature, with stiffness value of 300 MPa. The burned RAP type has an effect on the stiffness and m-values and thus could influence low temperature of the modified binders. Moreover, it can be noted that the binder grade also plays an important role in determining the minimum low temperature of a modified binder.

Similarly, the m-values also can be used to conduct the minimum low temperature of the modified binder with a corresponding m-value of 0.300. Figure 5-35 through Figure 5-37 show these minimum low temperatures. It can be noted that the m-values of the modified binders have values greater than 0.300 regardless of RAP type, burned RAP content and test temperature. Minimum low temperatures are less than -18 °C. One main reason is that virgin PG 58-28 is generally soft compared to other higher grades.

When a virgin PG 64-22 binder was used, the m-values are shown in Figure 5-36. It can be noted that the minimum low temperature is less than -18 °C when 5% burned RAP was used. The modified binders with other percentages of burned RAP have minimum low temperature greater than -18 °C. Similar trends can be found in Figure 5-37 when a PG 76-22 binder was used.

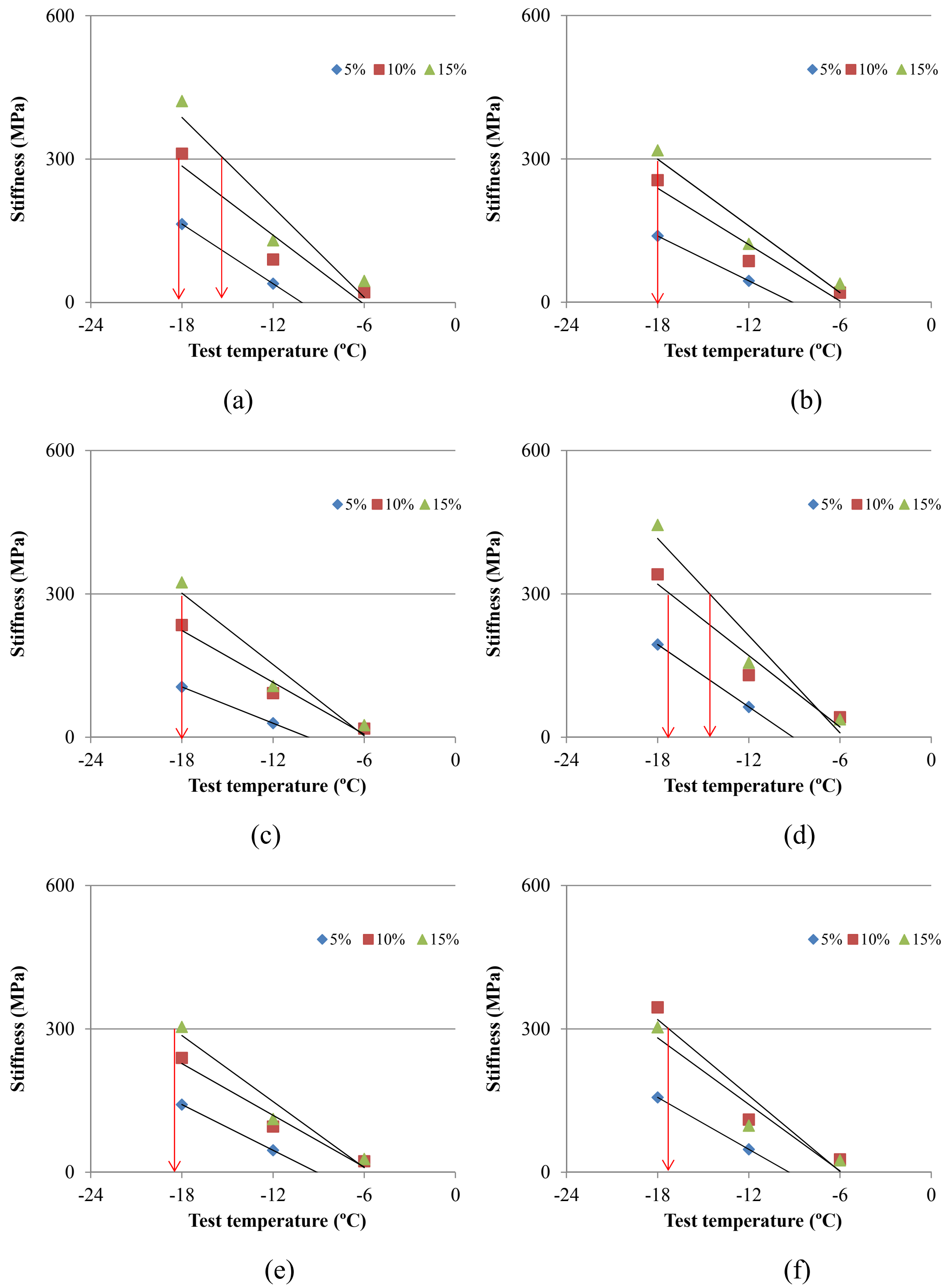


Figure 5-32: Low temperature determinations of burned RAP sources A-F containing virgin binder PG 58-28 in terms of stiffness

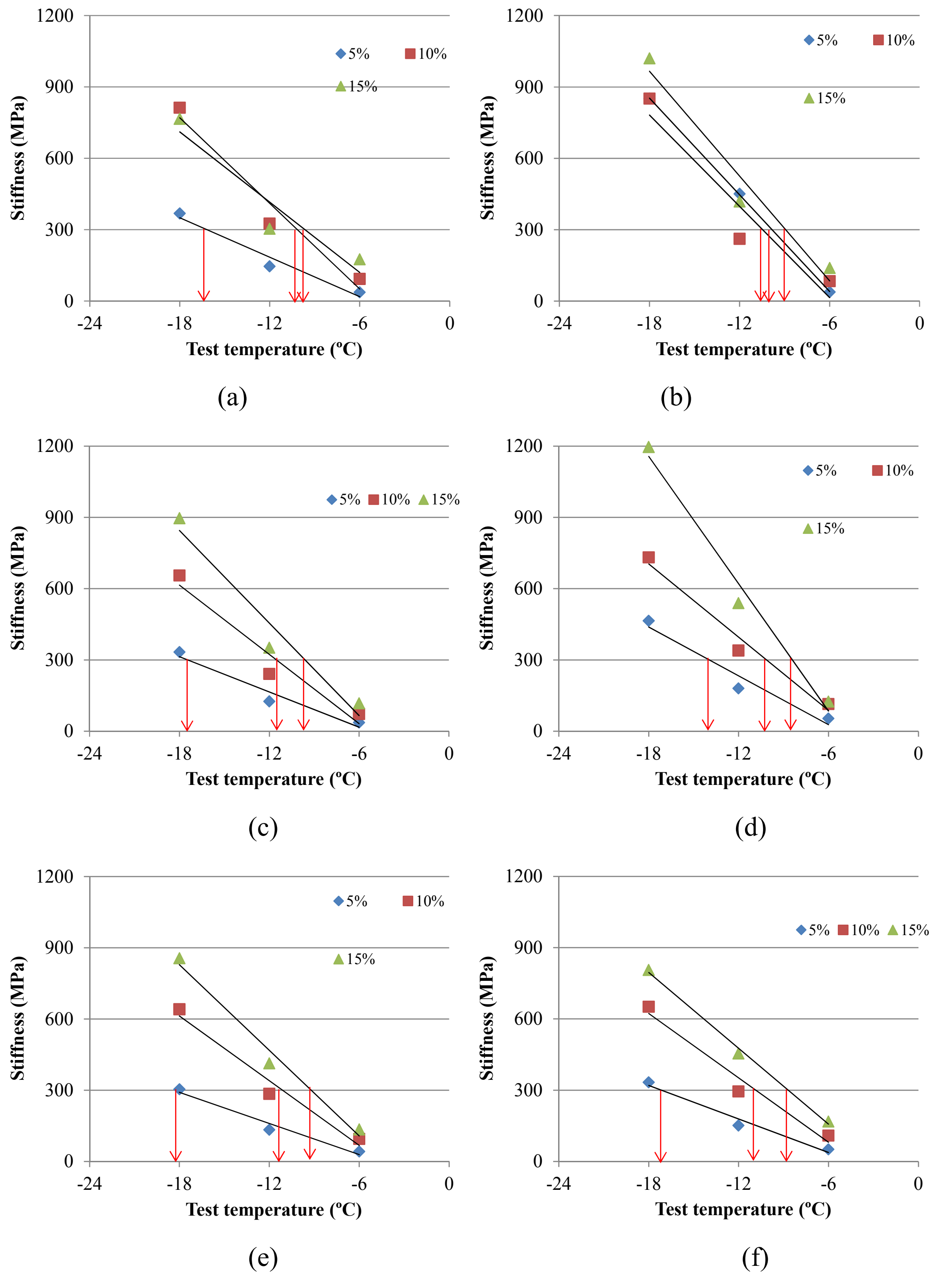


Figure 5-33: Low temperature determinations of burned RAP sources A-F containing virgin binder PG 64-22 in terms of stiffness

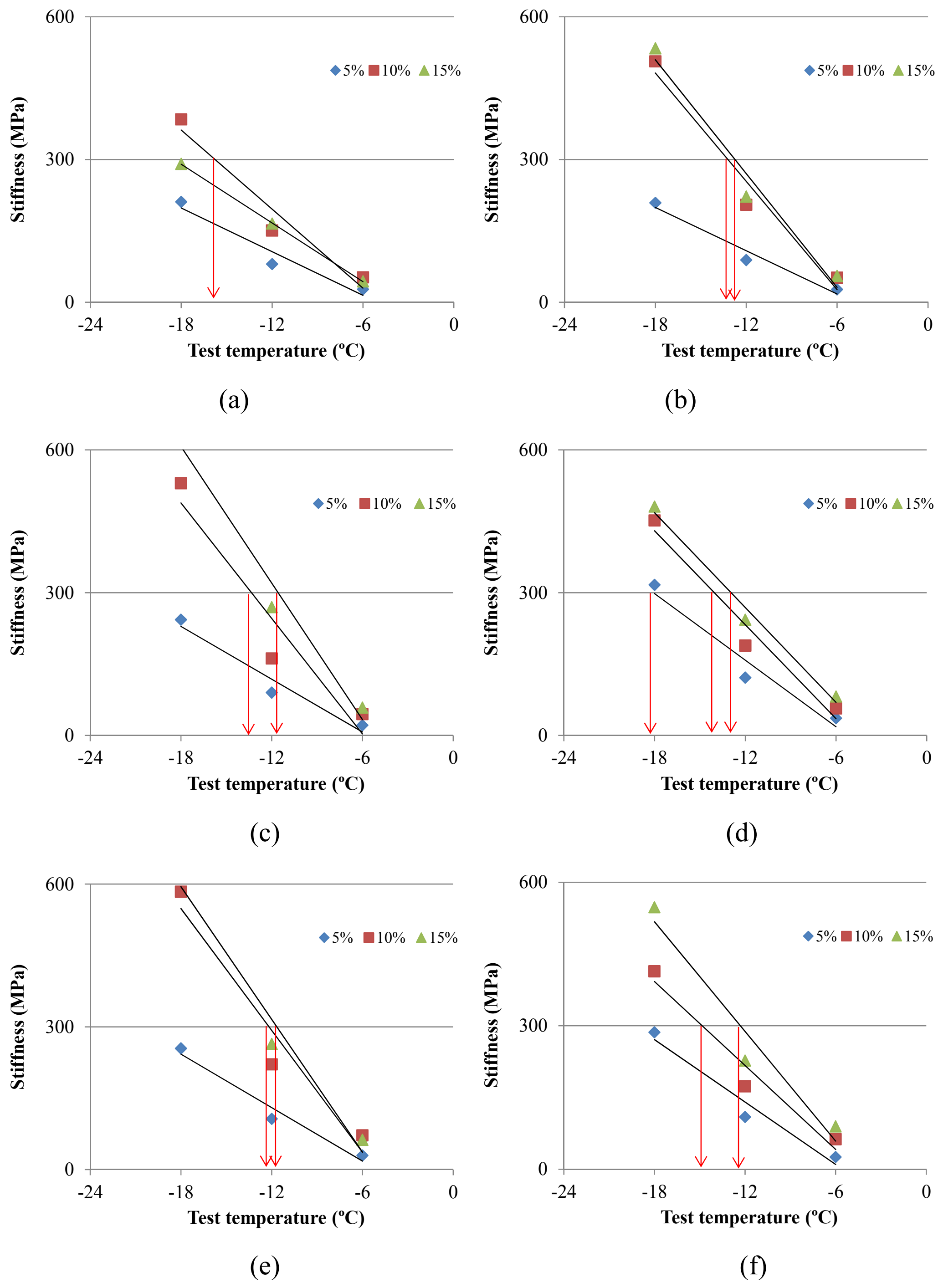


Figure 5-34: Low temperature determinations of burned RAP sources A-F containing virgin binder PG76-22 in terms of stiffness

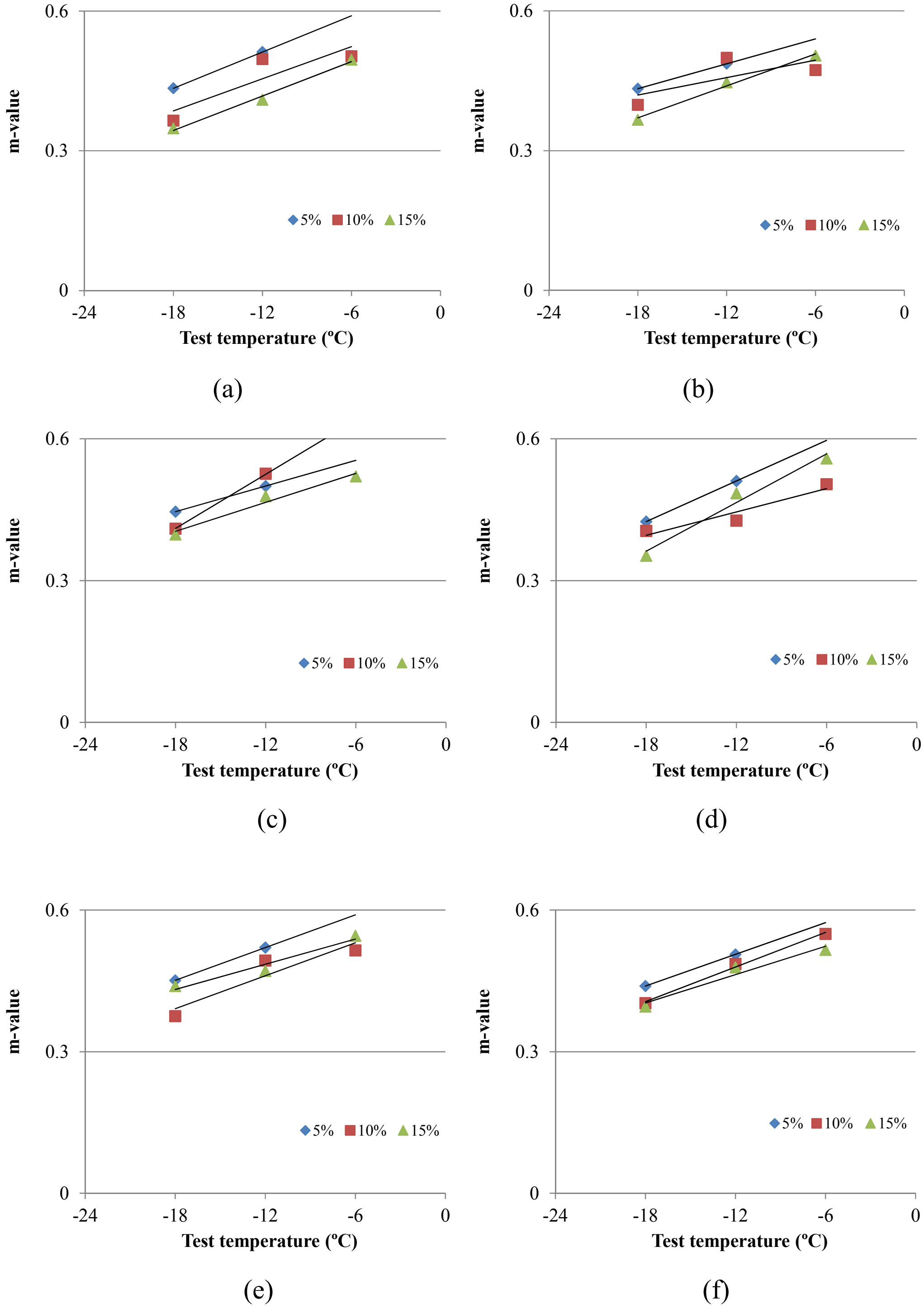


Figure 5-35: Low temperature determinations of burned RAP sources A-F containing virgin binder PG 58-28 in terms of m-value

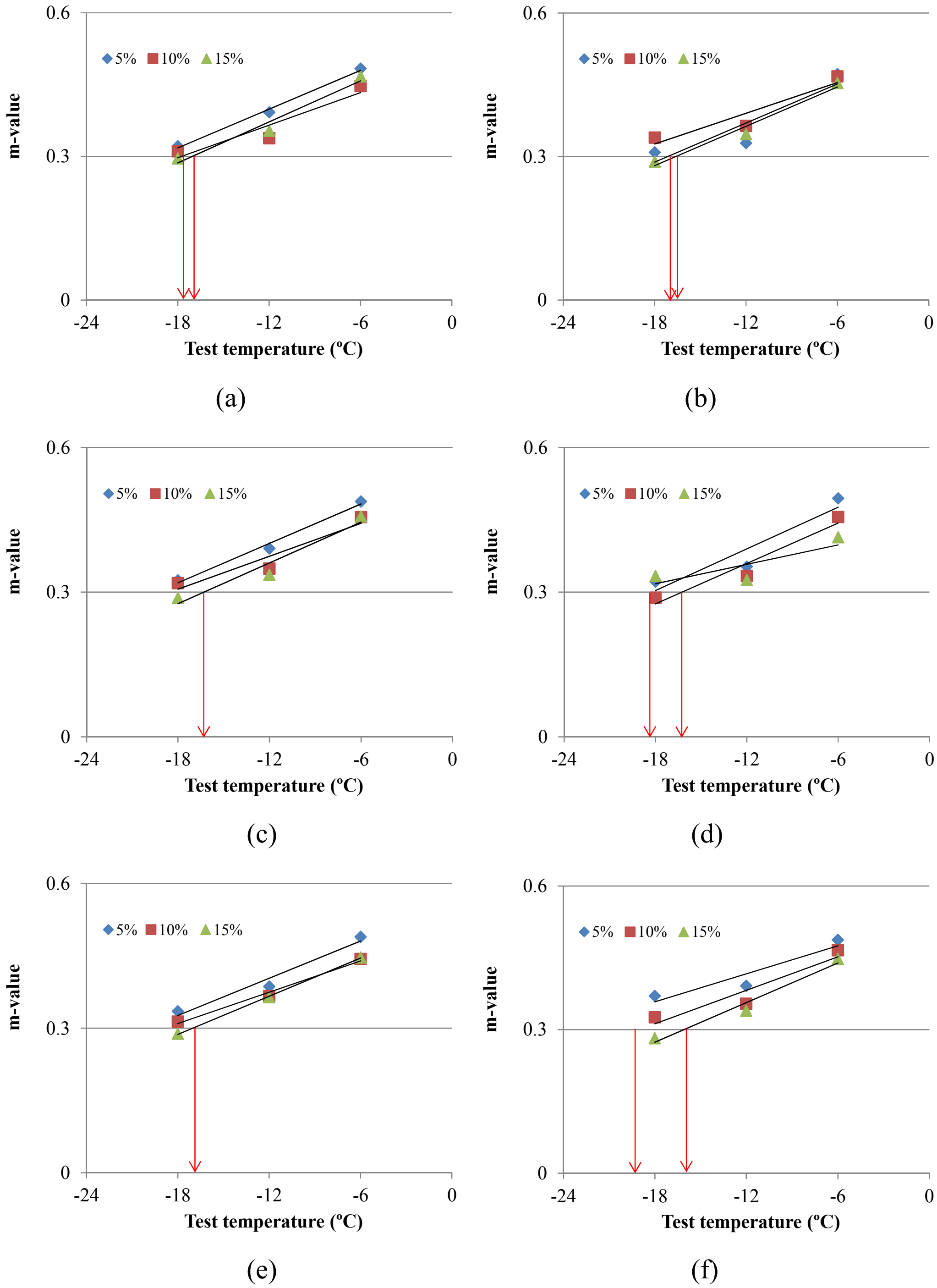


Figure 5-36: Low temperature determinations of burned RAP sources A-F containing virgin binder PG 64-22 in terms of m-value

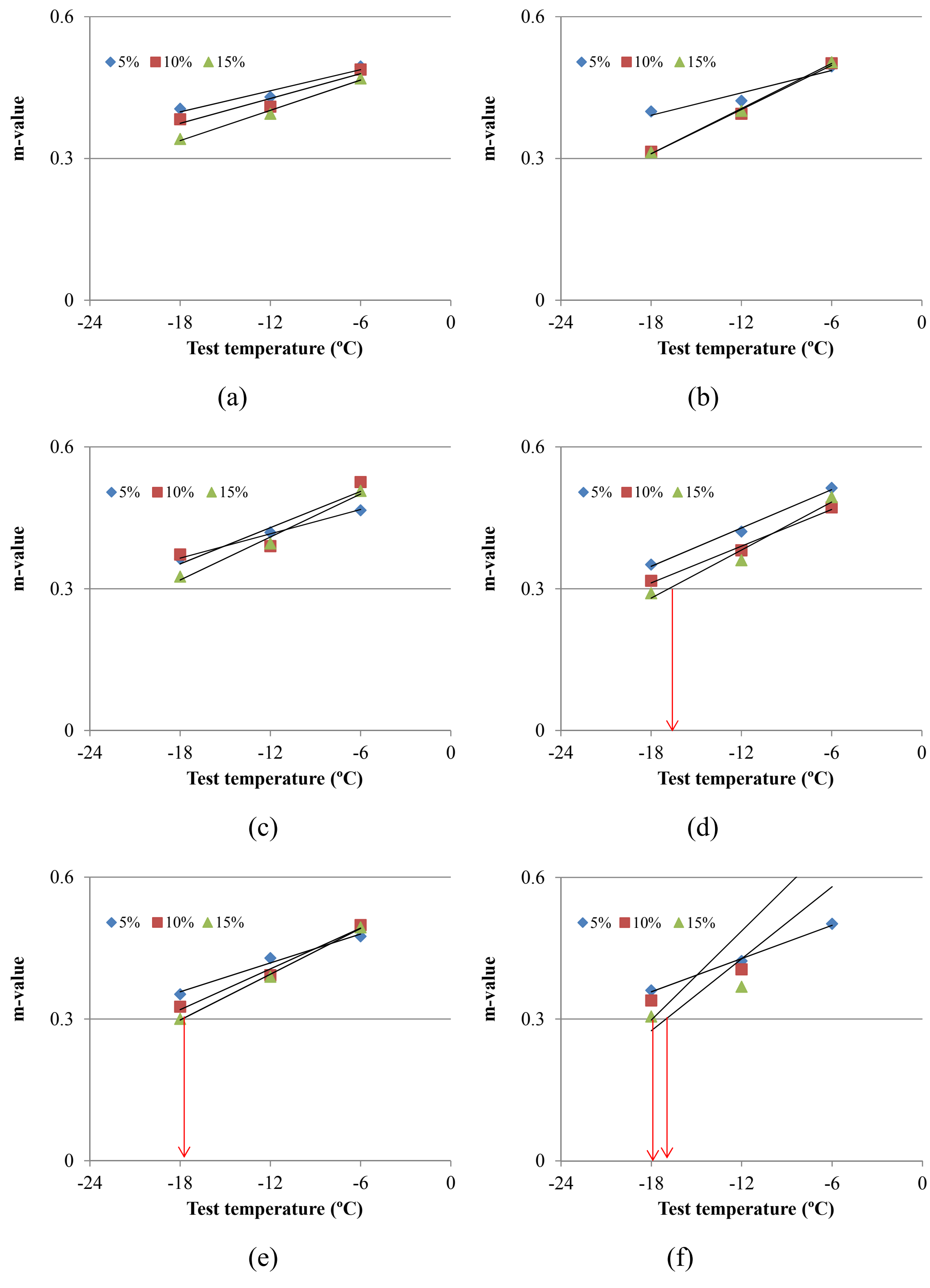


Figure 5-37: Low temperature determinations of burned RAP sources A-F containing virgin binder PG 76-22 in terms of m-value

Table 5-10 through Table 5-12 show the minimum low temperatures of various modified binders mixed with various RAP sources, burned aged binder contents, and virgin binder types, derived from the conducted regression analysis.

Table 5-10: Minimum low temperatures of burned RAP sources A-F containing virgin binder PG 58-28

RAP Source	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	<-24	-18.2	-15.3	<-24	<-24	-21.9	**<-24**	**-18.2**	**-15.3**
B	<-24	-21.8	-17.9	<-24	<-24	-23.3	**<-24**	**-21.8**	**-17.9**
C	<-24	-22	-17.8	<-24	-23.7	<-24	**<-24**	**-22**	**-17.8**
D	-23.1	-17.3	-14.7	<-24	<-24	-21.6	**-23.1**	**-17.3**	**-14.7**
E	<-24	-22.3	-18.4	<-24	<-24	<-24	**<-24**	**-22.3**	**-18.4**
F	<-24	-17.4	-19.5	<-24	<-24	<-24	**<-24**	**-17.4**	**-19.5**

Table 5-11: Minimum low temperatures of burned RAP sources A-F containing virgin binder PG 64-22

RAP Source	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	-16.3	-10.2	-9.6	-19.4	-17.7	-16.9	**-16.3**	**-10.2**	**-9.6**
B	-9.9	-10.4	-9	-17.1	-20.5	-16.4	**-9.9**	**-10.4**	**-9**
C	-17.5	-11.6	-9.7	-19.7	-18.6	-16.3	**-17.5**	**-11.6**	**-9.7**
D	-14.1	-10.2	-8.6	-18.3	-16.2	-20.6	**-14.1**	**-10.2**	**-8.6**
E	-18	-11.2	-9.3	-20.2	-19.1	-16.9	**-18**	**-11.2**	**-9.3**
F	-17.2	-10.8	-8.7	<-24	-19.6	-15.8	**-17.2**	**-10.8**	**-8.7**

Table 5-12: Minimum low temperatures of burned RAP sources A-F containing virgin binder PG 76-22

RAP Source	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	<-24	-15.8	-18.2	<-24	<-24	-21.3	**<-24**	**-15.8**	**-18.2**
B	<-24	-13.4	-12.7	<-24	-18.4	-18.5	**<-24**	**-13.4**	**-12.7**
C	-21.6	-13.5	-11.7	<-24	-21.7	-18.8	**-21.6**	**-13.5**	**-11.7**
D	-18.3	-14.2	-13	-21.3	-19.1	-17.8	**-18.3**	**-14.2**	**-13**
E	-21.3	-12.2	-11.7	-23.6	-19.1	-17.8	**-21.3**	**-12.2**	**-11.7**
F	-19.4	-14.8	-12.3	-22.8	-17.9	-16.8	**-19.4**	**-14.8**	**-12.3**

5.5 The Modified Binder of Burned RAP Mortar Mixed with RTFO Binder

5.5.1 Stiffness and M-Values of the Modified Binders during Various Test Durations

This section presents the test results of the modified binders mixed with various burned RAP (sand) and three short-term aged (RTFO) binders (PG 58-28, PG 64-22, and PG 76-22). The fabricated BBR samples were tested at three temperatures (-6 °C, -12 °C, and -18 °C). The main test results are shown in the following figures.

As shown in Figure 5-38 through Figure 5-40, it can be seen that, at -6 °C, all modified binders mixed with burned RAP and RTFO binders show the increased m-values and decreased stiffness values during a loading process. It is also noted that, as expected, the modified binders mixed with RTFO binder and a higher burned RAP has a greater stiffness value.

In addition, it can be observed that the stiffness values of modified binders are higher when RTFO aged PG 76-22 binder was used, followed by PG 64-22 and PG 58-28 binders.

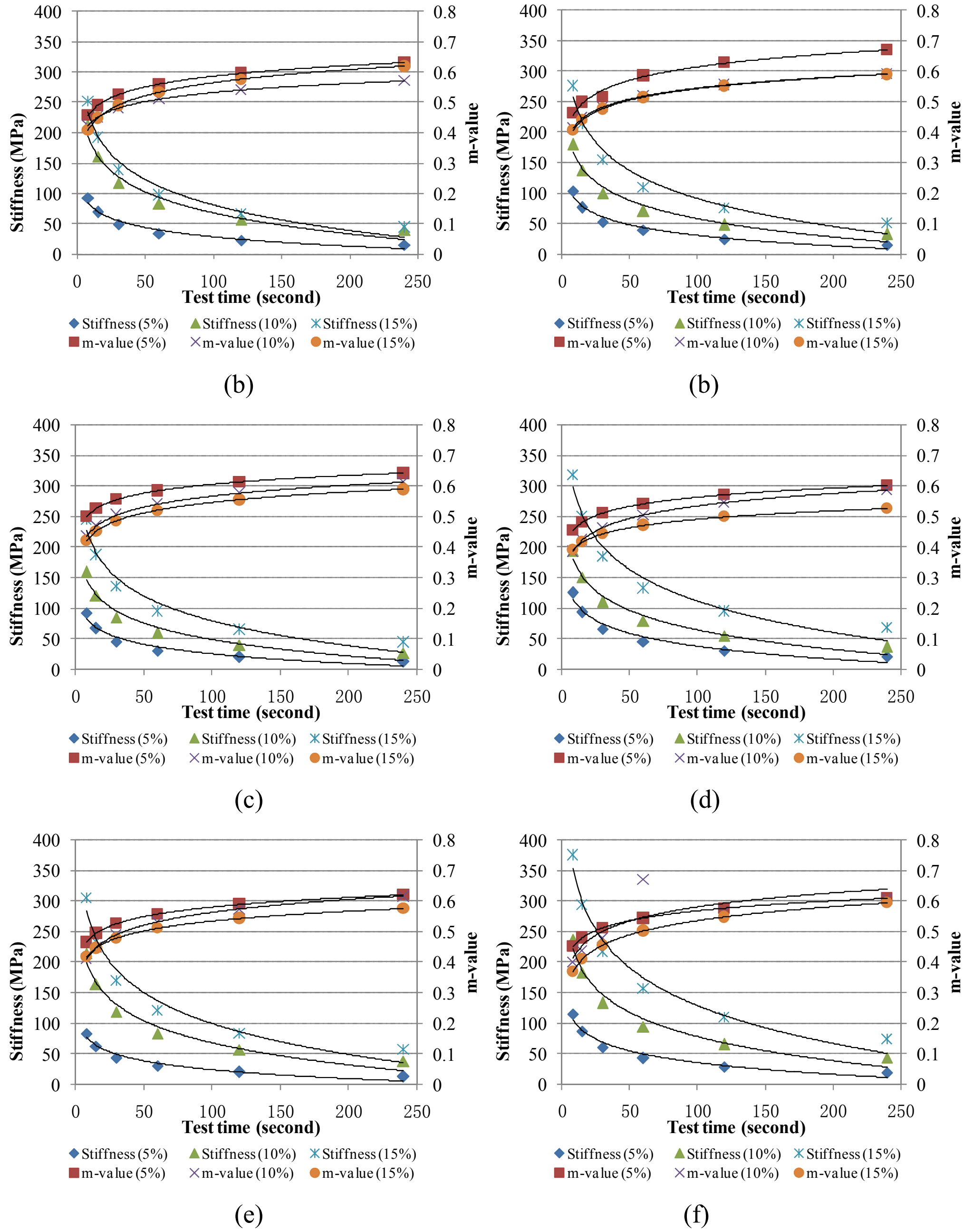


Figure 5-38: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 58-28

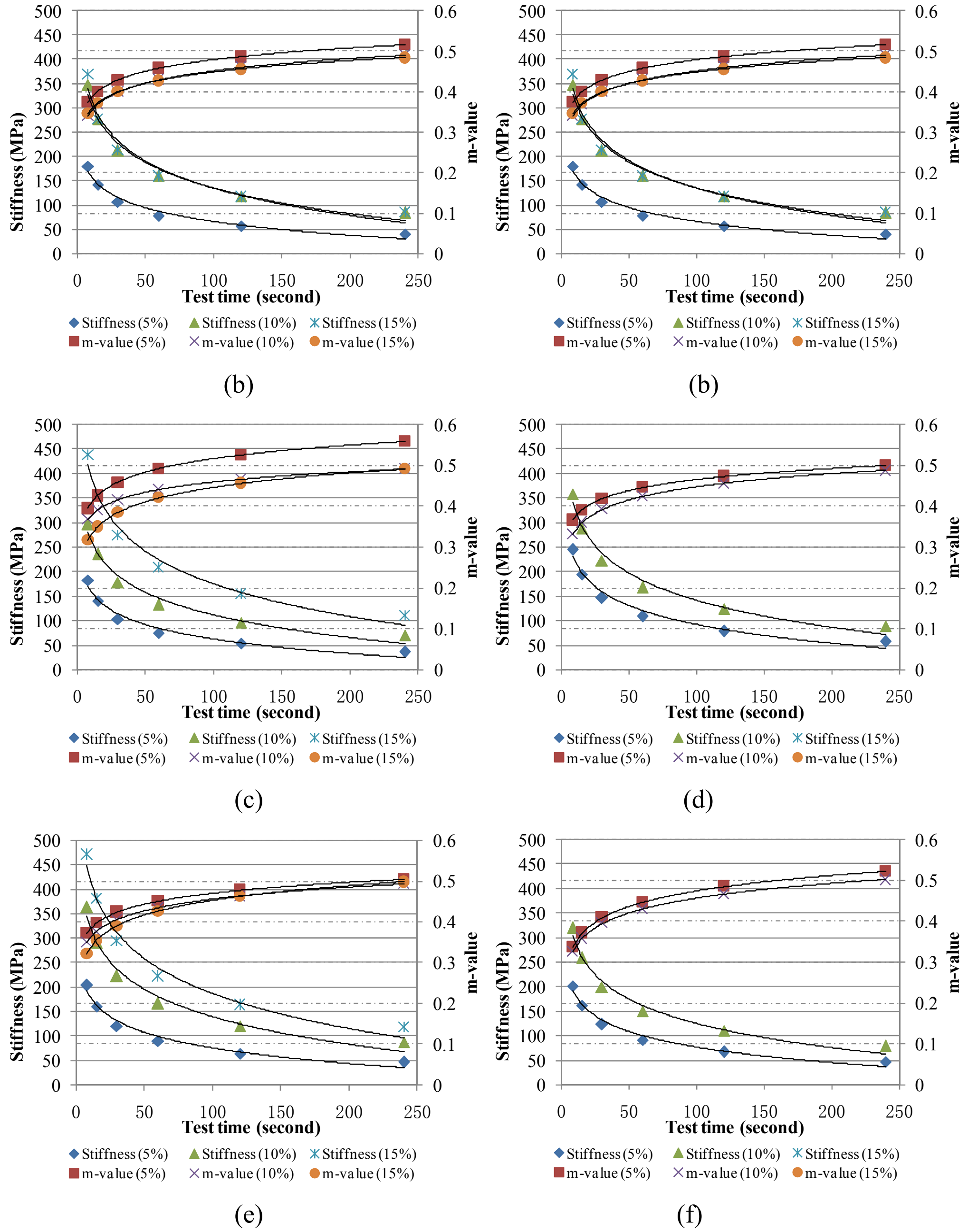
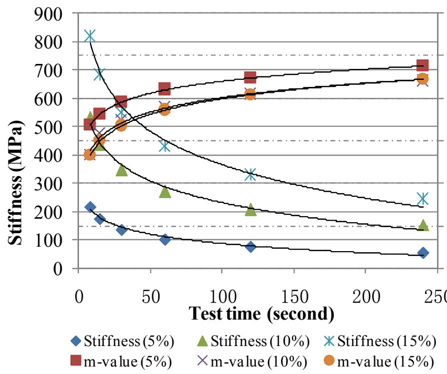
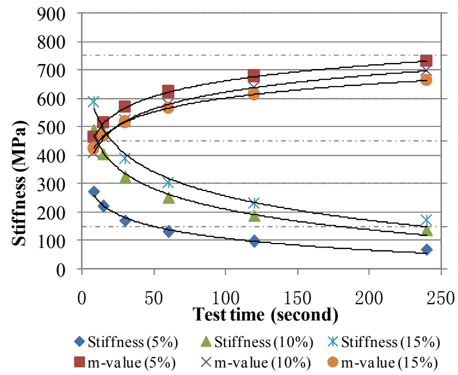


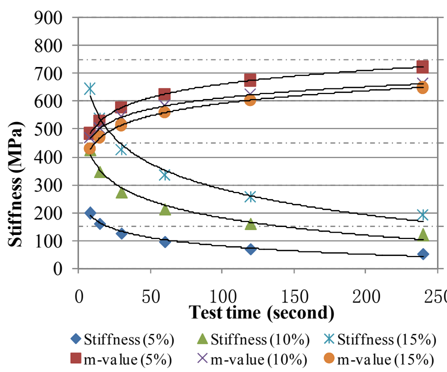
Figure 5-39: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 64-22



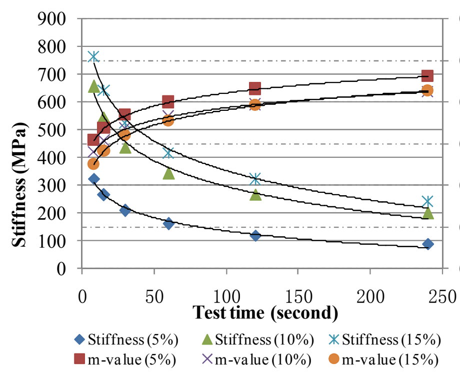
(b)



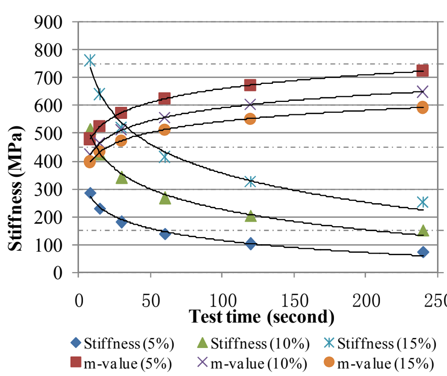
(b)



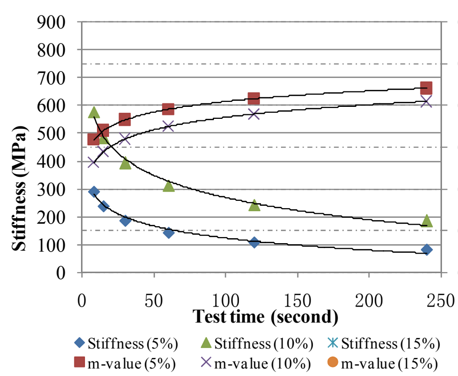
(c)



(d)



(e)



(f)

Figure 5-40: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 76-22

Other stiffness and m-values of the modified binders mixed with burned RAP mortars (A-F) and RTFO binders (PG 58-22, PG 64-22, and PG 76-22) at -12 °C and -18 °C are presented in Appendix E. Generally, similar trends can be found regardless of burned RAP source, binder grade, and test temperatures used in this study.

5.5.2 Low Temperature Determinations of the Modified Binders Based on Stiffness and M-Values

This section describes the determinations of low temperatures of various burned RAP mortars mixed with RTFO aged binders. Figure 5-41 through Figure 5-43 indicate low temperature determinations of the modified binders with PG 58-28, PG 64-22, and PG 76-22, respectively. It can be seen that a higher burned RAP resulted in a higher stiffness value; thus, its minimum low temperature is generally higher than -18 °C. In addition, a low burned RAP (5%) may result in a minimum low temperature less than -18 °C for the materials used in this study.

In addition, the m-values of the modified binders mixed with burned RAP (sand) and RTFO aged binders also can determine the minimum low temperatures of these binders. Similar to previous analysis, the findings are shown in Figure 5-44 through Figure 5-46. It can be seen that in Figure 5-44, all m-values of the modified binders are greater than 0.300 regardless of RAP type and percentage. These minimum low temperatures are lower than -18 °C. In addition, some of the modified binders have m-values less than 0.300 when a high percentage of burned RAP was used. Thus, some minimum low temperatures of these modified binders are higher than -18 °C. Moreover, when PG 76-22 binder was used, the m-values greater than 0.300 result in the minimum low temperatures lower than -18 °C for the materials used in this study.

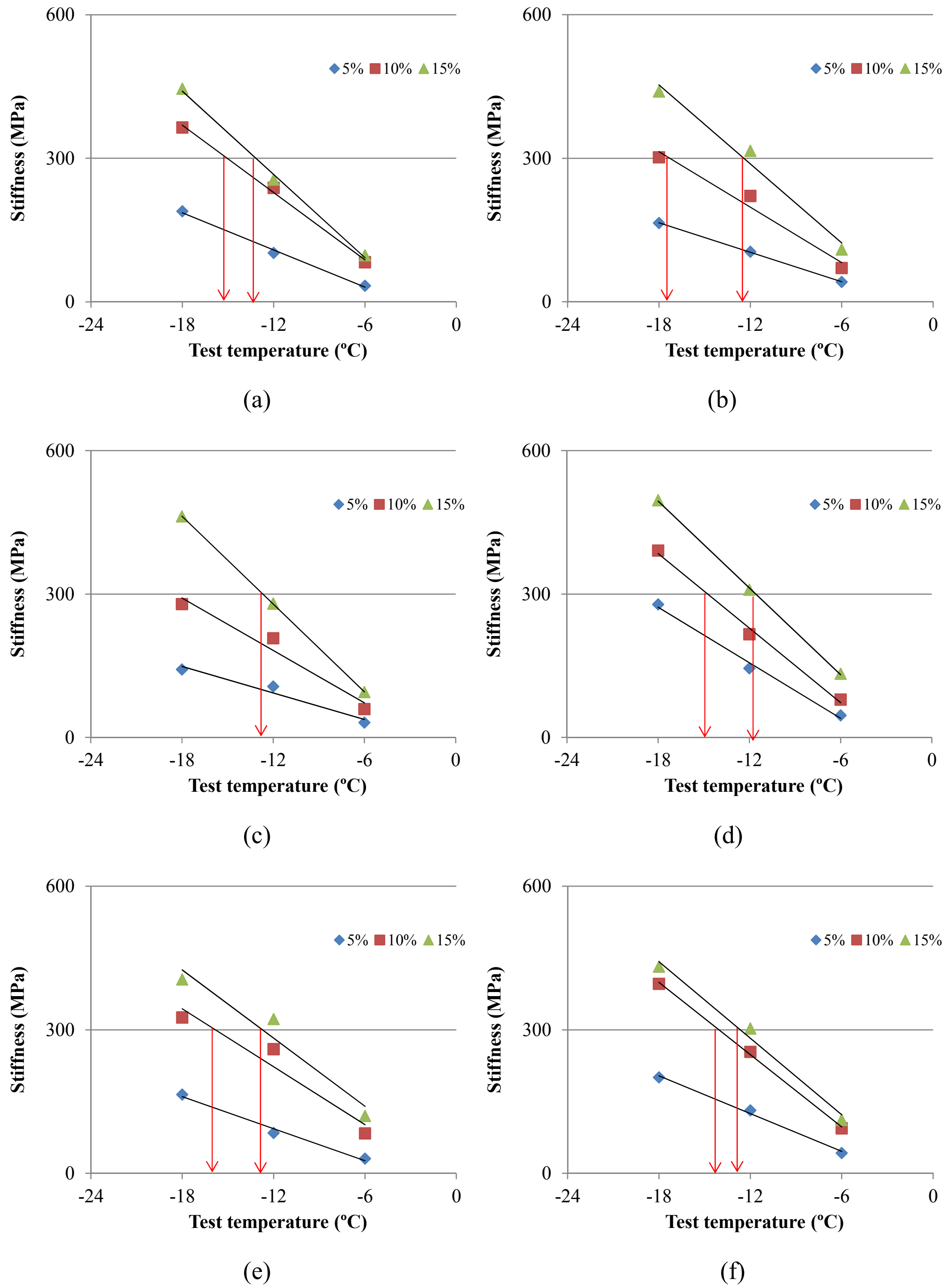


Figure 5-41: Low temperature determinations of burned RAP sources A-F containing RTFO binder PG 58-28 in terms of stiffness

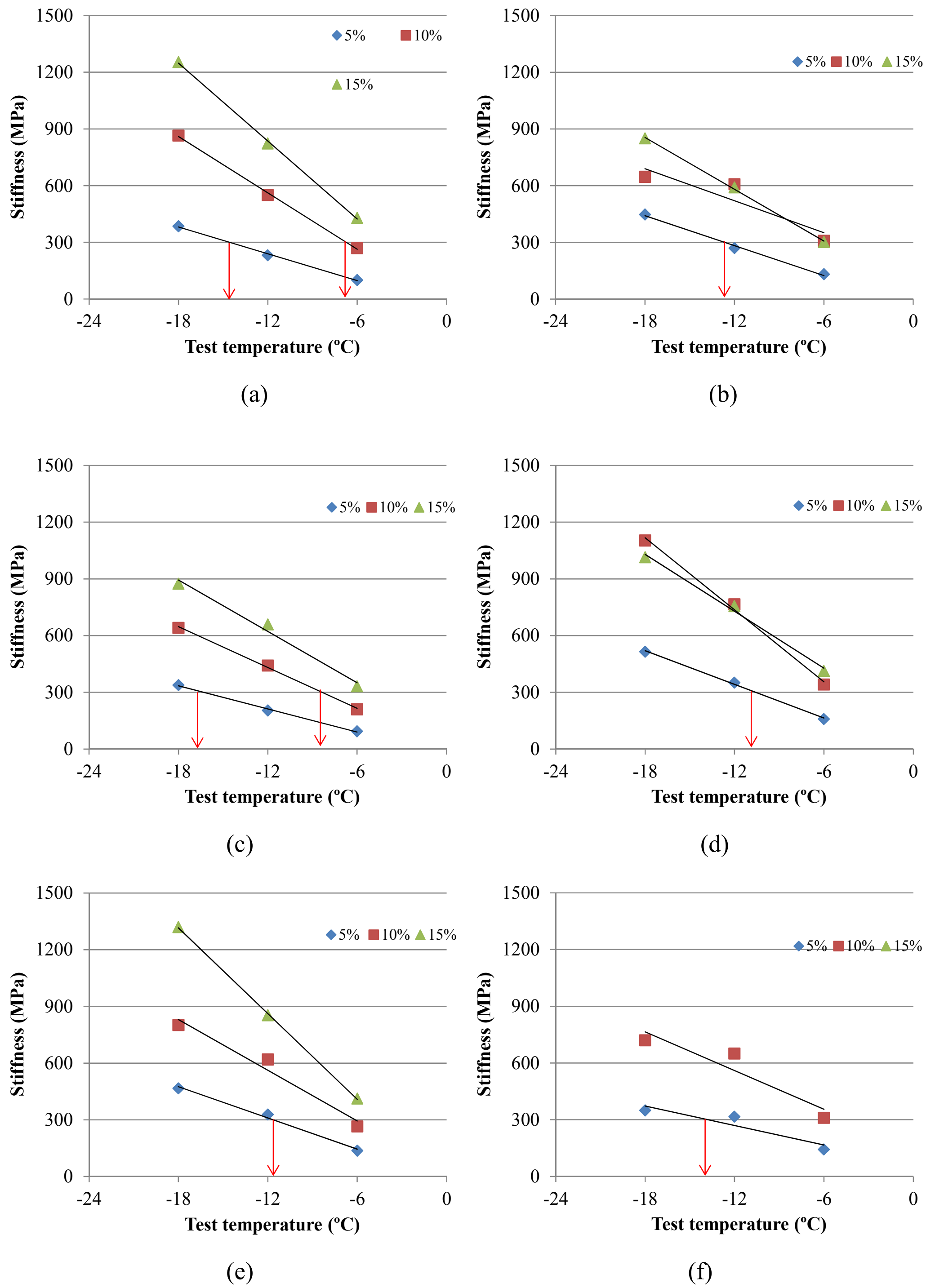


Figure 5-42: Low temperature determinations of burned RAP sources A-F containing RTFO binder PG 64-22 in terms of stiffness

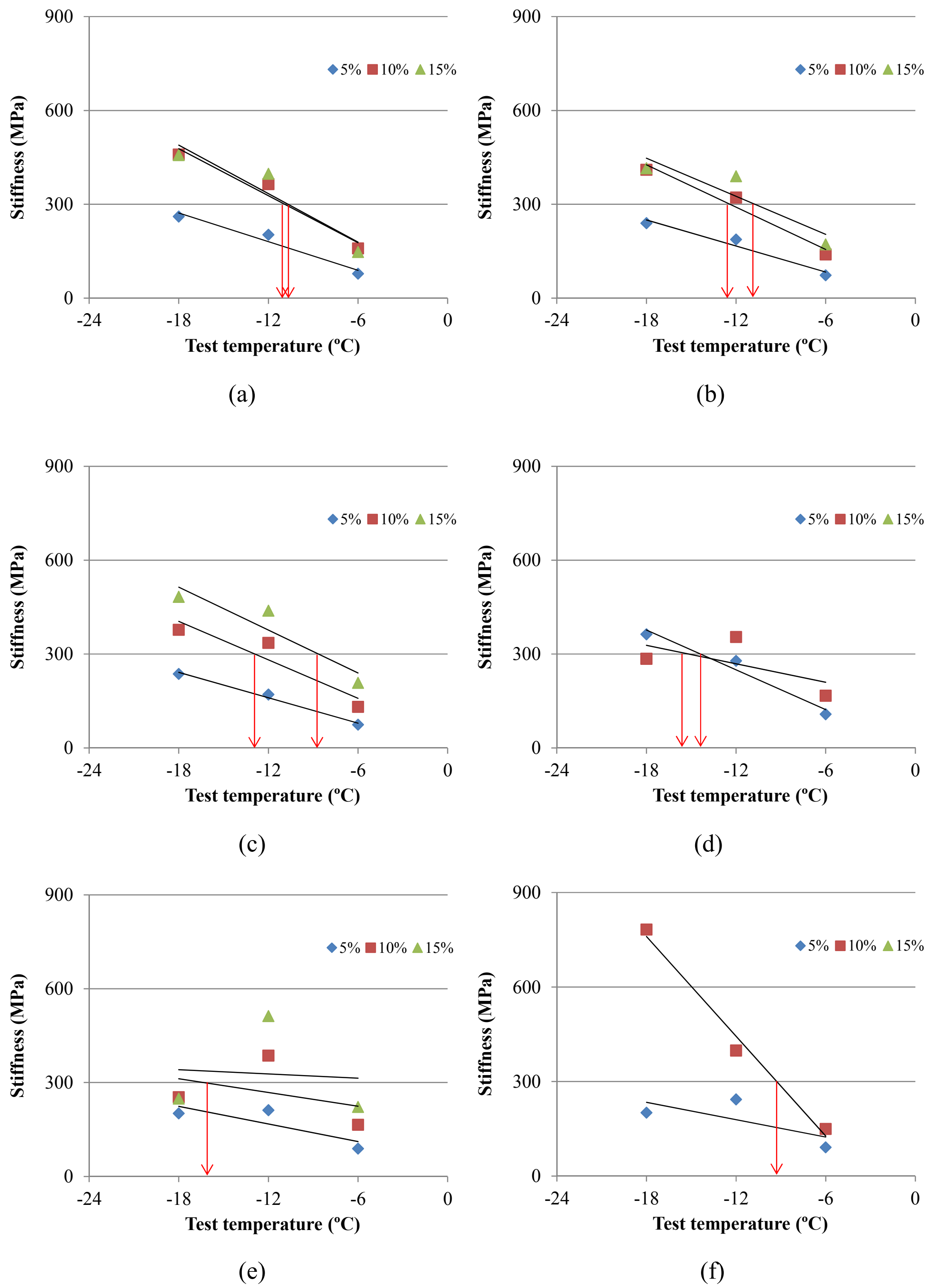


Figure 5-43: Low temperature determinations of burned RAP sources A-F containing RTFO binder PG 76-22 in terms of stiffness

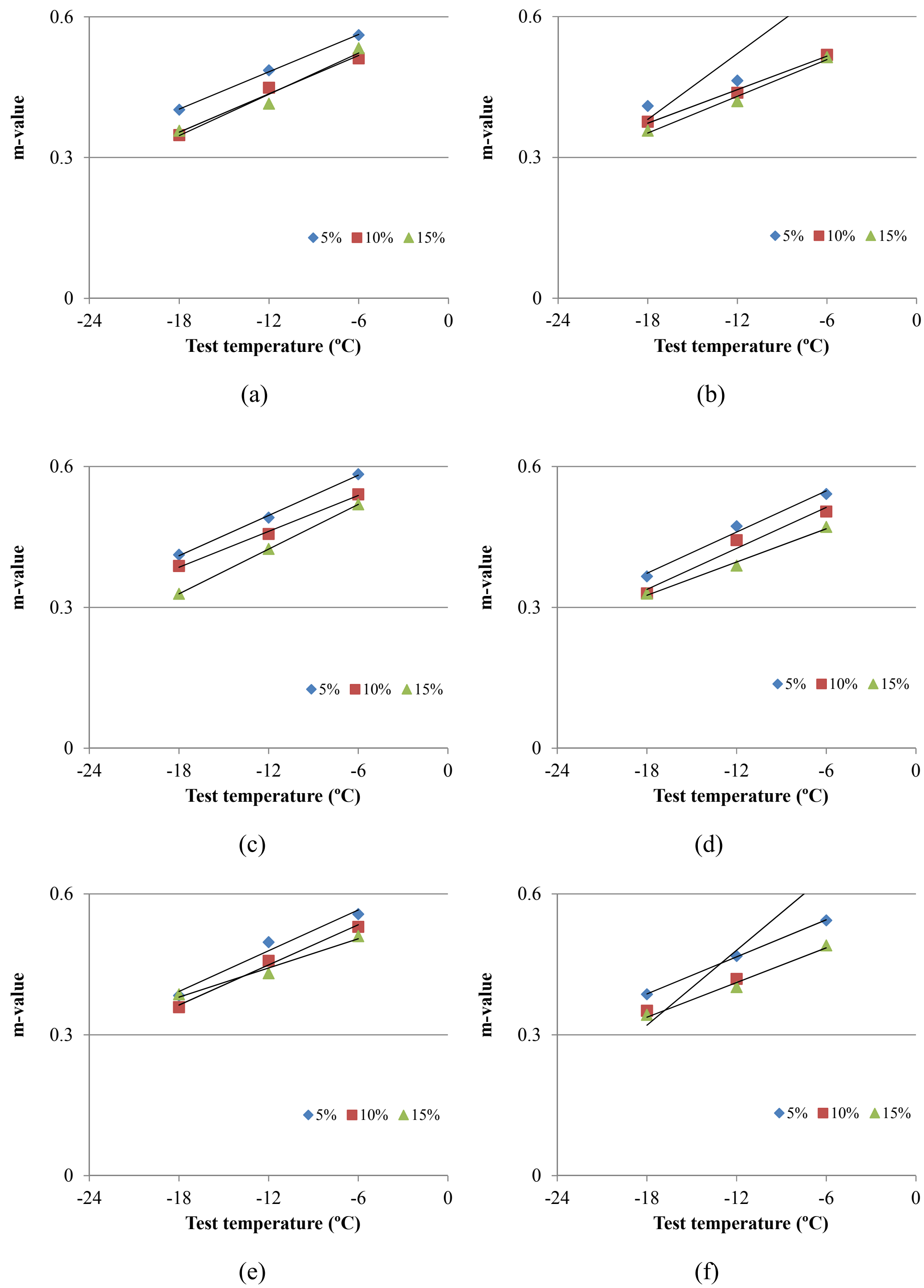


Figure 5-44: Low temperature determinations of burned RAP sources A-F containing RTFO binder PG 58-28 in terms of m-value

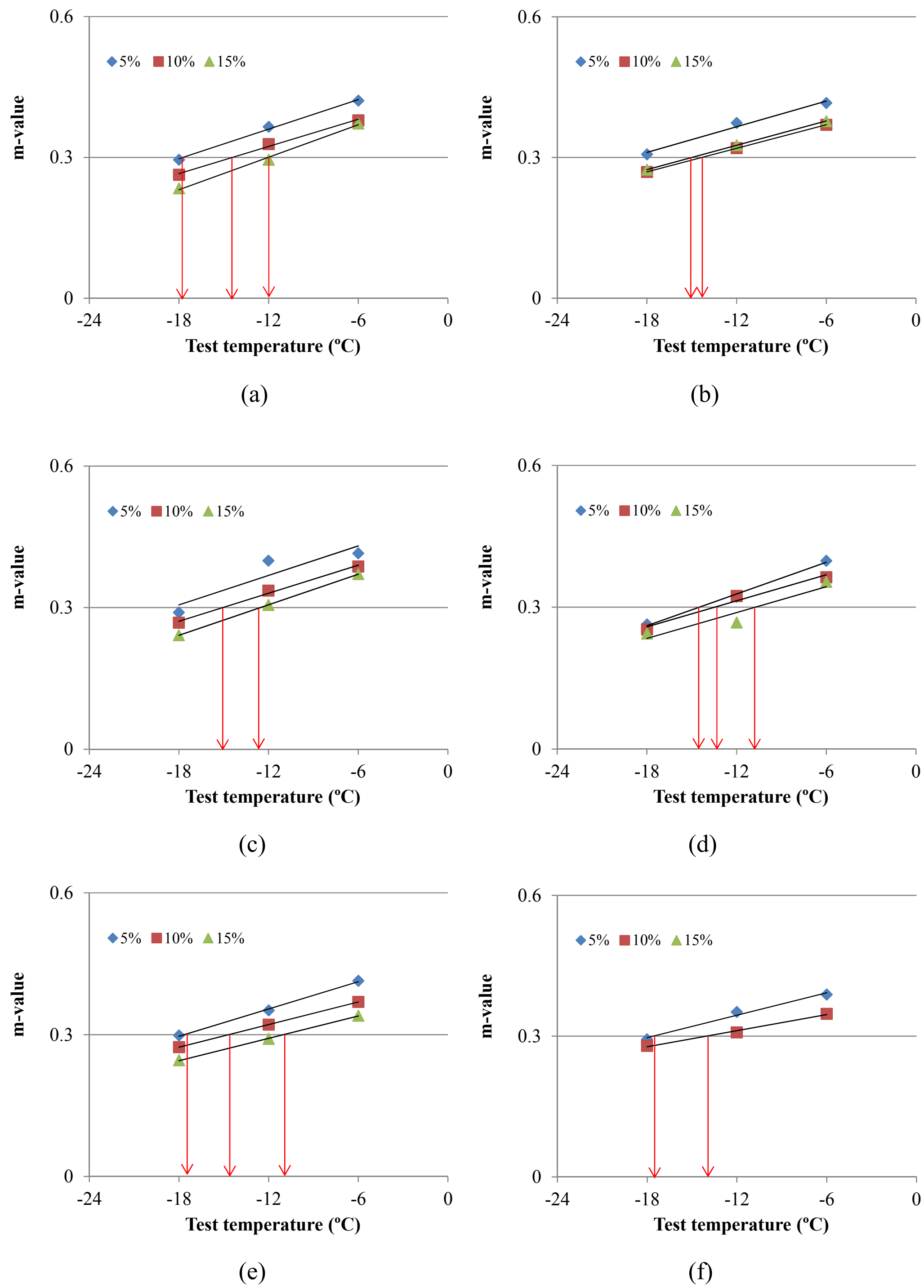


Figure 5-45: Low temperature determinations of burned RAP sources A-F containing RTFO binder 64-22 in terms of m-value

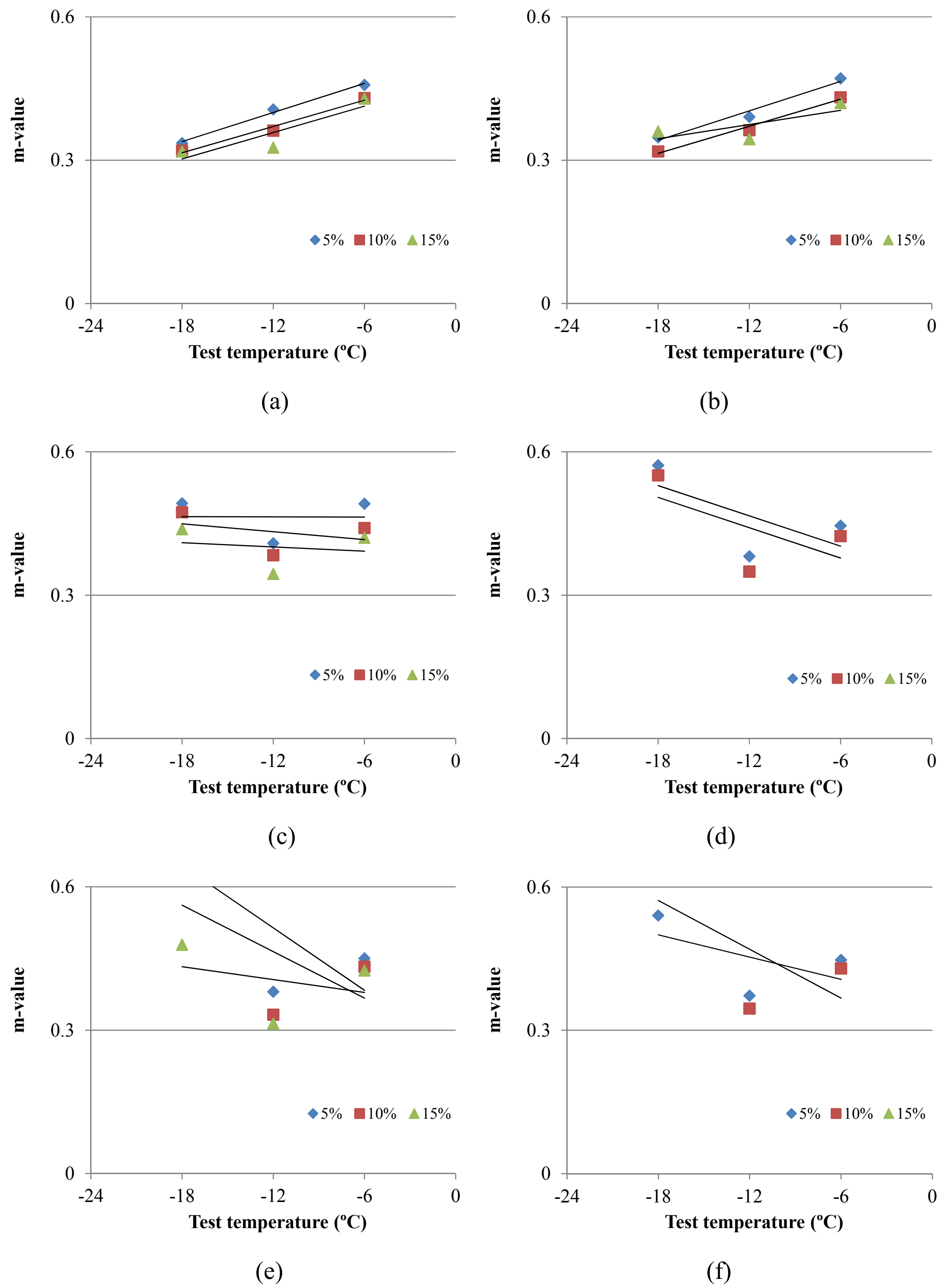


Figure 5-46: Low temperature determinations of burned RAP sources A-F containing RTFO binder PG 76-22 in terms of m-value

The minimum low temperatures of various modified binders mixed with various RAP sources, burned aged binder contents, and RTFO binder types are shown in Table 5-13 through Table 5-15. It can be observed that the low temperatures derived from the conducted regression analysis were summarized from stiffness and m-values.

Table 5-13: Minimum low temperatures of burned RAP sources A-F containing RTFO binder PG 58-28

RAP Source	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	<-24	-15.2	-13.3	<-24	-20.9	-21.6	**<-24**	**-15.2**	**-13.3**
B	<-24	-17.8	-12.4	-21	<-24	-21.8	**-21**	**-17.8**	**-12.4**
C	<-24	-18.2	-12.7	<-24	<-24	-19.8	**<-24**	**-18.2**	**-12.7**
D	-19.3	-14.8	-11.7	-23	-20.4	-19.9	**-19.3**	**-14.8**	**-11.7**
E	<-24	-15.9	-12.7	<-24	-22.3	<-24	**<-24**	**-15.9**	**-12.7**
F	<-24	-14.1	-12.5	<-24	-21.4	-18.7	**<-24**	**-14.1**	**-12.5**

Table 5-14: Minimum low temperatures of burned RAP sources A-F containing RTFO binder PG 64-22

RAP Source	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	-14.7	-6.9	-4.2	-17.8	-14.4	-12	**-14.7**	**-6.9**	**-4.2**
B	-12.8	-4.3	-6	-19.3	-15.2	-14.4	**-12.8**	**-4.3**	**-6**
C	-16.7	-8.3	-5	-18.3	-15.2	-12.7	**-16.7**	**-8.3**	**-5**
D	-10.6	-5.3	-3.6	-14.4	-13.3	-10.8	**-10.6**	**-5.3**	**-3.6**
E	-11.8	-6.2	-4.6	-17.4	-14.6	-11	**-11.8**	**-6.2**	**-4.6**
F	-14.1	-4.8	-	-17.6	-13.9	-	**-14.1**	**-4.8**	**-**

Table 5-15: Minimum low temperatures of burned RAP sources A-F containing RTFO binder PG 76-22

RAP Source	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	-19.6	-10.8	-10.7	-22.1	-19.8	-18.3	**-19.6**	**-10.8**	**-10.7**
B	-21.9	-12.6	-10.7	-22.1	-19.1	<-24	**-21.9**	**-12.6**	**-10.7**
C	-21.8	-12.9	-8.6	-	-	-	**-21.8**	**-12.9**	**-8.6**
D	-14.5	-15.5	-	3.8	1	-	**3.8**	**1**	**-**
E	<-24	-16.3	-5.3	-2.4	-1.9	9.8	**-2.4**	**-1.9**	**9.8**
F	<-24	-9.4	-	6.9	-2.1	-	**6.9**	**-2.1**	**-**

5.6 The Modified Binder of Burned RAP Mortar Mixed with PAV Binder

5.6.1 Stiffness and M-Values of the Modified Binders during Various Test Durations

This section presents the test results of the modified binders mixed with various burned RAP (sand) and three pressured aging vessel (PAV) aged binders (PG 58-28, PG 64-22, and PG 76-22). The fabricated BBR samples were tested at three temperatures (-6 °C, -12 °C, and -18 °C). The main test results are shown in the following figures.

As shown in Figure 5-47 through Figure 5-49, it can be found that, similar to virgin and RTFO binders, all modified binders mixed with burned RAP and PAV binders show the increased m-values and the decreased stiffness values during a loading process at -6 °C. It is also noted that, as expected, the modified binders mixed with PAV binder and a higher burned RAP has a greater stiffness value.

In addition, it can be observed that the stiffness values of modified binders are higher when PAV aged PG 76-22 binder was used, followed by PG 64-22 and PG 58-28 binders.

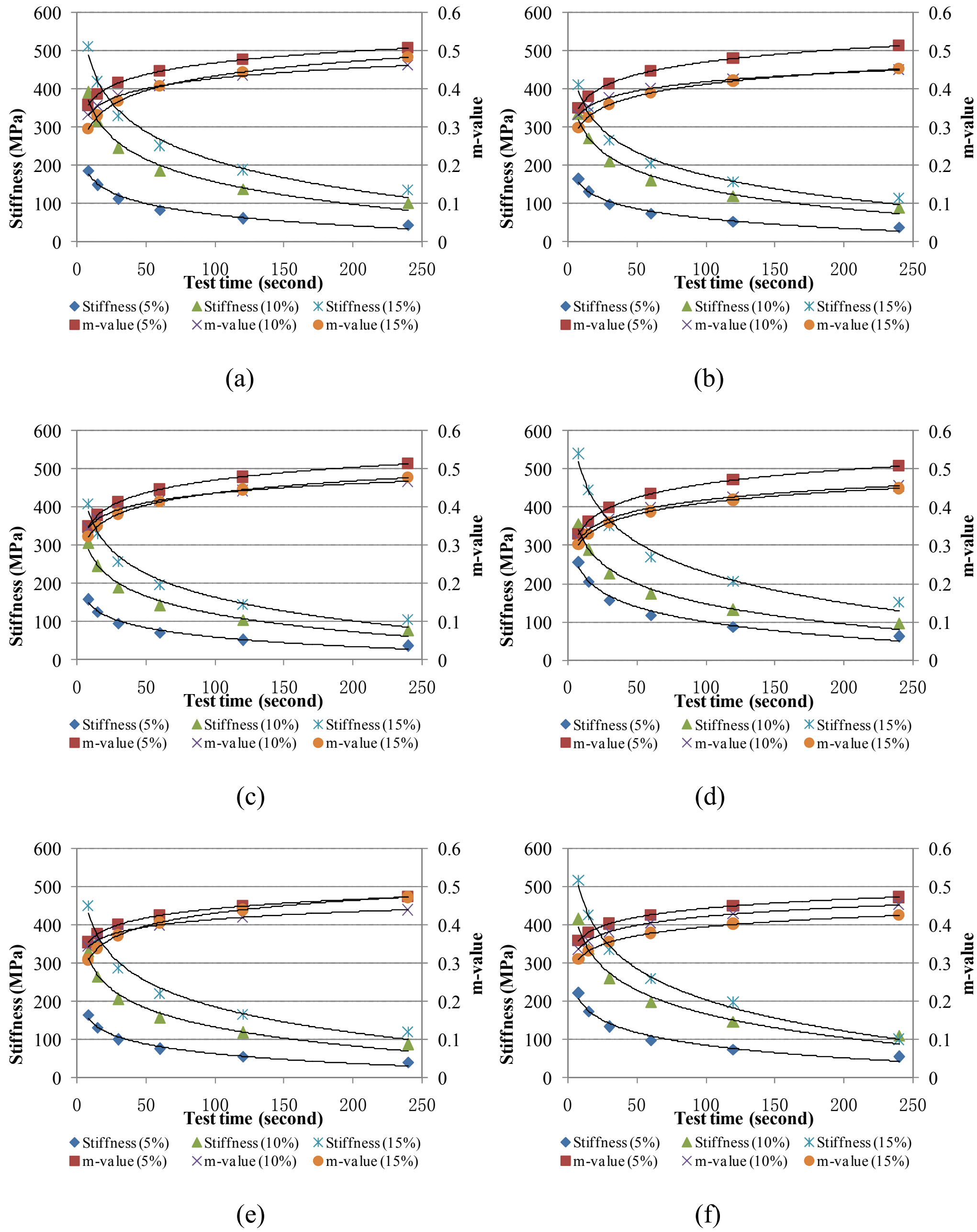


Figure 5-47: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 58-28

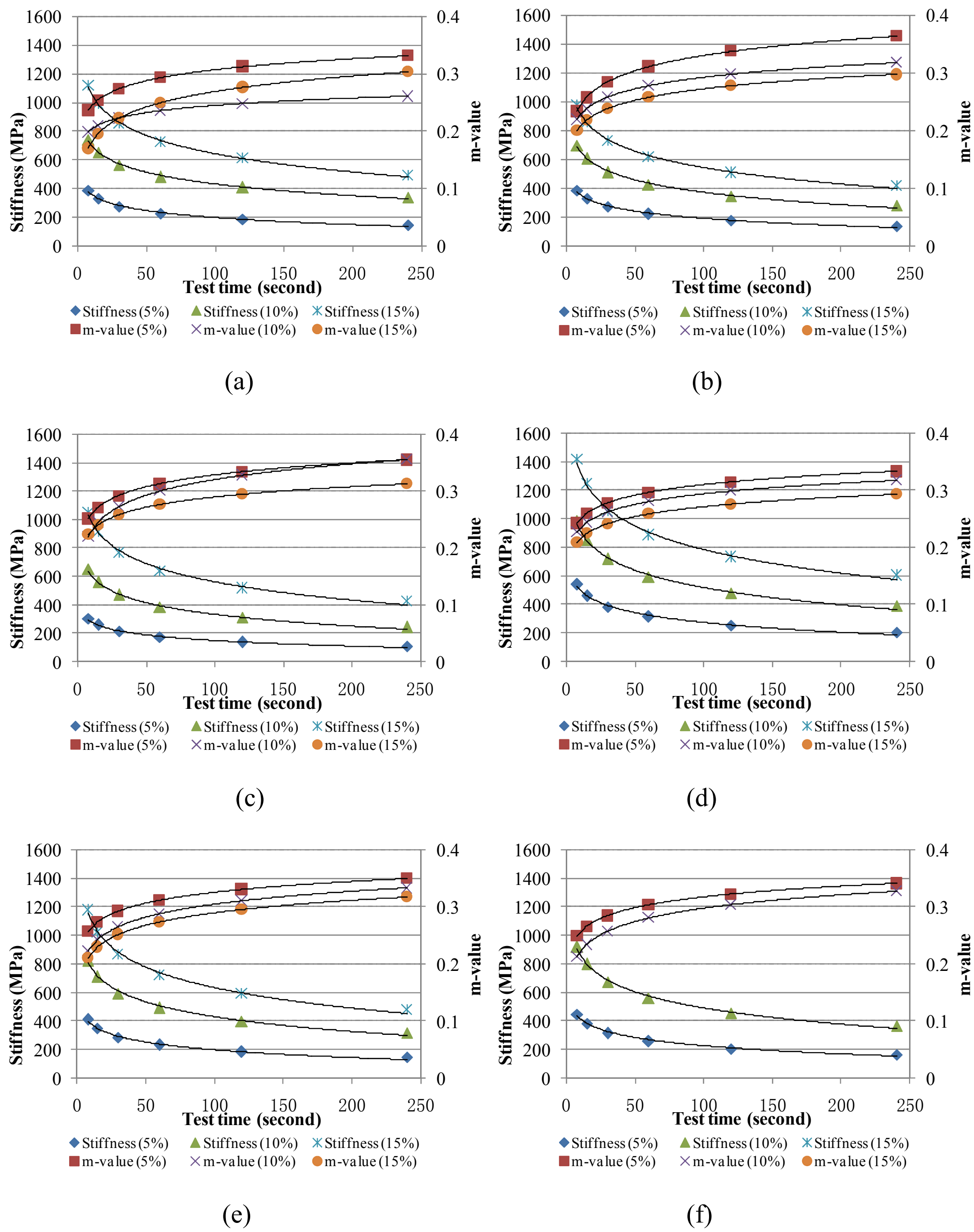


Figure 5-48: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 64-22

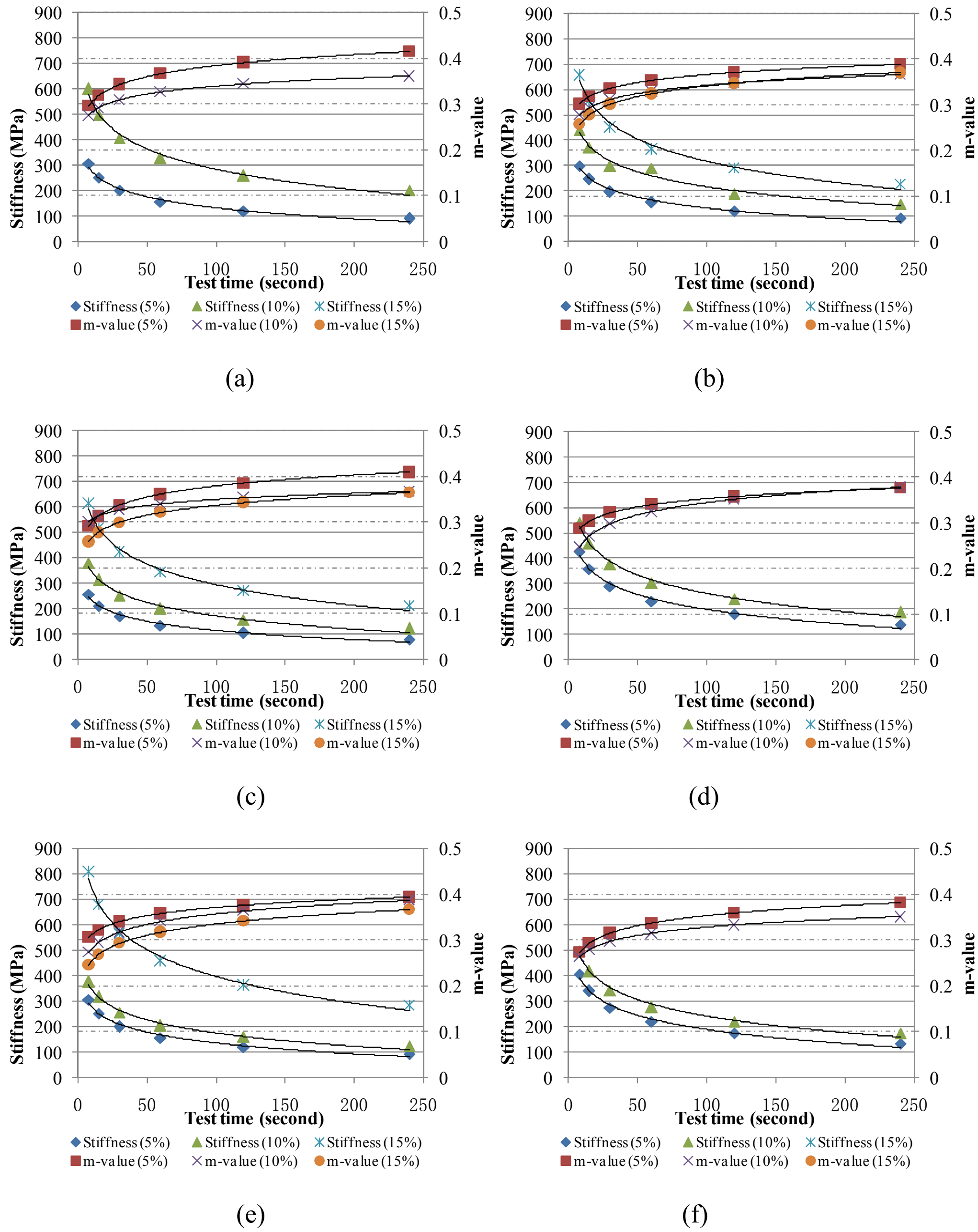


Figure 5-49: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 76-22

Similarly, other stiffness and m-values of the modified binders mixed with burned RAP mortars (A-F) and PAV binders (PG 58-22, PG 64-22, and PG 76-22) at -12 °C and -18 °C are presented in Appendix F. Generally, it can be found that the similar trends can be found regardless of burned RAP source, binder grade, and test temperatures used in this study.

5.6.2 Low Temperature Determinations of the Modified Binders Based on Stiffness and M-Values

This section describes the determinations of low temperatures of various burned RAP mortars mixed with PAV aged binders. Figure 5-50 through Figure 5-52 indicate low temperature determinations of the modified binders with PG 58-28, PG 64-22, and PG 76-22, respectively. It can be seen that, compared to virgin and RTFO binders, PAV binders mixed with a burned RAP results in a higher stiffness value and thus its minimum low temperature is generally higher than -18 °C. In addition, a low burned RAP (5%) even results in a minimum low temperature greater than -12 °C. As shown in Figure 5-51 and Figure 5-52, when PG 64-22 and PG 76-22 binders were used with a percentage of 15% burned RAP, the minimum low temperatures are generally greater than -6 °C for materials used in this study. In addition, it can be noted that when the burned 15% RAP was mixed with PAV aged PG 76-22, some of these binder mixtures were destroyed at a test temperature of -18 °C resulting in no test data presented in these figures.

The m-values of the modified binders mixed with burned RAP (sand) and PAV aged binders can be used to determine the minimum low temperatures of these binders. The analyzed values are shown in Figure 5-53 through Figure 5-55. In general, it can be found that in Figure 5-53, all m-values of the modified binders mixed PAV binder and 5% burned RAP are greater than other modified binders with 10% and 15% burned RAP regardless of RAP type and binder type. As shown in Figure 5-53 through Figure 5-55, all minimum low temperatures are higher than -18 °C, a corresponding m-value of 0.300. In some cases, the m-values are lower than 0.300 when mixed with PAV aged PG 64-22 binder and PG 76-22 binder. Thus, minimum low temperatures are higher than -6 °C.

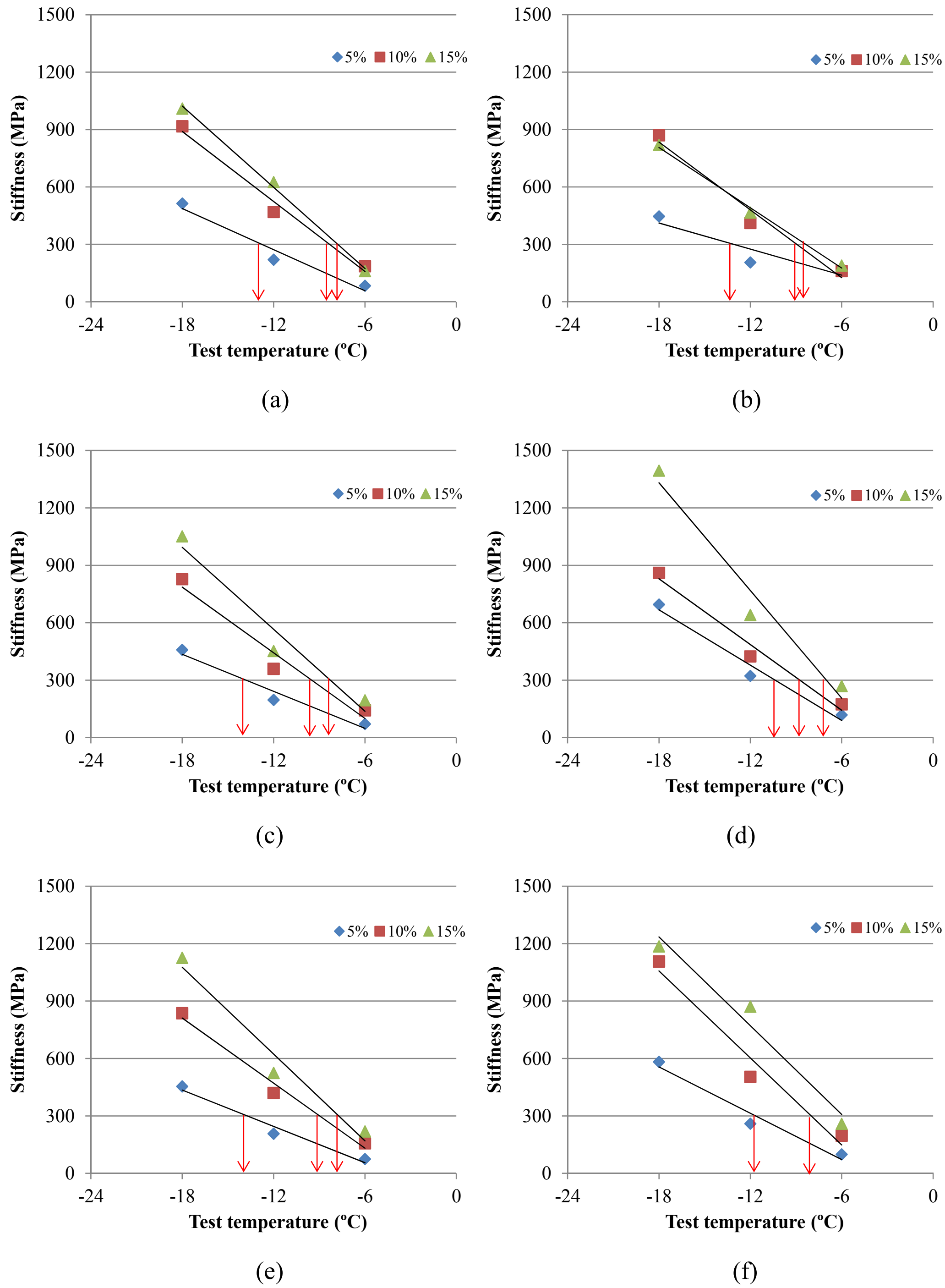


Figure 5-50: Low temperature determinations of burned RAP sources A-F containing PAV binder PG 58-28 in terms of stiffness

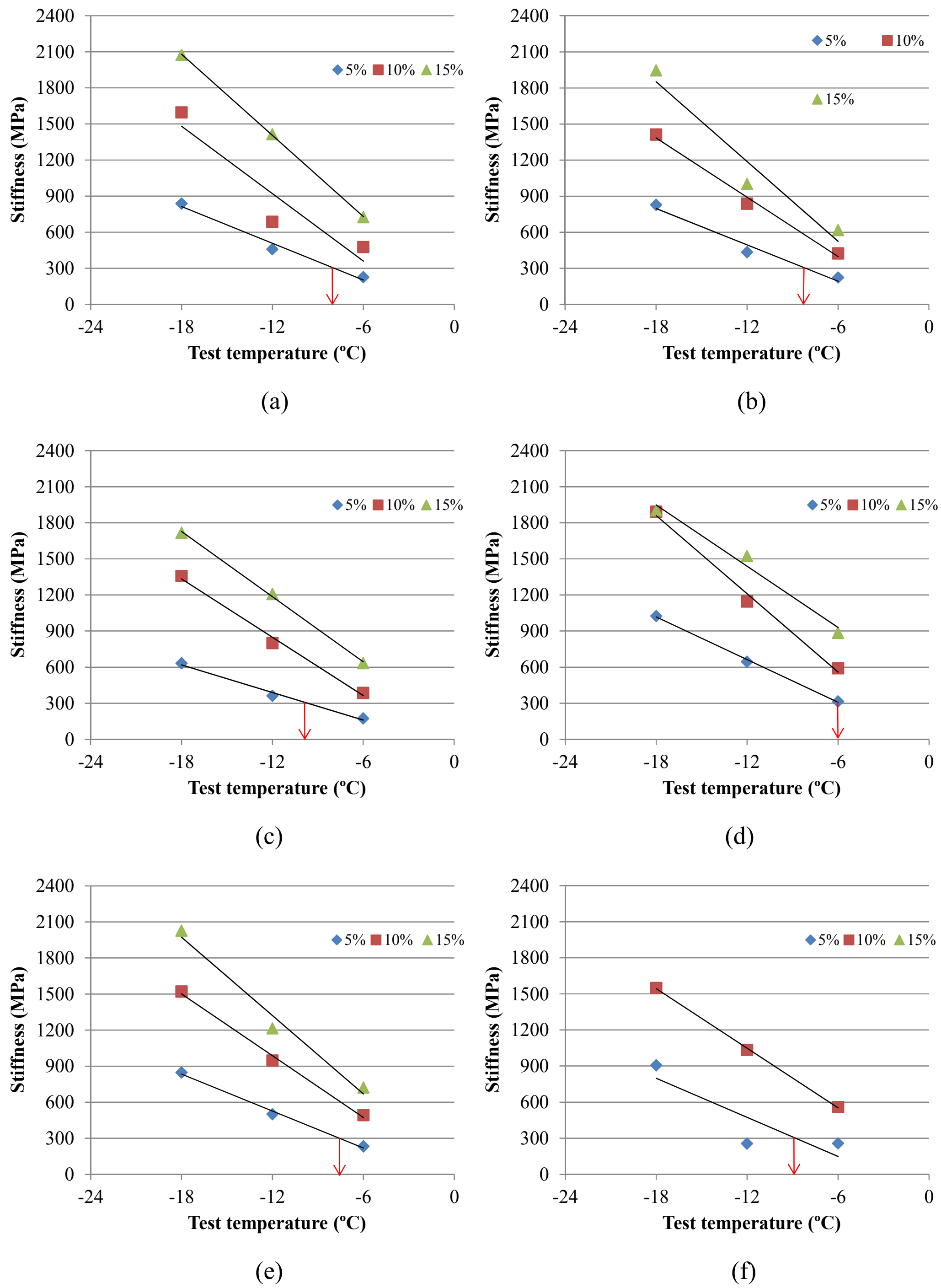
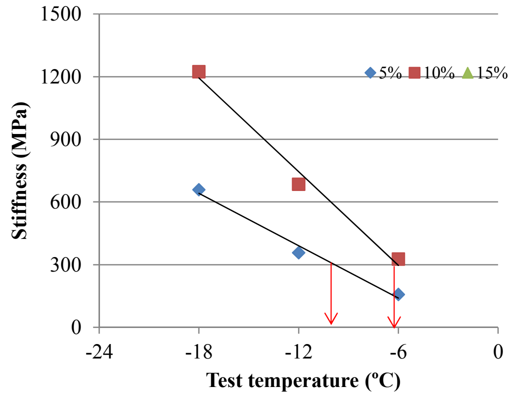
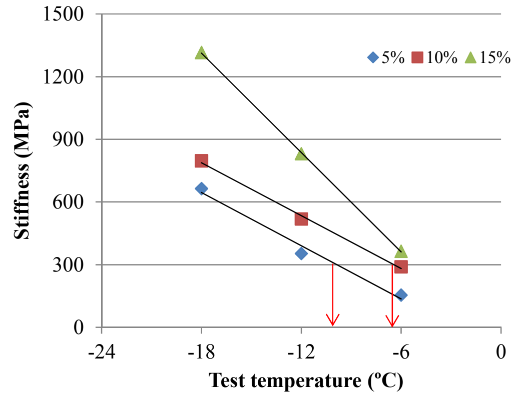


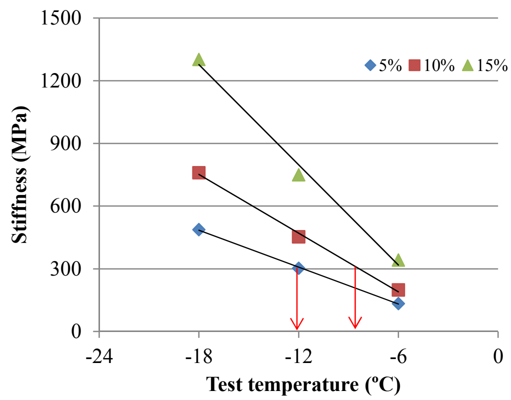
Figure 5-51: Low temperature determinations of burned RAP sources A-F containing PAV binder PG 64-22 in terms of stiffness



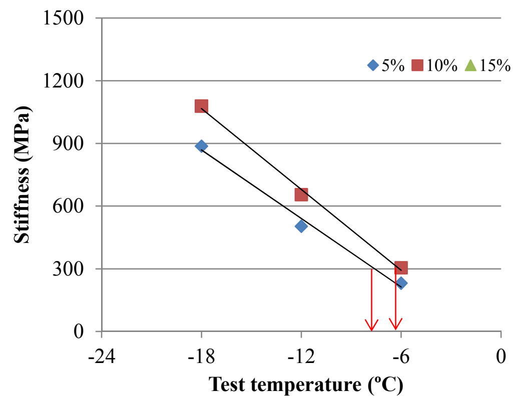
(a)



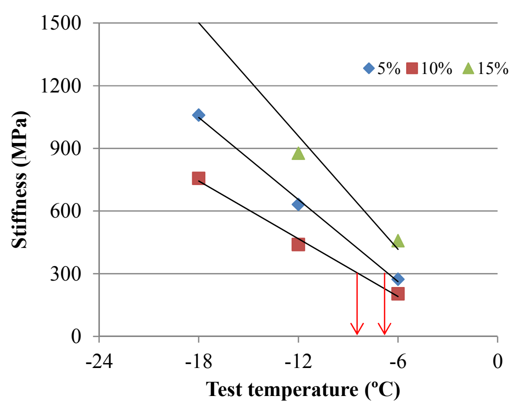
(b)



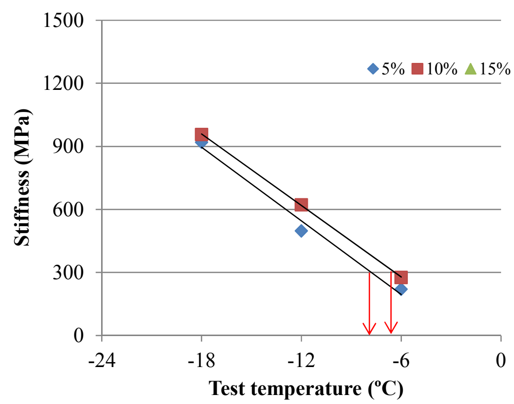
(c)



(d)



(e)



(f)

Figure 5-52: Low temperature determinations of burned RAP sources A-F containing PAV binder PG 76-22 in terms of stiffness

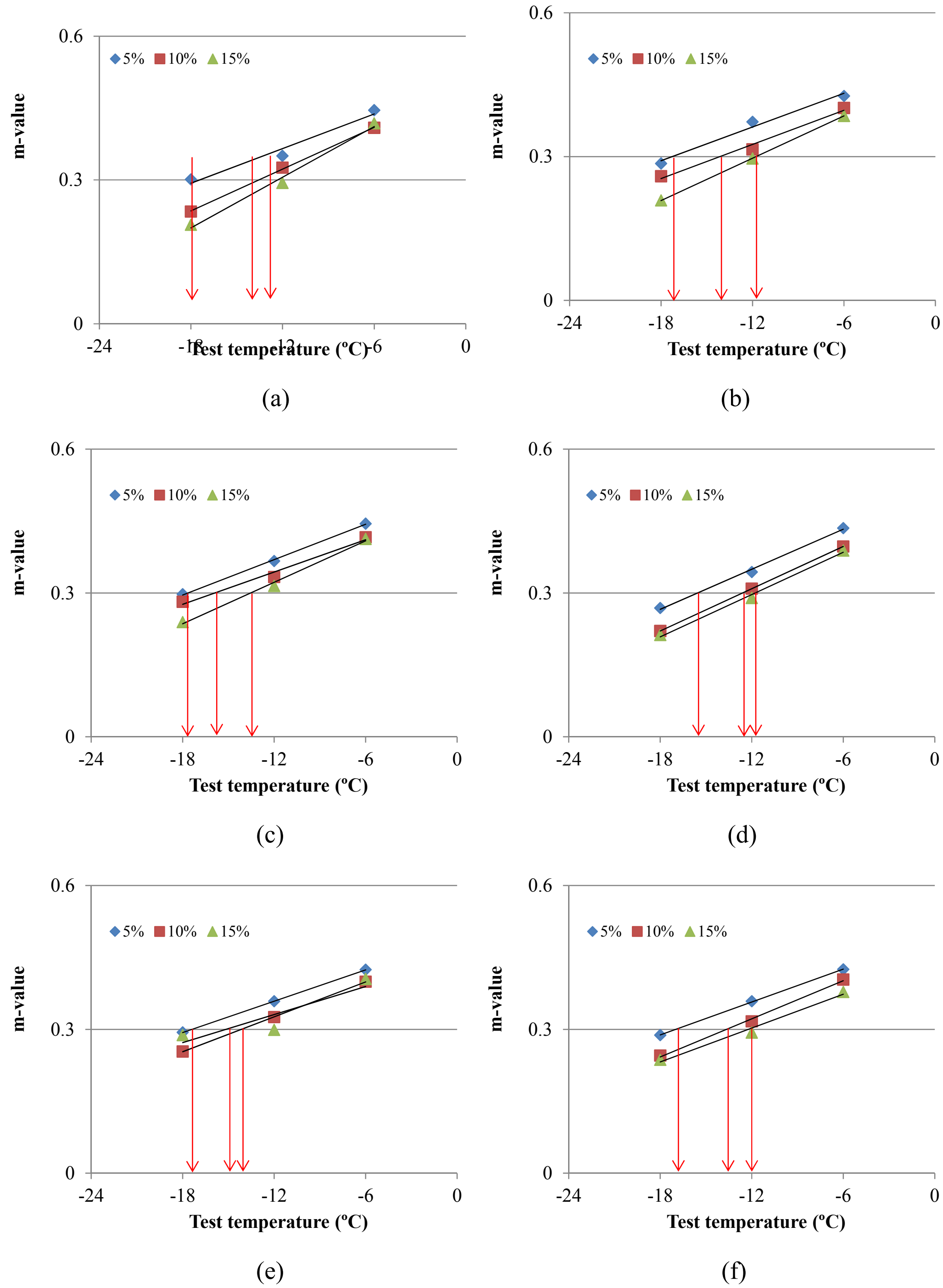


Figure 5-53: Low temperature determinations of burned RAP sources A-F containing PAV binder PG 58-28 in terms of m-value

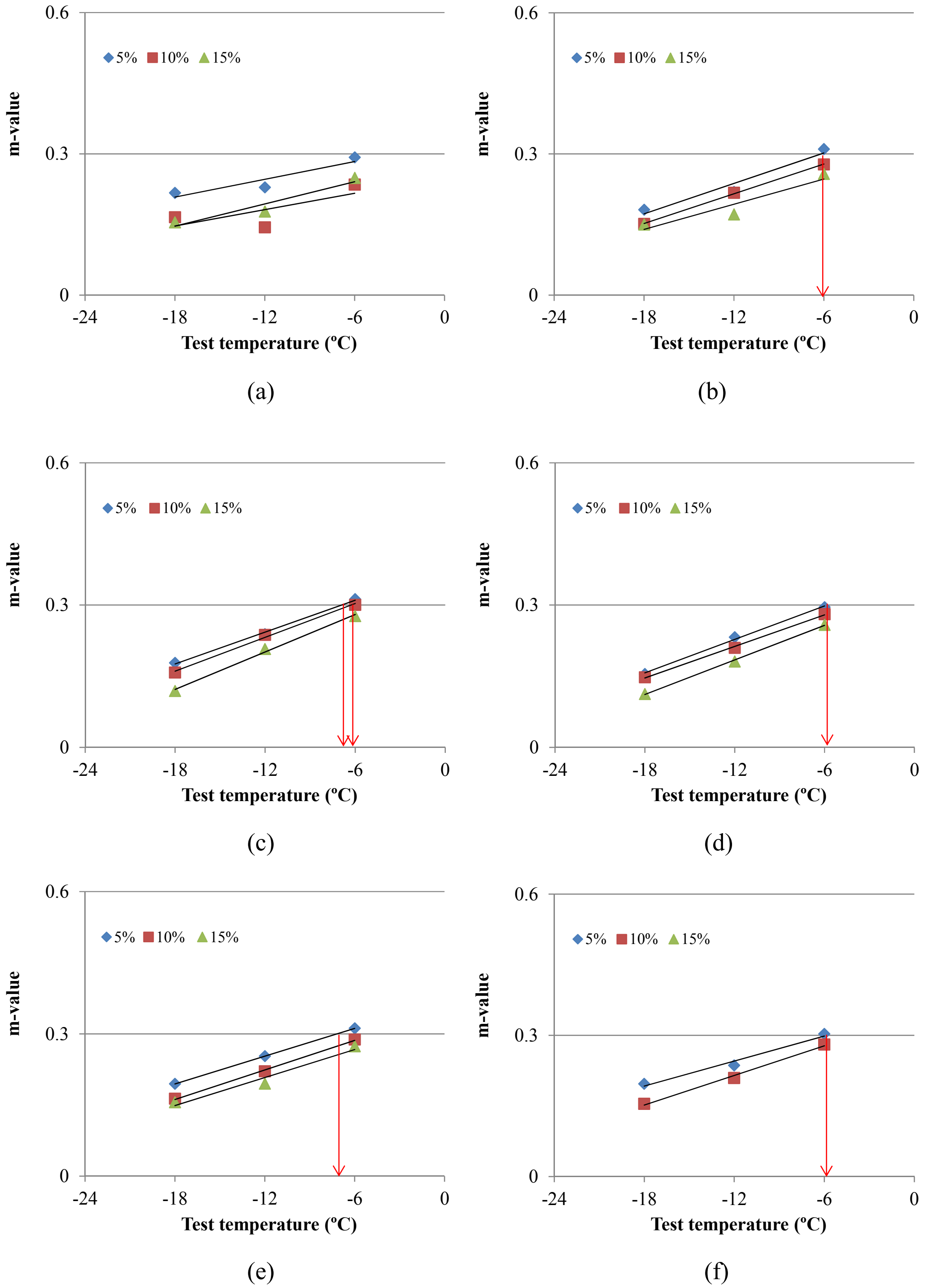


Figure 5-54: Failure temperature determinations of burned RAP sources A-F containing PAV binder PG 64-22 in terms of m-value

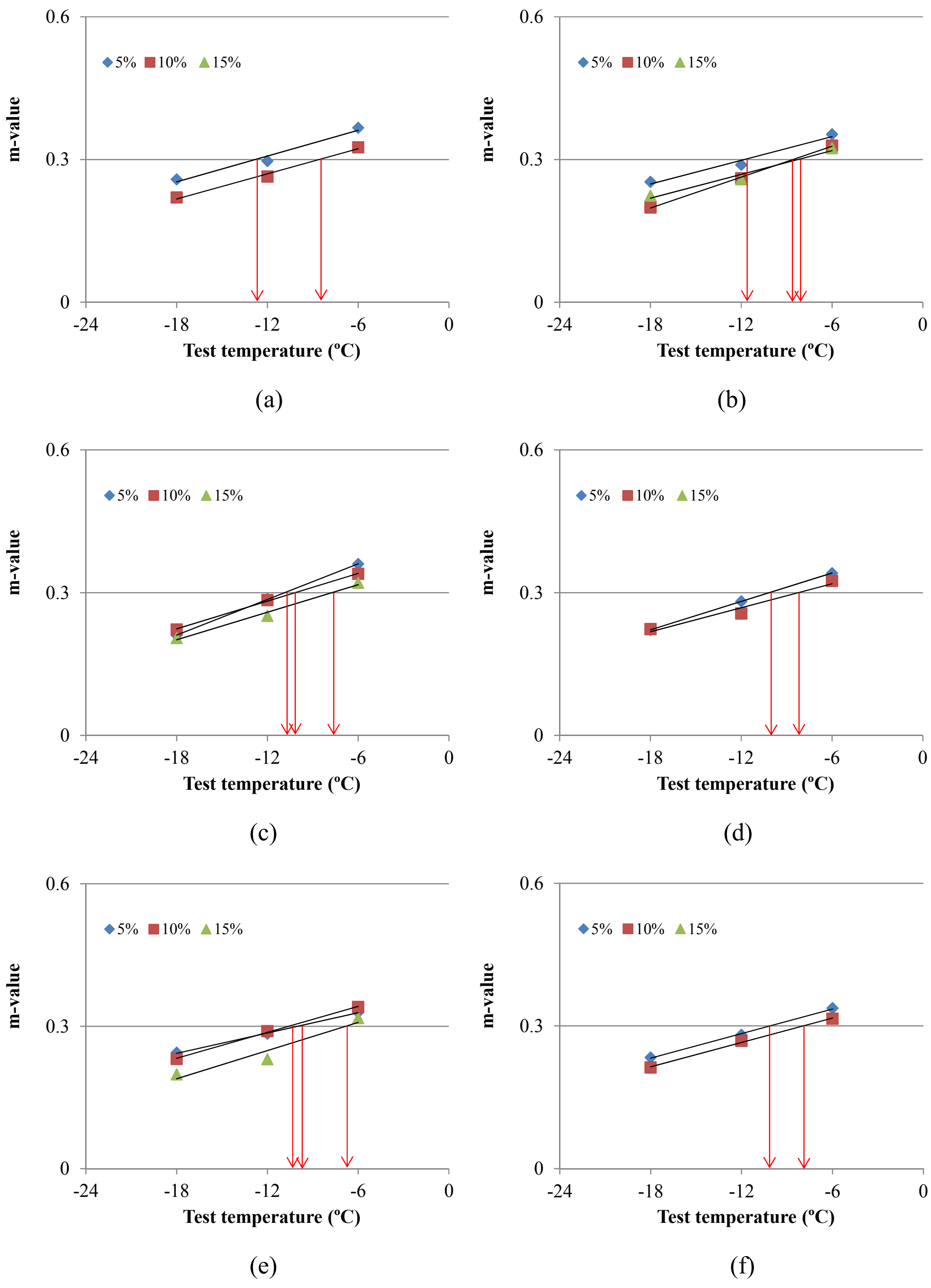


Figure 5-55: Low temperature determinations of burned RAP sources A-F containing PAV binder PG 76-22 in terms of m-value

The minimum low temperatures of various modified binders mixed with various RAP sources, burned aged binder contents, and PAV binder types are shown in Table 5-16 through Table 5-18. These minimum low temperatures derived from the conducted regression analysis were determined from stiffness and m-values.

Table 5-16: Minimum low temperatures of burned RAP sources A-F containing PAV binder PG 58-28

RAP Source	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	-12.7	-8.3	-7.9	-17.3	-13.5	-12.3	**-11.7**	**-7.9**	**-6**
B	-13.2	-8.8	-8.3	-17.2	-14.1	-11.6	**-13.2**	**-8.8**	**-8.3**
C	-14.1	-9.4	-8.2	-17.6	-15.8	-13.5	**-14.1**	**-9.4**	**-8.2**
D	-10.5	-8.8	-7	-15.3	-12.5	-11.8	**-10.5**	**-8.8**	**-7**
E	-13.8	-9.1	-7.8	-17.5	-15.1	-14	**-13.8**	**-9.1**	**-7.8**
F	-11.7	-7.9	-6	-16.8	-15.6	-12	**-11.7**	**-7.9**	**-6**

Table 5-17: Minimum low temperatures of burned RAP sources A-F containing PAV binder PG 64-22

RAP Source	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	-8.1	-5.3	-2.3	-3.8	7.8	2.2	**-3.8**	**7.8**	**2.2**
B	-8.4	-4.7	-4.1	-6.1	-3.8	0.4	**-6.1**	**-3.8**	**0.4**
C	-9.8	-5.2	-2.4	-6.9	-6.1	-4.4	**-6.9**	**-5.2**	**-2.4**
D	-6	-3.7	2.3	-5.8	-4.2	-2.1	**-5.8**	**-3.7**	**2.3**
E	-7.7	-4.1	-2.8	-7.1	-4.8	-2.6	**-7.1**	**-4.1**	**-2.6**
F	-8.8	-3.2	-	-5.9	-3.8	-	**-5.9**	**-3.2**	**-**

Table 5-18: Minimum low temperatures of burned RAP sources A-F containing PAV binder PG 76-22

RAP Source	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	-10	-6.2	-	-12.7	-8.4	-	**-10**	**-6.2**	**-**
B	-9.8	-6.5	-5.4	-11.7	-8.6	-8.1	**-9.8**	**-6.5**	**-5.4**
C	-11.8	-8.5	-5.7	-10.8	-10.1	-7.7	**-10.8**	**-8.5**	**-5.7**
D	-7.5	-6.3	-	-10	-8.3	-	**-7.5**	**-6.3**	**-**
E	-8.4	-6.7	-5.2	-9.7	-10.3	-6.8	**-8.4**	**-6.7**	**-5.2**
F	-7.9	-6.4	-	-10.2	-7.9	-	**-7.9**	**-6.4**	**-**

6 BBR Results for Extracted RAP Binder

6.1 <u>The Modified PAV Binder of Extracted Aged Binder Mixed with Virgin Binder</u>

6.1.1 Stiffness and M-Values of the Modified PAV Binders

Three virgin binders (PG 58-28, PG 64-22, and PG 76-22) were blended with two percentages of extracted aged binders (15% and 30%) from six RAP sources (A-F). These binders were performed a long-term aging procedure per Superpave specification. The fabricated BBR samples were tested at three temperatures (-6 °C, -12 °C and -18 °C). Most of the test results are shown in the following figures.

As shown in Figure 6-1, at -6 °C, it can be observed that, as expected, the stiffness values of virgin binders with extracted aged binders generally decrease while m-values increase when the loading duration increases with logarithmic trends regardless of RAP source. In addition, the stiffness and m-values of the modified binders blended from virgin PG 58-28 binders and RAP mortar could not be obtained because these binders were too soft at the testing temperature of -6 °C. As shown in Figure 6-1, it can be found that a higher percentage of extracted aged binder results in a higher stiffness value and a lower m-value regardless of test time and RAP source.

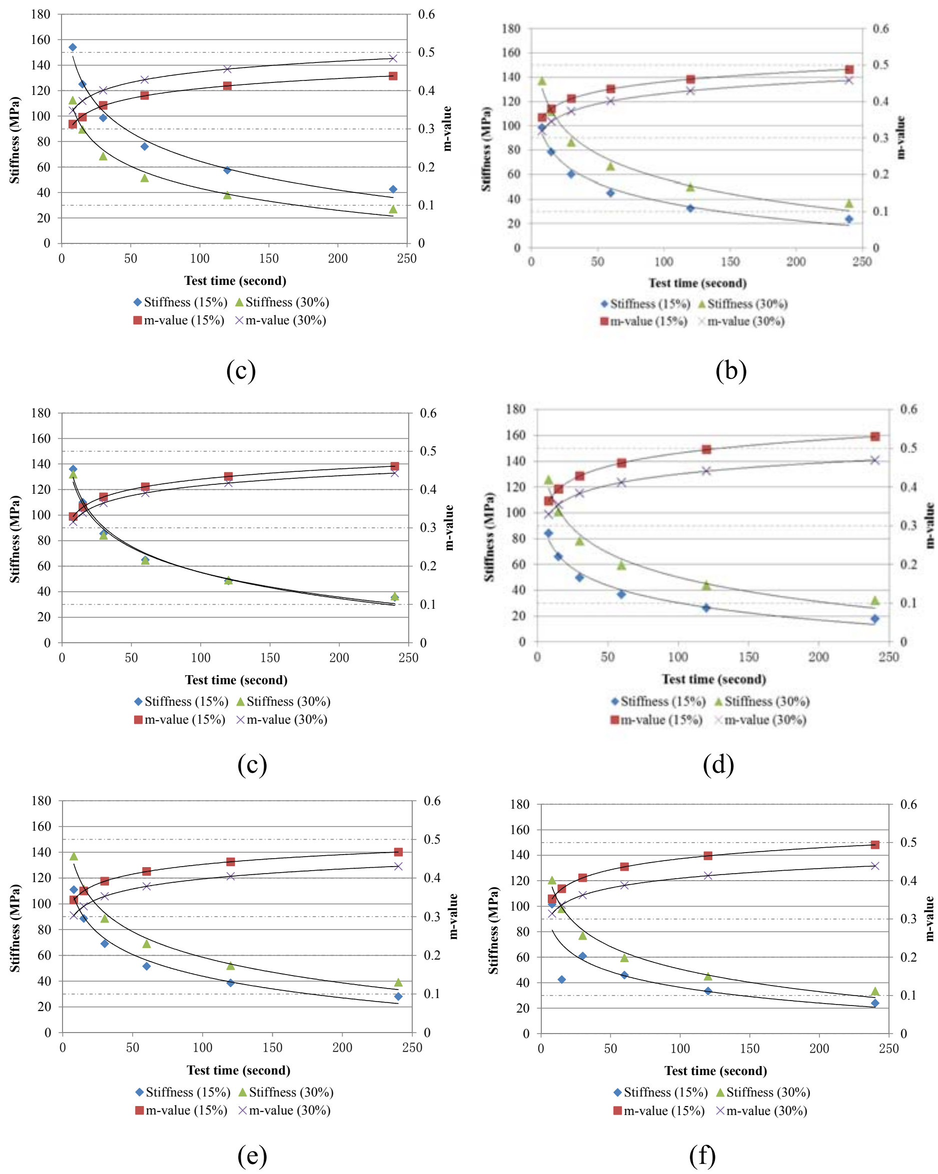


Figure 6-1: Stiffness and m-values of the modified PAV binder mixed with extracted binders A-F and virgin binder PG 58-28 at -6ºC

The stiffness and m-values of the modified PAV binders originally mixed with PG 64-22 binders and extracted aged binders (15% and 30%) are shown in Figure 6-2. Similar to Figure 6-1, stiffness and m-values of the modified PAV binders are following logarithmic trends regardless of RAP source. Similarly, the stiffness values were reduced and m-values increased when the test time increased. Apart from the materials used in Figure 6-1, all modified PAV binders are stiff enough to be tested in BBR. In addition, these stiffness values are generally greater than those values from the modified binders blended with PG 58-28.

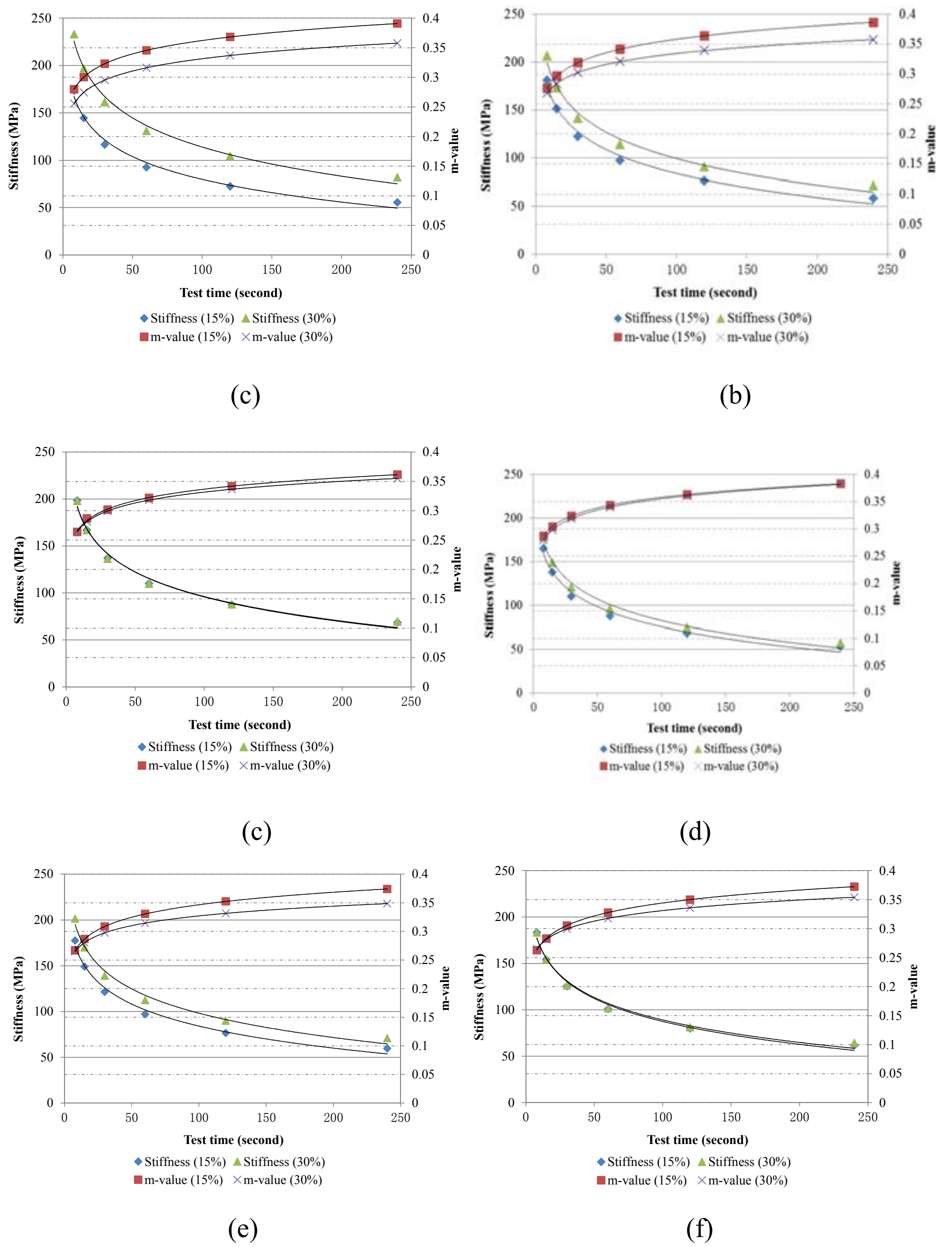
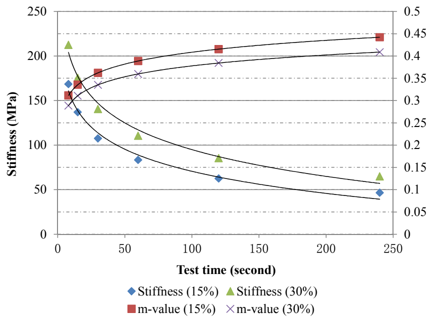
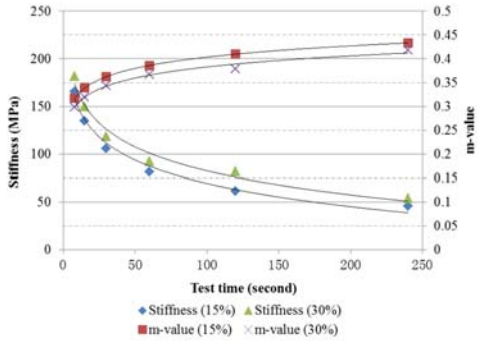


Figure 6-2: Stiffness and m-values of the modified PAV binder mixed with extracted binders A-F and virgin binder PG 64-22 at -6ºC

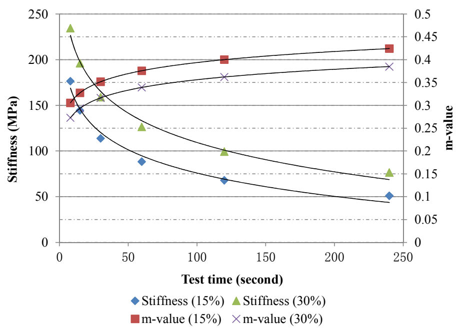
Figure 6-3 shows the stiffness and m-values of the modified PAV binders mixed with PG 76-22 binders and extracted aged binders (15% and 30%). Similar to Figure 6-1, stiffness and m-values of the modified PAV binders are following logarithmic trends regardless of RAP source. Also, the stiffness values reduced and m-values were increased when the test time increased.



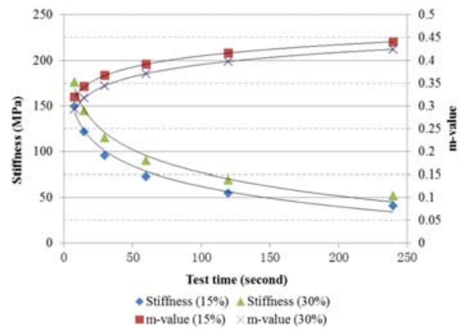
(c)



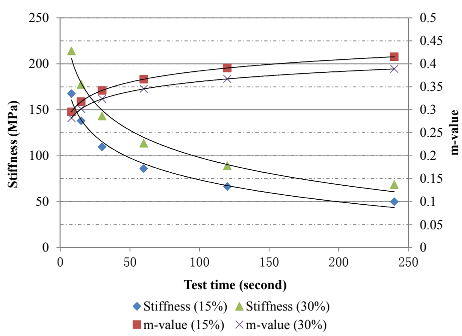
(b)



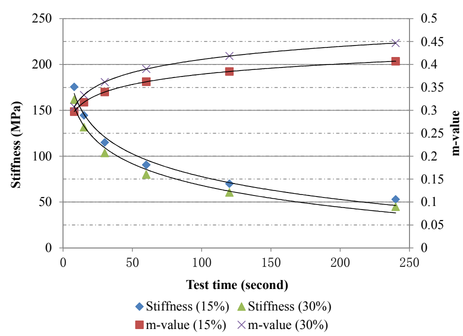
(c)



(d)



(e)



(f)

Figure 6-3: Stiffness and m-values of RAP sources A-F modified with virgin binder PG 76-22 at -6°C

Other stiffness and m-values of the modified PAV binders mixed with extracted binders (A-F) and binders (PG 58-22, PG 64-22, and PG 76-22) at -12 °C and -18 °C are presented in Appendix G. Generally, similar trends can be found regardless of RAP source, binder grade, and test temperatures used in this study.

6.1.2 Low Temperature Determinations of the Modified PAV Binders Based on Stiffness and M-Values

Figure 6-4 shows the minimum low temperatures at a certain stiffness, 300 MPa, of various modified PAV binders originally mixed with extracted binders (15% and 30%) and virgin binder PG 58-28. It can be noted that an increase in test temperature reduces the stiffness value of modified PAV binders. In addition, a higher aged binder significantly has a greater stiffness value regardless of test temperature and RAP source. Meanwhile, it can be seen that, in some cases, the modified PAV binders containing 15% aged binder have stiffness values less than 300 MPa at the lowest temperature of -18 °C used in this study.

Additionally, Figure 6-4 indicates that, generally, when the binders were modified with 30% aged binder and they have a stiffness value of 300 MPa, their corresponding low temperatures are typically less than -12 °C but greater than -18 °C. Therefore, an increased aged binder can results in a reduction of low temperature resistance.

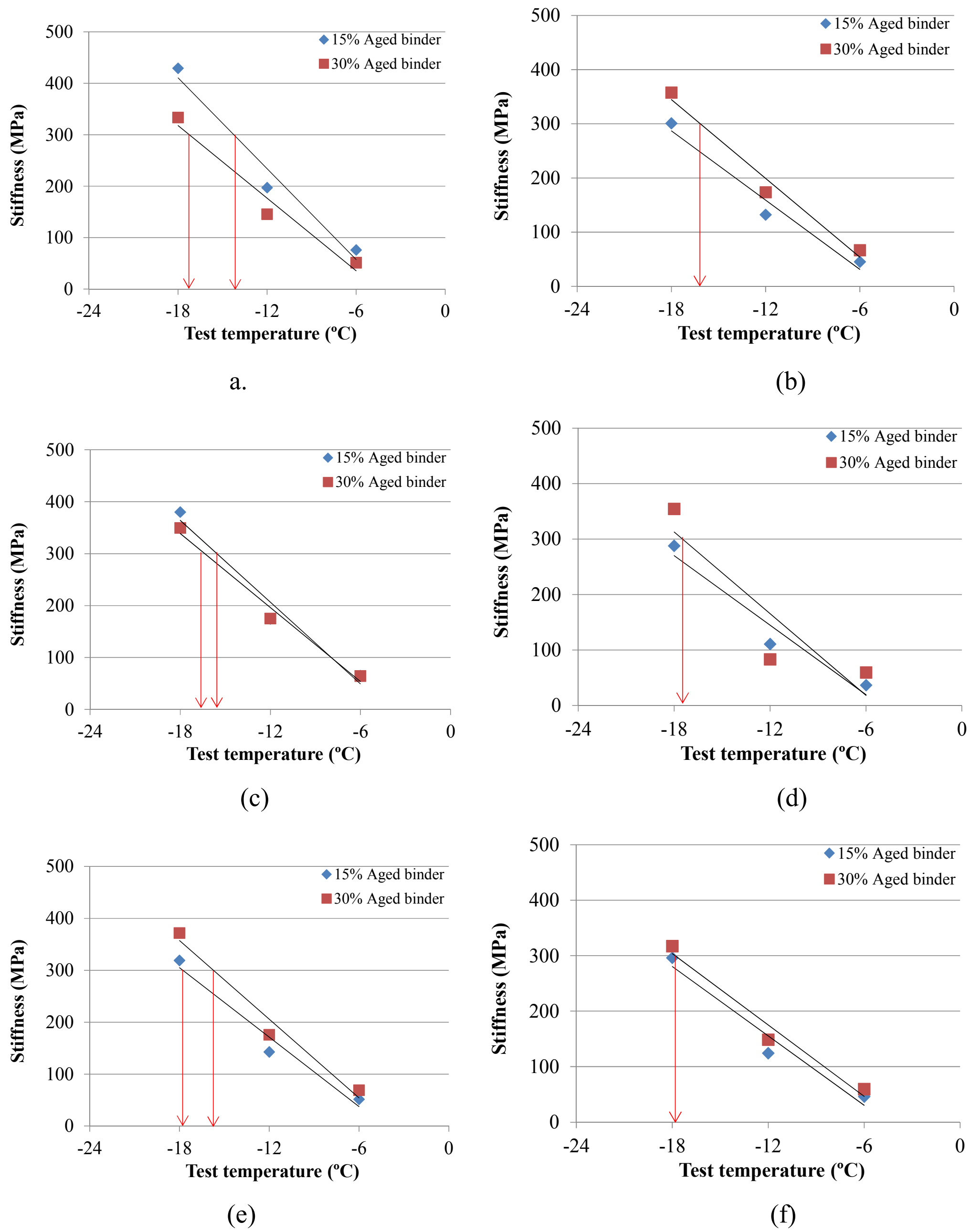


Figure 6-4: Low temperature determinations of modified PAV binders A-F with binder PG 58-28 in terms of stiffness

Similarly, the minimum low temperatures, at a stiffness equaling to 300 MPa, of various modified PAV binders originally mixed with binder PG 64-22 and the extracted binders (15% and 30%) are shown in Figure 6-5. Similar to Figure 6-4, a higher temperature results in a lower stiffness value. In addition, a higher aged binder content also leads to a higher stiffness regardless of RAP source and test temperature.

In addition, Figure 6-5 shows that the modified binders mixed with 15% aged binder and PG 64-22 binder generally have the low temperatures greater than -12 °C, which is higher than those modified binders mixed with PG 58-22 binder containing same percentage of aged binder. Moreover, when the modified binders blended with 30% aged binder, their low temperatures are generally close to -12 °C. This generally meets the low temperature requirement of a PG 64-22 binder. Therefore, a 30% aged binder can be used in the mixture without affecting the low temperature cracking resistance.

The stiffness values of modified PAV binders originally mixed with extracted aged binders (15% and 30%) and PG 76-22 binder at different test temperatures are shown in Figure 6-6. Similar to Figure 6-4 and Figure 6-5, an increase in test temperature results in a reduction of stiffness, but an increased extracted aged binder content leads to an increase of stiffness regardless of RAP source.

From these stiffness values, it can be observed that the minimum low temperatures at a stiffness of 300 MPa of various modified binders generally are less than -12 °C when 15% and 30% aged binders were used regardless of RAP source. Therefore, similar to the modified binder with PG 64-22, a 30% aged binder can be used in the PG 76-22 mixture without affecting the low temperature cracking resistance.

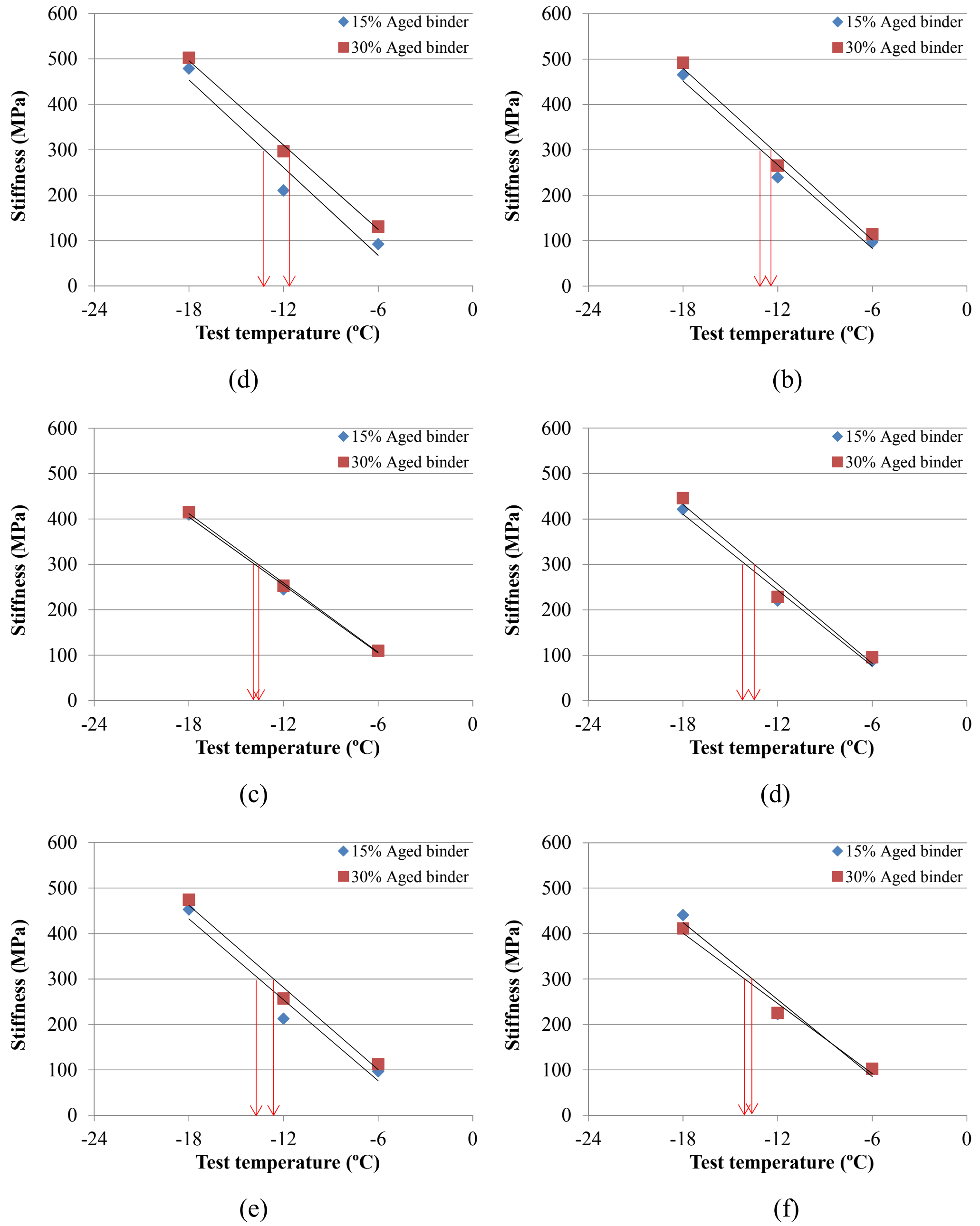


Figure 6-5: Low temperature determinations of modified PAV binders A-F with binder PG 64-22 in terms of stiffness

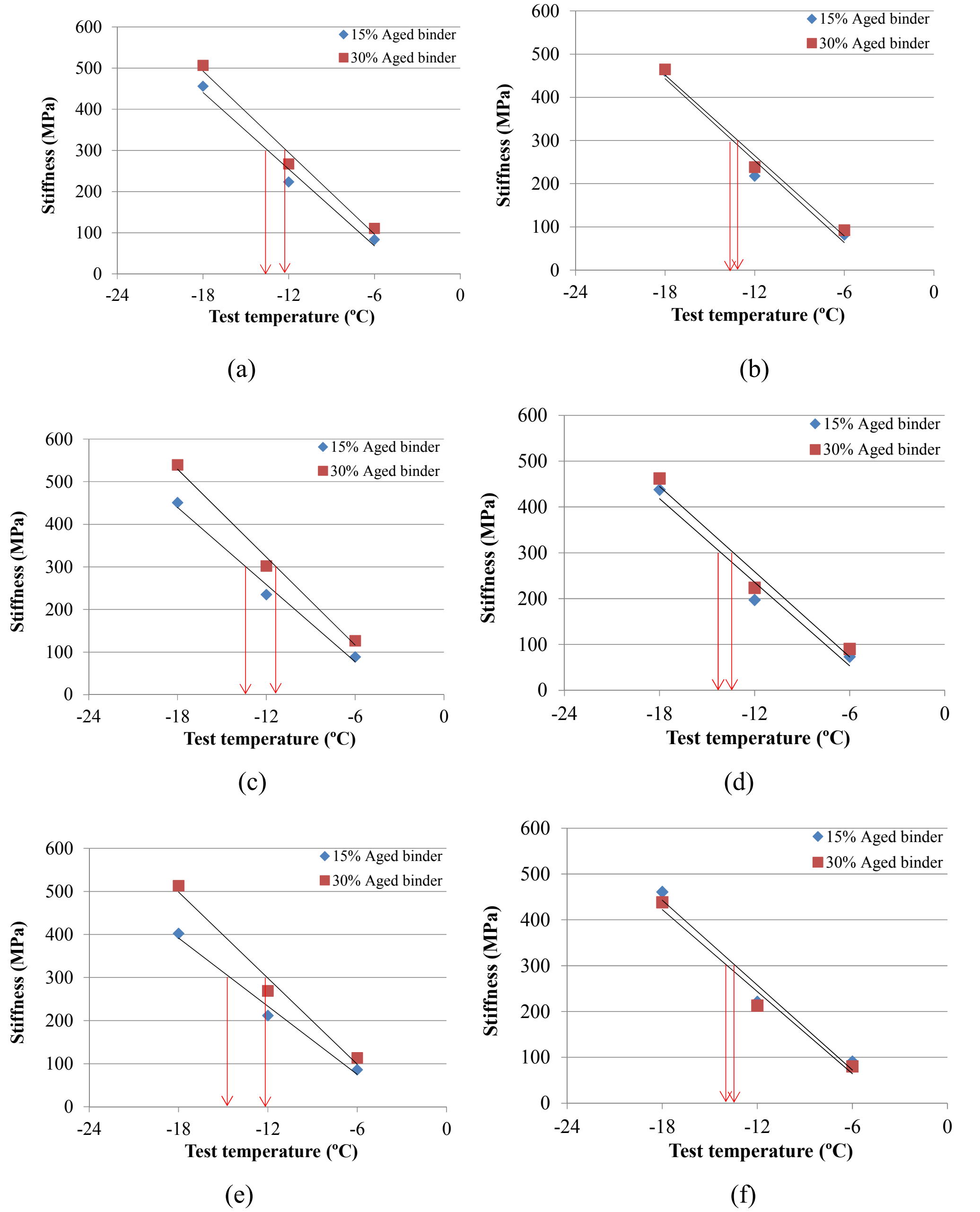


Figure 6-6: Low temperature determinations of modified PAV binders A-F with binder PG 76-22 in terms of stiffness

The low temperature determination of the modified binders originally mixed with various extracted binders (15% and 30%) and binder PG 58-28 with respect to m-values are shown in Figure 6-7. It can be observed that the m-values are greater than 0.300 at temperatures greater than -18 °C regardless of RAP source and extracted binder content. Therefore, this would result in a reduction of low temperature resistance of PG 58-28 binder.

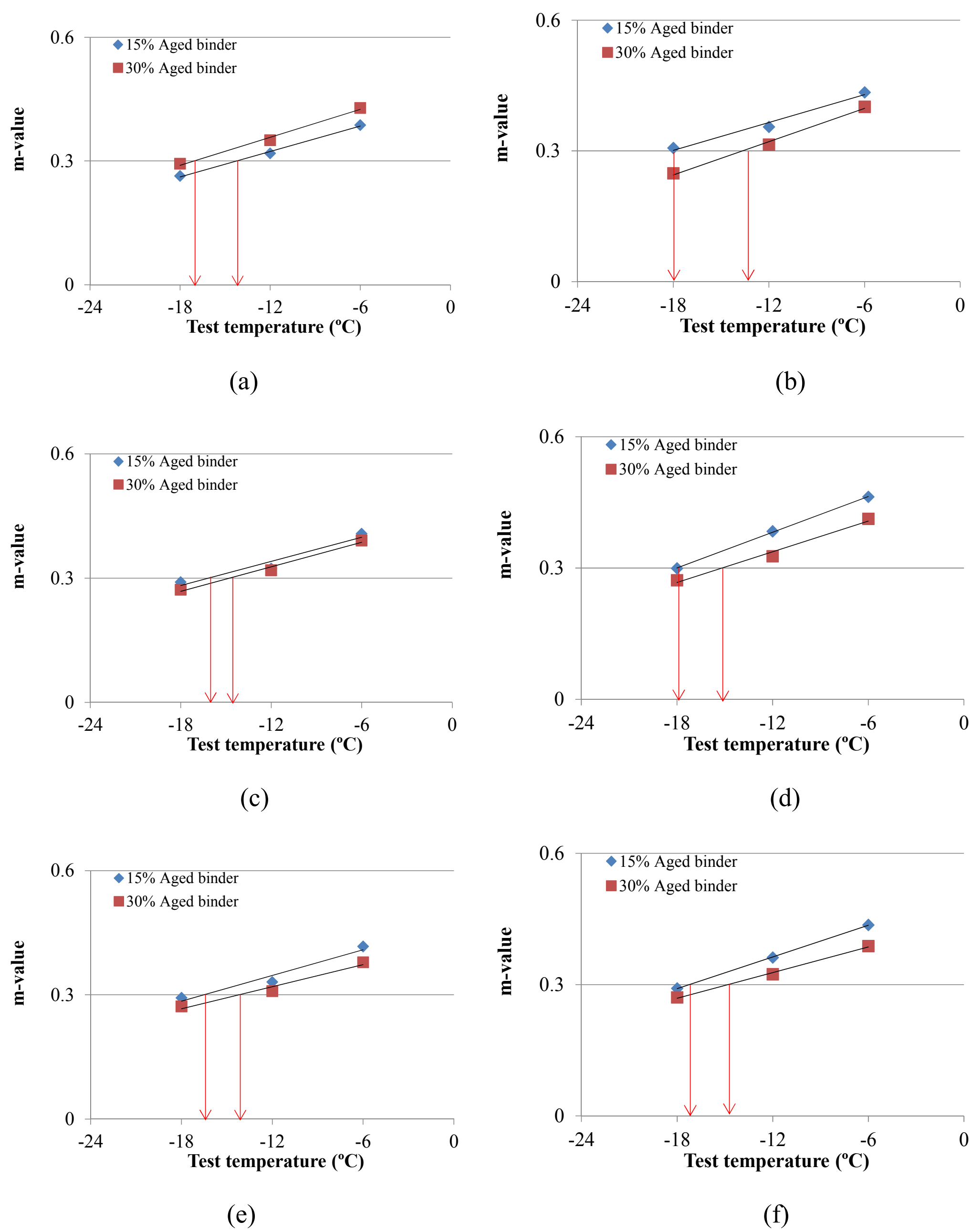


Figure 6-7: Low temperature determinations of modified PAV binders A-F with binder PG 58-28 in terms of m-value

As shown in Figure 6-8, the modified binders originally mixed with various extracted binders and PG 64-22 have m-values greater than 0.300 when the tested temperatures are greater than -12 °C. The modified binders with 15% aged binder, generally, have higher m-values compared the modified binder containing 30% aged binder when tested at same temperature. In addition, it can be observed that the minimum low temperatures are generally in the range of -12 °C to -6 °C with a corresponding m-value of 0.300. Therefore, these modified binders generally do not meet the requirement of low temperature crack resistance of a PG 64-22 binder.

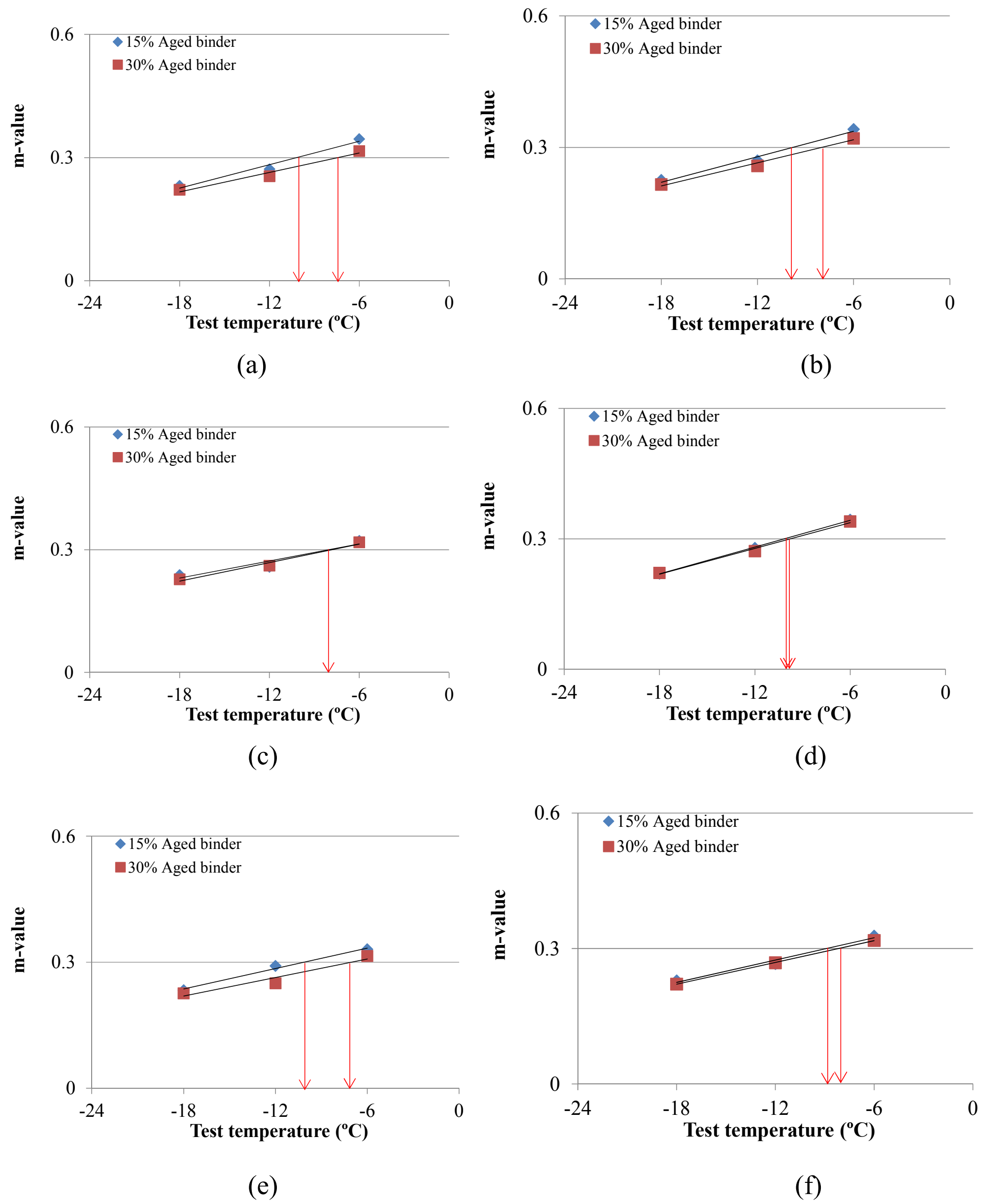


Figure 6-8: Low temperature determinations of modified PAV binders A-F with binder PG 64-22 in terms of m-value

In Figure 6-9, it can be noted that m-values of the modified PAV binders mixed with various extracted binders and PG 76-22 are generally close to 0.300 at -12 °C when the extracted aged binder is 30%. All minimum low temperatures are less than -12 °C when used 15% extracted binder but slightly greater than -12 °C when contained 30% extracted binder regardless of RAP sources used in this study. Appendix I shows the results of extracted RAP plus virgin binders at -12 and -18 °C.

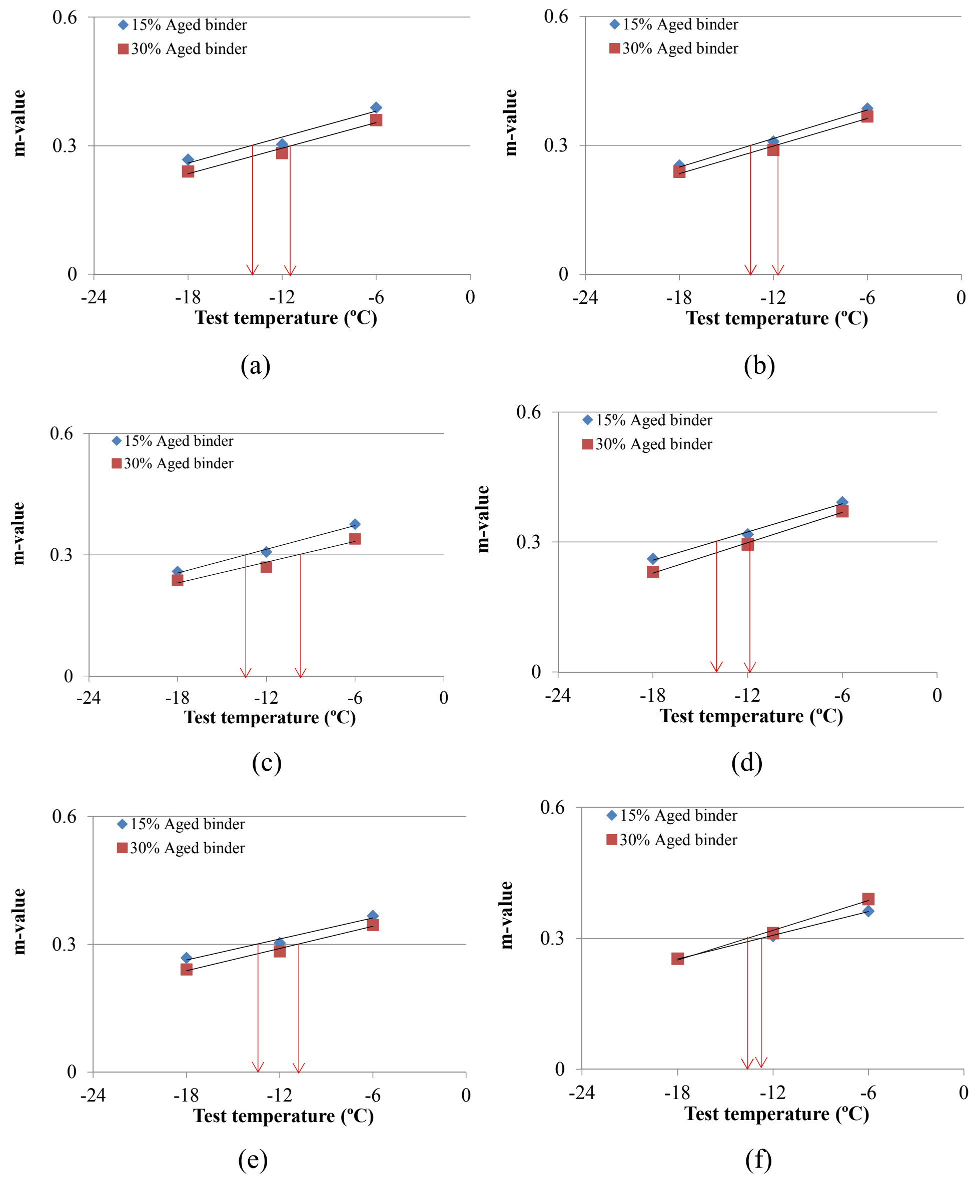


Figure 6-9: Low temperature determinations of modified PAV binders A-F with binder PG 76-22 in terms of m-value

Table 6-1 through

Table 6-3 show the minimum low temperature of various modified PAV binders mixed with extracted aged binder contents and virgin binder types. These values were obtained from stiffness and m-values, derived from the conducted regression analysis. A higher temperature was selected as a minimum low temperature in this portion of the study because this could satisfy the demand of the asphalt binder to resist the pavement cracking at a low temperature.

Table 6-1: Minimum low temperatures of modified PAV binders A-F mixed with binder PG 58-28

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	15%	30%	15%	30%	**15%**	**30%**
A	-7.2	-14.1	-14.1	-17	-7.2	-14.1
B	-18.8	-16.2	-17.9	-13.4	-17.9	-13.4
C	-16.6	-15.7	-16	-14.5	-16	-14.5
D	-19.4	-17.5	-17.9	-15.2	-17.9	-15.2
E	-17.9	-15.8	-16.3	-14.1	-16.3	-14.1
F	-19	-17.8	-17.3	-14.7	-17.3	-14.7

Table 6-2: Minimum low temperatures of modified PAV binders A-F mixed with binder PG 64-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	15%	30%	15%	30%	**15%**	**30%**
A	-13.2	-11.6	-10	-7.4	-10	-7.4
B	-13.2	-12.4	-9.8	-7.9	-9.8	-7.9
C	-13.9	-13.6	-7.9	-8	-7.9	-8
D	-14.2	-13.5	-10.1	-9.7	-10.1	-9.7
E	-13.7	-12.6	-10.2	-7.2	-10.2	-7.2
F	-14.1	-13.7	-8.8	-8	-8.8	-8

Table 6-3: Minimum low temperatures of modified PAV binders A-F mixed with binder PG 76-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	15%	30%	15%	30%	**15%**	**30%**
A	-13.8	-12.2	-13.8	-11.6	-13.8	-11.6
B	-13.8	-13	-13.6	-11.7	-13.6	-11.7
C	-13.5	-11.6	-13.4	-9.8	-13.4	-9.8
D	-14.2	-13.7	-13.9	-11.8	-13.9	-11.8
E	-14.8	-12.2	-13.4	-10.7	-10.7	-10.7
F	-14	-13.5	-12.7	-13.6	-13.6	-13.5

7 BBR Comparisons and BBR Results after One Year

7.1 <u>Comparisons of Low Temperature Properties of Modified Binders in Terms of Unburned and Burned RAP Mortars</u>

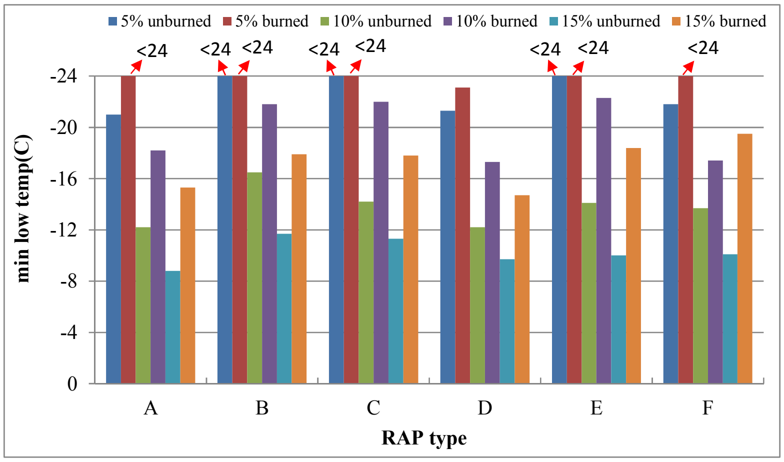
7.1.1 Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with Virgin Binder

The minimum low temperatures were determined by stiffness and m-values of the modified binders, which were produced from three virgin binders (PG 58-28, PG 64-22, and PG 76-22) and six unburned and burned RAPs. This section describes the low temperature alterations due to the effects from the removal of aged binder in the RAP mortar.

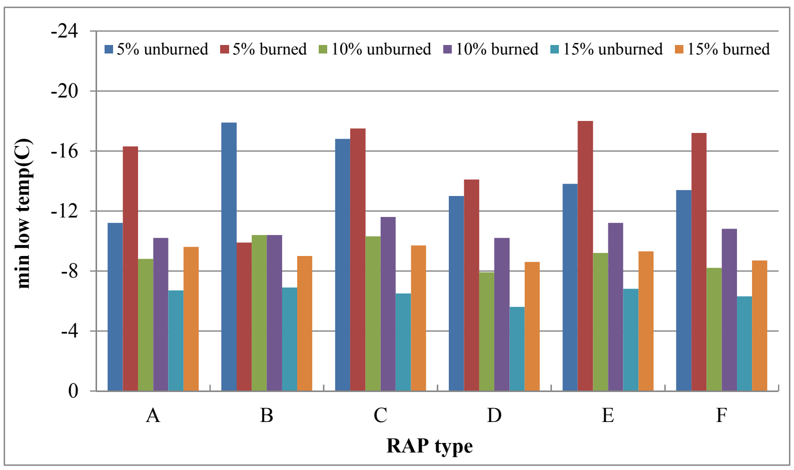
Figure 7-1 presents the differences of minimum low temperatures of various percentages of unburned and burned RAP mortars. In Figure 7-1(a), it can observed that all the modified binders mixed with burned RAPs have lower temperatures compared to those binders mixed with unburned RAPs regardless of RAP source when used same percentage of RAPs and virgin PG 58-28 binder. In addition, a higher percentage RAP content results in a higher minimum low temperatures for the materials used in this study. Similar trends can be seen in Figure 7-1(b) and (c). However, it can be found that the minimum low temperatures of the modified binders mixed with virgin PG 64-22 is higher than other modified binders mixed with PG 58-28 and PG 76-22 binders.

Therefore, it can be concluded that the removal (burned) of aged binder can reduce the minimum low temperatures of the modified binders regardless of RAP source, binder type, and RAP content. The minimum low temperatures are generally determined by the nature of various RAPs and virgin binder types.

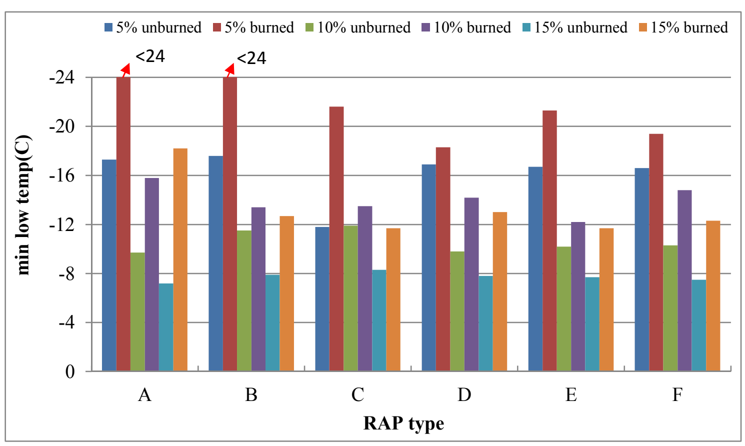
In addition, the compared stiffness and m-values of the modified binders mixed with virgin binders with respect to the unburned and burned RAPs are also studied. The summarized results are shown in Appendix J.



(a)



(b)



(c)

Figure 7-1: Comparisons of minimum low temperatures of the modified binders mixed with six unburned and burned RAP mortars and three virgin binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with RTFO Binder

This section describes the comparisons of minimum low temperatures in terms of the short-term aging procedure. Six RAPs and three RTFO binders were utilized to fabricate the modified binders. The determined minimum low temperatures are summarized in Figure 7-2. It can be observed that, similar to Figure 7-1, the minimum low temperatures of the modified binders mixed with burned RAP mortars are lower than those low temperatures from unburned RAP mortars. The aged binder of unburned RAP generally weakens the resistance of the binder to low temperature.

In addition, some minimum low temperatures are greater than 0^{o} C due to a high RAP content when RTFO PG 64-22 binder were used in this portion of the study. Moreover, as shown in Figure 7-2(a), some minimum low temperature could not be obtained because the BBR samples were destroyed during testing.

Meanwhile, it can be noted that, as expected, the minimum low temperatures of the modified binders mixed with RTFO binders are generally higher than those temperatures with virgin binders.

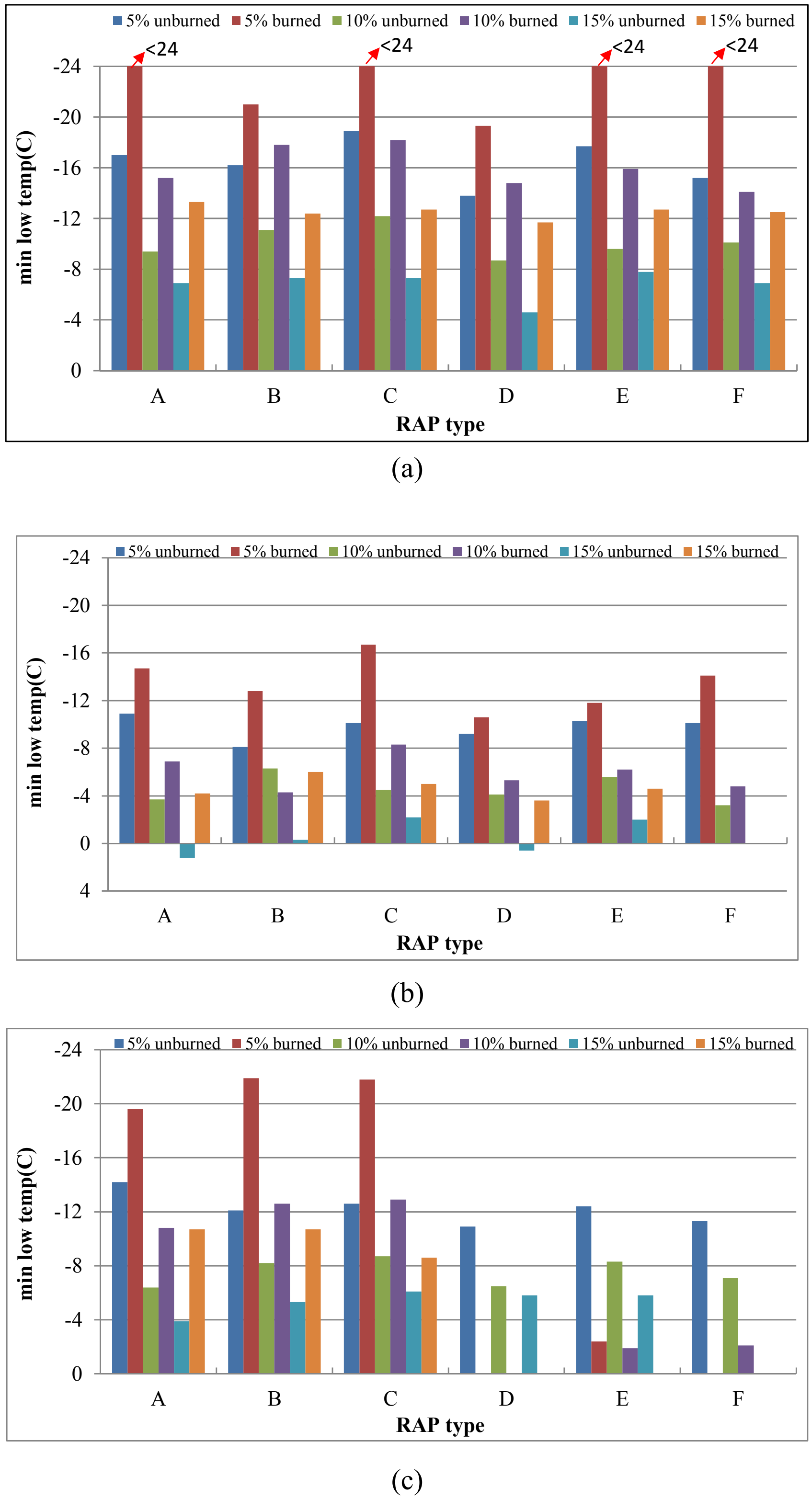


Figure 7-2: Comparisons of minimum low temperatures of the modified binders mixed with six unburned and burned RAP mortars and three RTFO binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

Similarly, the stiffness and m-values of the modified binders mixed with RTFO binders with respect to the unburned and burned RAPs are compared. The summarized results are shown in Appendix J.

Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with PAV Binder

This section introduces the comparisons of minimum low temperatures in terms of the long-term aging procedure. Six RAPs and three PAV binders were employed to fabricate the modified binders. The determined minimum low temperatures are summarized in Figure 7-3. It can be observed that, similar to Figure 7-1 and Figure 7-2, the minimum low temperatures of the modified binders mixed with burned RAP mortars are lower than those low temperatures from unburned RAP mortars.

Similarly, some minimum low temperatures are greater than 0 ^{o} C due to a high RAP content when PAV PG 64-22 binder were employed in this study. Moreover, as shown Figure 7-3(a) and (b), some minimum low temperature could not be obtained because the BBR samples were destroyed during testing.

Meanwhile, it can be noted that, as expected, the minimum low temperatures of the modified binders mixed with PAV binders are generally higher than those temperatures with RTFO binders and followed by virgin binders.

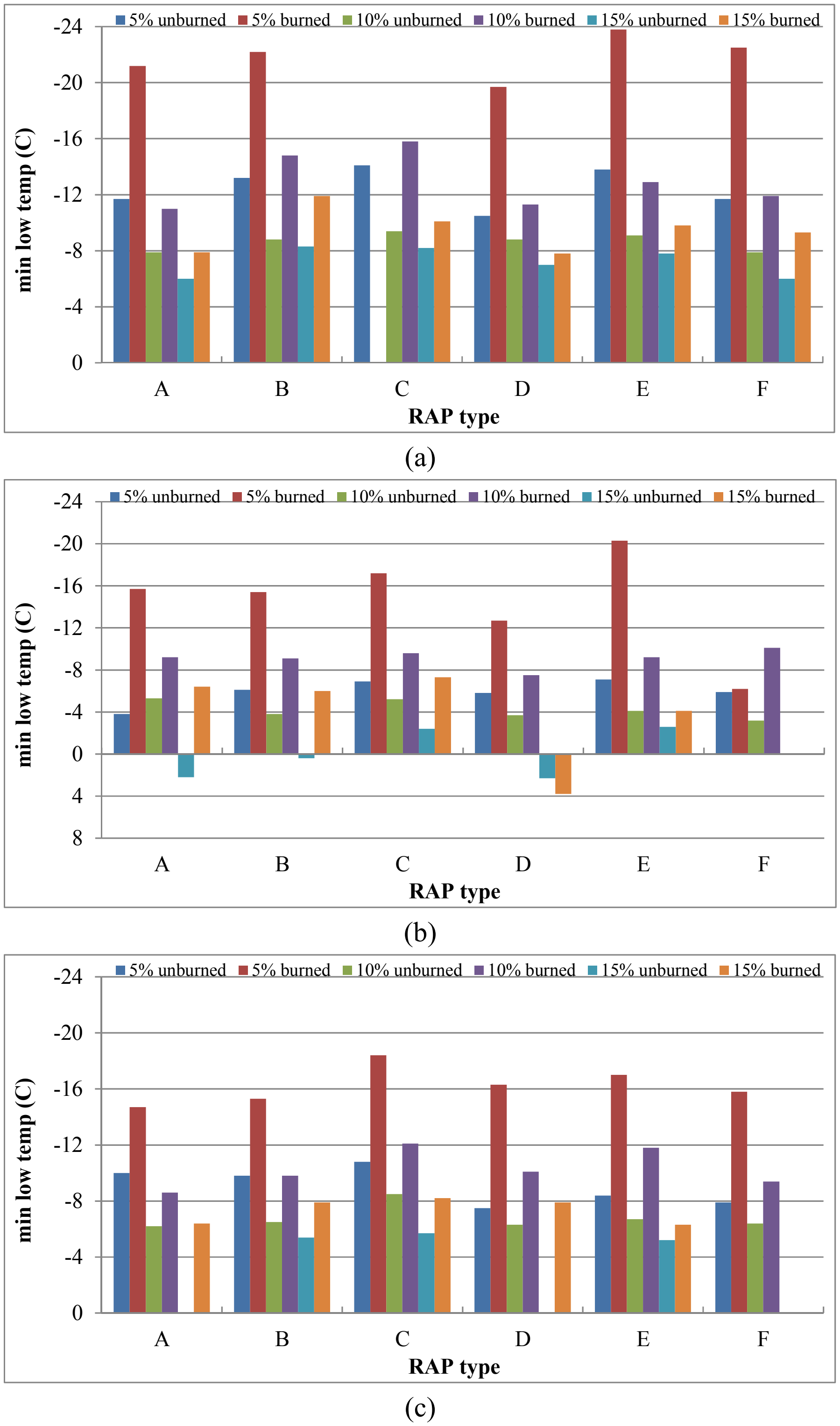


Figure 7-3: Comparisons of minimum low temperatures of the modified binders mixed with six unburned and burned RAP mortars and three PAV binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

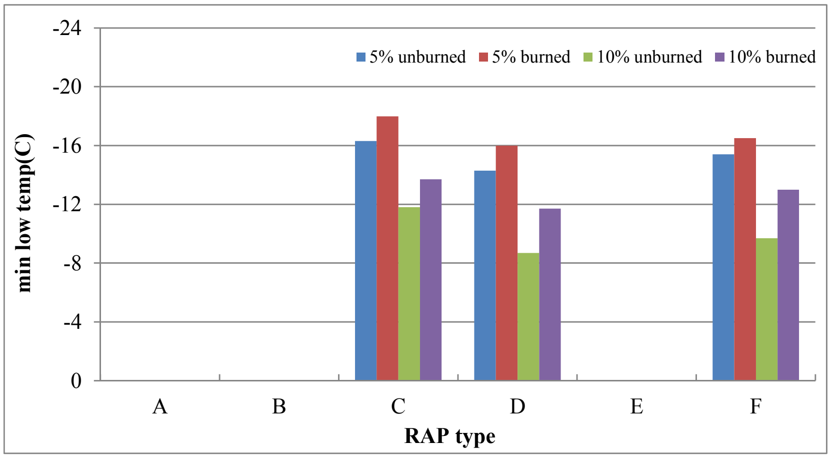
In addition, the stiffness and m-values of the modified binders mixed with PAV binders with respect to the unburned and burned RAPs are compared. The summarized results are shown in Appendix J.

7.2 Comparisons of Low Temperature Properties of Modified Binder in Terms of Unburned and Burned RAP Mortars after One Year

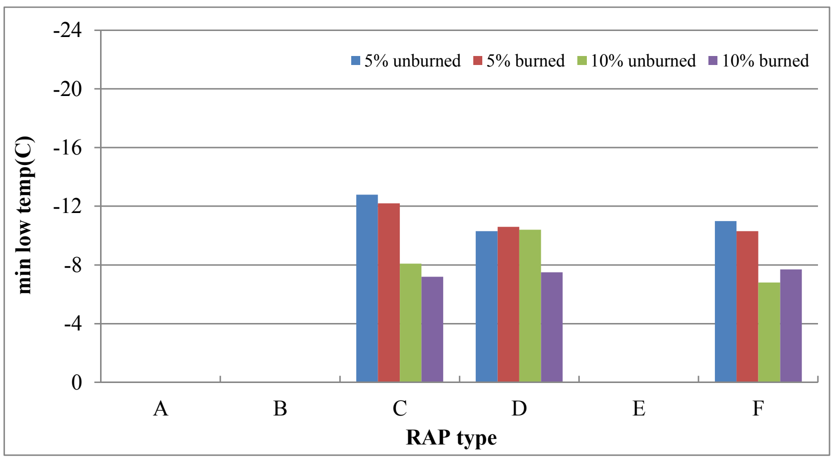
7.2.1 Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with Virgin Binder

The minimum low temperatures were determined by stiffness and m-values of the modified binders, which were produced from three virgin binders (PG 58-28, PG 64-22, and PG 76-22) and three unburned and burned RAPs (C, D, and F), which were selected from the same source after one year. This section describes the low temperature alterations due to the effects from the removal of aged binder in RAP mortar.

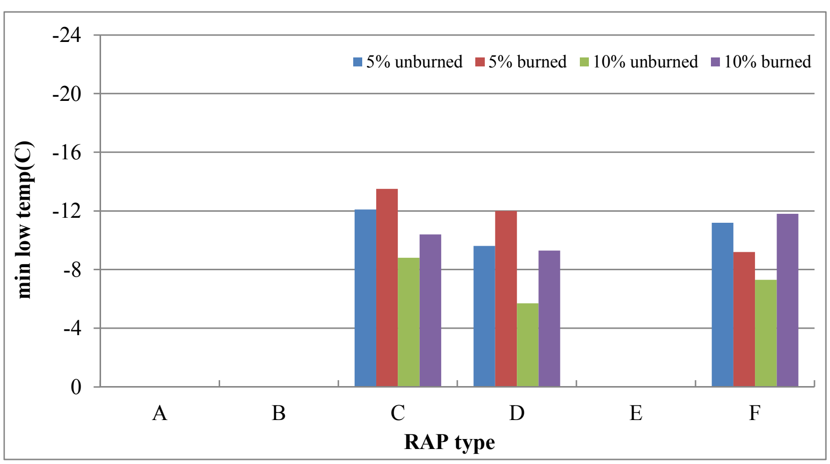
In Figure 7-4(a), it can observed that all the modified binders mixed with burned RAPs have lower temperatures compared to those binders mixed with unburned RAPs regardless of RAP source. In addition, a higher percentage RAP content results in a higher minimum low temperatures for the materials used in this study. Similar trends can be seen in Figure 7-4(b) and (c). Similar findings can be obtained that the removal (burned) of aged binder can reduce the minimum low temperatures of the modified binders regardless of RAP source, binder type, and RAP content. The minimum low temperatures are generally determined by the nature of various RAPs and virgin binder types.



(a)



(b)



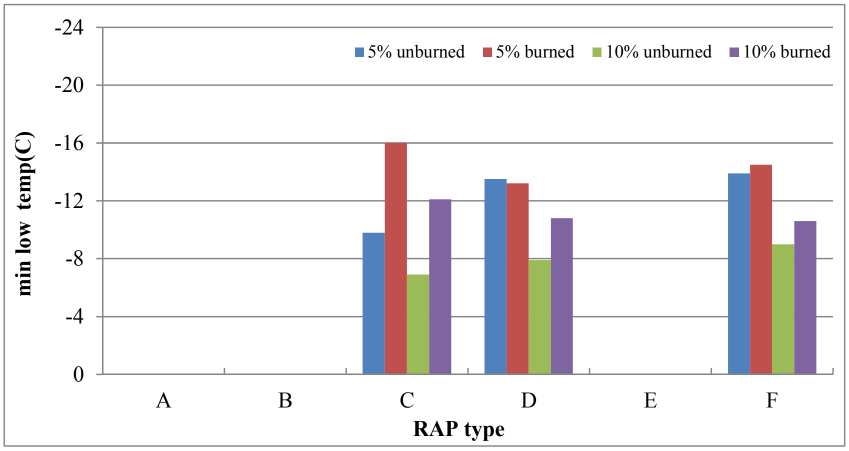
(c)

Figure 7-4: Comparisons of minimum low temperatures of the modified binders mixed with six unburned and burned RAP mortars and three virgin binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

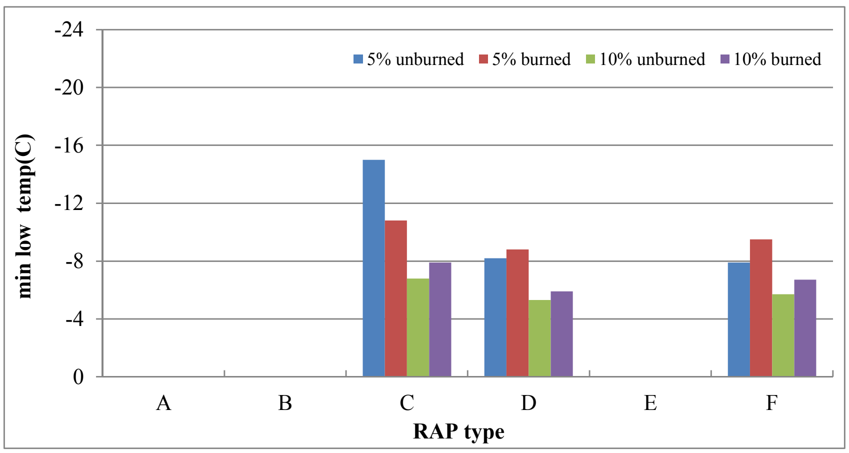
Similarly, the stiffness and m-values of the modified binders mixed with virgin binders with respect to three unburned and burned RAPs are compared. The summarized results are shown in Appendix J.

7.2.2 Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with RTFO Binder

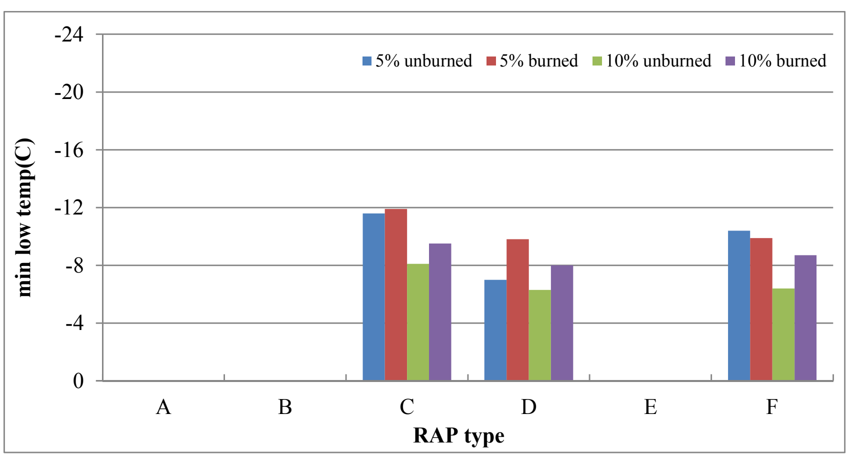
This section introduces the comparisons of minimum low temperatures in terms of the short-term aging procedure. Three RAPs and three RTFO binders were employed to fabricate the modified binders. The determined minimum low temperatures are summarized in Figure 7-5. It can be observed that, similar to Figure 7-4, the minimum low temperatures of the modified binders mixed with burned RAP mortars are lower than those low temperatures from unburned RAP mortars. The aged binder of unburned RAP generally weakens the resistance of low temperature.
In addition, it can be noted that the modified binders mixed with RAP C do not have a lower temperatures compared to the modified binders mixed with RAPs D and F even though the initial stiffness of RAP C is the lowest.



(a)



(b)



(c)

Figure 7-5: Comparisons of minimum low temperatures of the modified binders mixed with three unburned and burned RAP mortars and three RTFO binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

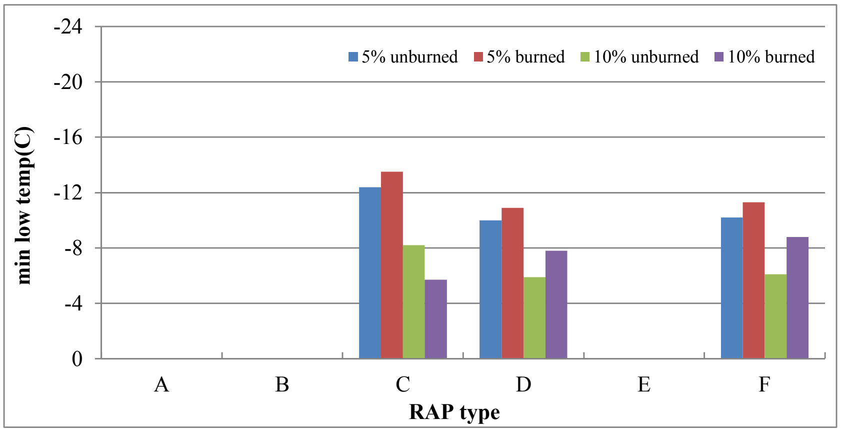
Similarly, the stiffness and m-values of the modified binders mixed with RTFO binders with respect to three unburned and burned RAPs are compared. The summarized results are shown in Appendix J.

7.2.3 Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with PAV Binder

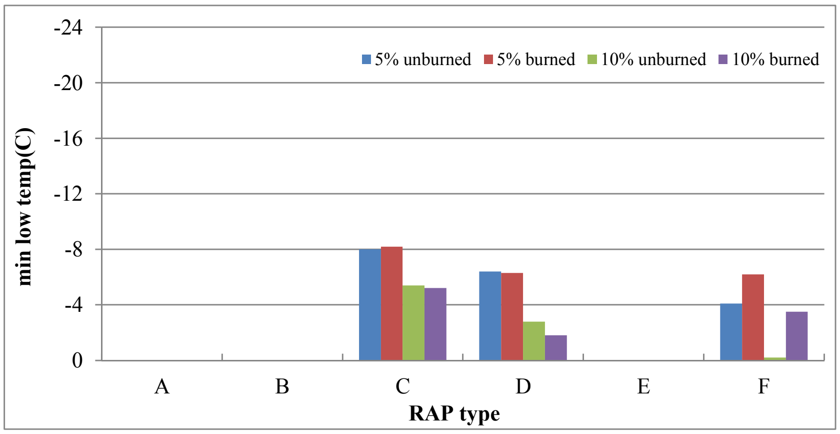
This section introduces the comparisons of minimum low temperatures in terms of the long-term aging procedures. Three RAPs and three PAV binders were utilized to fabricate the modified binders. The determined minimum low temperatures are summarized in Figure 7-6. It can be observed that, similar to Figure 7-4 and Figure 7-5, the minimum low temperatures of the modified binders mixed with burned RAP mortars are lower than those low temperatures from unburned RAP mortars.

In addition, the modified binders mixed with three RAPs generally have different minimum low temperatures. Moreover, it can be noted that, as expected, the minimum low temperatures of the modified binders mixed with PAV binders are generally higher than those temperatures with RTFO binders and followed by virgin binders.

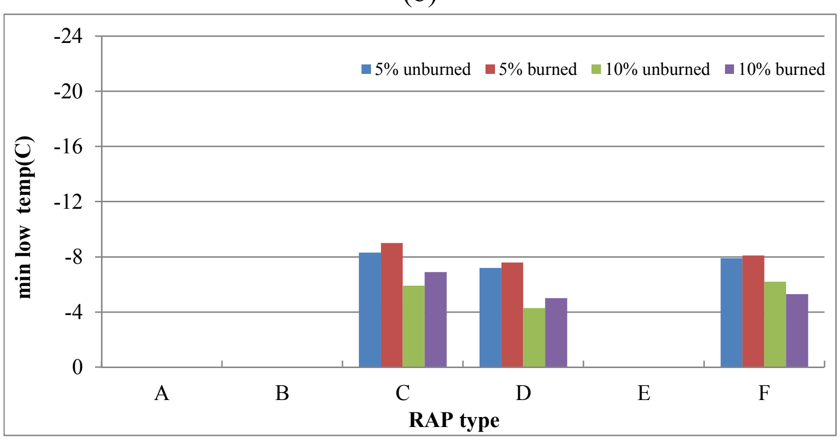
In addition, the stiffness and m-values of the modified binders mixed with PAV binders with respect to the unburned and burned RAPs are compared. The summarized results are shown in Appendix J.



(a)



(b)



(c)

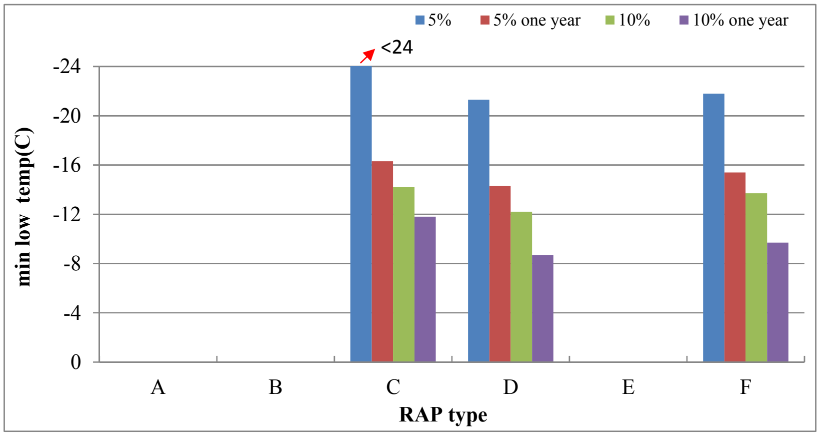
Figure 7-6: Comparisons of minimum low temperatures of the modified binders mixed with three unburned and burned RAP mortars and three PAV binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

7.3 Comparisons of Low Temperature Properties of Modified Binder Mixed with Unburned RAP Mortars after One Year

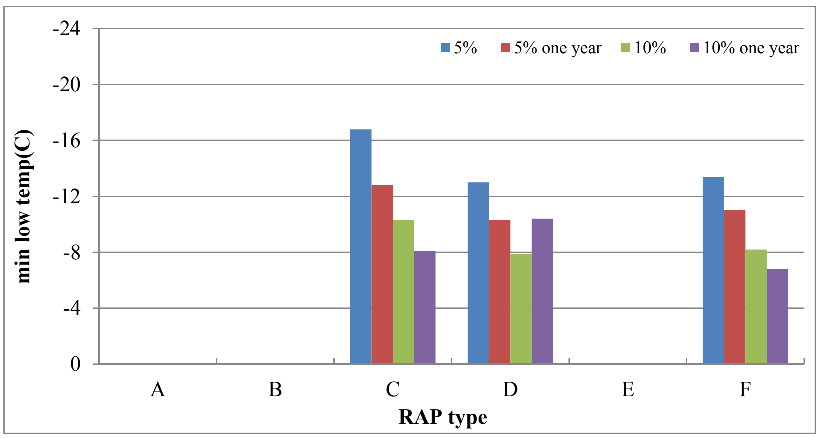
7.3.1 Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with Virgin Binder

The minimum low temperatures were determined in terms of stiffness and m-values of the modified binders, which were produced from three virgin binders (PG 58-28, PG 64-22, and PG 76-22) and three unburned RAPs (C, D, and F), which were selected from same source as tested before and after one year. This section describes the low temperature alterations due to the effects of one year on the RAP sources in the field.

In Figure 7-7(a), it can be observed that all the modified binders mixed with the RAPs after one year generally have higher temperatures compared to those binders mixed with initial RAPs regardless of RAP source. Similar trends can be seen in Figure 7-7(b) and Figure 7-7(c). Therefore, a one-year duration in the field did make the RAPs having lower resistance to low temperature regardless of RAP type and binder type.



(a)



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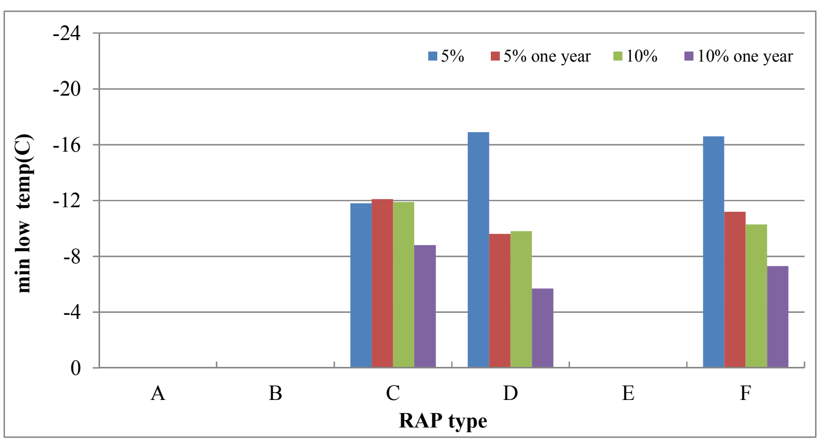


(c)

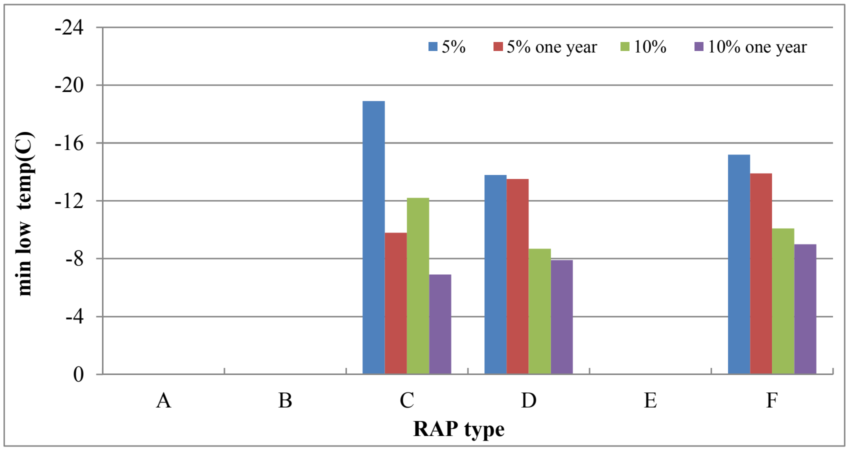
Figure 7-7: Comparisons of minimum low temperatures of the modified binders mixed with three unburned mortars before and after one year and virgin binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

Similarly, the stiffness and m-values of the modified binders mixed with virgin binders with respect to three unburned RAPs before and after one year were compared. The summarized results are shown in Appendix J.

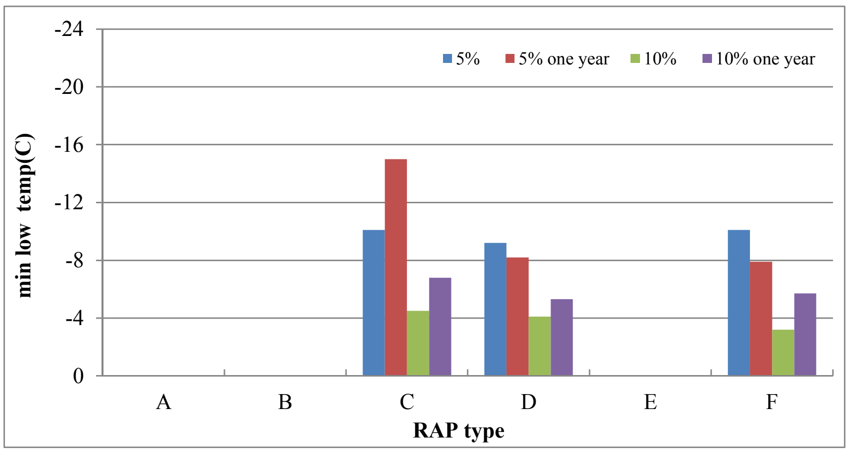
Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with RTFO Binder

This section introduces the comparisons of minimum low temperatures in terms of the short-term aging procedure. Three RAPs selected before and after one year and three RTFO binders were employed to fabricate the modified binders. The determined minimum low temperatures are summarized in Figure 7-8. It can be observed that, similar to Figure 7-7, the minimum low temperatures of the modified binders mixed with initial RAP mortars are generally lower than those low temperatures from RAP mortars after one year. One year duration generally lowers the resistance of low temperature of the modified binders.

Similarly, the stiffness and m-values of the modified binders mixed with RTFO binders with respect to three unburned RAPs before and after one year were compared. The summarized results are shown in Appendix J.



(a)



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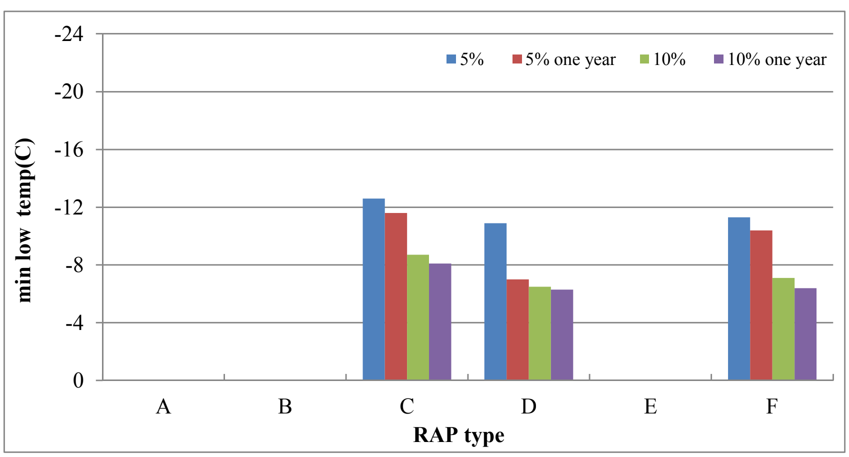


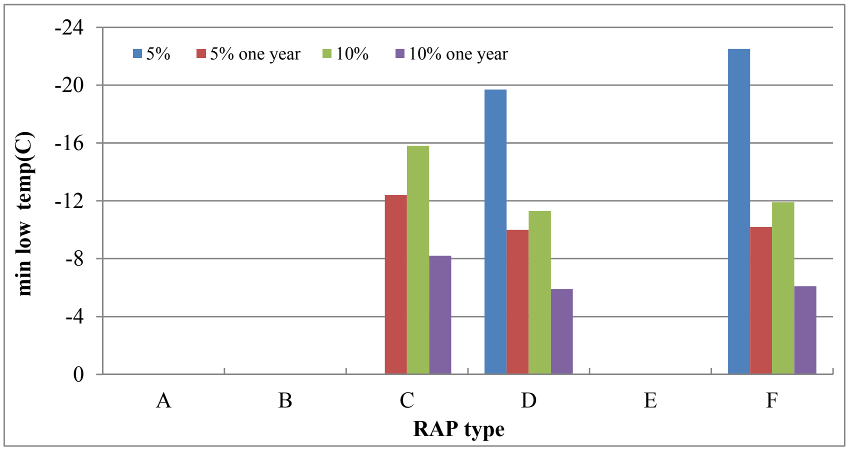
(c)

Figure 7-8: Comparisons of minimum low temperatures of the modified binders mixed with three unburned mortars before and after one year and RTFO binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

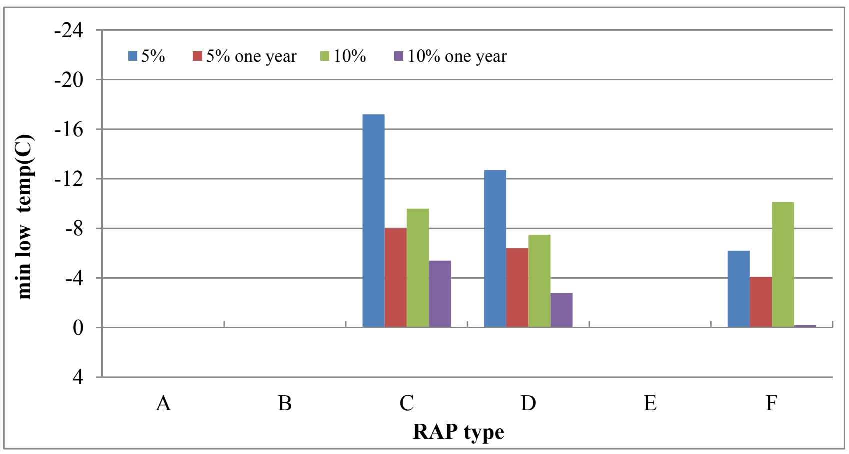
7.3.2 Comparisons of Minimum Low Temperatures of the Modified Binders Mixed with PAV Binder

This section introduces the comparisons of minimum low temperatures in terms of the long-term aging procedures. Three RAPs selected before and after one year and three PAV binders were employed to fabricate the modified binders. The determined minimum low temperatures are summarized in Figure 7-9. It can be observed that, similar to Figure 7-8, the minimum low temperatures of the modified binders mixed with initial RAP mortars are generally lower than those low temperatures from RAP mortars after one year. It appears that one year duration, generally, lowers the resistance of low temperature of the modified binders.

Similarly, the stiffness and m-values of the modified binders mixed with PAV binders with respect to three unburned RAPs before and after one year were compared. The summarized results are shown in Appendix J.



(a)



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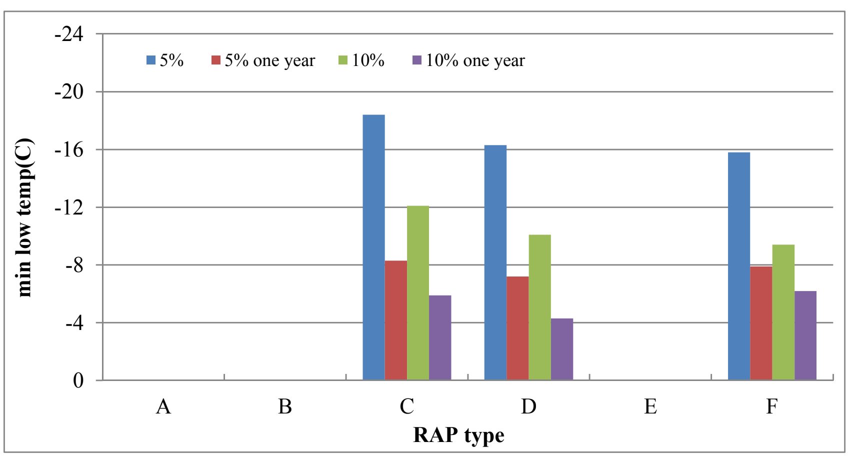


(c)

Figure 7-9: Comparisons of minimum low temperatures of the modified binders mixed with three unburned mortars before and after one year and PAV binders, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

7.4 Comparisons of Low Temperature Properties of Modified Binder Mixed with burned RAP Mortars in After One Year

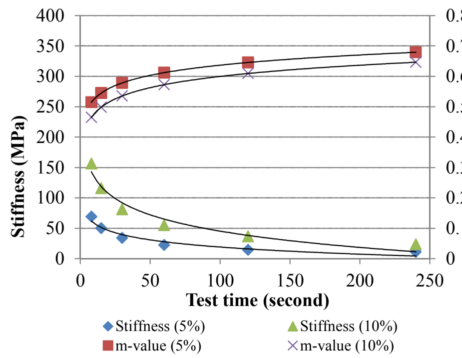
The modified binders mixed with burned RAP and base binders (three aging states) before and after one year duration were found to be similar to the unburned RAP mortars. The results and analysis are summarized in Appendix J.

7.5 The Modified Binder Mixed with Virgin Binder and RAP Mortar (One Year Later)

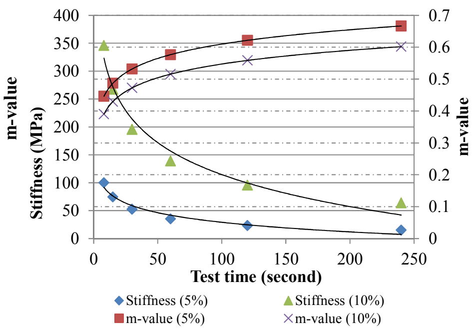
7.5.1 Stiffness and M-Values of the Modified Binders

Three virgin binders (PG 58-28, PG 64-22, and PG 76-22) were blended with two percentages of aged binders (5% and 10%) from three RAP sources (one has the highest stiffness, one has the lowest stiffness, and one has medium stiffness of the six RAP sources). These RAPs were selected, after one year, from the same sources that were tested before. The fabricated BBR samples were tested at three temperatures (-6 ºC, -12 ºC and -18 ºC). Most of the test results are shown in the following figures.

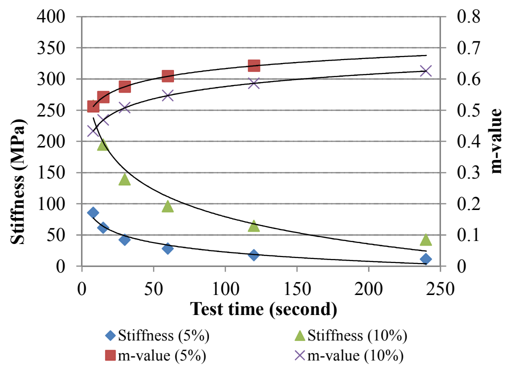
As shown in Figure 7-10, at -6 ºC, it can be observed that, as expected, the stiffness values of virgin binders with RAP mortars generally decrease while m-values increase when the loading duration increases with logarithmic trends regardless of RAP source. As shown in Figure 7-10, it can be found that a higher percentage of aged binder results in a higher stiffness value and a lower m-value regardless of test time and RAP source. Meanwhile, when comparing the stiffness and m-values of RAP sources C, D, and F, it is noted that these aged binders from three RAP sources values significantly vary.



(a)



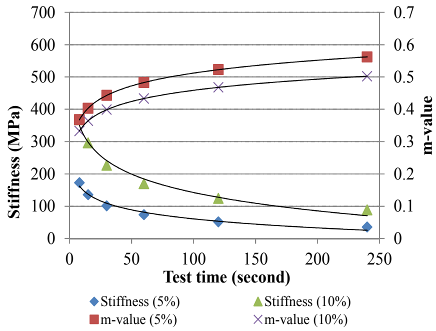
(b)



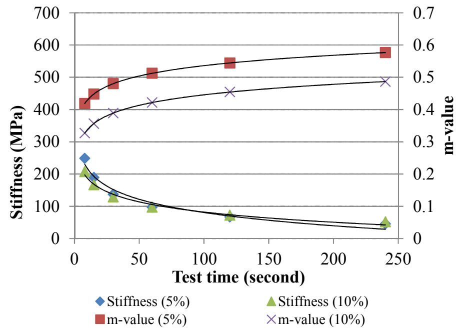
(c)

Figure 7-10: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 58-28 at -6ºC

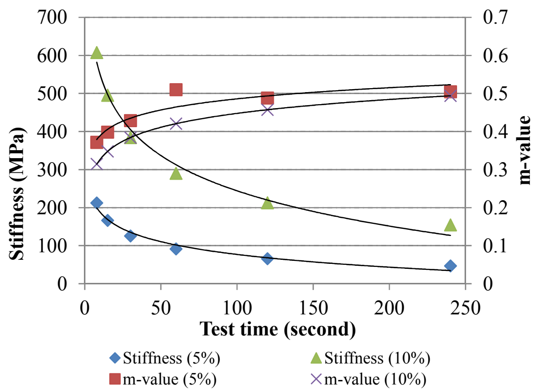
The stiffness and m-values of the modified binders blended with PG 64-22 virgin binders and RAP mortar are shown in Figure 7-11. Similar to Figure 7-10, stiffness and m-values of the modified binders are following logarithmic trends regardless of RAP source. Similarly, the stiffness values reduced and m-values increased when the test time increased. In addition, these stiffness values are generally greater than those values from the modified binders blended with PG 58-28.



(e)



(b)



(c)

Figure 7-11: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 64-22 at -6ºC

Figure 7-12 shows the stiffness and m-values of the modified binders blended with PG 76-22 virgin binders and RAP mortar. Similar to Figure 7-10, stiffness and m-values of the modified binders are following logarithmic trends regardless of RAP source. Also, the stiffness values reduce and m-values increase when the test time increases.

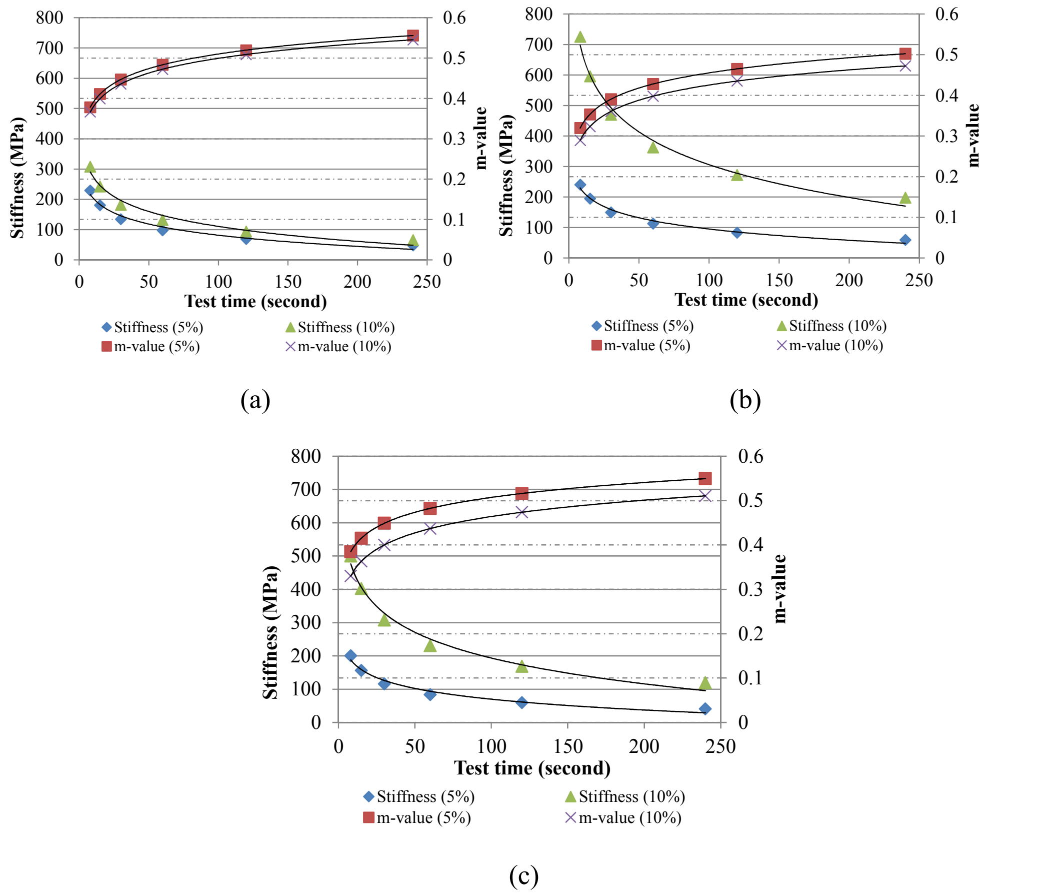


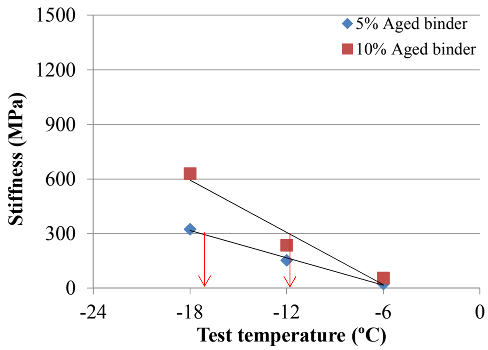
Figure 7-12: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 64-22 at -6ºC

Other stiffness and m-values of the modified binders mixed with RAP mortars (C, D, and F) and virgin binders (PG 58-22, PG 64-22, and PG 76-22) at -12 ºC and -18 ºC are presented in Appendix H. Generally, similar trends can be found regardless of RAP source, binder grade, and test temperatures used in this study.

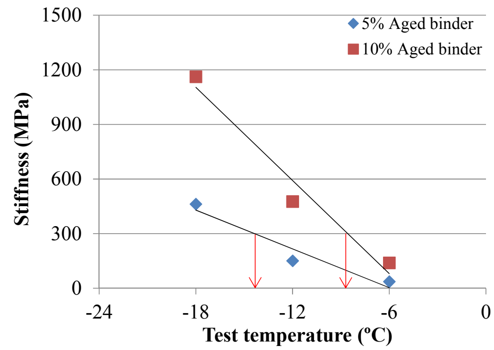
7.5.2 Low Temperature Determinations of the Modified Binders Based on Stiffness and M-Values

Figure 7-13 shows the minimum low temperatures at a certain stiffness (e.g., 300 MPa) of various modified binders mixed with RAP mortar and virgin binder PG 58-22. It can be noted that an increase in test temperature reduces the stiffness value of modified binders. In addition, a higher aged binder significantly has a greater stiffness value regardless of test temperature and RAP source.

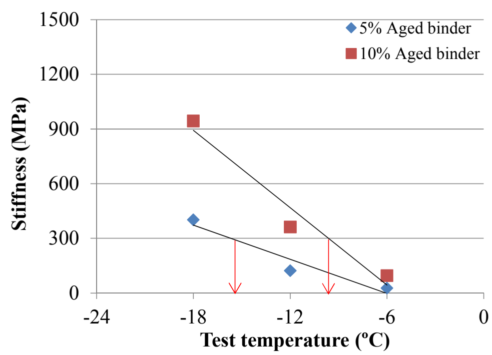
Additionally, Figure 7-13 indicates that, generally, when the binders were modified with 10% aged binder and they have a stiffness value of 300 MPa, their corresponding low temperatures are typically greater than -12 ºC.



(a)



(b)



(c)

Figure 7-13: Low temperature determinations of RAP sources C, D, and F modified with virgin binder PG 58-22 in terms of stiffness

The minimum low temperatures at a stiffness equaling to 300 MPa of various modified binder mixed with virgin binder PG 64-22 and different RAP sources are shown in Figure 7-14. Similar to Figure 7-13, a higher temperature results in a higher stiffness value. In addition, a higher aged binder content also leads to a higher stiffness regardless of RAP source and test temperature. In addition, it can be noted that the modified binders with 5% and 10% aged binders generally have a low temperature greater than -12 ºC, with a stiffness equaling to 300 MPa. This significantly affects the application scopes of these modified binders due to a high risk to low temperature cracking.

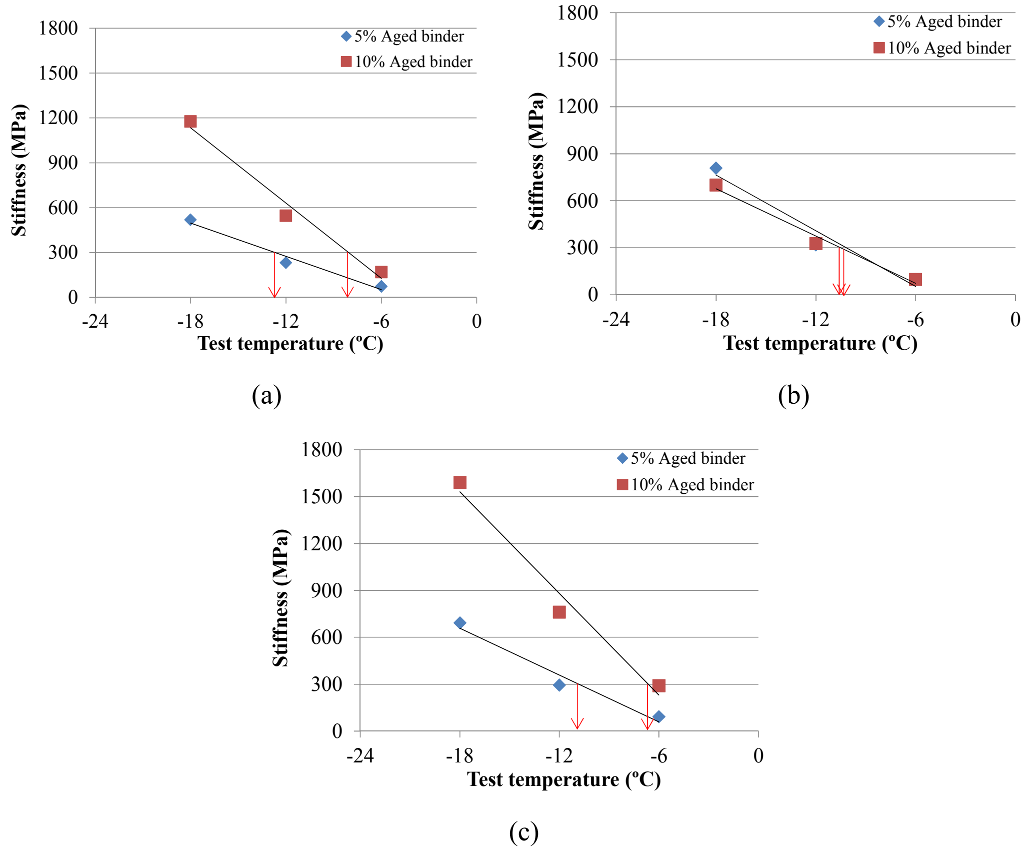
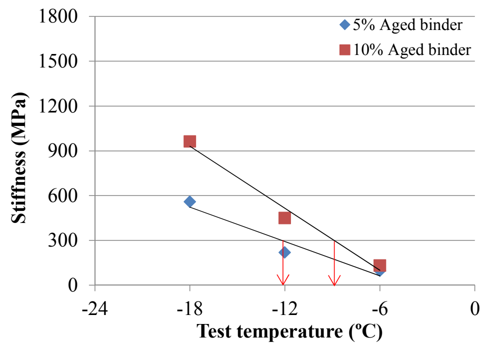


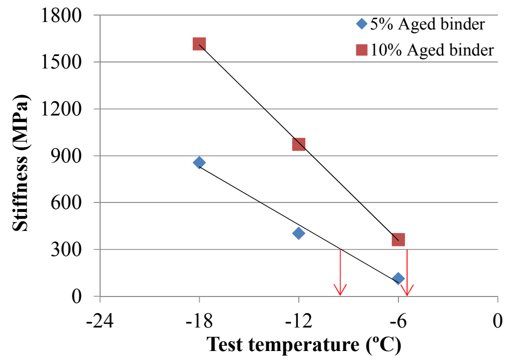
Figure 7-14: Low temperature determinations of RAP sources C, D, and F modified with virgin binder PG 64-22 in terms of stiffness

The stiffness values of modified binders mixed with RAP mortar and PG 76-22 virgin binder at different test temperatures are shown in Figure 7-15. Similar to Figure 7-13 and Figure 7-14, an increased in test temperature resulted in a reduction of stiffness values, but an increased aged binder content leads to an increase of stiffness regardless of RAP source.

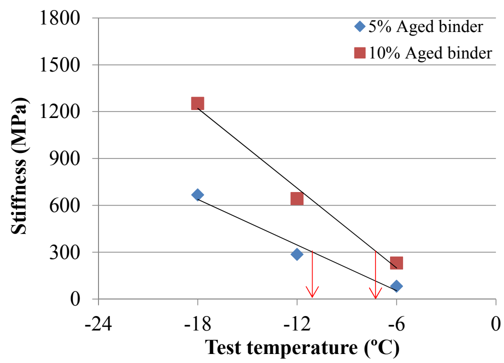
From these stiffness values, it can be observed that all the modified binders containing 5% and 10% aged binders typically had temperatures greater than -12 ºC. This would result in the reduction of low temperature cracking resistance of the modified binders at a temperature of -22 ºC.



(a)



(b)



(c)

Figure 7-15: Low temperature determinations of RAP sources C, D, and F modified with virgin binder PG 76-22 in terms of stiffness

The low temperature determination of the modified binders mixed with various RAP sources and PG 58-28 with respect to m-values are shown in Figure 7-16. It can be observed that the m-values are greater than 0.300 when used 5% aged binder at -18 ºC because the virgin binder PG 58-28 is generally soft.

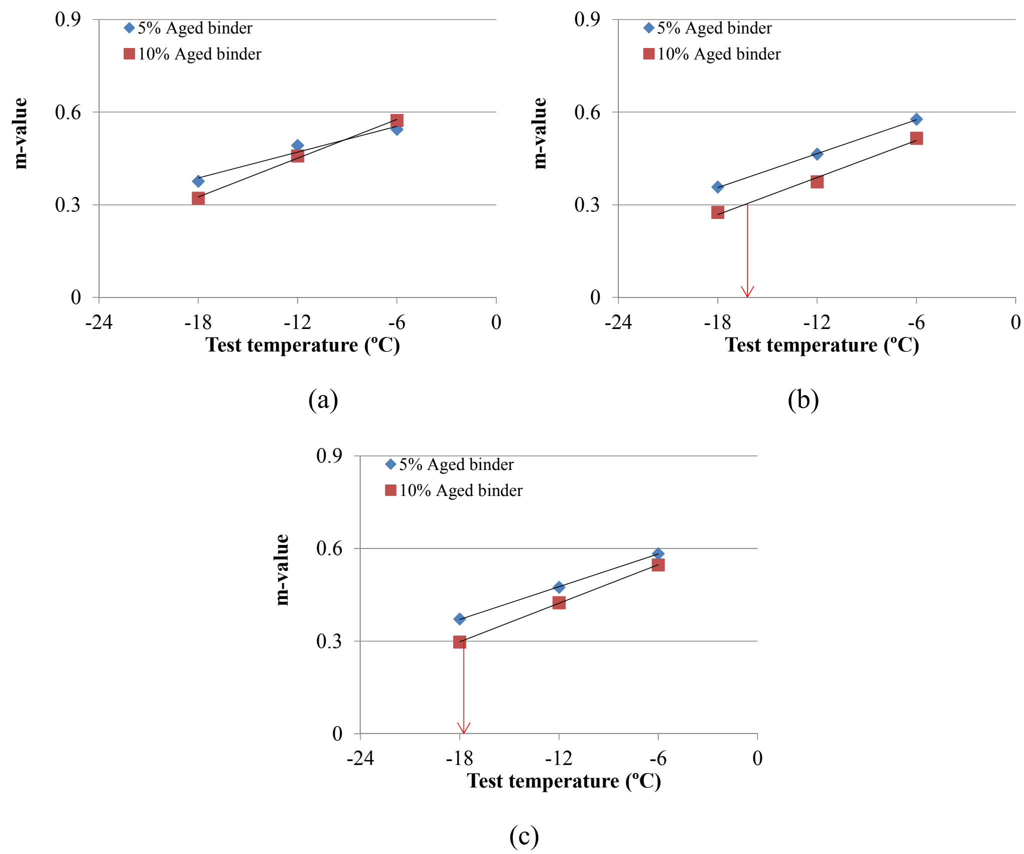


Figure 7-16: Low temperature determinations of RAP sources C, D, and F modified with virgin binder PG 58-28 in terms of m-value

As shown in Figure 7-17, the modified binders mixed with various RAP sources and PG 64-22 have m-values equaling to 0.300 when the minimum low temperatures are generally in the range of -12 ºC to -18 ºC. Therefore, additional 5% and 10% aged binders generally did not affect the low temperature cracking resistance.

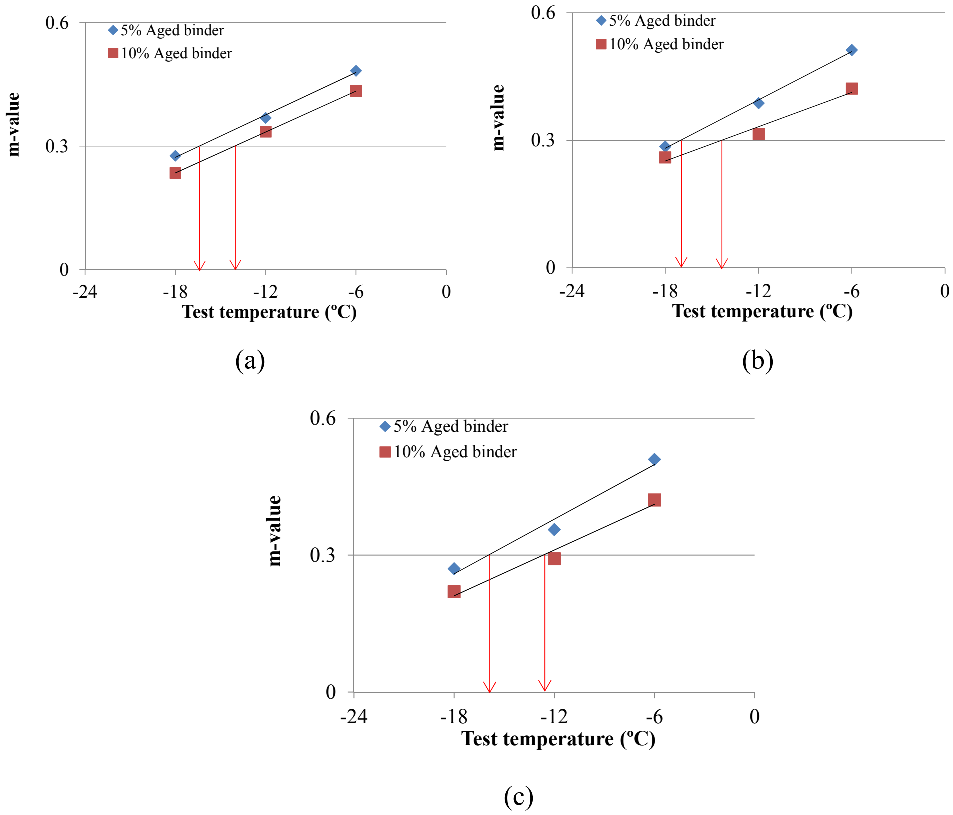
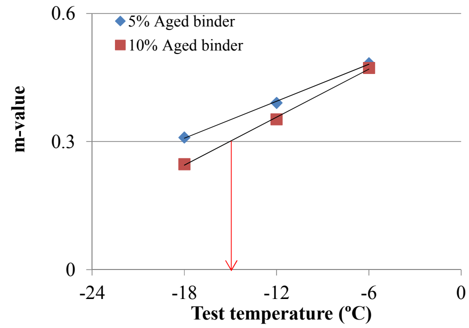
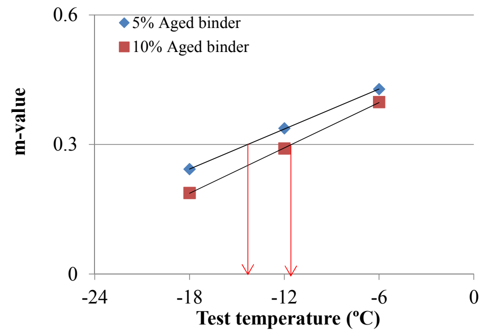


Figure 7-17: Low temperature determinations of RAP sources C, D, and F modified with virgin binder PG 64-22 in terms of m-value

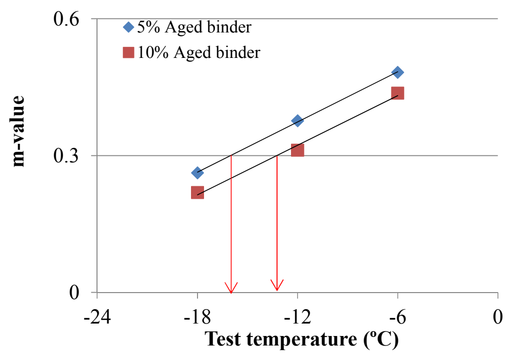
In Figure 7-18, it can be noted that m-values of the modified binders mixed with various RAP sources and PG 76-22 are generally greater than 0.300 at -18 ºC when the aged binder percentages are 5% and 10%. All minimum low temperatures are generally less than -12 ºC regardless of aged binder contents and RAP sources used in this study.



(a)



(b)



(c)

Figure 7-18: Low temperature determinations of RAP sources C, D, and F modified with virgin binder PG 76-22 in terms of m-value

Table 7-1 through Table 7-3 show the minimum low temperature of various modified binders mixed with various RAP sources, aged binder contents, and virgin binder types. These values were obtained from stiffness and m-values, derived from the conducted regression analysis. 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 7-1: Minimum low temperatures of RAP sources C, D, and F mixed with virgin binder PG 58-28

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-16.3	-11.8	<-24	-19.2	-16.3	-11.8
D	-14.3	-8.7	-21.1	-16.3	-14.3	-8.7
F	-15.4	-9.7	-22	-17.8	-15.4	-9.7

Table 7-2: Minimum low temperatures of RAP sources C, D, and F mixed with virgin binder PG 64-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-12.8	-8.1	-16.3	-14	-12.8	-8.1
D	-10.3	-10.4	-16.9	-14.2	-10.3	-10.4
F	-11	-6.8	-15.9	-12.4	-11	-6.8

Table 7-3: Minimum low temperatures of RAP sources C, D, and F mixed with virgin binder PG 76-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-12.1	-8.8	-18.7	-14.9	-12.1	-8.8
D	-9.6	-5.7	-14.2	-11.7	-9.6	-5.7
F	-11.2	-7.3	-16	-13.2	-11.2	-7.3

7.6 The Modified Binder Mixed with RTFO Binder and RAP Mortar (One Year Later)

7.6.1 Stiffness and M-Values of the Modified Binders during Test Duration

This section presents the test results of the modified binders mixed with various selected RAP mortars (C, D, and F) and three short term aged (RTFO) binders (PG 58-28, PG 64-22, and PG 76-22). The fabricated BBR samples were tested at three temperatures (-6 ºC, -12 ºC, and -18 ºC). The general trends of these modified RTFO binders are similar to those modified virgin binders and are shown in Appendix H.

7.6.2 Low Temperature Determination of the Modified Binders Based on Stiffness and M-Values

Low temperatures of the modified RTFO binders can be determined by stiffness and m-values, similar to modified virgin binders. The presented results can be found in Appendix H.

The minimum low temperatures of various modified binders mixed with various RAP sources, aged binder contents, and RTFO binder types are shown in Table 7-4 through Table 7-6. The low temperatures derived from the conducted regression analysis are summarized from stiffness 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 7-4: Minimum low temperatures of RAP sources C, D, and F mixed with RTFO binder PG 58-28

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-9.8	-6.9	-15.8	-13.4	-9.8	-6.9
D	-13.5	-7.9	-18.1	-16.3	-13.5	-7.9
F	-13.9	-9	-19.8	-17.2	-13.9	-9

Table 7-5: Minimum low temperatures of RAP sources C, D, and F mixed with RTFO binder PG 64-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-15	-6.8	-20.1	-11.8	-15	-6.8
D	-8.2	-5.3	-12.9	-9.4	-8.2	-5.3
F	-7.9	-5.7	-13.4	-10.6	-7.9	-5.7

Table 7-6: Minimum low temperatures of RAP sources C, D, and F mixed with RTFO binder PG 76-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-11.6	-8.1	-15.5	-13.4	-11.6	-8.1
D	-7	-6.3	-13.9	-11.6	-7	-6.3
F	-10.4	-6.4	-15.2	-12.1	-10.4	-6.4

7.7 The Modified Binder Mixed with PAV Binder and RAP Mortar (One Year Later)

7.7.1 Stiffness and M-Values of the Modified Binders during Test Duration

This section presents the test results of the modified binders mixed with various RAP mortars (C, D, and F) and three long-term aged (PAV) binders (PG 58-28, PG 64-22, and PG 76-22). The fabricated BBR samples were tested at three temperatures (-6 ºC, -12 ºC, and -18 ºC). The general trends of these modified PAV binders are similar to those modified virgin and RTFO binders. Therefore, these data are shown in Appendix H.

7.7.2 Low Temperature Determination of the Modified Binders Based on Stiffness and M-Values

Similar to virgin and RTFO binders, the stiffness and m-values of the modified binders mixed with PAV binders can determine the minimum low temperatures of various binders with a specified value of stiffness equaling to 300 MPa and an m-value of 0.300. These determined values are shown in Appendix H.

Table 7-7 through Table 7-9 show the minimum low temperatures of various modified binders mixed with various RAP sources (C, D, and F), aged binder contents, and PAV binder types, derived from the conducted regression analysis. As mentioned 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.

Table 7-7: Minimum low temperatures of RAP sources C, D, and F mixed with PAV binder PG 58-28

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-12.4	-8.2	-16.4	-13.9	-12.4	-8.2
D	-10	-5.9	-13.2	-10.9	-10	-5.9
F	-10.2	-6.1	-16.6	-12.2	-10.2	-6.1

Table 7-8: Minimum low temperatures of RAP sources C, D, and F mixed with PAV binder PG 64-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-8.4	-5.4	-8	-5.9	-8	-5.4
D	-6.4	-3.8	-7	-2.8	-6.4	-2.8
F	-6.2	-3.2	-4.1	-0.2	-4.1	-0.2

Table 7-9: Minimum low temperatures of RAP sources C, D, and F mixed with PAV binder PG 76-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-8.3	-5.9	-9.4	-6.1	-8.3	-5.9
D	-7.2	-4.3	-9.7	-6.3	-7.2	-4.3
F	-7.9	-6.2	-9.9	-8.7	-7.9	-6.2

7.8 The Modified Binder Mixed with Virgin Binder and Burned RAP Mortar (One Year Later)

7.8.1 Stiffness and M-Values of the Modified Binders during Test Duration

This section presents the test results of the modified binders mixed with various burned RAP mortars (C, D, and F) and virgin binders (PG 58-28, PG 64-22, and PG 76-22). The fabricated BBR samples were tested at three temperatures (-6 ºC, -12 ºC, and -18 ºC). The general trends of these modified binders with burned RAP mortar are similar to those modified binders containing unburned RAP mortar and are shown in Appendix H.

7.8.2 Low Temperature Determination of the Modified Binders Based on Stiffness and M-Values

Similar to unburned RAP mortars, the stiffness and m-values of the modified binders mixed with virgin binders can determine the minimum low temperatures of various binders with a specified value of stiffness equaling to 300 MPa and an m-value of 0.300. These determined values can be found in Appendix H.

Table 7-10 through Table 7-12 show the minimum low temperatures of various modified binders mixed with various burned RAP sources (C, D, and F), aged binder contents, and virgin binder types, derived from the conducted regression analysis. As mentioned 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 7-10: Minimum low temperatures of burned RAP sources C, D, and F mixed with virgin binder PG 58-28

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-18	-13.7	-20.2	-22.1	-18	-13.7
D	-16	-11.7	-22.2	-19.8	-16	-11.7
F	-16.5	-13	-21.7	-19.4	-16.5	-13

Table 7-11: Minimum low temperatures of burned RAP sources C, D, and F mixed with virgin binder PG 64-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-12.2	-7.2	-16.8	-15.7	-12.2	-7.2
D	-10.6	-7.5	-15.9	-13.7	-10.6	-7.5
F	-10.3	-7.7	-16.2	-14.6	-10.3	-7.7

Table 7-12: Minimum low temperatures of burned RAP sources C, D, and F mixed with virgin binder PG 76-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-13.5	-10.4	-17.7	-16.8	-13.5	-10.4
D	-12	-9.3	-17.9	-15.8	-12	-9.3
F	-9.2	-11.8	-17	-16.1	-9.2	-11.8

7.9 The Modified Binder Mixed with RTFO Binder and Burned RAP Mortar (One Year Later)

7.9.1 Stiffness and M-Values of the Modified Binders during Test Duration

This section presents the test results of the modified binders mixed with various burned RAP mortars (C, D, and F) and three short term aged (RTFO) binders (PG 58-28, PG 64-22, and PG 76-22). The fabricated BBR samples were tested at three temperatures (-6 ºC, -12 ºC, and -18 ºC). The general trends of these modified RTFO binders are similar to those modified virgin binders and are presented in Appendix H.

7.9.2 Low Temperature Determination of the Modified Binders Based on Stiffness and M-Values

Low temperatures of the modified RTFO binders can be determined by stiffness and m-values, similar to modified virgin binders. The presented results can be found in Appendix H.

The minimum low temperatures of various modified binders mixed with various burned RAP sources, aged binder contents, and RTFO binder types are shown in Table 7-13 through Table 7-15. The low temperatures derived from the conducted regression analysis are summarized from stiffness 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 7-13: Minimum low temperatures of burned RAP sources C, D, and F mixed with virgin binder PG 76-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-16	-12.1	-21	-19.6	-16	-12.1
D	-13.2	-10.8	-21.6	-19.2	-13.2	-10.8
F	-14.5	-10.6	-20.9	-18.8	-14.5	-10.6

Table 7-14: Minimum low temperatures of burned RAP sources C, D, and F mixed with RTFO binder PG 64-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-10.8	-7.9	-14.1	-13.5	-10.8	-7.9
D	-8.8	-5.9	-13	-11.3	-8.8	-5.9
F	-9.5	-6.7	-13.4	-11.9	-9.5	-6.7

Table 7-15: Minimum low temperatures of burned RAP sources C, D, and F mixed with RTFO binder PG 76-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-11.9	-9.5	-15.6	-15.2	-11.9	-9.5
D	-9.8	-8	-15.8	-14.3	-9.8	-8
F	-9.9	-8.7	-17.2	-14.1	-9.9	-8.7

7.10 <u>The Modified Binder Mixed with PAV Binder and Burned RAP Mortar (One Year Later)</u>

7.10.1 Stiffness and M-Values of the Modified Binders during Test Duration

This section presents the test results of the modified binders mixed with various burned RAP mortars (C, D, and F) and three long-term aged (PAV) binders (PG 58-28, PG 64-22, and PG 76-22). The fabricated BBR samples were tested at three temperatures (-6 ºC, -12 ºC, and -18 ºC). The general trends of these modified PAV binders are similar to those modified virgin and RTFO binders and are presented in Appendix H.

7.10.2 Low Temperature Determination of the Modified Binders Based on Stiffness and M-Values

Similar to virgin and RTFO binders, the stiffness and m-values of the modified binders mixed with PAV binders can determine the minimum low temperatures of various binders with a specified value of stiffness equaling to 300 MPa and an m-value of 0.300. These determined values can be found in Appendix H.

Table 7-16 through

Table 7-18 show the minimum low temperatures of various modified binders mixed with various burned RAP sources (C, D, and F), aged binder contents, and PAV binder types, derived from the conducted regression analysis. As mentioned 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 7-16: Minimum low temperatures of burned RAP sources C, D, and F mixed with PAV binder PG 58-28

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-13.5	-9.8	-17	-5.7	-13.5	-5.7
D	-10.9	-7.8	-15.7	-14.3	-10.9	-7.8
F	-11.3	-8.8	-17.8	-14.2	-11.3	-8.8

Table 7-17: Minimum low temperatures of burned RAP sources C, D, and F mixed with PAV binder PG 64-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-8.4	-5.2	-8.2	-6.1	-8.2	-5.2
D	-6.3	-5.8	-6.3	-1.8	-6.3	-1.8
F	-6.5	-3.5	-6.2	-4.1	-6.2	-3.5

Table 7-18: Minimum low temperatures of burned RAP sources C, D, and F mixed with PAV binder PG 76-22

RAP Source	Stiffness		M-value		**Low temperature determination**	
	Aged binder percentage		Aged binder percentage		Aged binder percentage	
	5%	10%	5%	10%	**5%**	**10%**
C	-9	-6.9	-11.9	-9.9	-9	-6.9
D	-7.6	-5	-9.4	-7.6	-7.6	-5
F	-8.1	-5.3	-10.4	-8.3	-8.1	-5.3

8 DSR, BBR, ITS, SCB Results, and Development of New Methodology for Determination of Low Temperature Properties

In this section, all test results for this portion of the project are summarized and analyzed, including DSR test results of asphalt binders with extracted asphalt binders at high and intermediate temperatures; the BBR test results of asphalt binders with various percentages of aged binders or RAP mortars at low temperature; ITS values of asphalt mixtures containing various RAP contents at intermediate and low temperatures; and SCB test results of different asphalt mixtures at low temperatures.

8.1 <u>DSR Test Results</u>

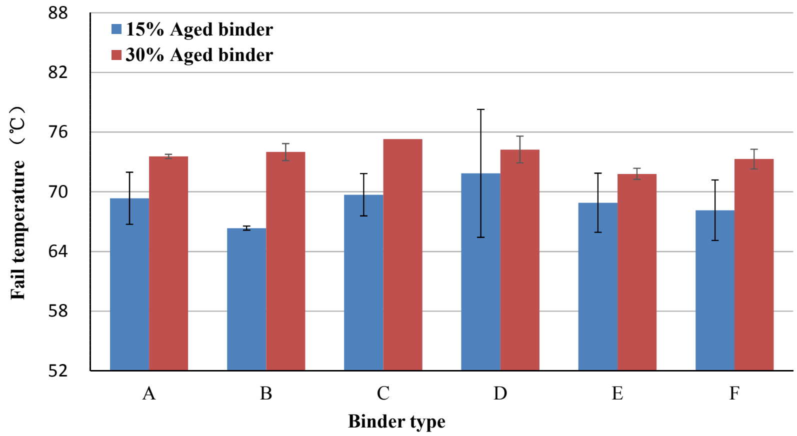
In this study, over 200 grams aged binder was extracted from each RAP source (RAP A-F) according to the specification. These extracted binders (15% and 30% by weight of total binder) were blended with three base binders (PG 58-28, PG 64-22, and PG 76-22) to produce the modified binders, which were tested to obtain the values of failure temperatures, G*, and phase angle at three aging states (virgin, rolling thin film oven (RTFO), and pressured aging vessel (PAV)) per Superpave binder specifications.

8.1.1 Virgin State

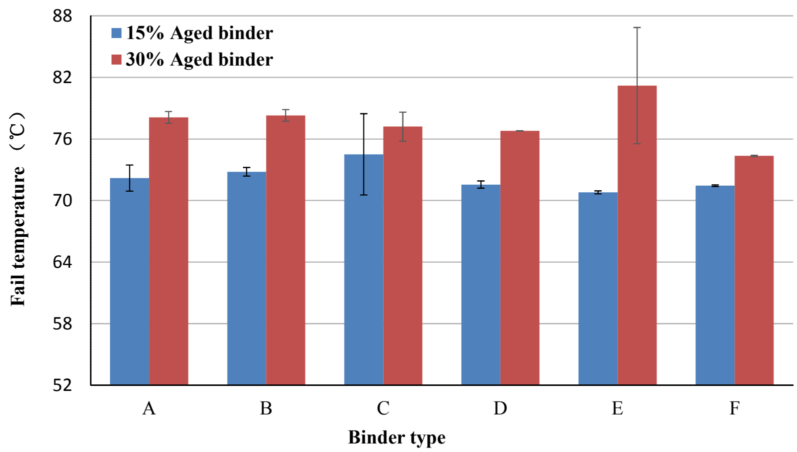
The failure temperatures of the modified binders mixed with extracted binders from six RAP sources (aged binder or RAP binder) and three base binders are shown in Figure 8-1. It can be noted that a higher aged binder resulted in a higher failure temperatures regardless of aged binder type and virgin binder type. As shown in Figure 8-1(a), all modified binders have a failure temperature greater than 64^{o} C even though the virgin binder is PG 58-28 binder, and failure temperature is over 70^{o} C when mixed with 30% aged binder.

Similarly, Figure 8-1(b) indicates that the failure temperatures of the modified binders are greater than 76^{o} C and 82^{o} C when 15% aged binder and 30% aged binder were used, respectively. In addition, as shown in Figure 8-1(c), the modified binders mixed with PG 76-22 binder generally have failure temperatures greater than 82^{o} C and 88^{o} C, respectively. Therefore, additional aged binder obviously increased the failure temperature of the modified binder regardless of RAP type. However, Figure 8-1 indicates that the RAP type slightly affects the failure temperatures.

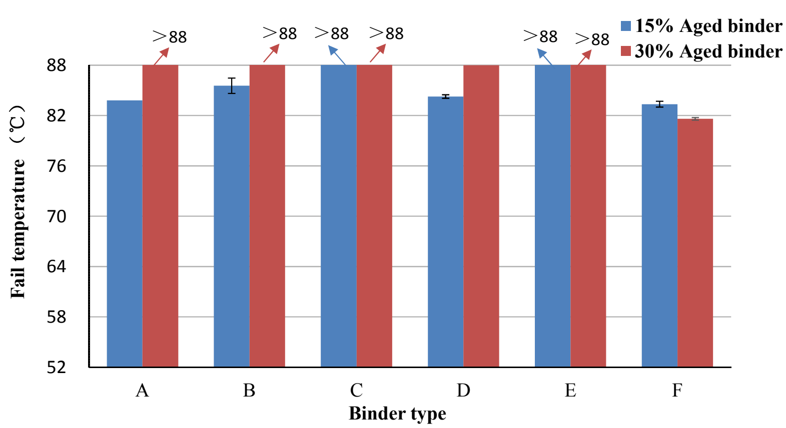
The G*/ sin δ values are shown in Figure 8-2. It can be found that, as expected, the modified binder containing 15% aged binder has a lower G*/ sin δ value than those binders containing 30% aged binder. In addition, a different base binder can result in a different G*/ sin δ value regardless of RAP binder type. As shown in Figure 8-2, a PG 76-22 binder mixed with RAP binder can resist a higher temperature since the G*/sinδ value is high when the modified binder is tested at a relatedly high temperature.



(a)

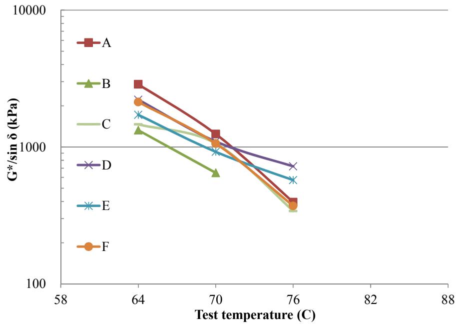


(b)

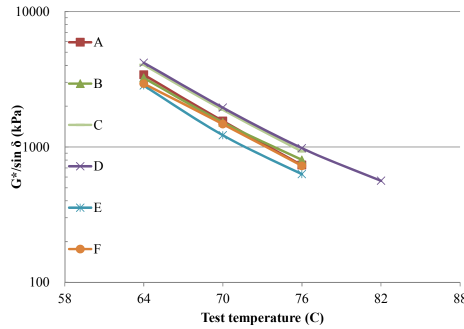


(c)

Figure 8-1: Failure temperatures of the modified binders with various RAP binders, (a) PG 58-28 binder, (b) PG 64-22 binder, (c) PG 76-22 binder



(a)



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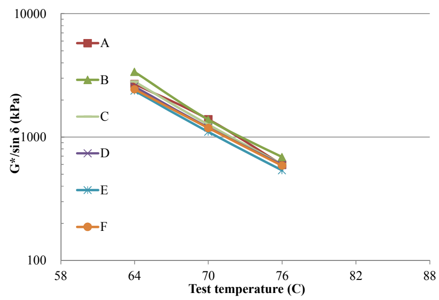
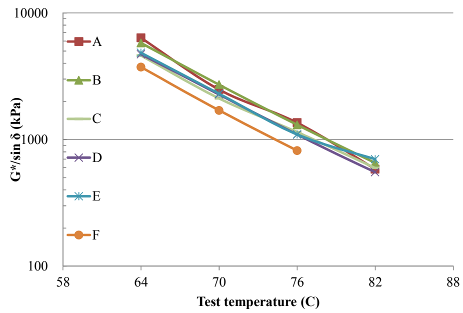
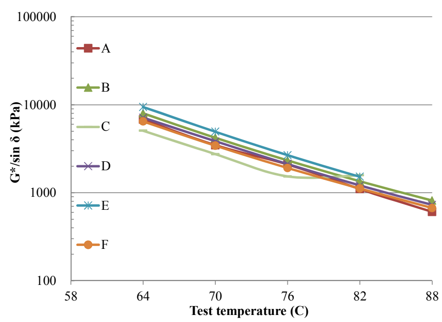


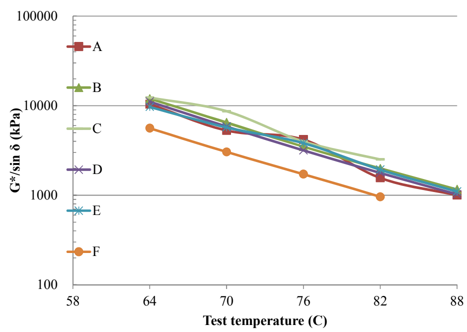
(c)



(d)



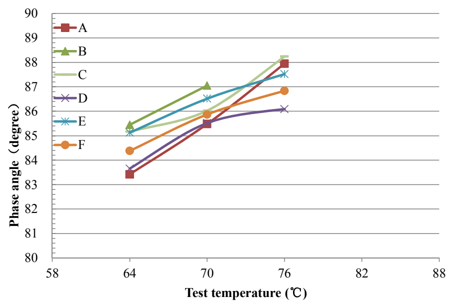
(e)



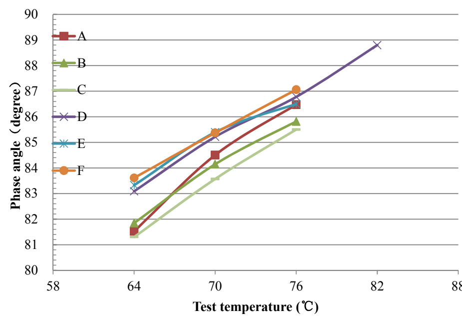
(f)

Figure 8-2: G*/sin δ of the modified binders with various RAP binders, (a) 15% RAP binder with PG 58-28 binder (b) 30% RAP binder with PG 58-28 binder, (c) 15% RAP binder with PG 64-22 binder, (d) 30% RAP binder with PG 64-22 binder (e) 15% RAP binder with PG 76-22

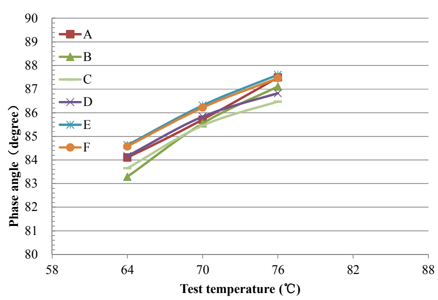
The phase angles of the modified binders mixed with RAP binders and three base binders are shown in Figure 8-3. It can be noted that the modified binder mixed with a 15% RAP binder has a higher phase angle. Various RAP binders generally have obvious effects on the phase angle. In addition, the modified binder with a PG 76-22 base binder has a lower phase angle, followed by PG 64-22 binder and PG 58-28 binder.



(a)



(b)



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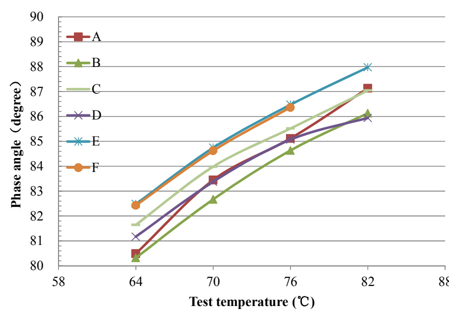

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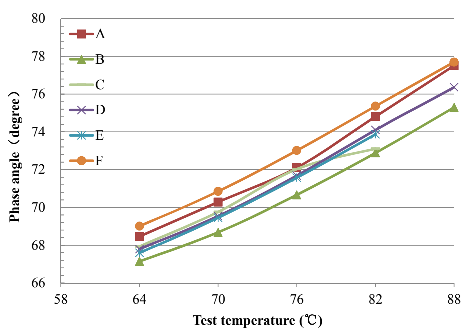

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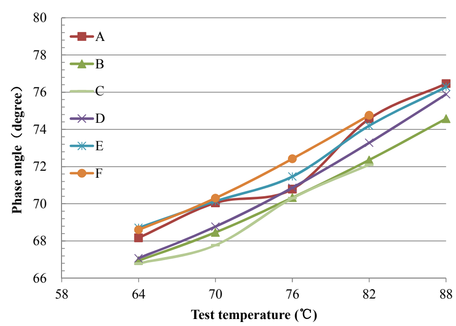


(f)

Figure 8-3: Phase angles of the modified binders with various RAP binders, (a) 15% RAP binder with PG 58-28 binder (b) 30% RAP binder with PG 58-28 binder, (c) 15% RAP binder with PG 64-22 binder, (d) 30% RAP binder with PG 64-22 binder (e) 15% RAP binder with PG 76-22

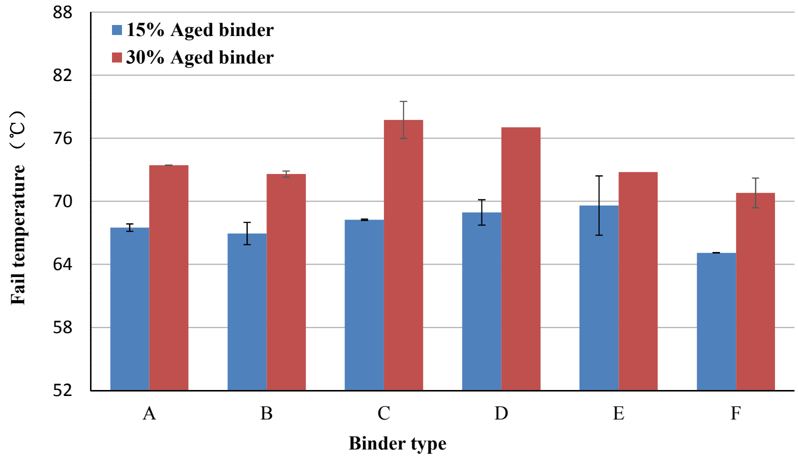
8.1.2 RTFO State

The modified binders produced from base binders and various extracted binders were aged through a short-term aging procedure at 163° C and 85 minutes per Superpave binder specification. These RTFO aged binders were tested to obtain the failure temperatures, G*/ sin δ values, and phase angles at different testing temperatures.

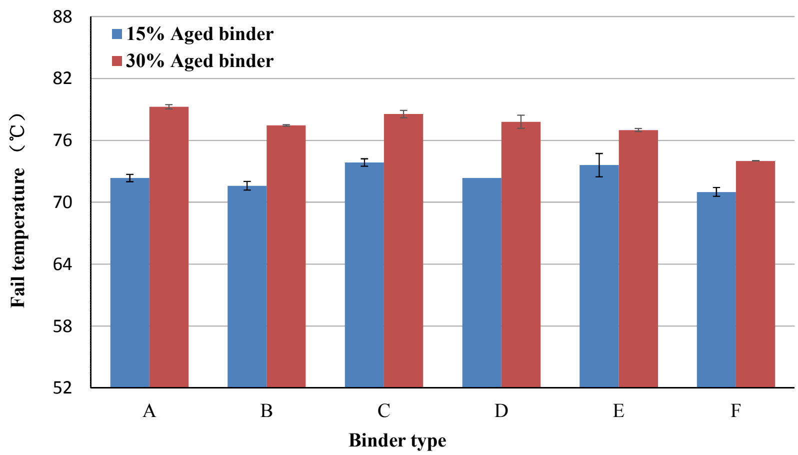
Similar to virgin state, the failure temperatures of the RTFO modified binders mixed with extracted binders from six RAP sources (aged binder or RAP binder) and three base binders are shown in Figure 8-4. It can be noted that, as described above, the failure temperatures of the RTFO modified binders with 15% aged binders are higher than those temperatures of the modified binders with 30% aged binders regardless of binder type and RAP source. There are some slightly differences in failure temperatures between any two modified binders. Therefore, as expected, RAP sources affect their aged binders and the results.

The $G^*/ \sin \delta$ values of the modified RTFO binders are shown in Figure 8-5. It can be observed that, similarly, the modified RTFO binder with 15% aged binder has a lower $G^*/ \sin \delta$ value than those binders containing 30% aged binder. In addition, as shown in Figure 8-5, a PG 76-22 binder (A) mixed with RAP binder can resist a higher temperature compared to PG 64-22 and PG 58-28 binders since its $G^*/ \sin \delta$ value is higher when the modified RTFO binder is performed at a high temperature. The modified binders from various extracted binders generally have different $G^*/ \sin \delta$ values due to the influence of the aged binder.

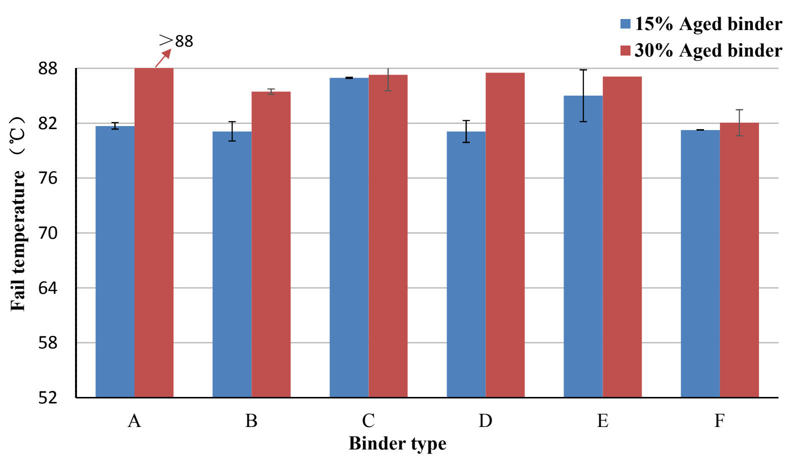
The phase angles of the modified RTFO binders mixed with aged binders and three binders are shown in Figure 8-6. It can be noted that the modified RTFO binder mixed with a 15% RAP binder has a relatively higher phase angle. Various RAP binders generally have obvious effects on the phase angle. In addition, the modified RTFO binder with a PG 76-22 base binder has a lower phase angle regardless of RAP type, as expected, followed by PG 64-22 binder and PG 58-28 binder.



(a)



(b)



(c)

Figure 8-4: Failure temperatures of the modified RTFO binders containing various RAP binders, (a) PG 58-28 binder, (b) PG 64-22 binder, (c) PG 76-22 binder

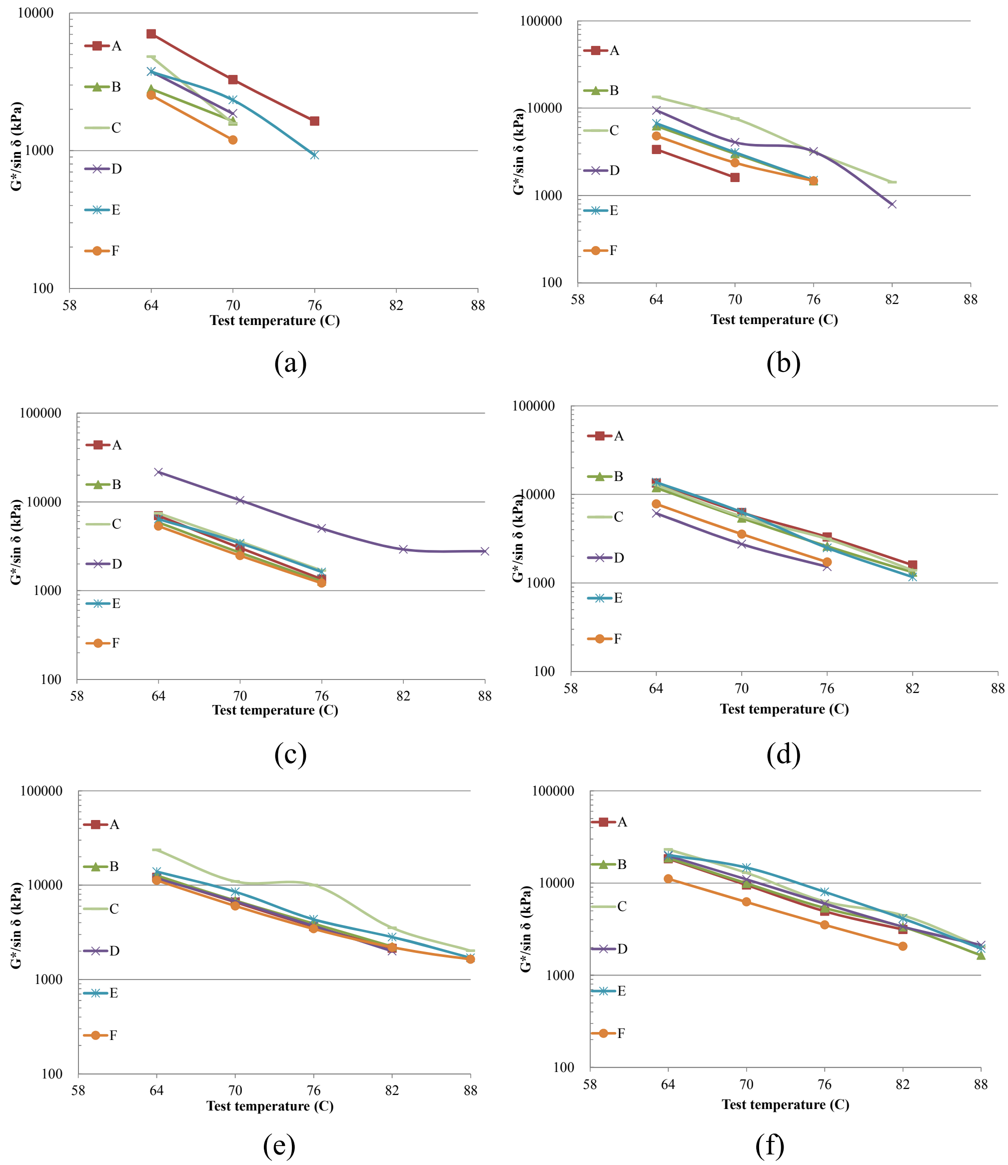


Figure 8-5: G*/sin δ of the modified RTFO binders with various RAP binders, (a) 15% RAP binder with PG 58-28 binder (b) 30% RAP binder with PG 58-28 binder, (c) 15% RAP binder with PG 64-22 binder, (d) 30% RAP binder with PG 64-22 binder (e) 15% RAP binder with PG 76-22 binder

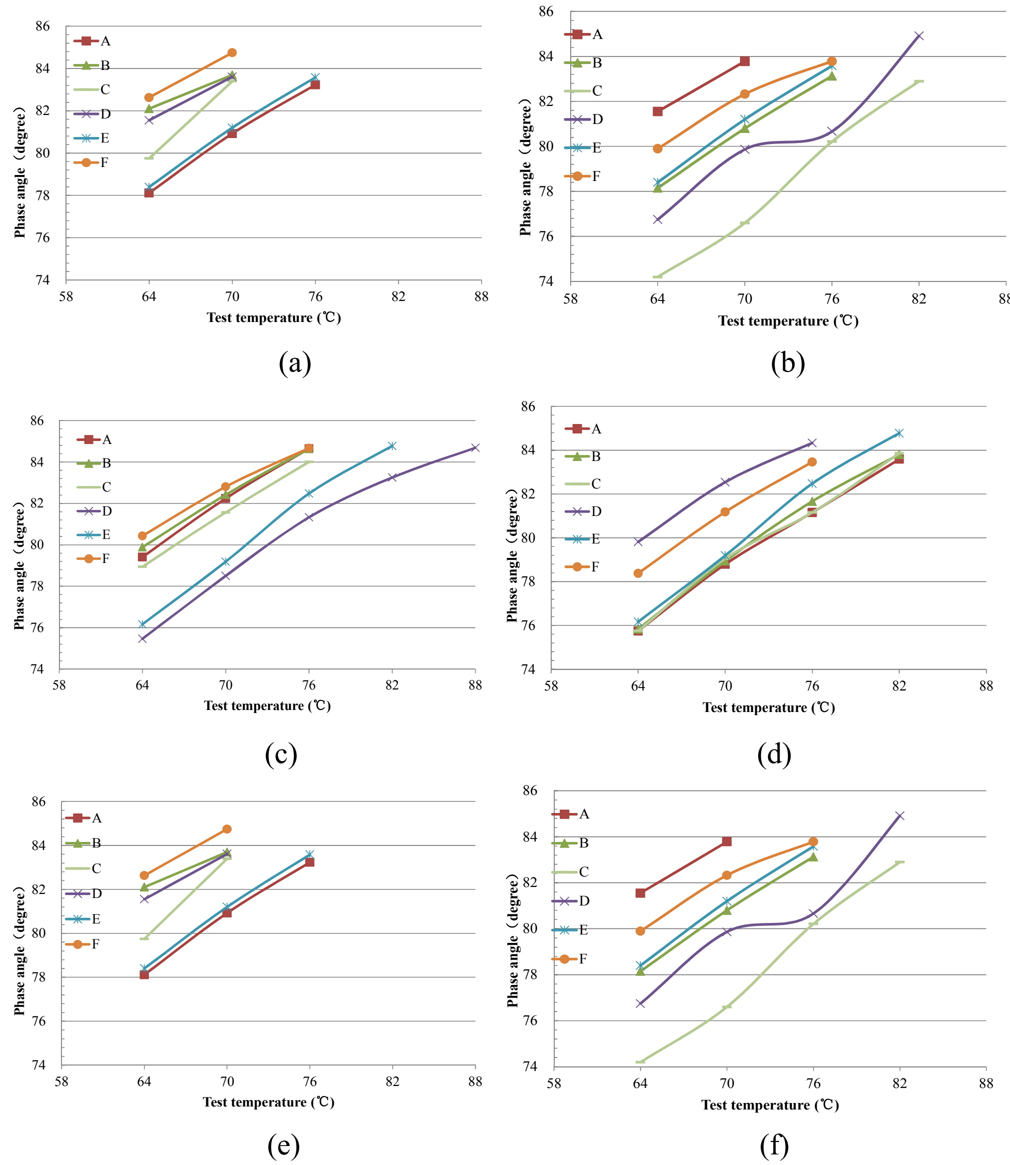


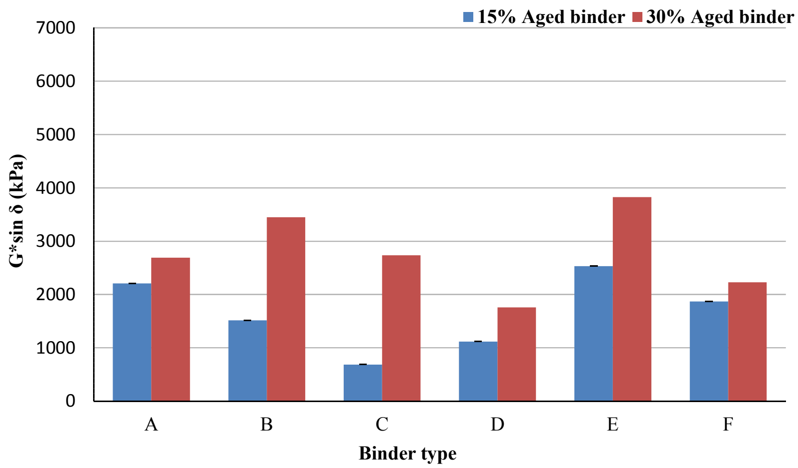
Figure 8-6: Phase angles of the modified RTFO binders with various RAP binders, (a) 15% RAP binder with PG 58-28 binder (b) 30% RAP binder with PG 58-28 binder, (c) 15% RAP binder with PG 64-22 binder, (d) 30% RAP binder with PG 64-22 binder (e) 15% RAP binder with PG 76-22 binder, (f) 30% RAP binder with PG 76-22 binder

8.1.3 PAV State

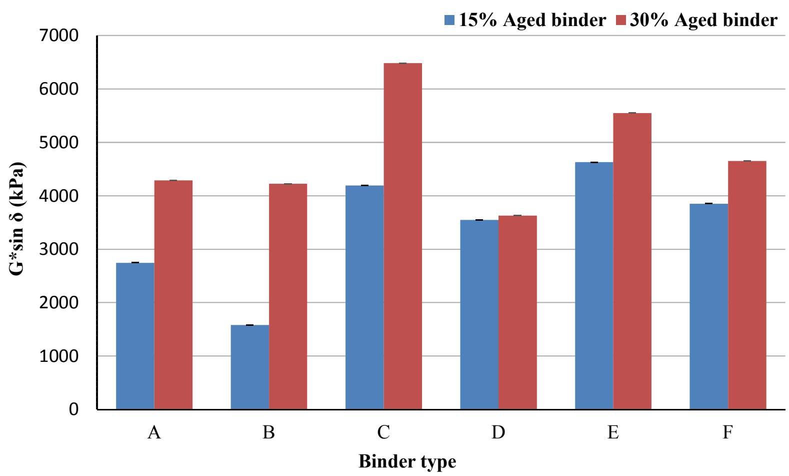
The modified RTFO binders were aged through a long-term aging procedure at 100^o C, 20-hour and an air pressure of controlled to 2.1 ± 0.1 MP per Superpave binder specification. These PAV aged binders were tested to explore the fatigue factors (G* sin δ) of various modified binders at an intermediate temperature of 31 ºC in terms of the binder grade of PG 76-22 and aged binder.

As shown in Figure 8-7, it can be seen that all G* sin δ values of the modified PAV binders mixed with PG 58-28 are less than 5000 kPa, a maximum value set by Superpave specification regardless of RAP type and aged binder content. However, the modified binders mixed with PG 64-22 binder and 30% RAPs C and E have G* sin δ values greater than 5000 kPa, and thus is difficult to resist the fatigue cracking. Similar results can be obtained from the modified binder mixed with PG 76-22 binder and 30% RAP C.

Figure 8-8 indicates that phase angles of the modified PAV binders containing 15% aged binder are lower than those binders containing 30% aged binder regardless of binder and RAP type. There are some differences in phase angles in terms of various binder and RAP types used in this study. The main reason is that the components of the aged binders from various RAP sources are generally different.



(a)



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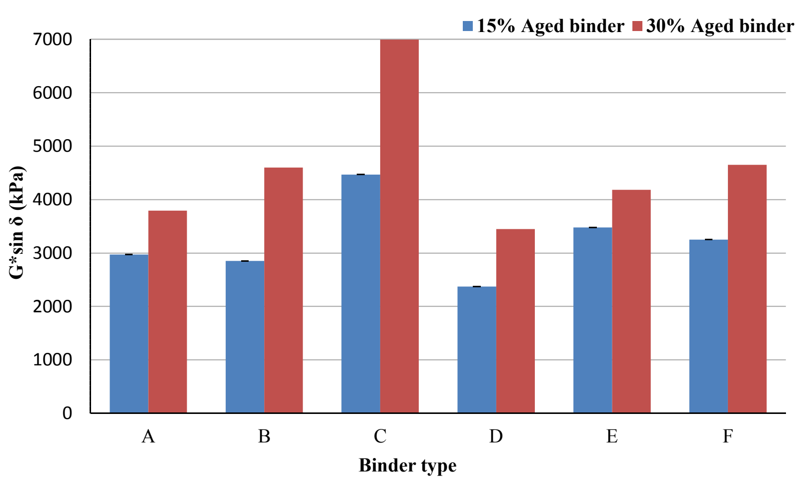
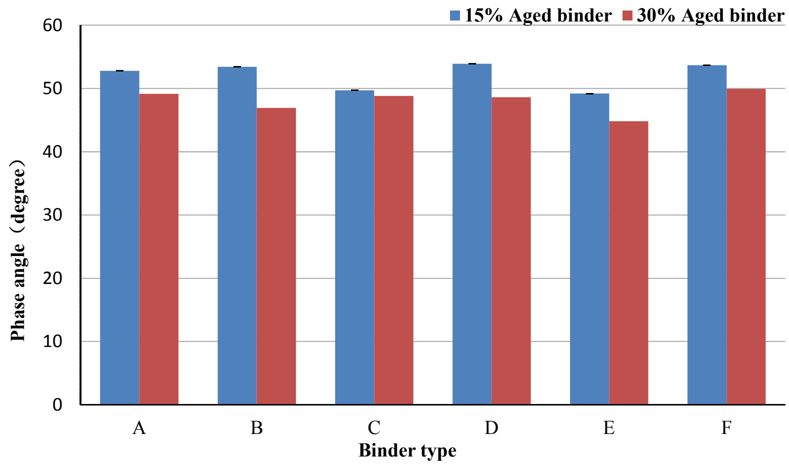
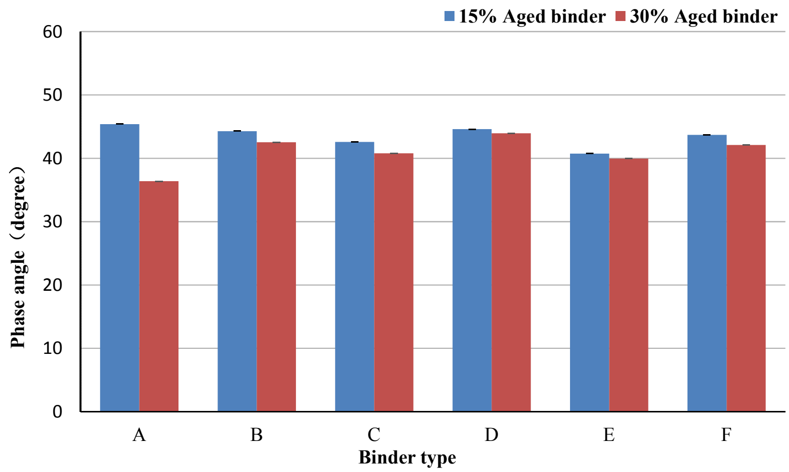


(c)

Figure 8-7: G* sin δ values of the modified PAV binders containing various RAP binders, (a) PG 58-28 binder, (b) PG 64-22 binder, (c) PG 76-22 binder



(a)



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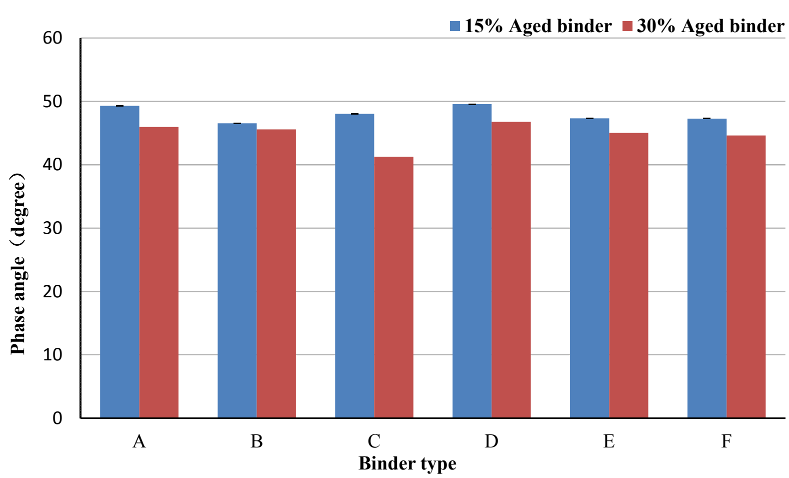


(c)

Figure 8-8: Phase angles of the modified PAV binders containing various RAP binders, (a) PG 58-28 binder, (b) PG 64-22 binder, (c) PG 76-22 binder

8.2 ITS Test Results

After the mix designs were completed, for each aggregate / binder / RAP combination, four Superpave gyratory compacted specimens, 150mm in diameter and 95mm in height, were prepared with 7 ± 1% air voids and then the samples were tested at 25 °C (77°F) to determine the indirect tensile strengths. Two of the samples were tested in dry condition and the other two in wet condition as per the SCDOT procedure for determining the moisture susceptibility (SC T 70).

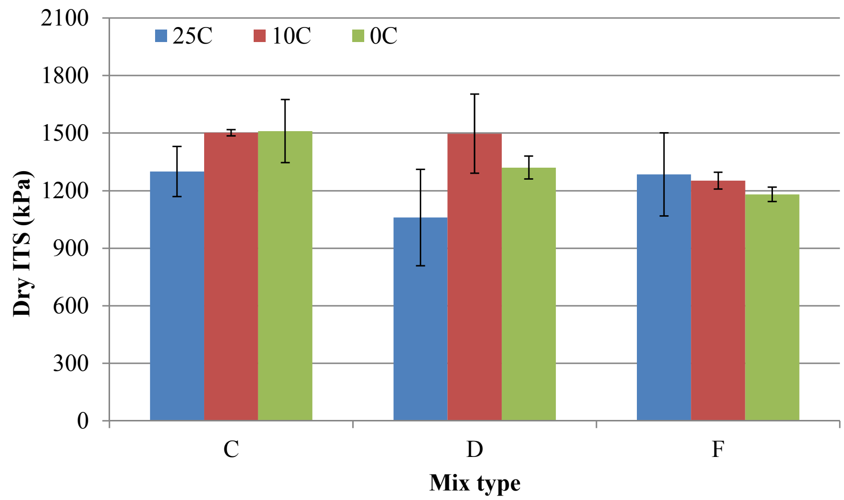
In addition, three selected RAP sources were employed to produce the ITS samples. RAPs C and F have the lowest and the highest stiffness values, respectively, amongst six RAP sources and RAP D had the medium stiffness in this study. Therefore, these three RAPs were selected to produce the ITS samples in accordance with the objectives of the proposal.

In this study, three different temperatures were employed to condition the samples. One set of ITS samples (dry and wet samples) were conditioned at 25 ºC (room temperature) for 24 hours before running the SC T 70 test procedures. Other sets of samples were conditioned at 10 ºC and 0 ºC for 24 hours first, and then were stored at 25 ºC for another 6 hours before conducting the SC T 70 testing procedures. The results of this section of testing are discussed in the following sections.

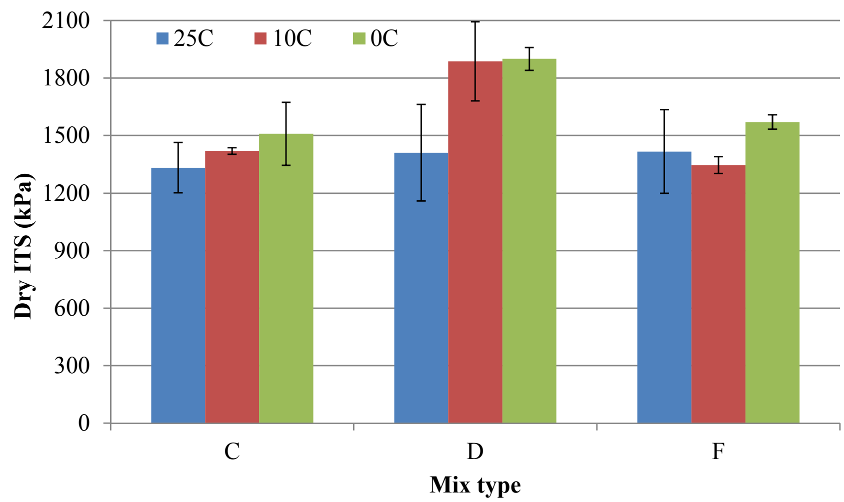
8.2.1 Dry ITS Analysis

The dry ITS values of the modified mixtures mixed with 15% aged binders from various RAP sources were compared and the results are shown in Figure 8-9(a). It is shown that all ITS values are greater than 900 kPa, and most of ITS values are close to 1200 kPa. No obvious trends in dry ITS values can be found for three set of samples. In addition, ITS values from the mixtures containing RAP F are not greater than other ITS values regardless of conditioned temperature even though RAP F has the highest stiffness value.

Similar trends can be found in Figure 8-9(b) when the mixtures mixed with 30% aged binders. However, compared to the dry ITS values in Figure 8-9(a) with those values in Figure 8-10(a), the mixtures mixed with 30% aged binders generally have greater dry ITS values. In addition, it can be seen that the ITS values are the highest when the samples were conditioned at 0 ºC regardless of the RAP type. Therefore, it can be concluded that the temperature used to condition the samples, generally, does not affect the dry ITS values.



(a)



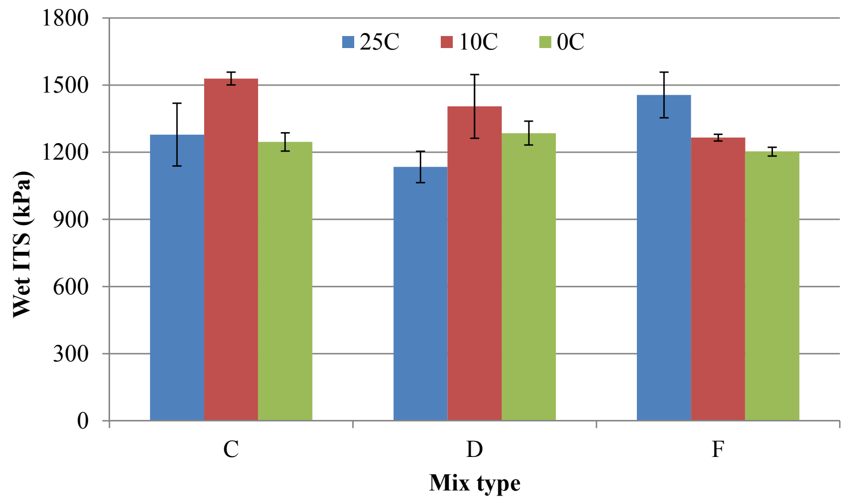
(b)

Figure 8-9: Dry ITS values of the modified mixtures with various RAP sources (a) 15% aged binder, (b) 30% aged binder

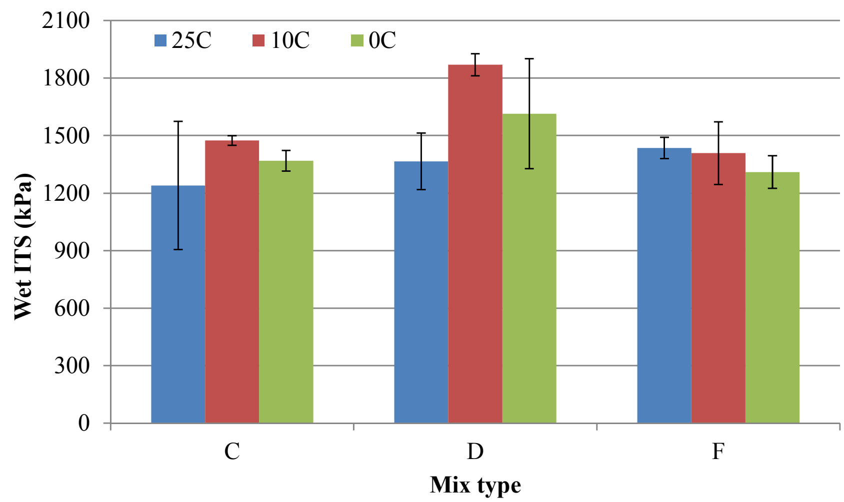
8.2.2 Wet ITS Analysis

The wet ITS values of the modified mixtures mixed with RAP sources C, D, and F are shown in Figure 8-10. It can be observed that all wet ITS values are close to 1200 kPa and greater than 448 kPa (65 psi) regardless of RAP content, RAP type, and temperatures used to condition the samples.

Similar to the dry ITS values, no trends in the ITS values can be found in terms of various conditioned temperatures for the mixtures containing both 15% and 30% aged binders. As shown in Figure 8-10, it can be found that the stiffness values of aged binders do not affect the wet ITS values in this study.



(a)

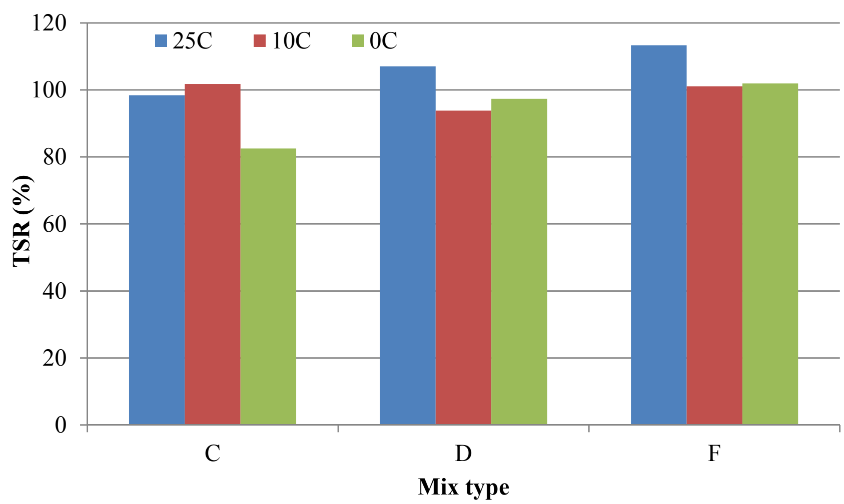


(b)

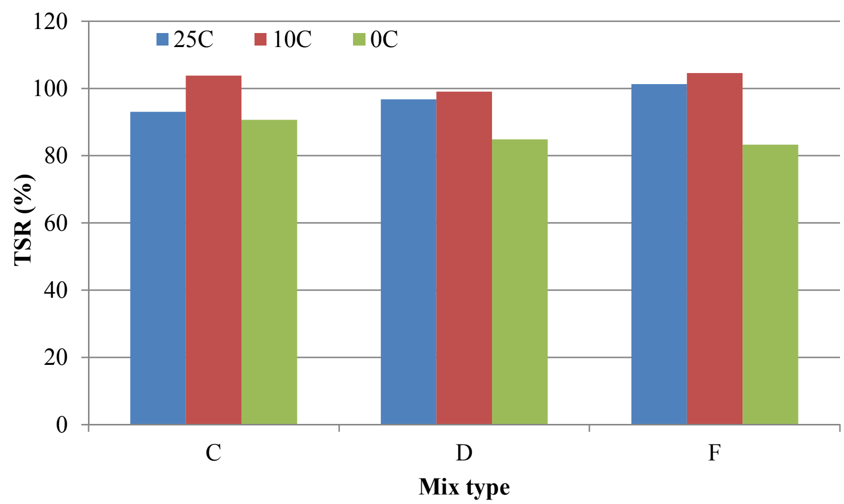
Figure 8-10: Wet ITS values of the modified mixtures with various RAP sources (a) 15% aged binder, (b) 30% aged binder

8.2.3 TSR Analysis

As shown in Figure 8-11, the TSR values of all mixtures are greater than 80% regardless of RAP type, conditioned temperature, and RAP content. It can be noted that the TSR values are generally lower when the samples were conditioned at a relative low temperature of 0 ºC. Some TSR values are less than 85%, a minimum value set by SCDOT. However, that requirement is set only for samples tested at 25 ºC No trends in TSR values can be found for various RAP sources.



(a)



(b)

Figure 8-11: TSR values of the modified mixtures with various RAP sources (a) 15% aged binder, (b) 30% aged binder

8.3 <u>Semi-Circle Bending Test Results</u>

The semi-circle bending (SCB) test procedures were followed to make the test specimens and test them. The following figures show the results of the testing. The red line represents the average value of the three tests conducted for each mix. The crack mouth opening displacement (CMOD), in mm, vs load (kN) of each mix was obtained and are presented below.

The SCB test is used to obtain the fracture energy of asphalt mixtures, lab or field specimens. This can be used in performance-type specifications to control various forms of cracking (e.g., thermal, reflective, block cracking) of asphalt pavements. In general, the testing is conducted at 10 ºC warmer than the PG low temperature grade. The sample preparation and testing procedures were explained in previous sections of this report.

Figure 8-12 through Figure 8-17 show that the aggregate source and the amount RAP affects the performance of the mixtures considering the crack moth opening displacement (CMOD) values. Figure 8-18 shows the comparison of all three sources with various amounts of RAP materials. The results show that, in general, specimens made with aggregate source Liberty, regardless of RAP percentages, performed the worst and Duncan mix performed the best.

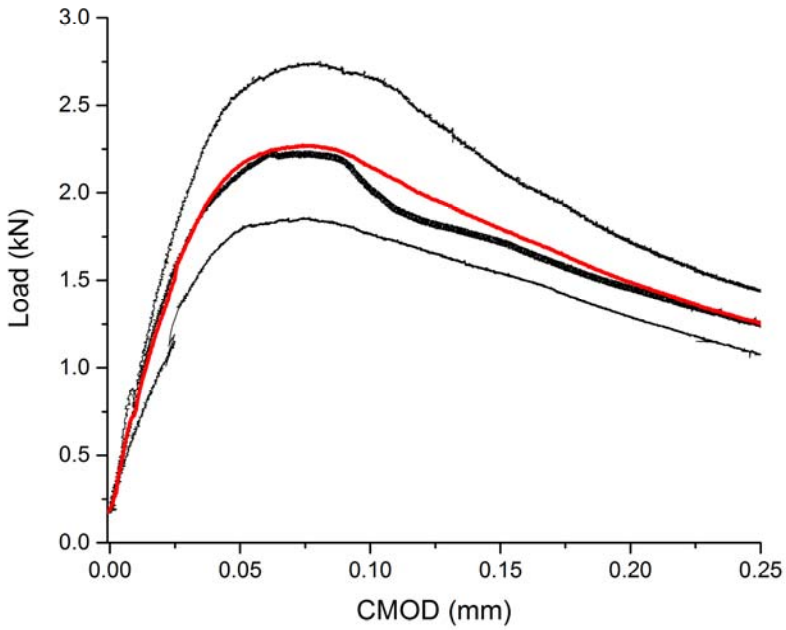


Figure 8-12: Crack Mouth Opening Displacement (CMOD), mm, of Duncan Materials Containing 15% RAP

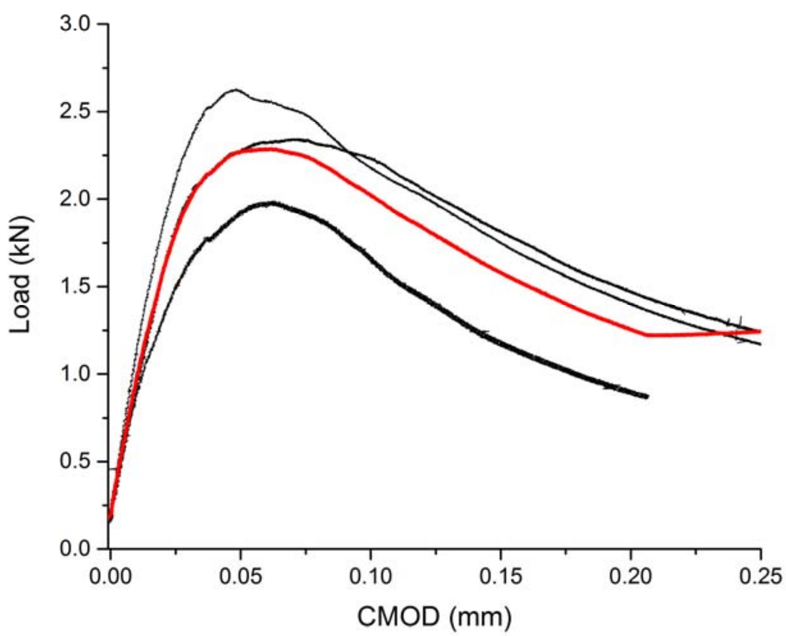


Figure 8-13: Crack Mouth Opening Displacement (CMOD), mm, of Duncan Materials Containing 30% RAP

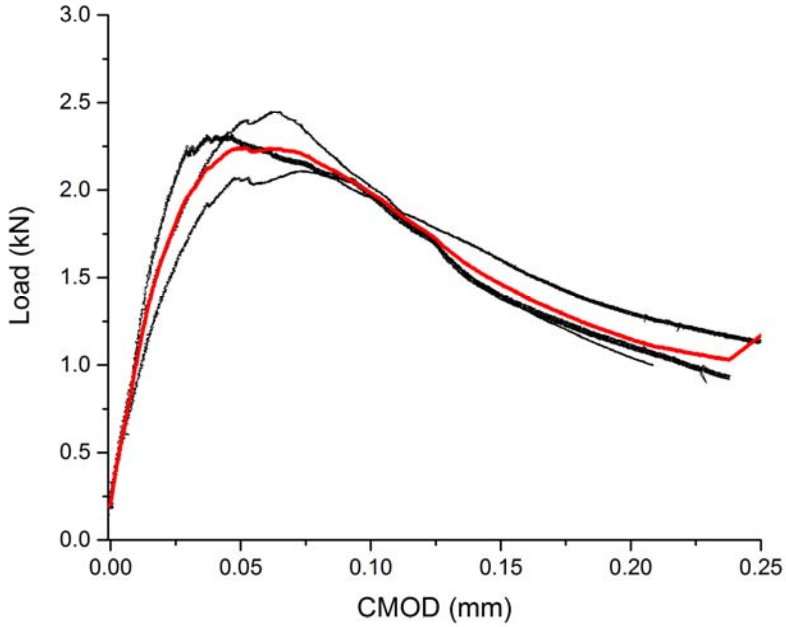


Figure 8-14: Crack Mouth Opening Displacement (CMOD), mm, of Jefferson Materials Containing 15% RAP

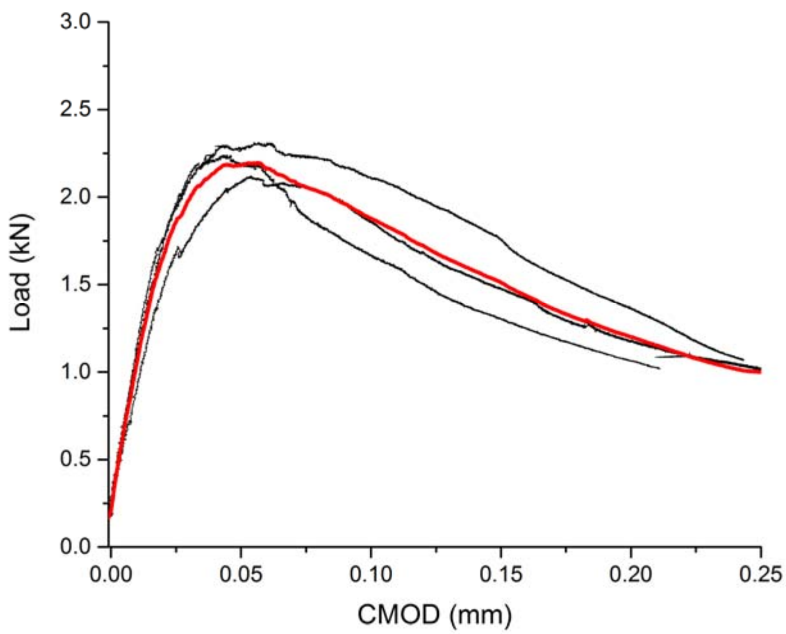


Figure 8-15: Crack Mouth Opening Displacement (CMOD), mm, of Jefferson Materials Containing 30% RAP

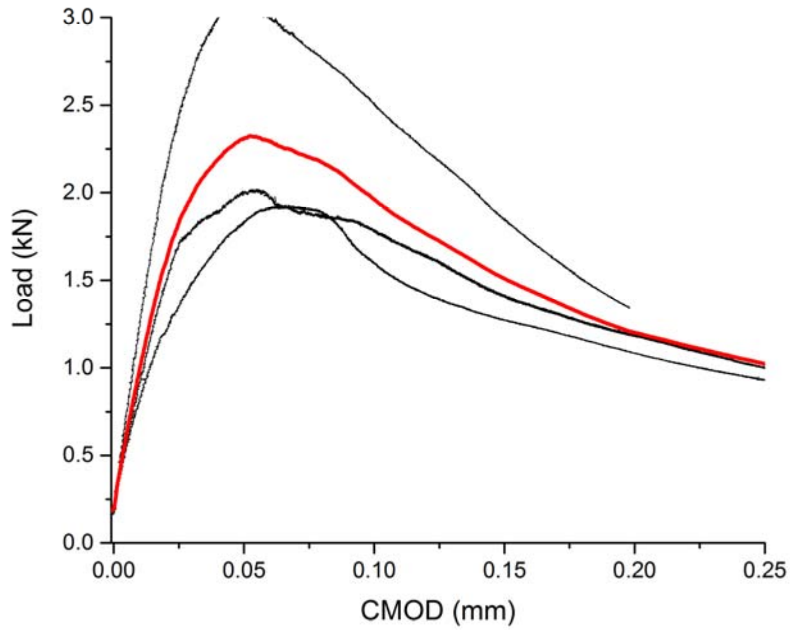


Figure 8-16: Crack Mouth Opening Displacement (CMOD), mm, of Liberty Materials Containing 15% RAP

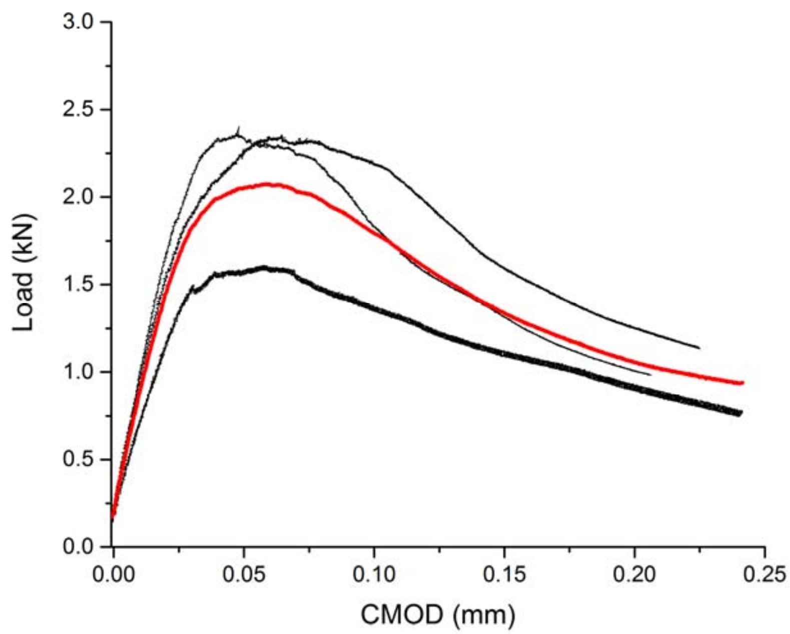


Figure 8-17: Crack Mouth Opening Displacement (CMOD), mm, of Liberty Materials Containing 30% RAP

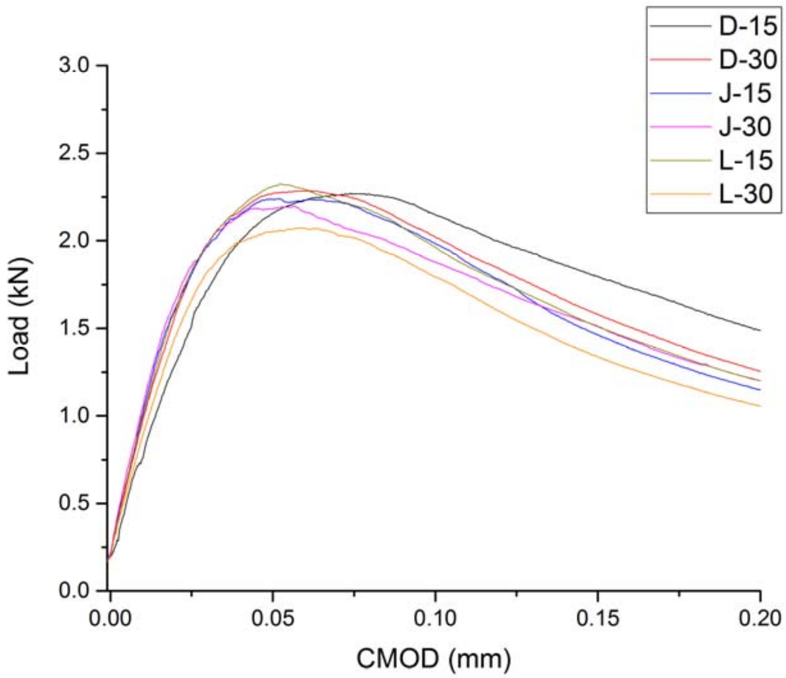


Figure 8-18: Crack Mouth Opening Displacement (CMOD), mm, of Three Sources Containing 15% and 30% RAP

8.4 Determination of Low Temperature Performance Grade from RAP Mortar with/without Extracted Binders

In order to develop a methodology to determine the low performance temperatures of the modified binder blended from extracted binder or RAP mortar, three base binders (PG 58-28, PG 64-22, and PG 76-22) were utilized to obtain the models determined based their stiffness and m-values. The main results and discussions have been presented in previous sections. The summarized data are shown in Table 8-1 and Table 8-2.

As shown in Table 8-1, the low temperatures of these modified binders with RAP mortars (5% aged binder) and PAV aged PG 58-28 binder are generally less than -28° C regardless of RAP type. Therefore, it can be concluded that, the modified binders blended with PG 58-28 binder and RAP mortar containing 5% aged binder have the same low temperature performance grade with PG 58-28 binder obtained without extraction using the BBR test. As shown in Table 8-1, similar finding can be noted for these binders blended with PG 64-22 and PG 76-22 binders

In addition, Table 8-1 indicates that, when RAP mortars were used containing 10% and 15% aged binders, the low temperatures of the modified binders are generally higher than -22 ºC and less than -16 ºC. Thus, their low temperature performance grades are altered from -28 ºC, -22 ºC, and -22 ºC to all of -16 ºC for PG 58-28, PG 62-22, and PG 76-22 binders, respectively. In other words, one performance grade

(6^{o} C) of the base binder is adjusted due to additional RAP mortar. Moreover, based on the data shown in Table 8-1, it can be observed that the impact of binder type on the low temperature performance grade is not generally noticeable.

Table 8-2 illustrates the low temperature performance grades of three PAV aged base binders with extracted binders from various RAPs. It can be shown that, when 15% extracted binder was used, the modified binders with PG 58-28 and PG 64-22 binders have low temperatures of higher than -28 ºC and -22 ºC, respectively, while those binders with PG 76-22 binder have the values close to -22 ºC. In addition, the modified binders containing 30% extracted binder have one performance grade (6 ºC) increase for the low temperature.

Table 8-1: Low temperature determinations of three PAV base binders blended with RAP mortars in terms of three aged percentage

RAP source	Base binder PG 58-28			Base binder PG 64-22			Base binder PG 76-22		
	5%	10%	15%	5%	10%	15%	5%	10%	15%
A	PG -31	PG -21	PG -17	PG -25	PG -19	PG -16	PG -24	PG -18	PG -16
B	PG -32	PG -24	PG -21	PG -25	PG -19	PG -16	PG -25	PG -19	PG -17
C	-	PG -25	PG -20	PG -27	PG -19	PG -17	PG -28	PG -22	PG -18
D	PG -29	PG -21	PG -17	PG -22	PG -17	PG -16	PG -26	PG -20	PG -17
E	PG -33	PG -22	PG -19	PG -30	PG -19	PG -14	PG -27	PG -21	PG -16
F	PG -32	PG -21	PG -19	PG -26	PG -20	-	PG -25	PG -19	-

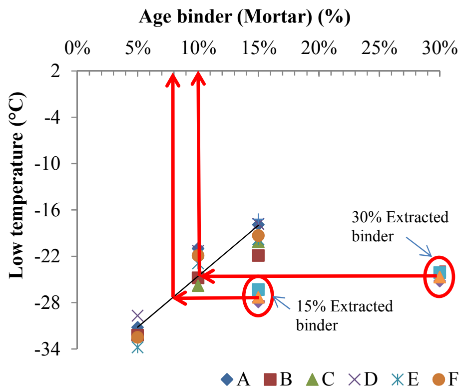
Table 8-2: Low temperature determinations of three base binders blended with extracted binders in terms of two aged percentage

RAP source	Base binder PG 58-28		Base binder PG 64-22		Base binder PG 76-22	
	15%	30%	15%	30%	15%	30%
A	PG -27	PG -24	PG -20	PG -17	PG -23	PG -21
B	PG -27	PG -23	PG -19	PG -17	PG -23	PG -21
C	PG -26	PG -24	PG -17	PG -18	PG -23	PG -19
D	PG -27	PG -25	PG -20	PG -19	PG -23	PG -21
E	PG -26	PG -24	PG -20	PG -17	PG -20	PG -20
F	PG -27	PG -24	PG -18	PG -18	PG -23	PG -23

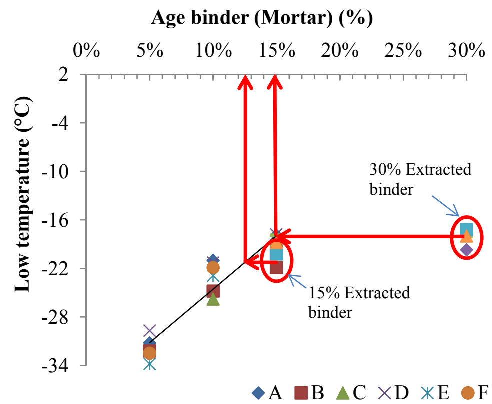
8.5 Determination of RAP Mortar Contents Based on Low-Temperature Performance Grades from Extracted Binders

The RAP mortar contents of the modified binder were determined by the properties of extracted binder in terms of their low temperature performance characteristics. Figure 8-19 indicates how to determine these percentages. For example, as shown in Figure 8-19(a), the modified binder blended with PG 58-28 binder and RAP mortar containing three percentages of aged binders have a linear relationship between aged binder and low temperature. In addition, the low temperatures of the modified binder with 15% and 30% extracted binders (from RAP) are presented in Figure 8-19(a). The average low temperatures of these six modified binders (from six RAP sources) can be used to determine the aged binder concentrations from RAP mortars by back-calculation process. In other words, the low temperature of the modified binder containing 15% extracted aged binder is the same as the modified binder blended with RAP mortar containing 8% aged binder. Additionally, the modified binder containing 30% extracted binder has the same low temperatures as the modified binder blended with RAP mortar with 10% aged binder. The detailed information is shown in Table 8-3.

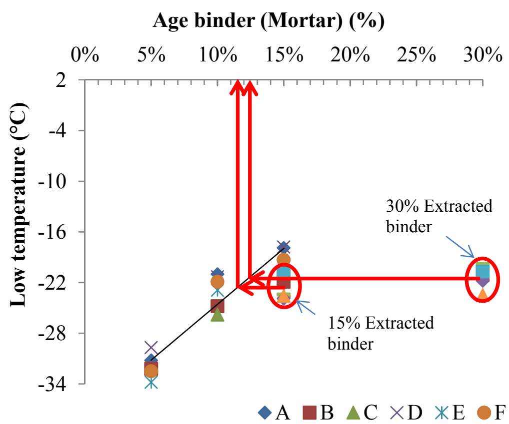
Similar findings can be noted when base binders PG 64-22 and PG 76-22 are used. Therefore, it can be concluded that the low temperature performance grade of the modified binder, blended with fine RAP, can be determined in terms of using common BBR test. No further extractions are needed in general to obtain these values. The conducted simple linear formulas can be employed to decision-making process of the implementation of RAP materials in the asphalt pavement paving industry with respect to the binder grade (PG 58-28, PG 64-22 and PG 76-22).



(a)



(b)



(c)

Figure 8-19: RAP mortar content determination of modified binder based on low temperature with respect to extracted binder percentage, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

Table 8-3: Transformations from extracted binder to aged binder of RAP mortar in terms of low temperature performance grades

RAP source	Base binder PG 58-28		Base binder PG 64-22		Base binder PG 76-22	
	Extracted binder	Aged binder from RAP mortar	Extracted binder	Aged binder from RAP mortar	Extracted binder	Aged binder from RAP mortar
A, B, C, D, E, F	15%=	8.0%	15%=	12.5%	15% =	11.5%
	30%=	10.0%	30%=	15.0%	30% =	12.5%

9 Summary, Findings, Conclusions and Recommendations

9.1 Summary

The original Superpave mix design procedures did not include the steps necessary to conduct a recycled HMA mix design. However, many state DOTs around the country, including SCDOT, used previously-developed procedures in late 1980s to conduct mix designs for mixtures containing RAP. In addition, for the PG grade changes that occur in the mix guidelines were developed by the FHWA's Superpave Expert Task Group (ETG) that were followed by many state DOTs to conduct mix designs. These procedures were evaluated in a research project, NCHRP Project 9-12, and the results indicated that the guidelines are helpful in developing a proper mix design. However, there is a major problem with this system since for some mixtures, the procedure does not consider the age of the binder and considers only the amount of binder in the mix.

In this research project, several testing procedures for binders, mortars, and mixtures were conducted to determine the low-temperature characteristics of mixtures containing aged binders and RAP materials from various sources around the state. These recommended testing procedures include: modified BBR for RAP mortar testing; Semi-Circular Bending (SCB); and Indirect Tensile Strength (ITS) testing at different temperatures.

For this research project, in order to determine the low-temperature characteristics of mortar made from fine material, six RAP sources (two with high stiffness, two with medium stiffness, and two with low stiffness) mixed with virgin asphalt binders were used. One size fractions of fine RAP materials (-#50 to +#100) and three asphalt binder grades (PG 58-28, PG 64-22, and PG 76-22) were utilized. In addition, two aged binder contents (30% and 15%) were used. These RAP mortar mixtures were used to test for low-temperature properties using the modified BBR procedures. In addition, other tests were utilized (e.g., DSR) in determining some other properties (e.g., aging characteristics) of these mortars. The binder grades and sources and RAP sources were selected by consultation with the research Steering Committee members. The characteristics of the modified binders containing different percentages of aged binders after RTFO and PAV conditioning were determined.

In addition, the same six RAP sources mentioned above were used in this portion of the research work in which included using the ignition oven in producing the fine aggregates used to make the samples. The same total binder content and the same size fraction of fine RAP materials (-#50 to +#100) that were used in the RAP mortar samples were used for this portion of the study. The fine aggregates from the burned RAP materials will be mixed with virgin asphalt binders (PG 58-28, PG 64-22, and PG 76-22) and tested. These blended mortars will be tested for low-temperature properties using the modified BBR procedures. In addition, DSR testing procedures will be used in determining other properties (e.g., aging characteristics) of these mortars. The RTFO and PAV aged binders were also tested and compared to the virgin state binders.

All of the above-mentioned testing procedures and binders were used in testing six RAP sources (two with high stiffness, two with medium stiffness, and two with low stiffness). However, three of these RAP sources (one of the high stiffness, one of the medium stiffness, and one of the low stiffness sources) were collected again after one year from the commencement of the research work, and all of the above-described testing procedures were repeated. For this phase of the research work, the effects of time (one year) on the low-temperature properties of RAP obtained from the same source were investigated.

In addition, another phase of this research project included testing of asphalt mixtures containing RAP for low-temperature characteristics. Several existing and newly-developed testing procedures were used. The testing procedures used included Indirect Tensile Strength (ITS), Semi-Circular Bending (SCB) and modified ITS procedures. The exact testing procedures were determined by consulting with the Research Steering Committee.

9.2 Findings and Conclusions

1. An extensive literature review was undertaken for this research project to determine the various research programs being conducted around the country regarding this topic. The results of the literature review indicated that the modification of the bending beam rheometer (BBR) and procedures can be used to test the modified asphalt binders mixed with fine RAP (passing #50 and retaining on #100 sieves) with base binders. The test results in some cases reported in literature indicated that the low temperature characteristics of RAP binders could be obtained without conducting the extraction process. However, detailed determinations of how to conduct the modification and test the samples were not provided.

2. The findings indicated that the fine RAP mortars (with different stiffness values) could be mixed with virgin binders to produce modified binders, which could be tested with a traditional bending beam rheometer (BBR) test apparatus without any modifications. The blending procedure of fine RAP with virgin binders is easy to control at a relative high mixing speed and a proper temperature based on the viscosity of the modified binders. In general, the stiffness values of the modified binders were high when incorporated with fine RAPs, and the samples might be destroyed at a test temperature of -18 °C when PG 64-22 and PG 76-22 binders were used. The minimum low temperatures could be determined based on the simple regression analysis. It was found that the fine RAP source affected the minimum low temperatures of various modifiers.

3. The results of another phase of the research indicated that the RTFO aged binders could be blended with fine RAP. The produced modifiers could be tested at a traditional BBR machine without any modifications as well. However, it was found that these modified binders have higher stiffness and lower m-values, as expected, compared to the modifier involved with virgin binders. The minimum low temperatures were relatively higher than those produced from virgin binders when same RAP source was used. Obviously, the short-term aged procedures could lower the resistance of low temperature to cracking.

4. The fine RAP blended with PAV aged binders could produce the modified binders. However, a relatively higher RAP percentage (15% RAP content) resulted in a very stiff modified binder, which was difficult to make BBR samples and needed a temperature over 180^{o} C to pour. This modified binder easily was destroyed at a test temperature of -18^{o} C during testing. The minimum low temperatures were higher than -6^{o} C when 10% and 15% fine RAP were used in the asphalt binder and it does not meet the requirements of an asphalt binder (PG *-22).

5. The burned fine RAP (sand), used in this research project, could be mixed with virgin binder very well. The stiffness values were generally lower and m values were relatively higher than those from the modified binders mixed with unburned RAP when used same RAP source and the same content. The main reason is that the aged binder was removed from the RAP. In addition, the modified binders produced from the burned fine RAPs (sand) mixed with PG 58-28 binder were soft and could not be tested at -6^{o} C. The minimum low temperatures were generally in range of an asphalt binder (PG *-22) grade.

6. The modified binders mixed with burned fine RAP and RTFO binders exhibited relatively lower stiffness and higher m-values compared to the modified binders incorporated with unburned fine RAP regardless of the RAP source and base binder type. In addition, each binder could be tested without any problems during the BBR testing procedures at three tested temperatures. In some cases, the minimum low temperatures were higher than -12^{o} C when 15% burned fine RAP was used.

7. The PAV aged binders blended with the burned fine RAP had the highest stiffness values and lowest m-values, as expected, compared to the modified binders with RTFO binders and virgin binders. Additionally, it was found that the modified binders mixed with 15% burned fine RAP were difficult to work and conduct the testing procedures. The obtained minimum low temperatures were generally greater than -12^{o} C when 10% and 15% burned fine RAP were used. In other words, it reduced the low temperature resistance of an asphalt binder within a grade.

8. The re-collected fine RAPs, after one year, from the same sources (one with the highest stiffness, one with the medium stiffness and one with the lowest stiffness) mixed with virgin base binders, RTFO base binders, and PAV base binders generally had higher stiffness and lower m-values regardless of base binder type, aging state, and RAP types. The minimum low temperatures of the modified binders with re-collected fine RAPs were slightly higher and thus the resistance to low temperature was weakened. Therefore, it could be concluded that, as expected, the RAP in the field would be further aged (i.e., oxidation from being on the pile for an additional year); therefore, it is important to use the RAP as soon as it has been collected.

9. As expected, the modified RAP mixed with burned fine RAP and base binders had lower stiffness, higher m-values and the corresponding minimum lower temperatures compared to those binders mixed with unburned fine RAP regardless of the RAP source and content due to nature of the aged binder in the RAP.

10. The ITS values of the mixtures from three RAP sources (one with the highest stiffness, one with the medium stiffness and one with the lowest stiffness) were obtained after the procedure of a conditioning of 25 ^{o} C, 10 ^{o} C and 0 ^{o} C. It was found that the conditioning did not remarkably change the dry and wet ITS values but slightly changed TSR values, especially at 0 ^{o} C. However, the ITS and TSR generally met the requirements of the specification and thus did not result in the moisture induced damage for the materials used in this study. It is recommended that SC DOT use 25 C as the testing temperature, as being used today.

11. The semi-circle bending (SCB) test results indicated that there are differences among various aggregate sources when considering the performance of modified binders at low temperatures. It is recommended that SC DOT consider using this test method and the procedures for testing described in this report for all of the mixtures in the future.

12. In this study, it could be found that the modified binders from fine RAP or burned fine RAP could provide their minimum low temperatures. In addition, a reasonable correlation could be established between the minimum low temperatures between un-extracted and extracted binders.

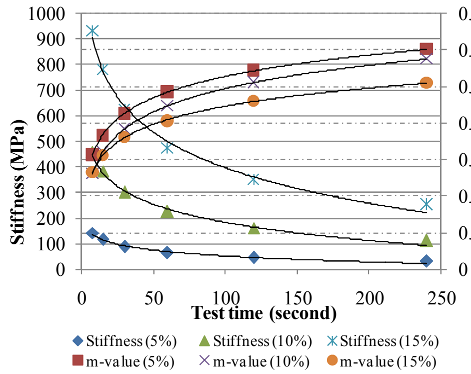
13. As describe in this study, the samples fabrication and test methodologies could be used to study the effects of low temperatures on the properties of the modified binders. These methods could be conducted to obtain the minimum low temperatures of the modified asphalt binders with fine RAP. Three low temperatures of -18 ^{o} C, -12 ^{o} C, and -6 ^{o} C are recommended to employ during the BBR test procedures.

9.3 Recommendations

It is recommended that at this point SCDOT use the developed methodology to determine the low temperature properties of the modified binders. In addition, it is recommended that SCDOT consider the utilization of semi-circle bending (SCB) testing procedures or consider the Disk-Shaped Compact Tension Test (DC(T)). This test is generally used, like SCB, to obtain the fracture energy of asphalt mixtures. Either test can be used in performance-type specifications to control various forms of cracking (e.g., thermal, reflective, and block cracking) of asphalt pavements.

10 Appendix A

BBR Data: RAP + Virgin Binder @ -12 °C and -18 °C



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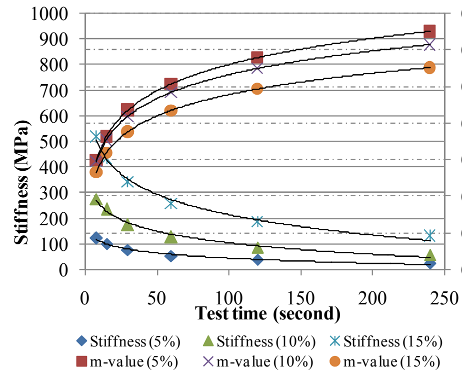

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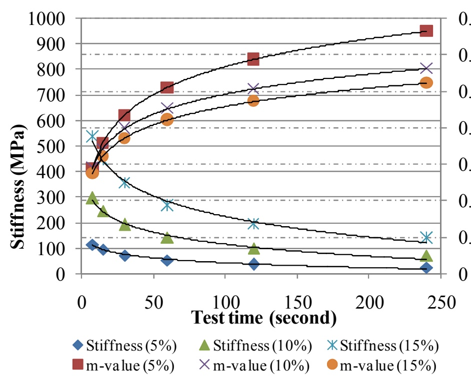

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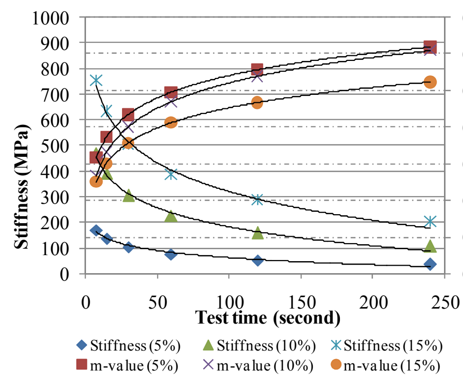

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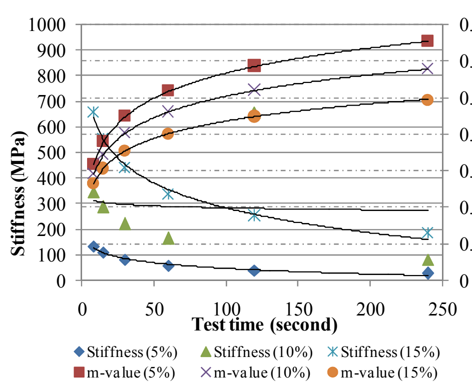

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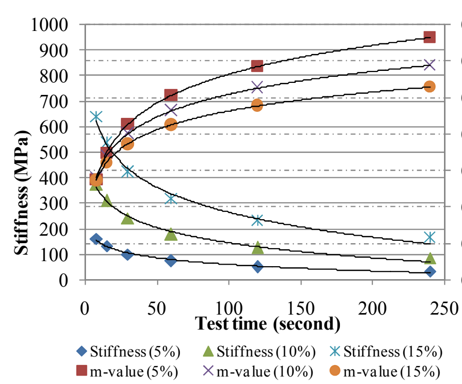


(f)

Figure 10-1: Stiffness and m-values of RAP sources A-F modified with virgin binder PG 58-28 at -12ºC

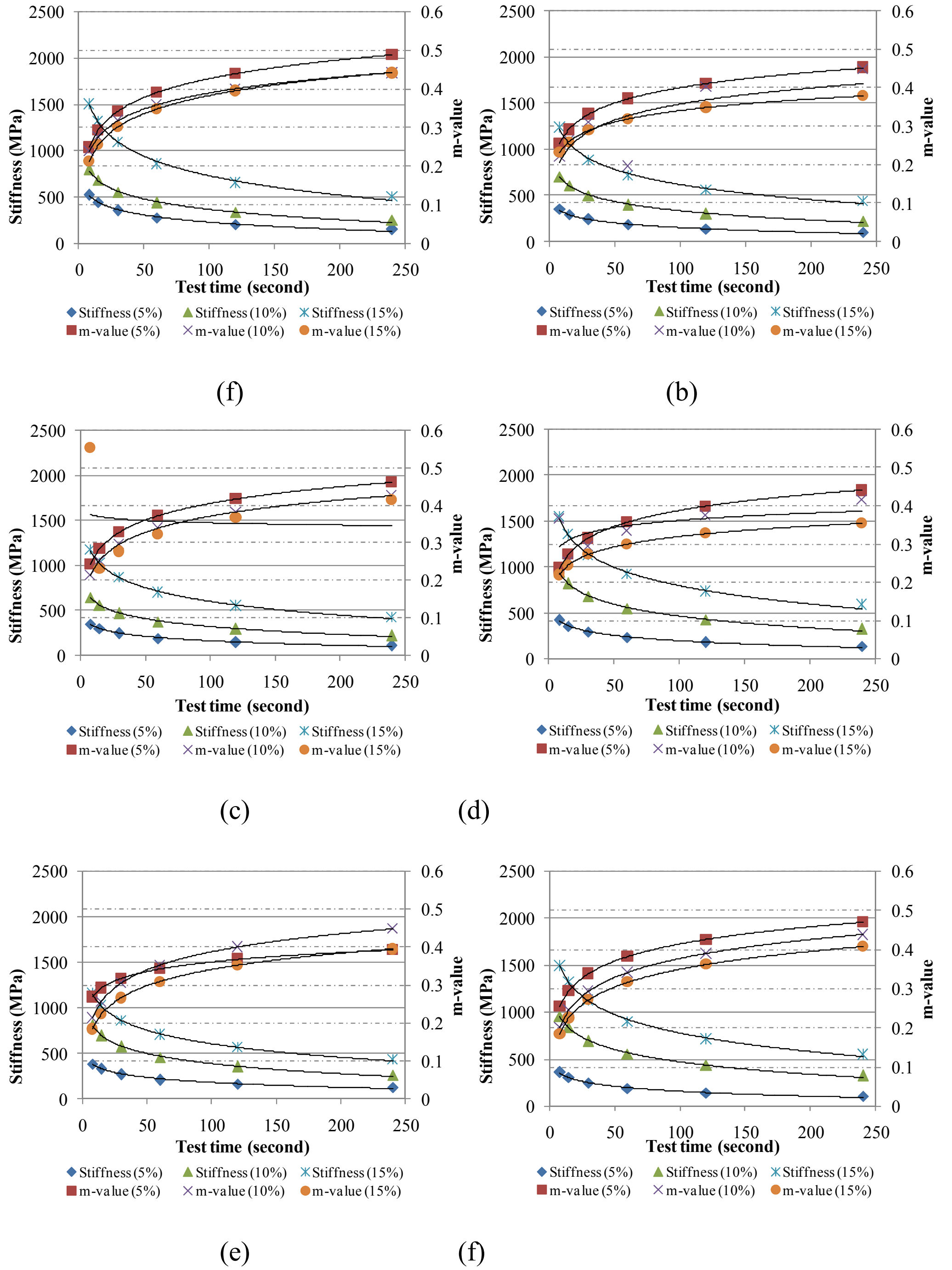


Figure 10-2: Stiffness and m-values of RAP sources A-F modified with virgin binder PG 64-22 at -12ºC

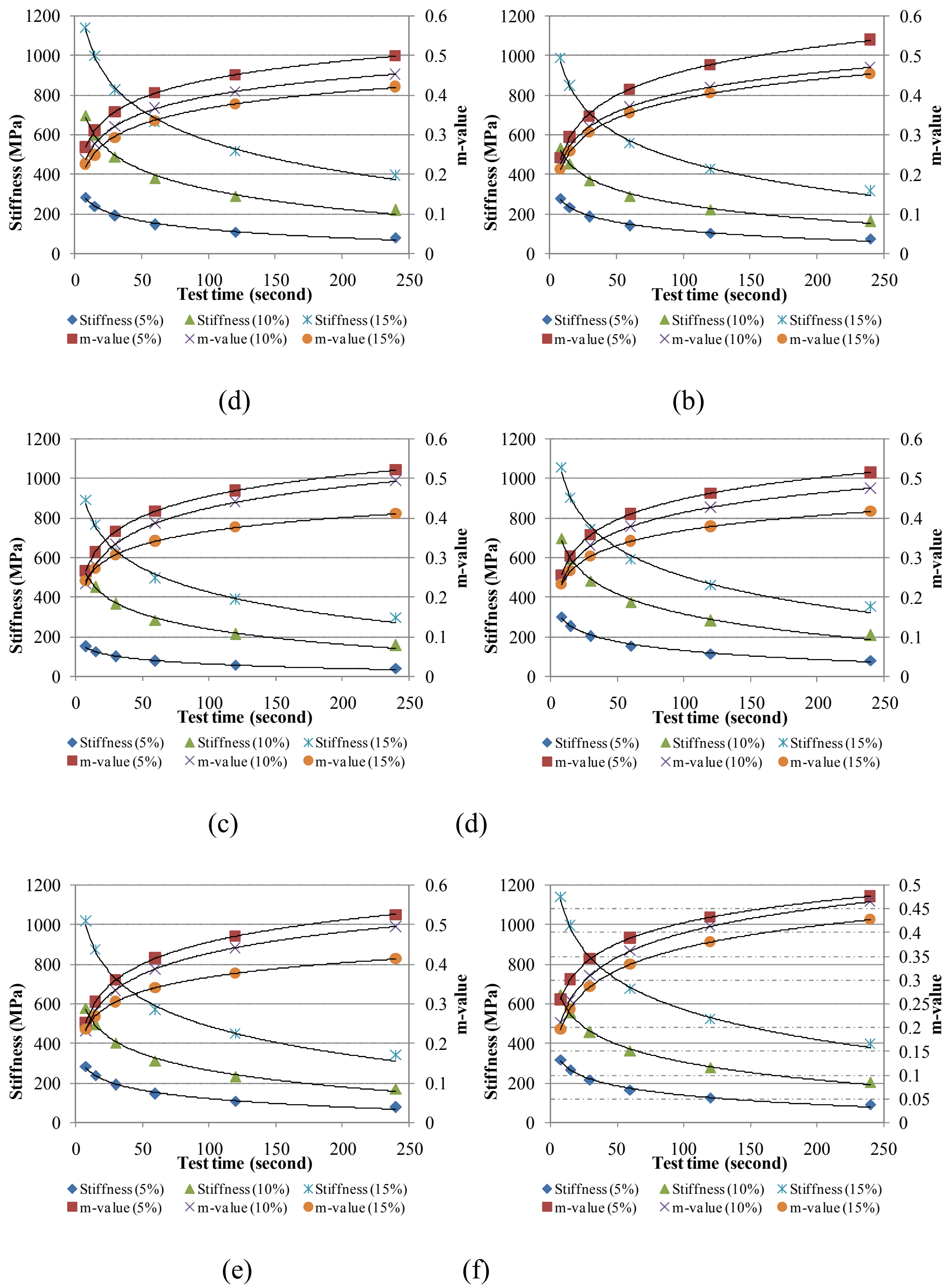
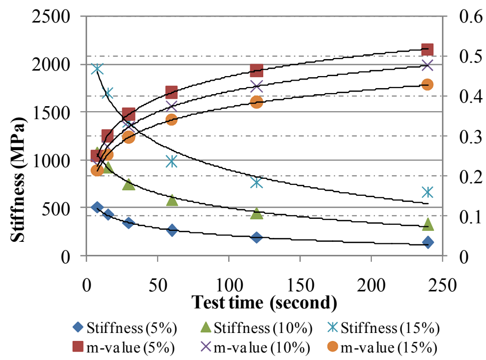


Figure 10-3: Stiffness and m-values of RAP sources A-F modified with virgin binder PG 76-22 at -12ºC



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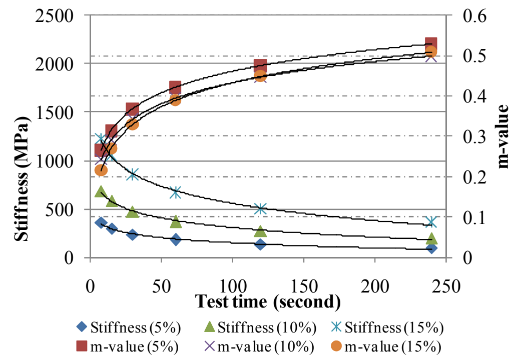

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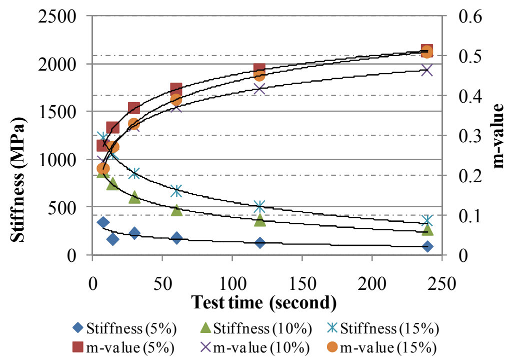

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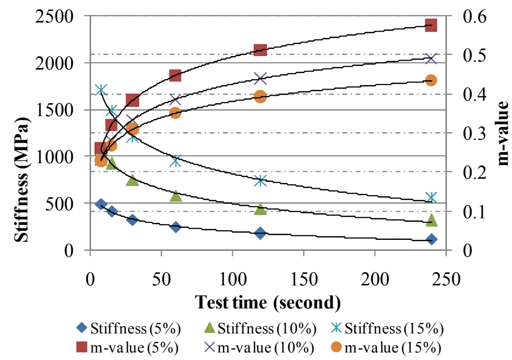

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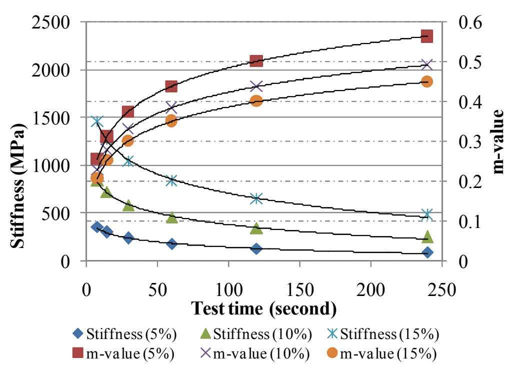

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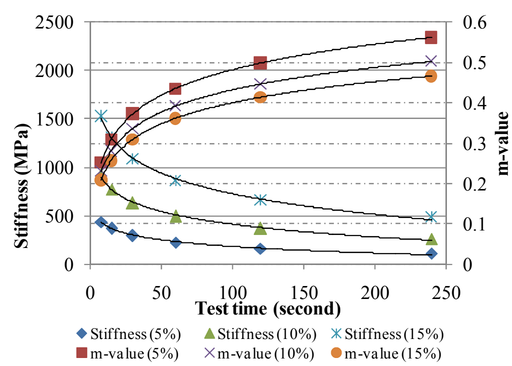


(f)

Figure 10-4: Stiffness and m-values of RAP sources A-F modified with virgin binder PG 58-28 at -18ºC

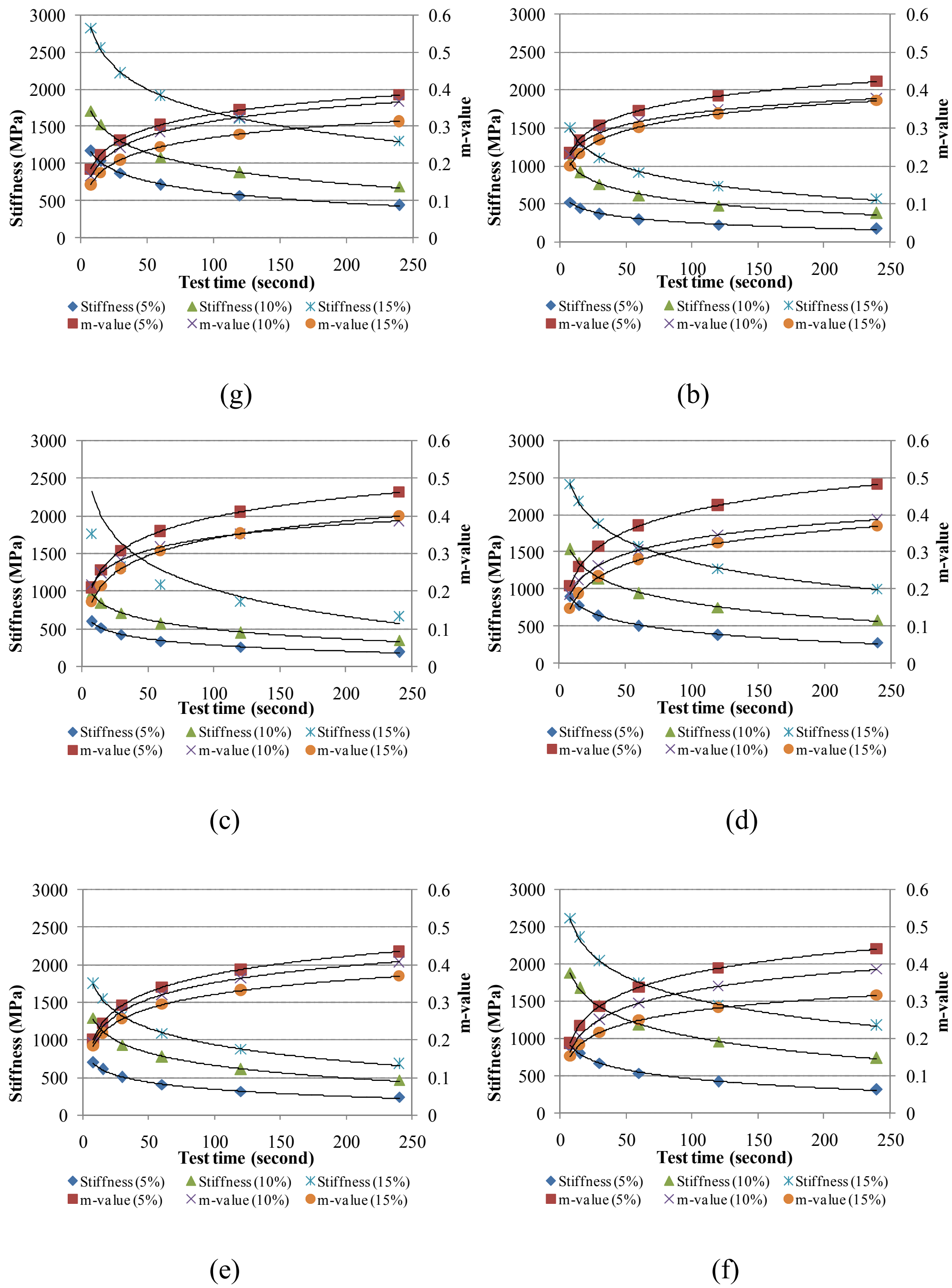
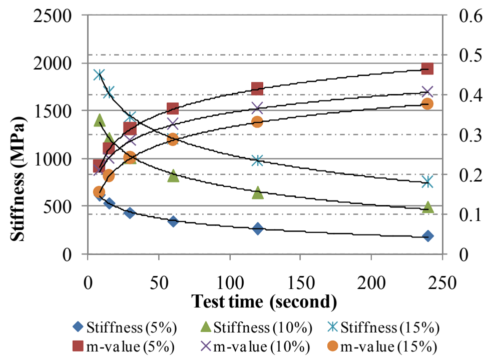


Figure 10-5: Stiffness and m-values of RAP sources A-F modified with virgin binder PG 64-22 at -18ºC



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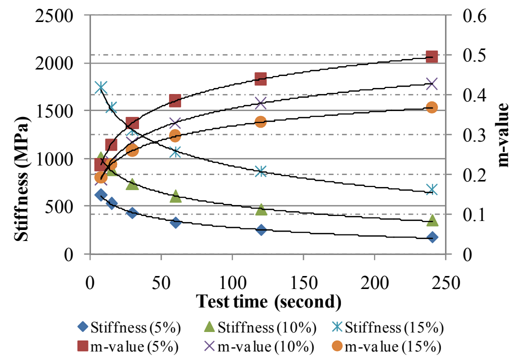

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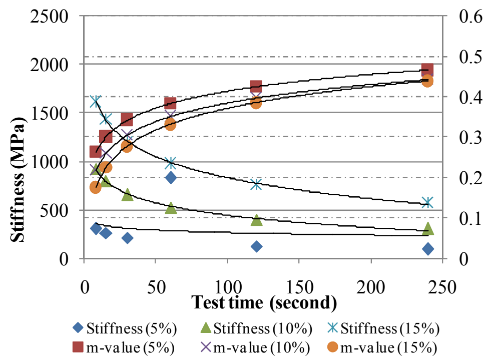

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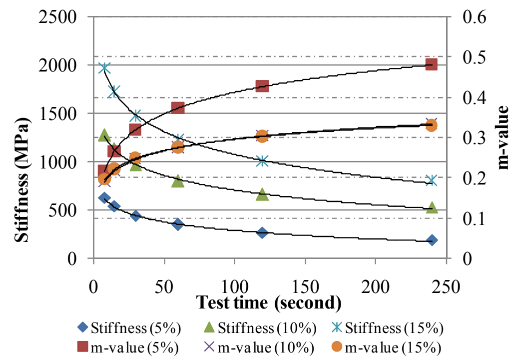

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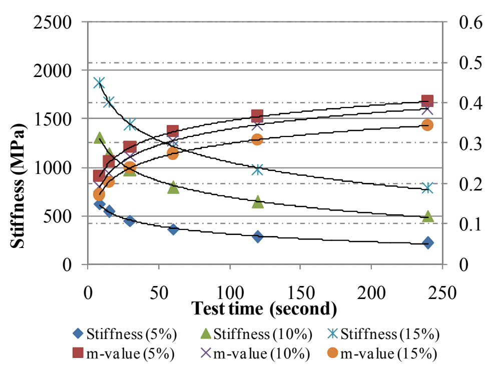

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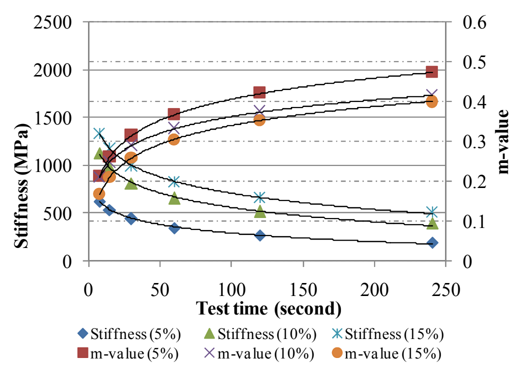
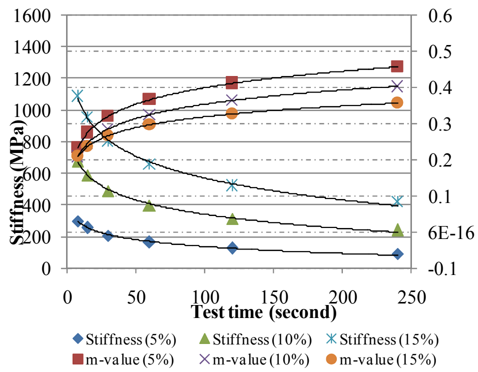


(f)

Figure 10-6: Stiffness and m-values of RAP sources A-F modified with virgin binder PG 76-22 at -18ºC

11 Appendix B

BBR Data: RAP + RTFO Binder @ -12 °C and -18 °C



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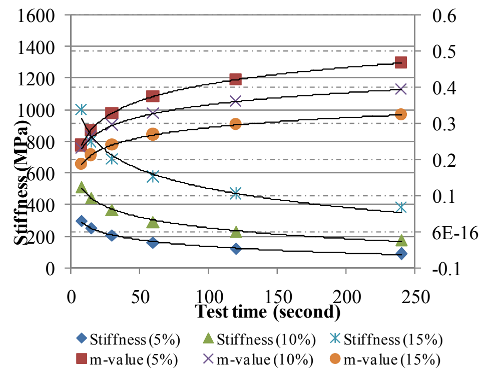

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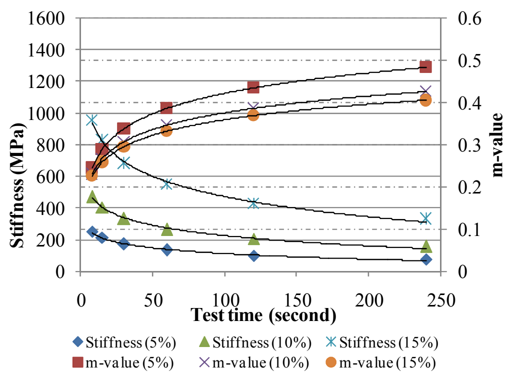

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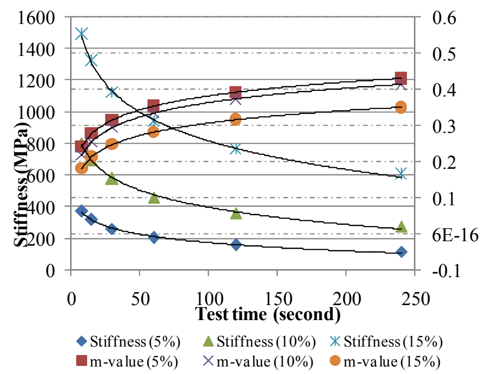

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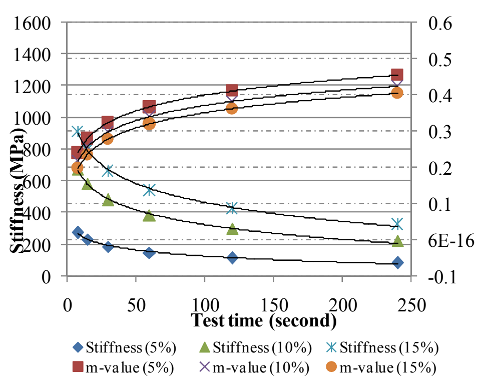

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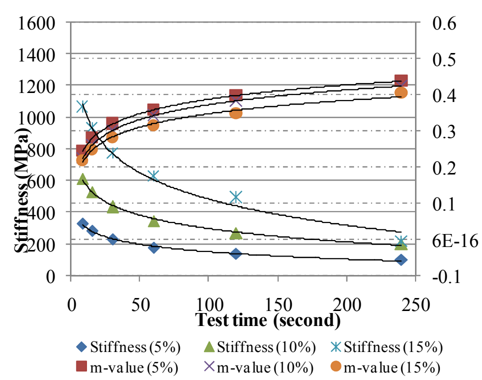
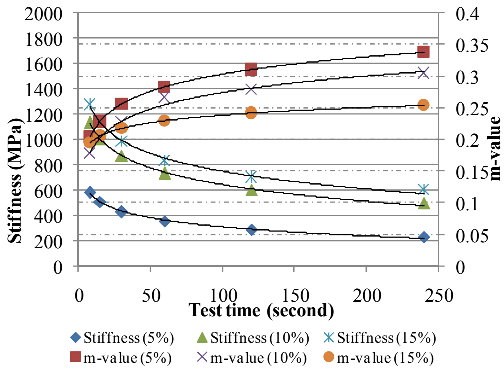
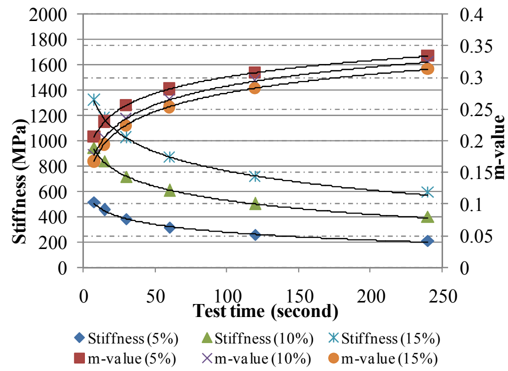


(f)

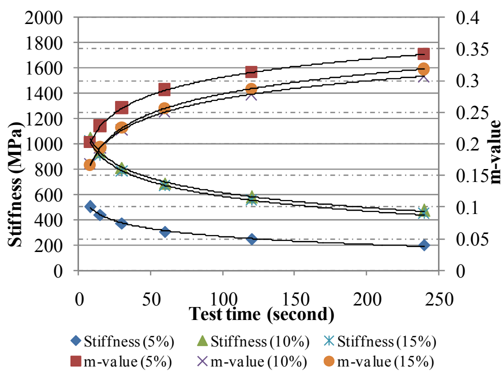
Figure 11-1: Stiffness and m-values of RAP sources A-F modified with RTFO binder PG 58-28 at -12ºC



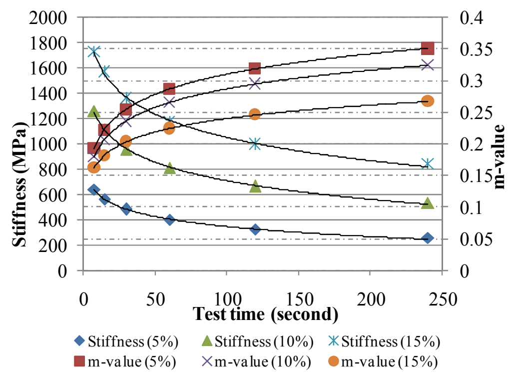
(h)



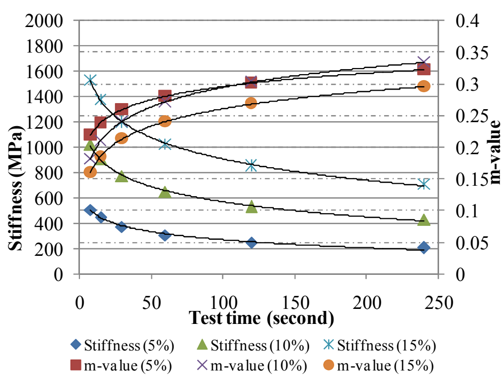
(b)



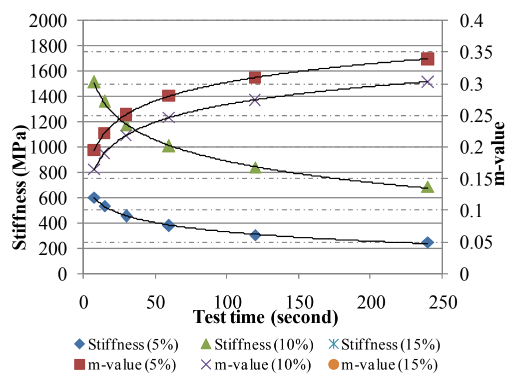
(c)



(d)

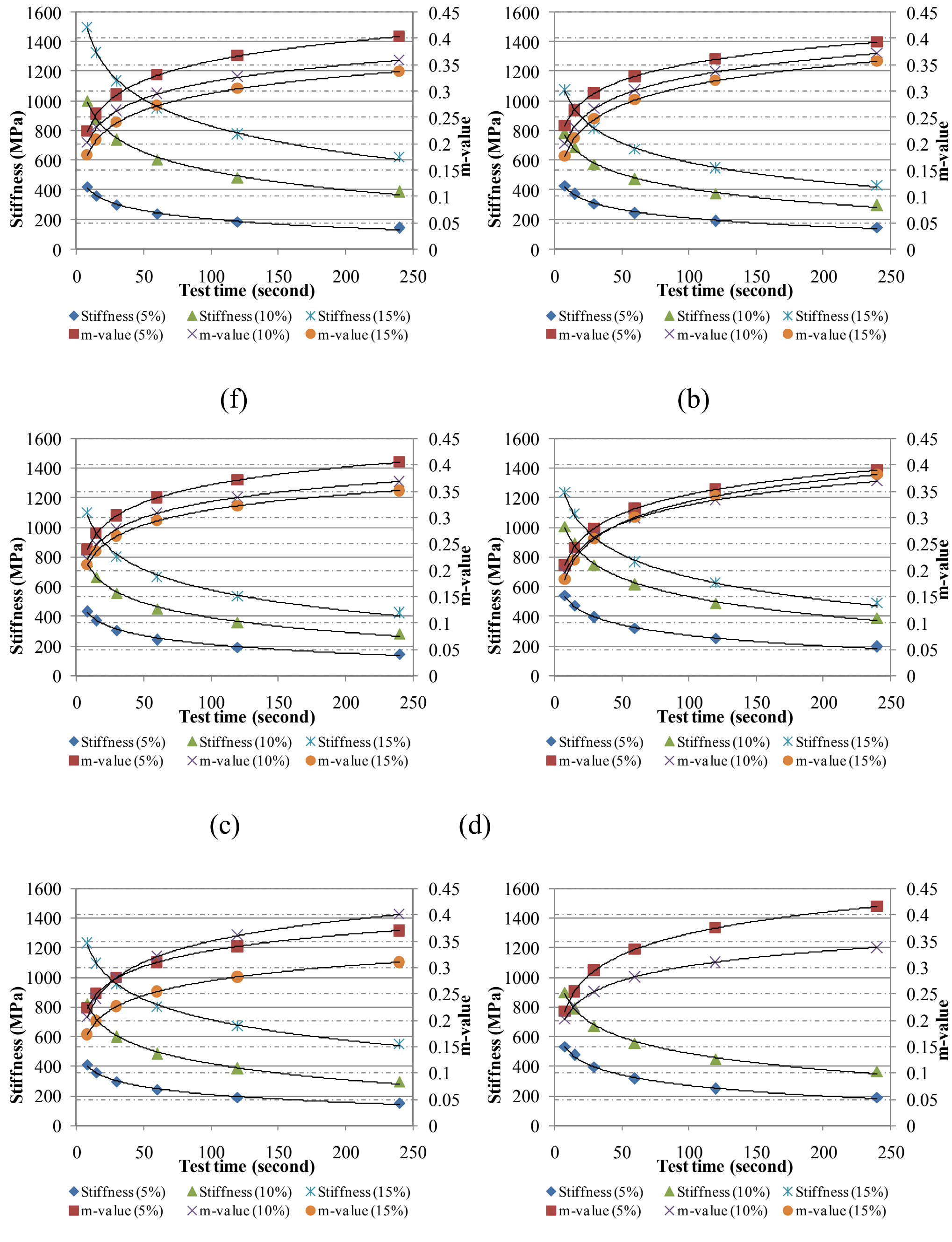


(e)



(f)

Figure 11-2: Stiffness and m-values of RAP sources A-F modified with RTFO binder PG 64-22 at -12ºC



(f) (b)

(c) (d)

(e) (f)

Figure 11-3: Stiffness and m-values of RAP sources A-F modified with RTFO binder PG 76-22 at -12ºC

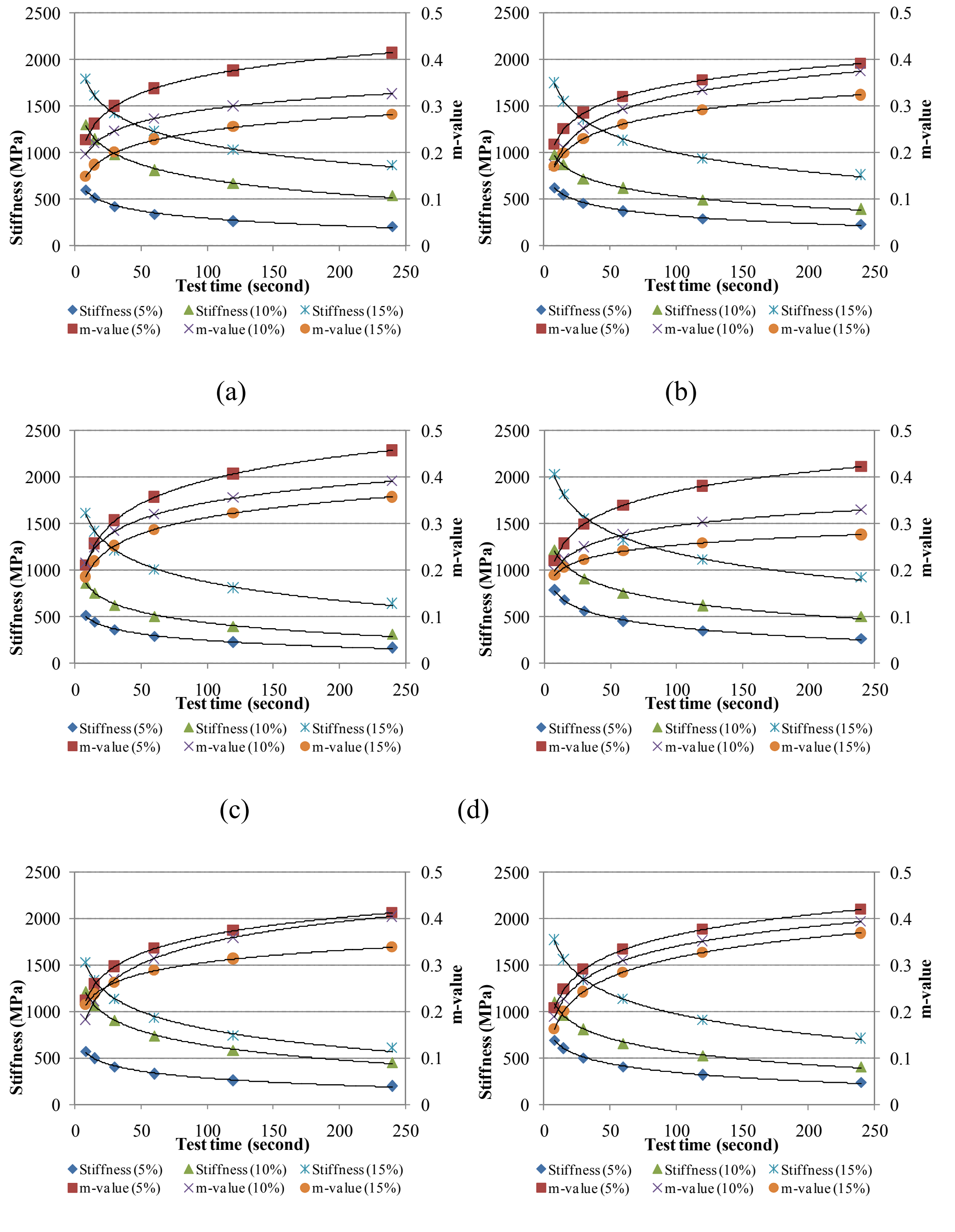


Figure 11-4: Stiffness and m-values of RAP sources A-F modified with RTFO binder PG 58-28 at -18ºC

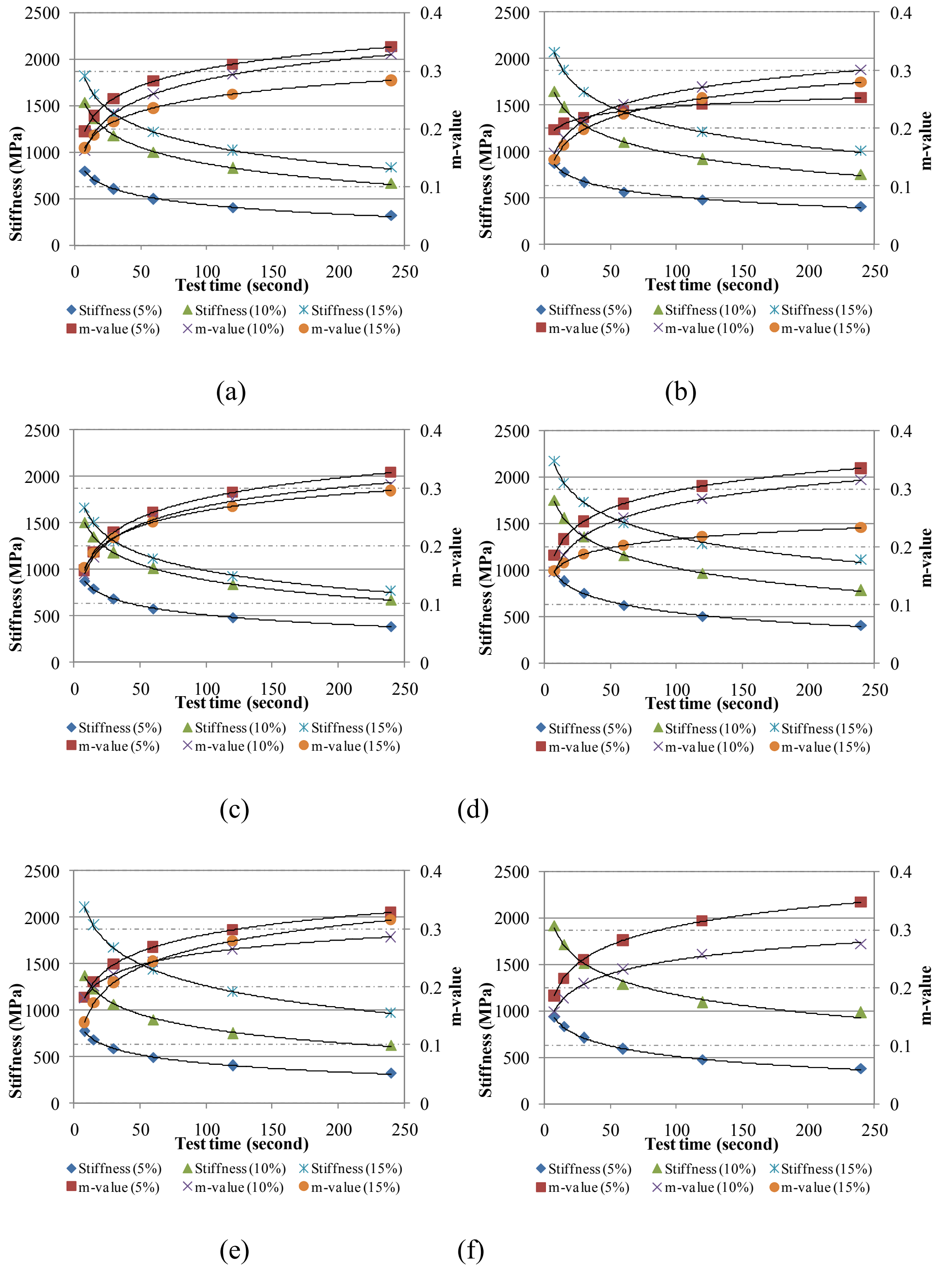


Figure 11-5: Stiffness and m-values of RAP sources A-F modified with RTFO binder PG 64-22 at -18ºC

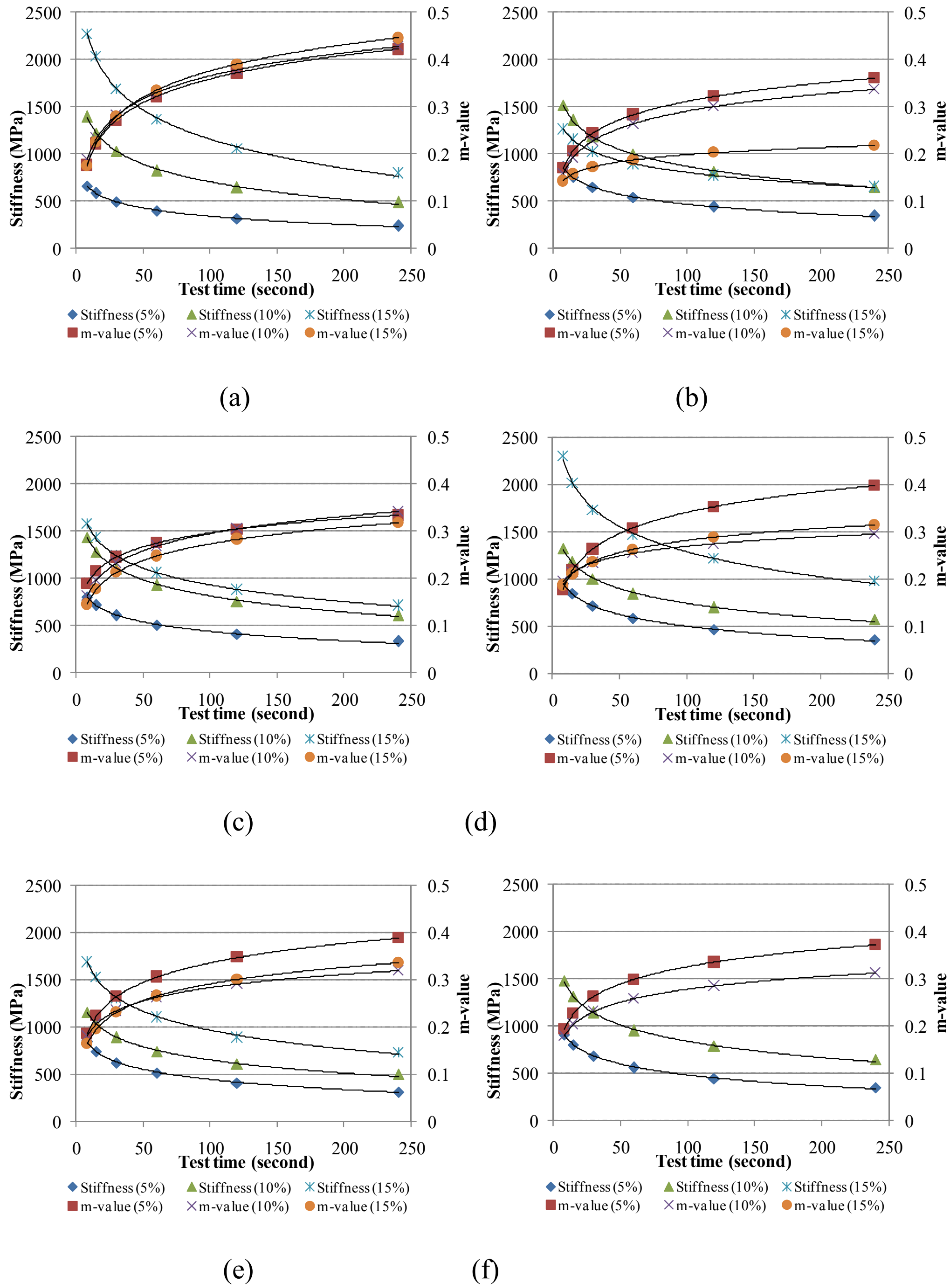
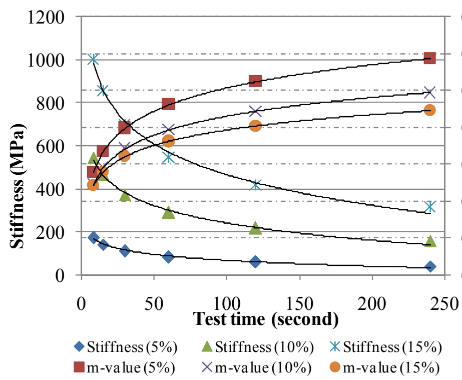
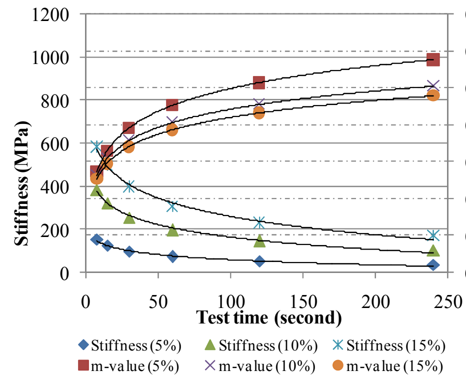


Figure 11-6: Stiffness and m-values of RAP sources A-F modified with RTFO binder PG 76-22 at -18ºC

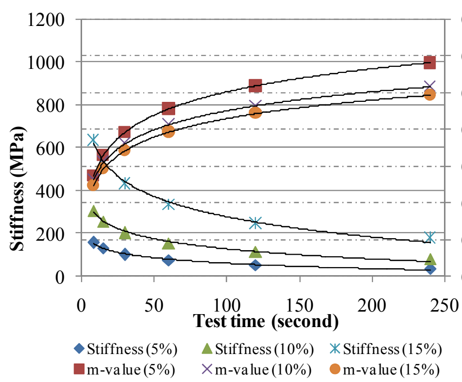
12 Appendix C

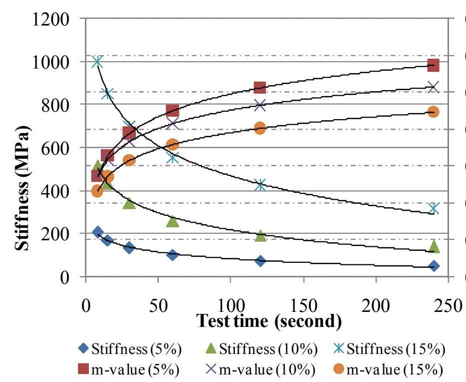
BBR Data: RAP + PAV Binder @ -12 °C and -18 °C



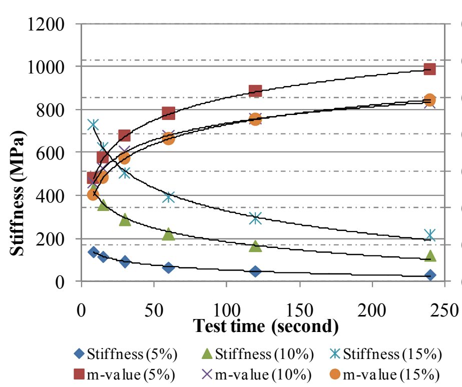


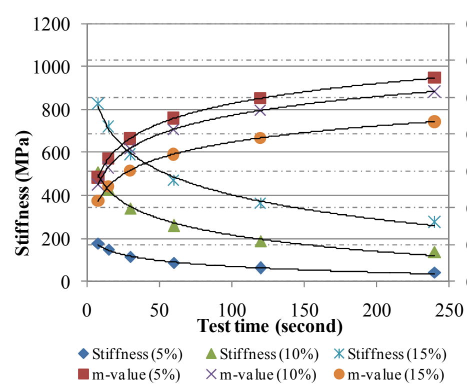
(g) (b)





(c) (d)





(e) (f)

Figure 12-1: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 58-28 at -12ºC

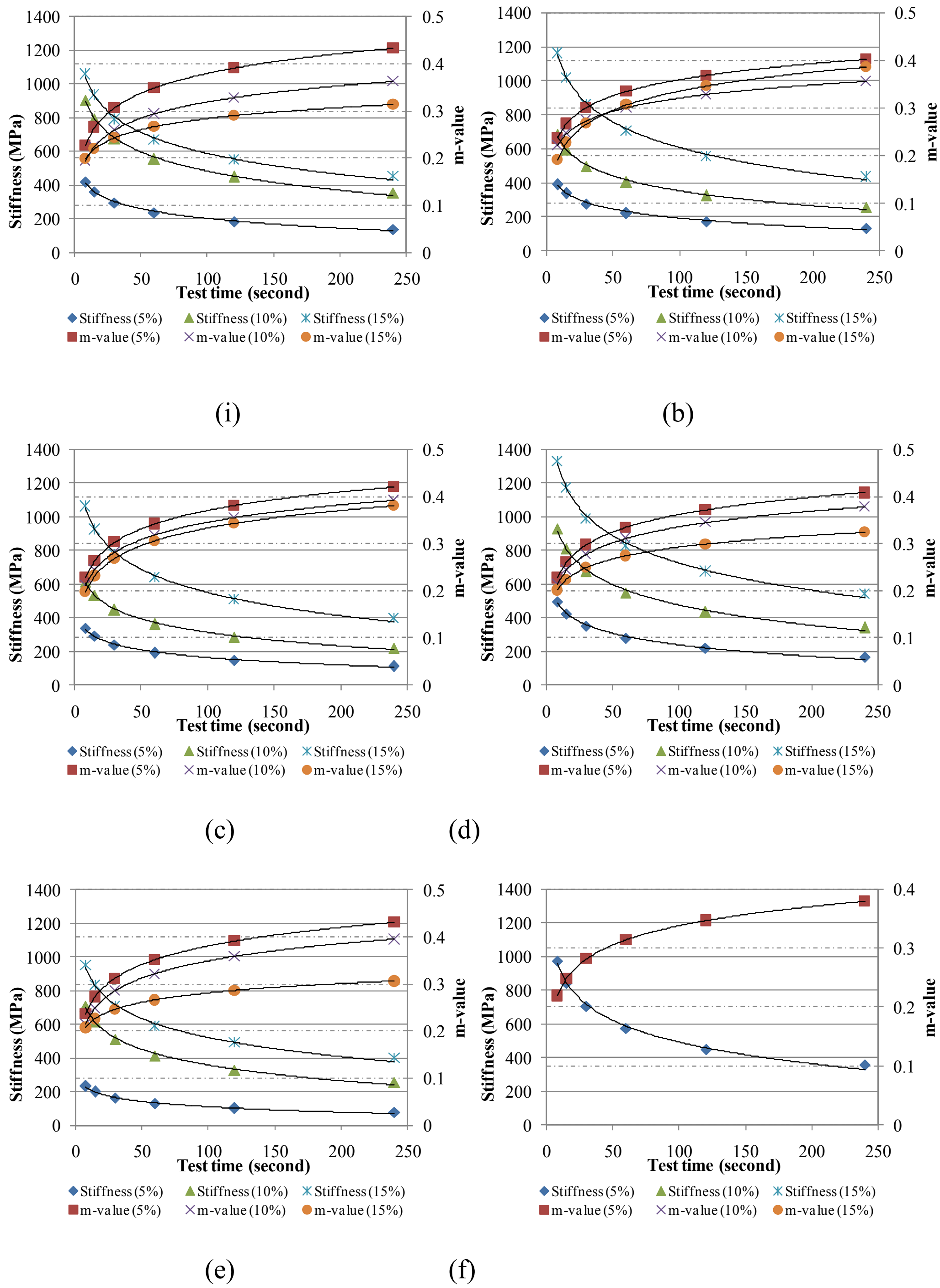


Figure 12-2: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 64-22 at -12ºC

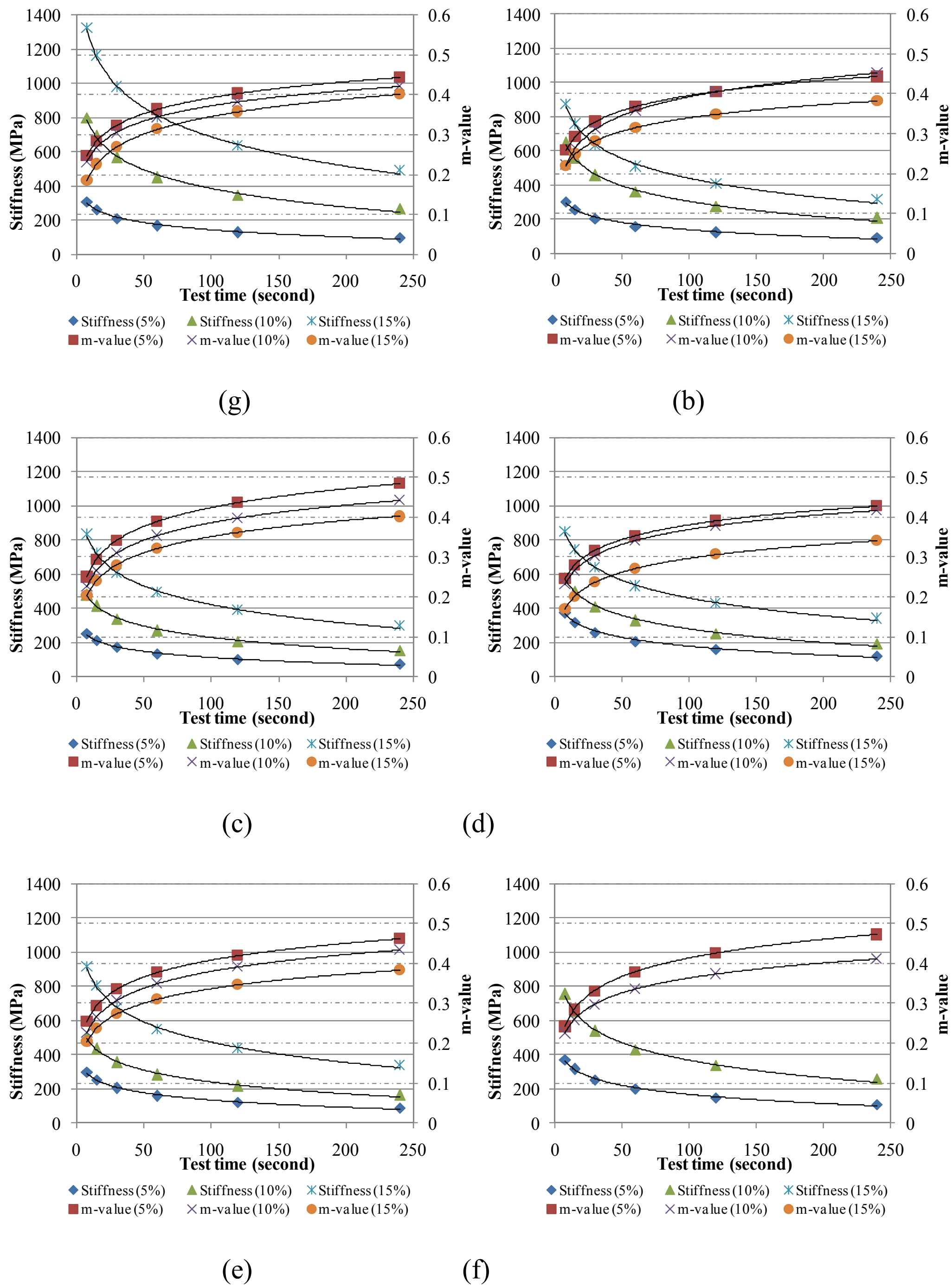


Figure 12-3: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 76-22 at -12ºC

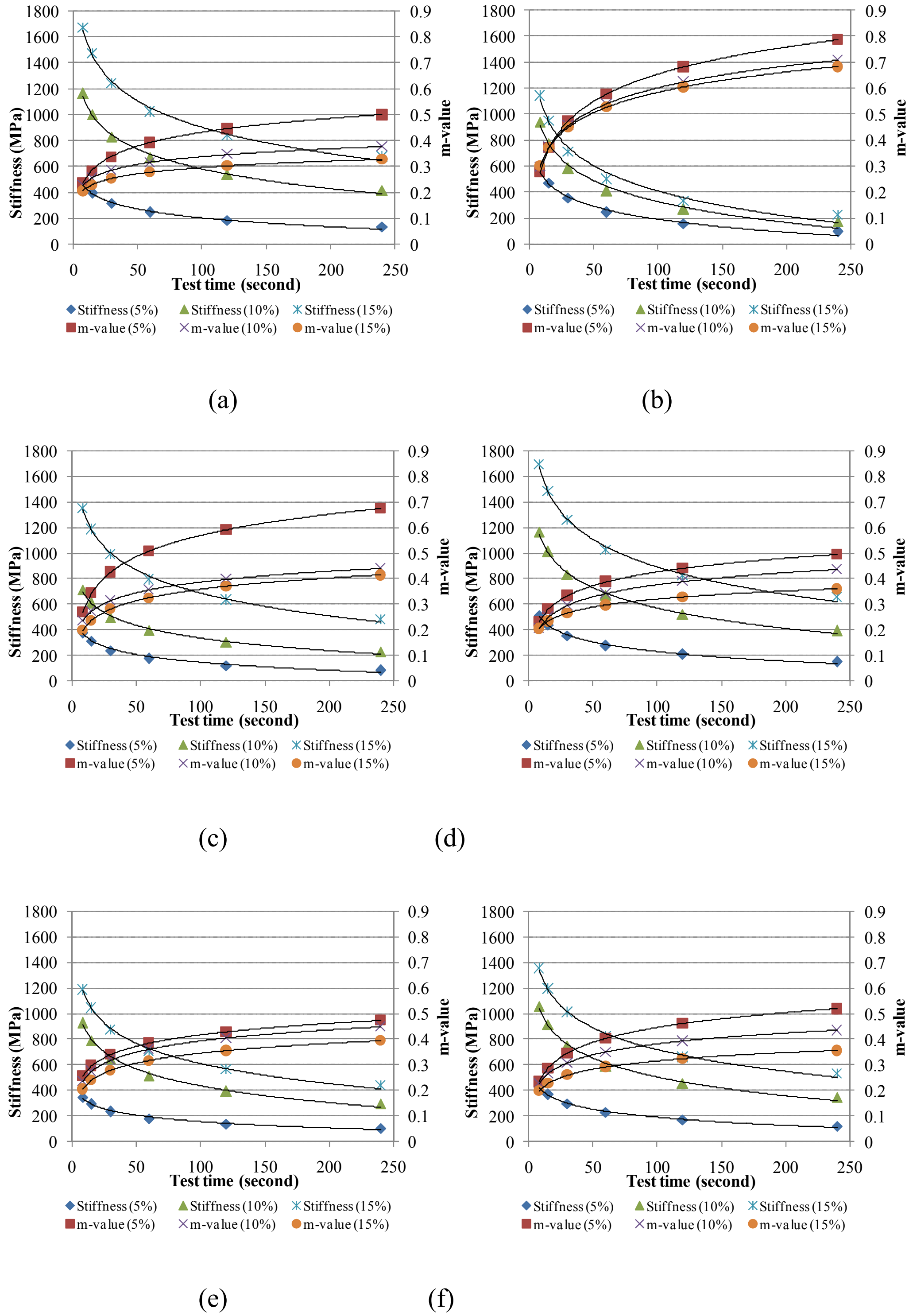


Figure 12-4: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 58-28 at -18ºC

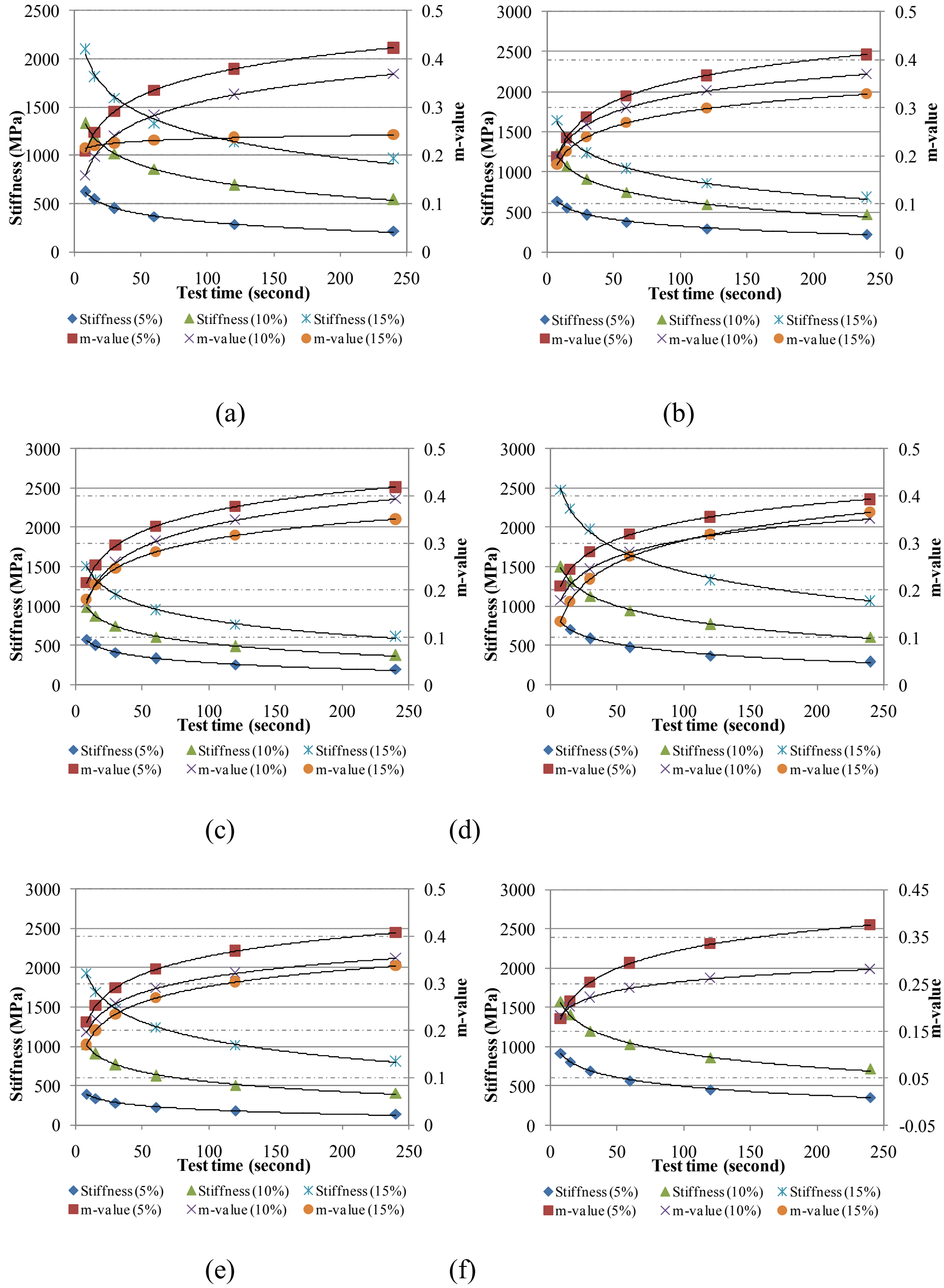


Figure 12-5: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 64-22 at -18ºC

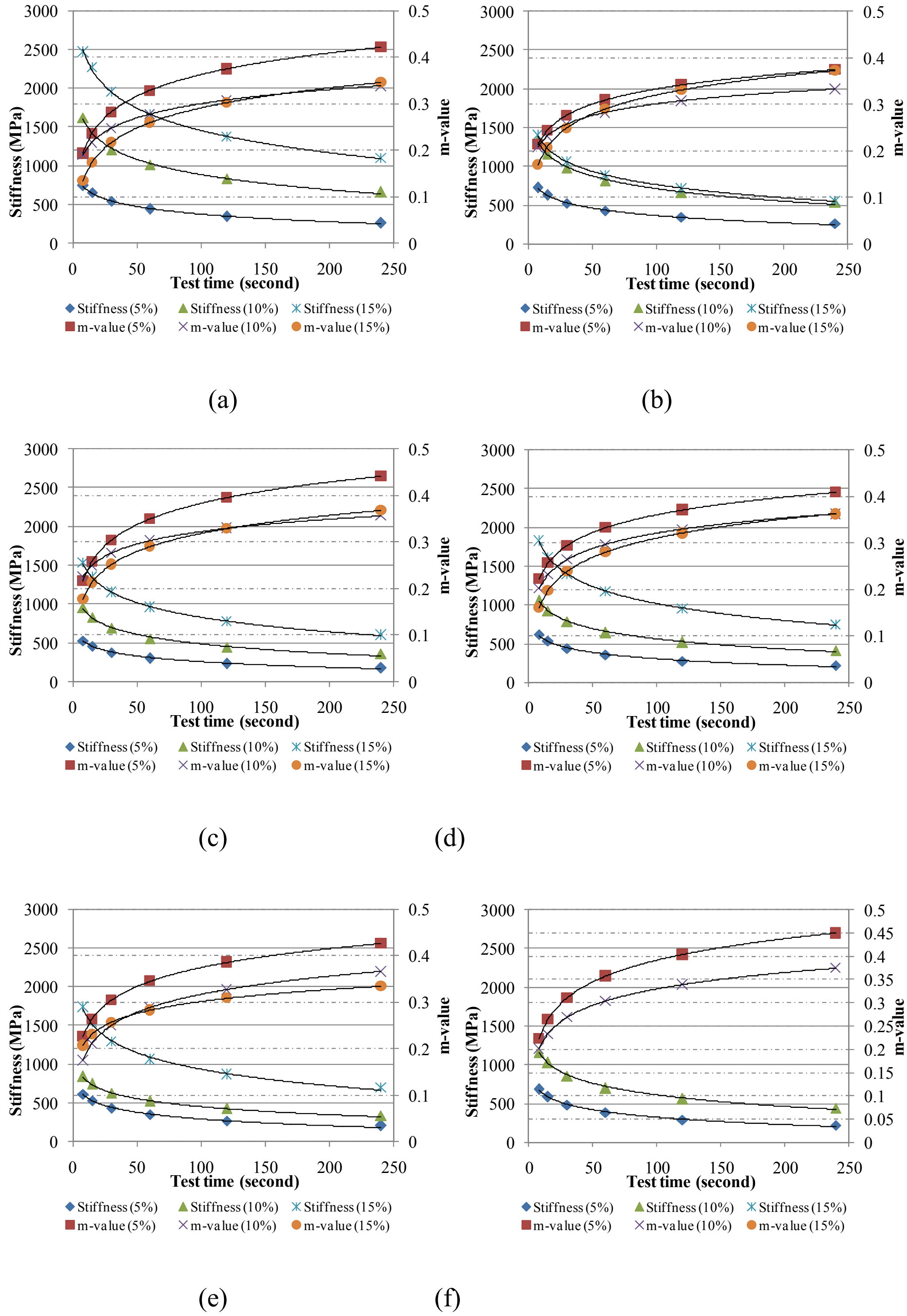
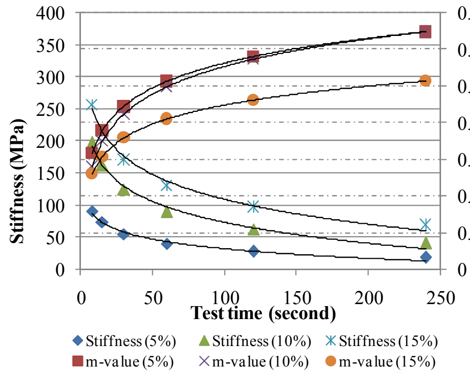


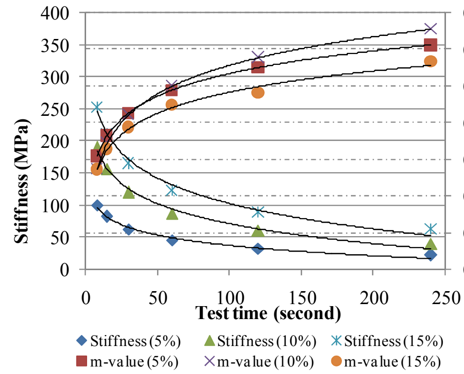
Figure 12-6: Stiffness and m-values of RAP sources A-F modified with PAV binder PG 76-22 at -18ºC

13 Appendix D

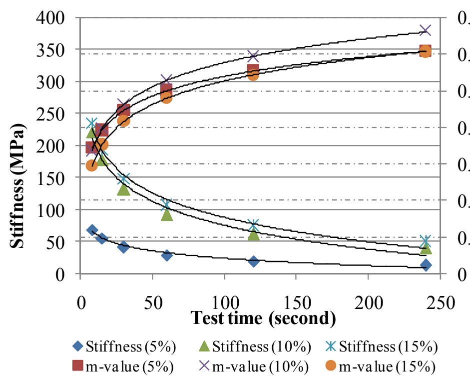
BBR Data: Burned RAP + Virgin Binder @ -12 °C and -18 °C



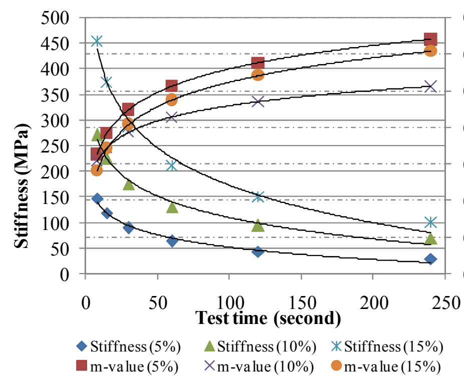
(h)



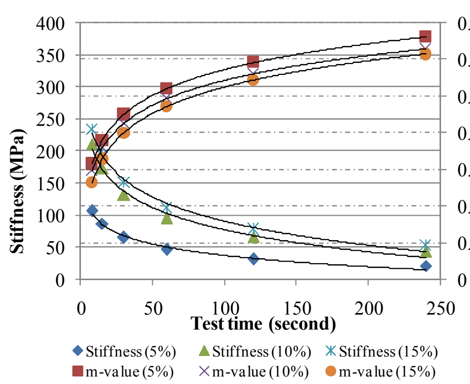
(b)



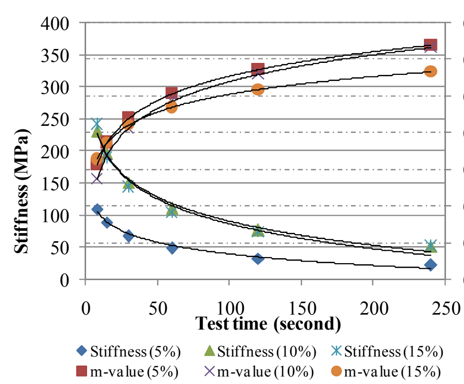
(c)



(d)

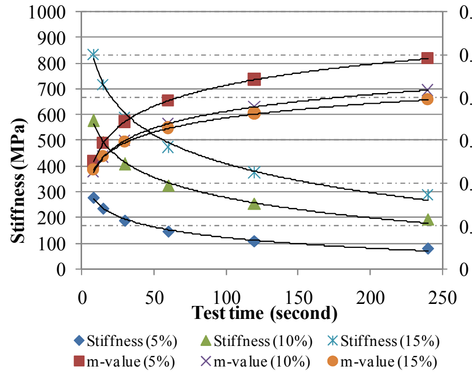


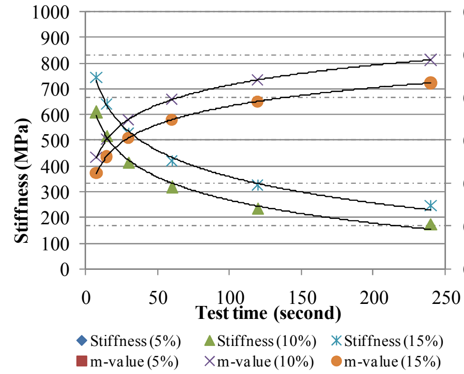
(e)



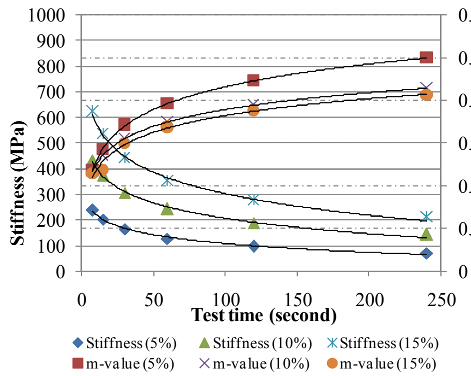
(f)

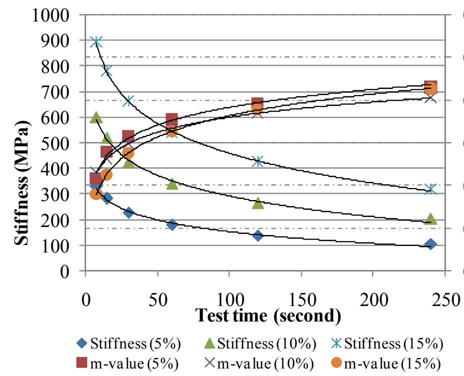
Figure 13-1: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 58-28 at -12ºC



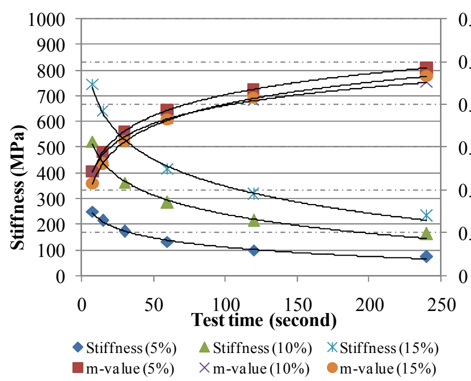


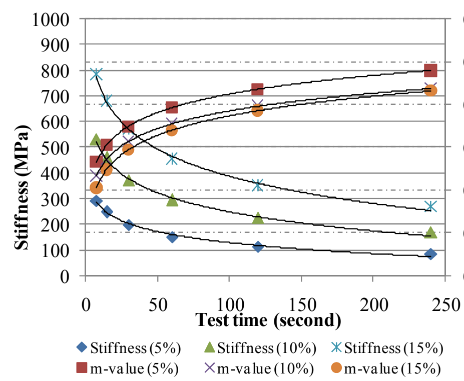
(j) (b)





(c) (d)





(e) (f)

Figure 13-2: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 64-22 at -12ºC

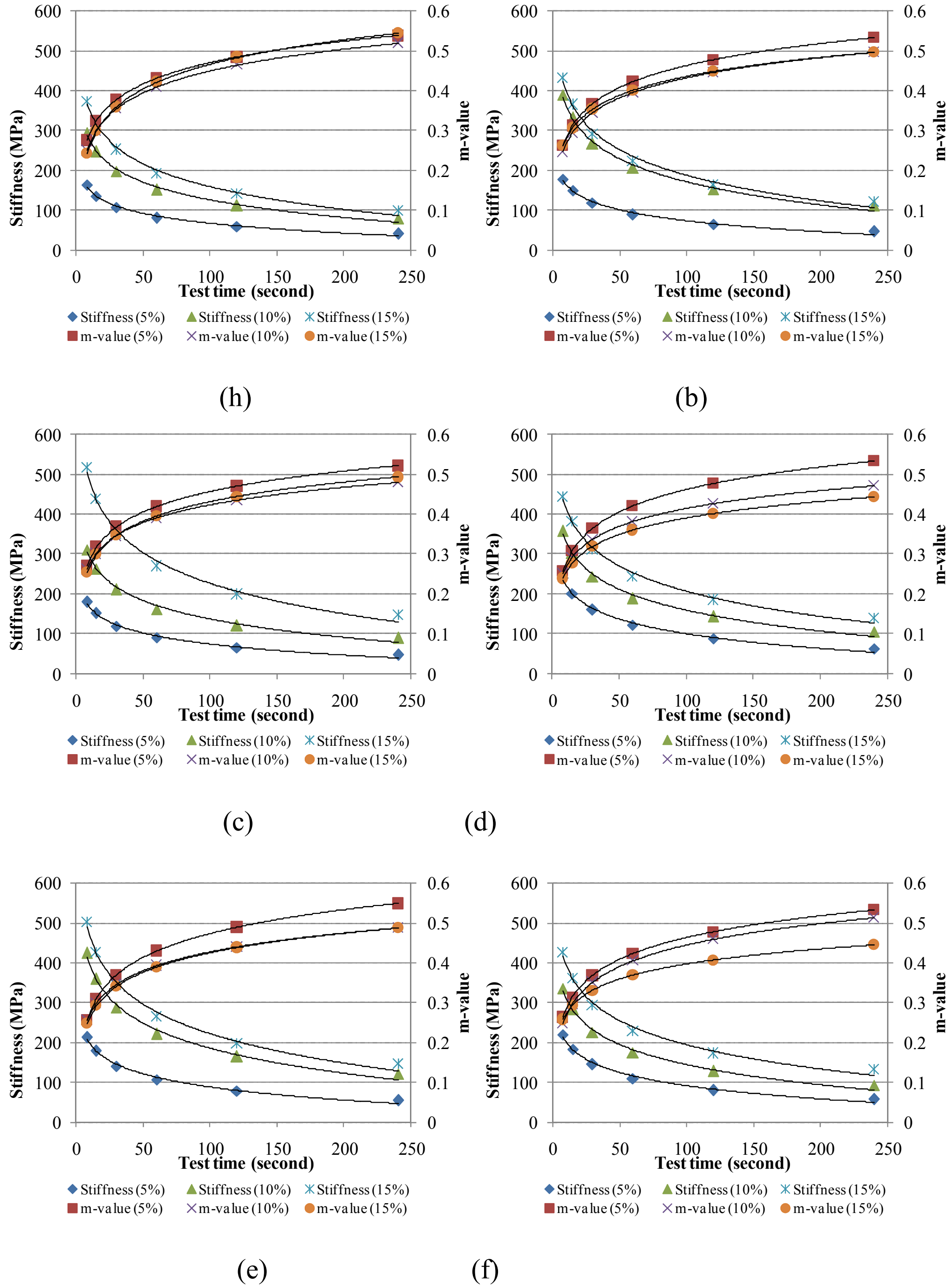


Figure 13-3: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 76-22 at -12ºC

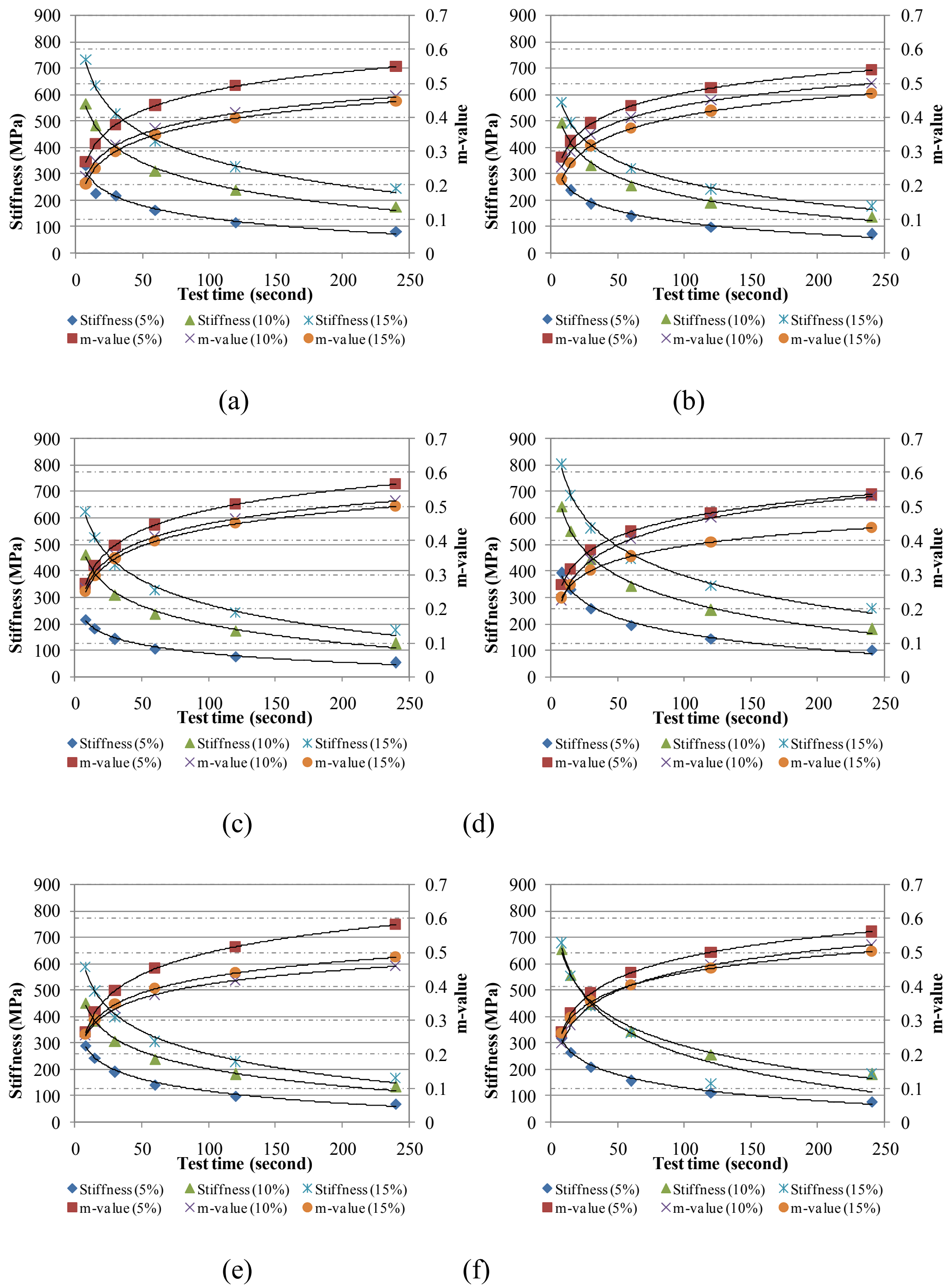


Figure 13-4: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 58-28 at -18ºC

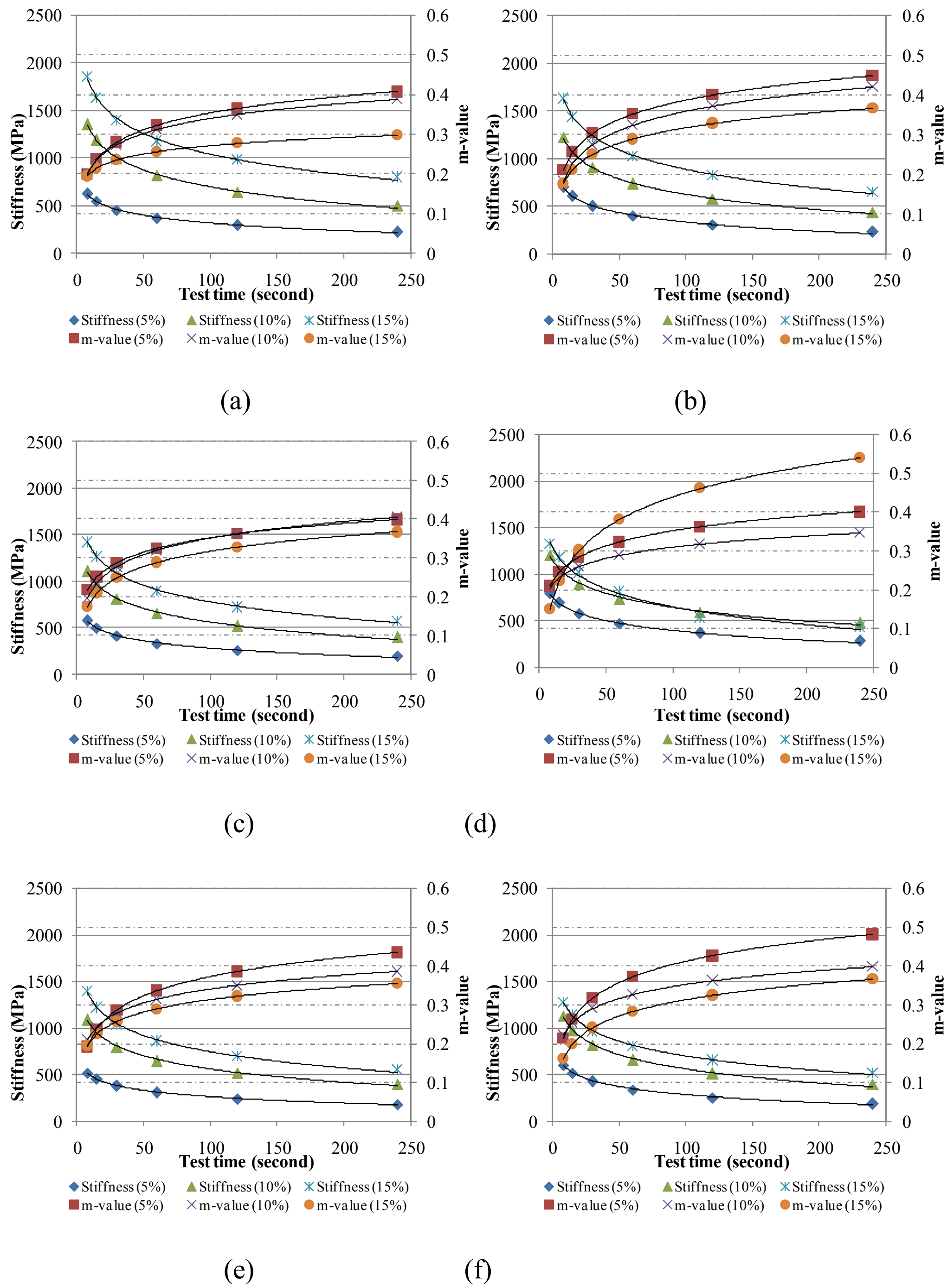


Figure 13-5: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 64-22 at -18ºC

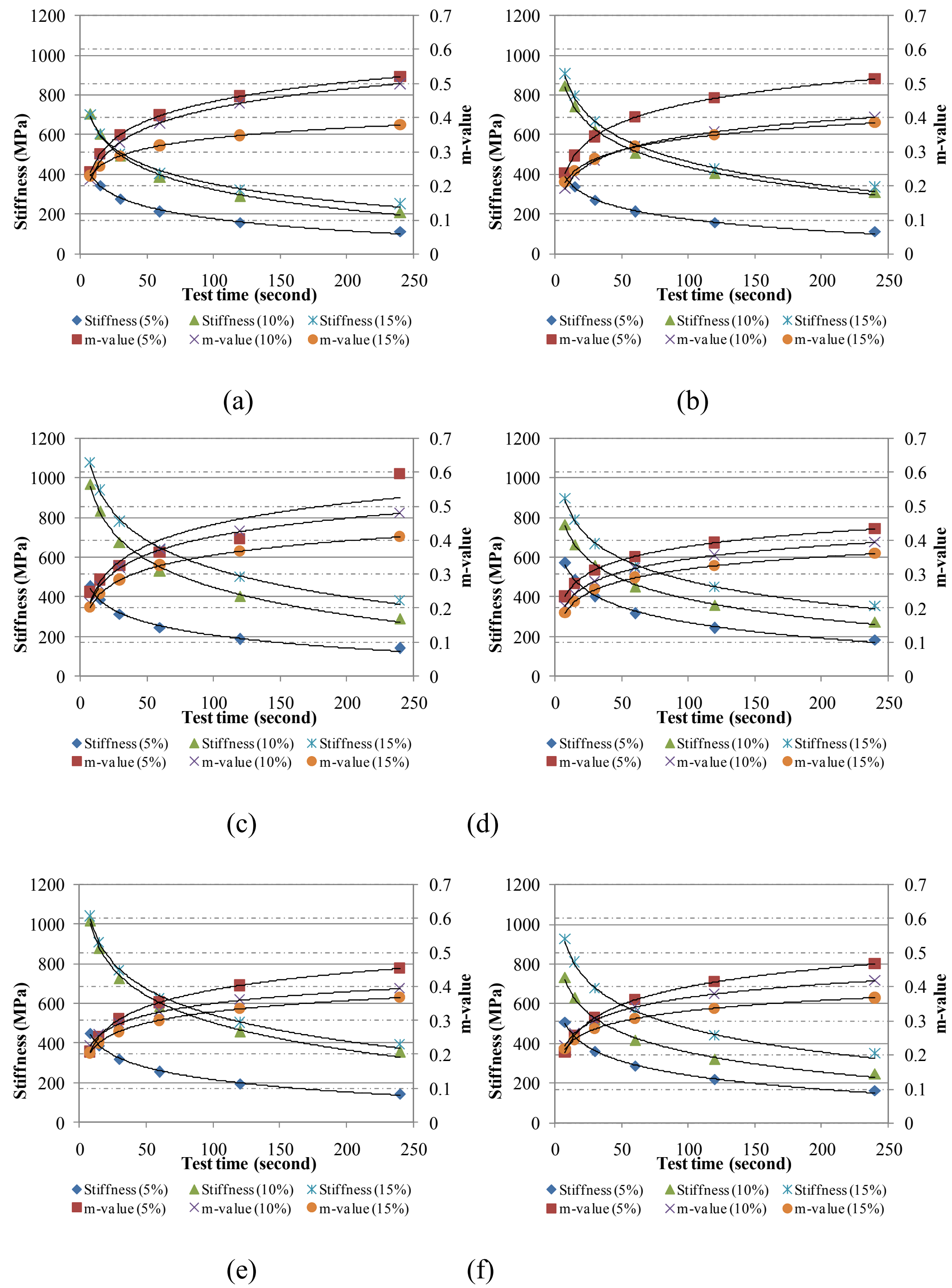
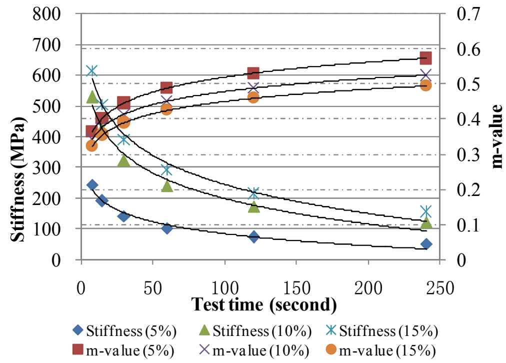


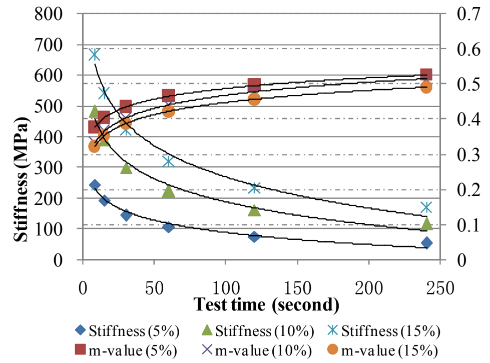
Figure 13-6: Stiffness and m-values of burned RAP sources A-F modified with virgin binder PG 76-22 at -18ºC

14 Appendix E

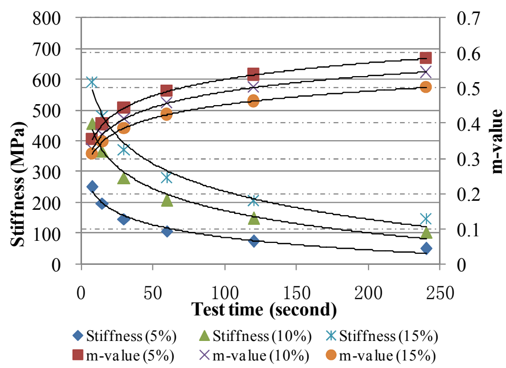
BBR Data: Burned RAP + RTFO Binder @ -12 °C and -18 °C



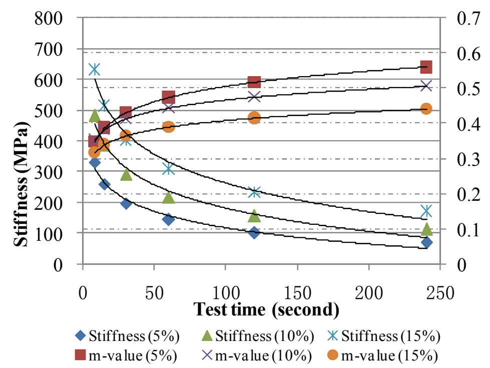
(i)



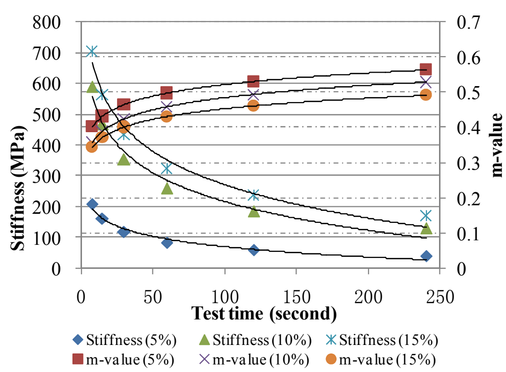
(b)



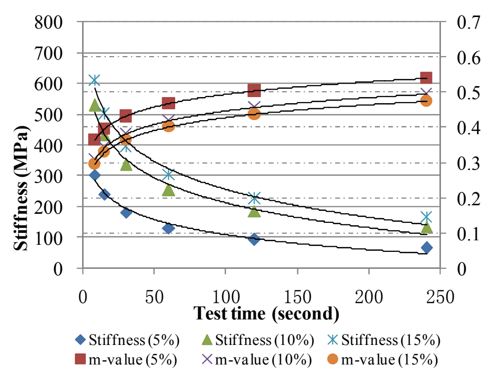
(c)



(d)



(e)



(f)

Figure 14-1: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 58-28 at -12ºC

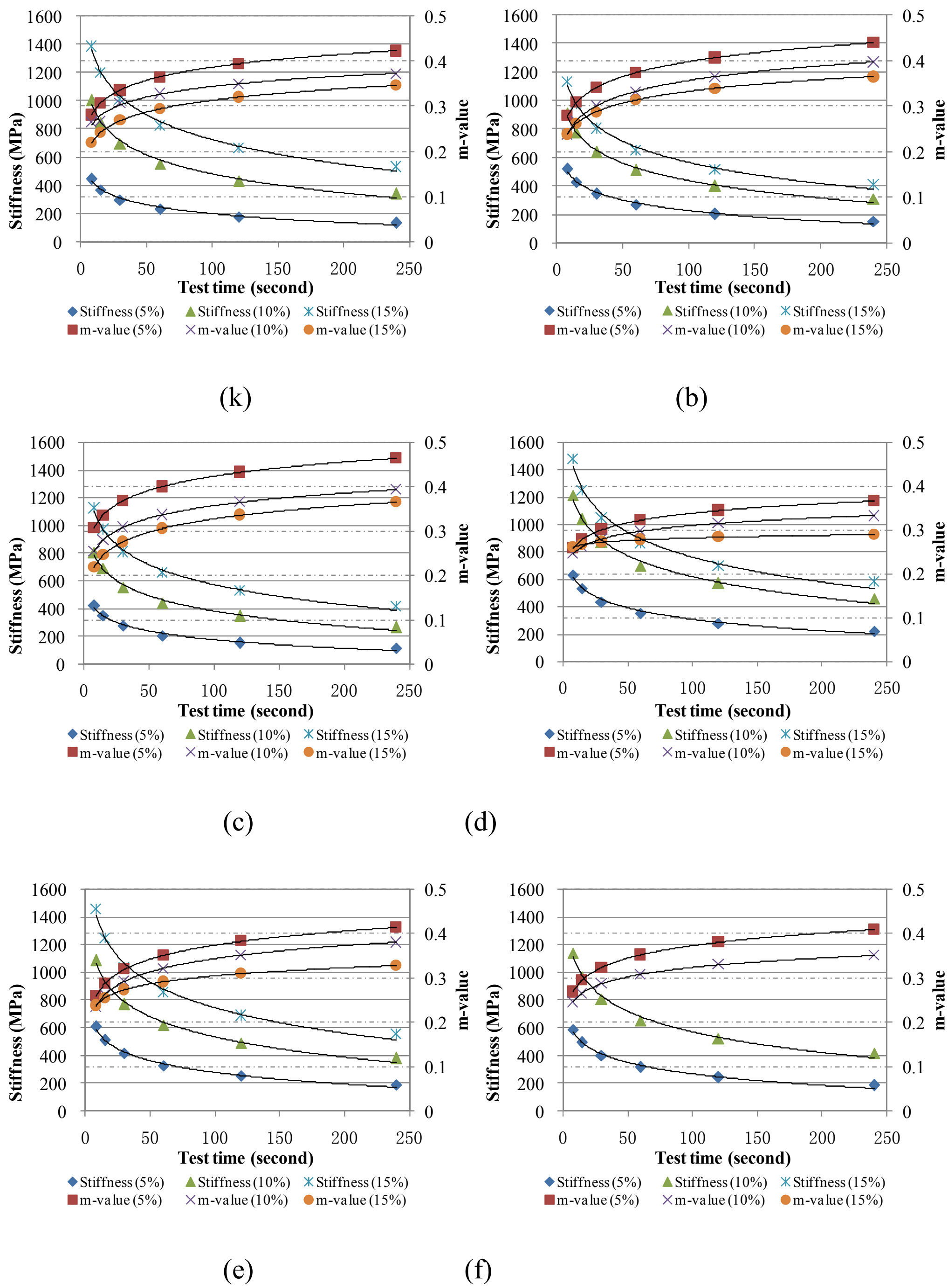
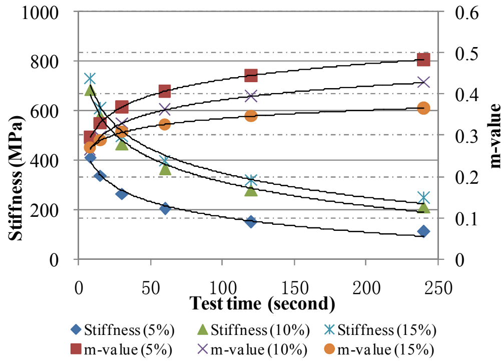
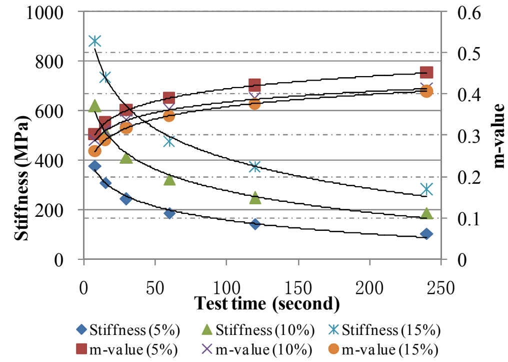


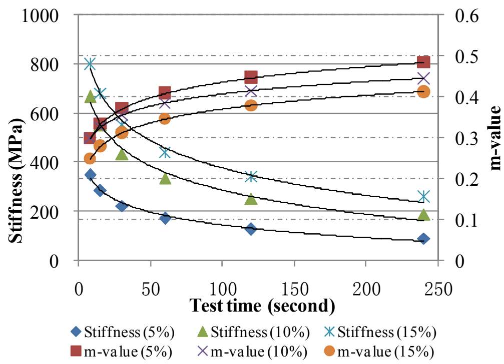
Figure 14-2: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 64-22 at -12ºC



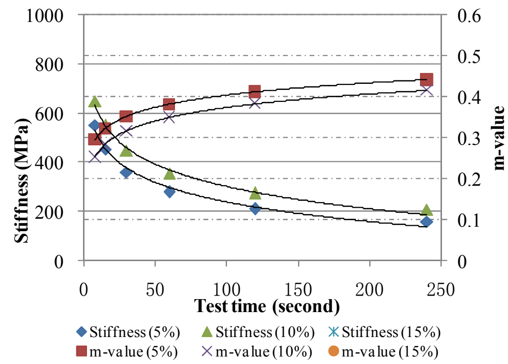
(i)



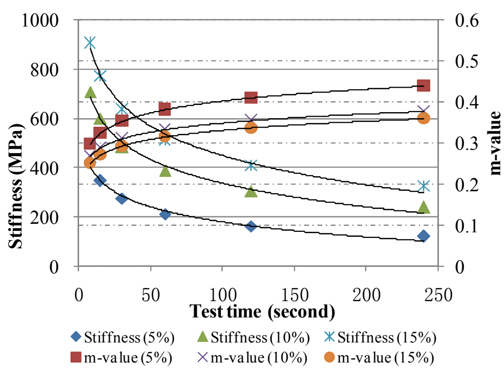
(b)



(c)



(d)



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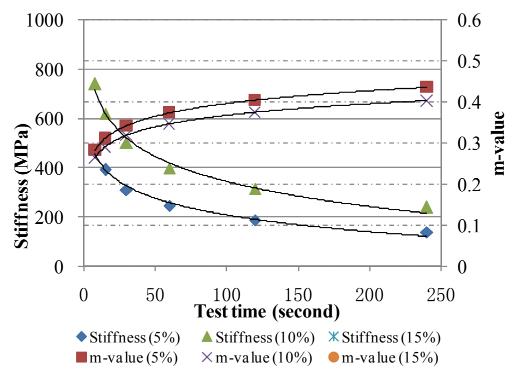


(f)

Figure 14-3: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 76-22 at -12ºC

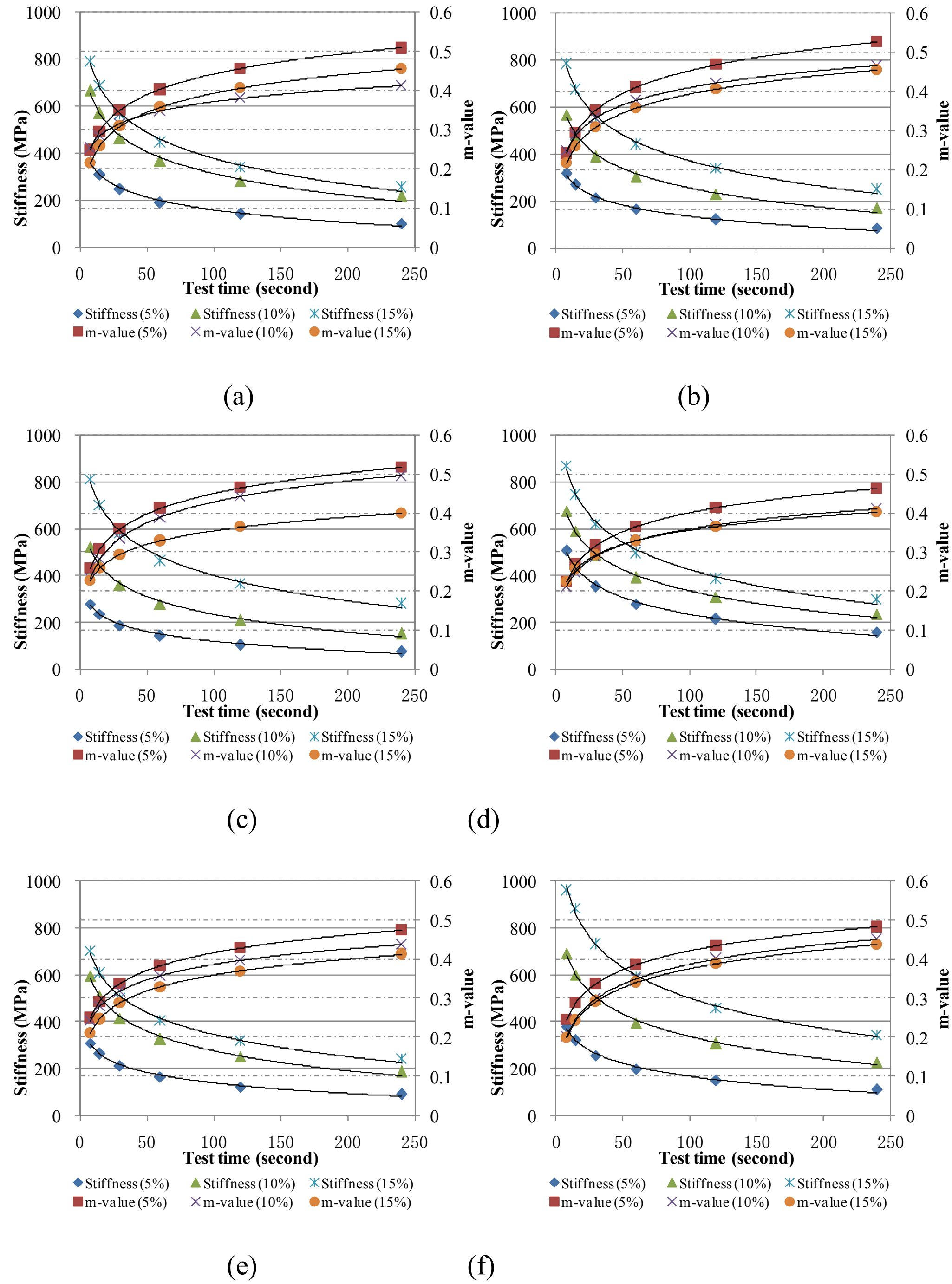
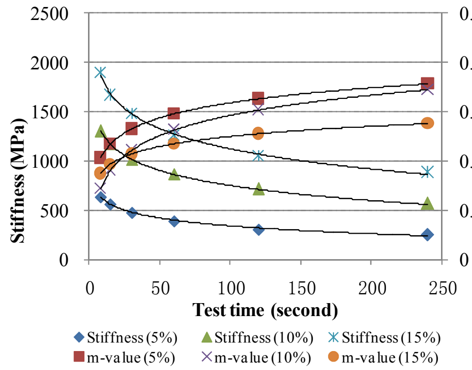
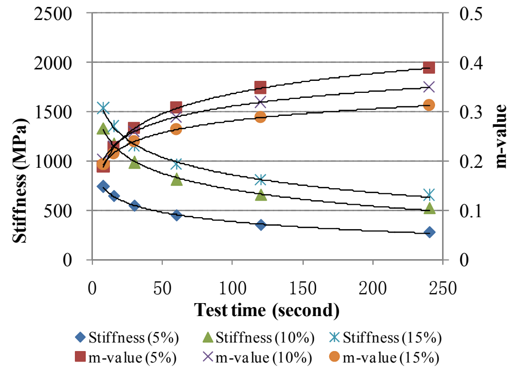


Figure 14-4: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 58-28 at -18ºC



(a)



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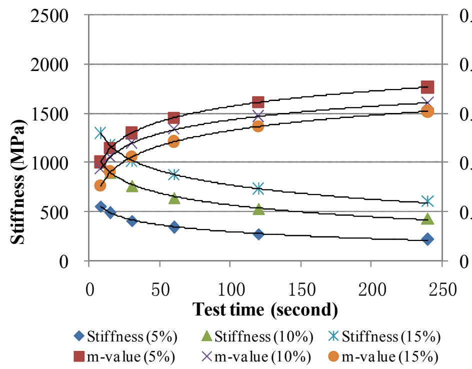
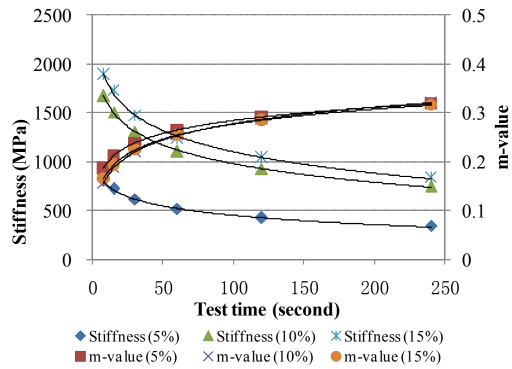


(c)



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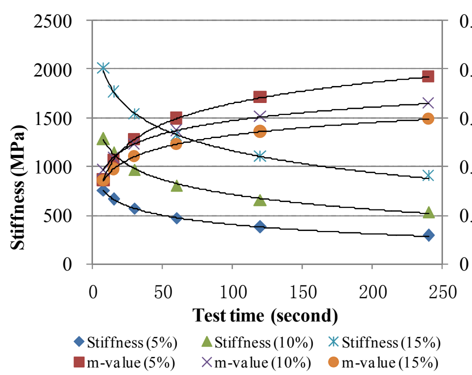
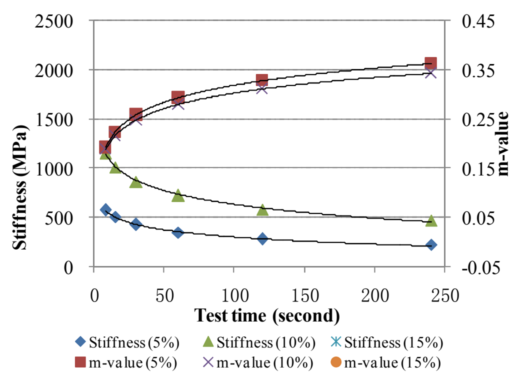


(e)



(f)

Figure 14-5: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 64-22 at -18ºC

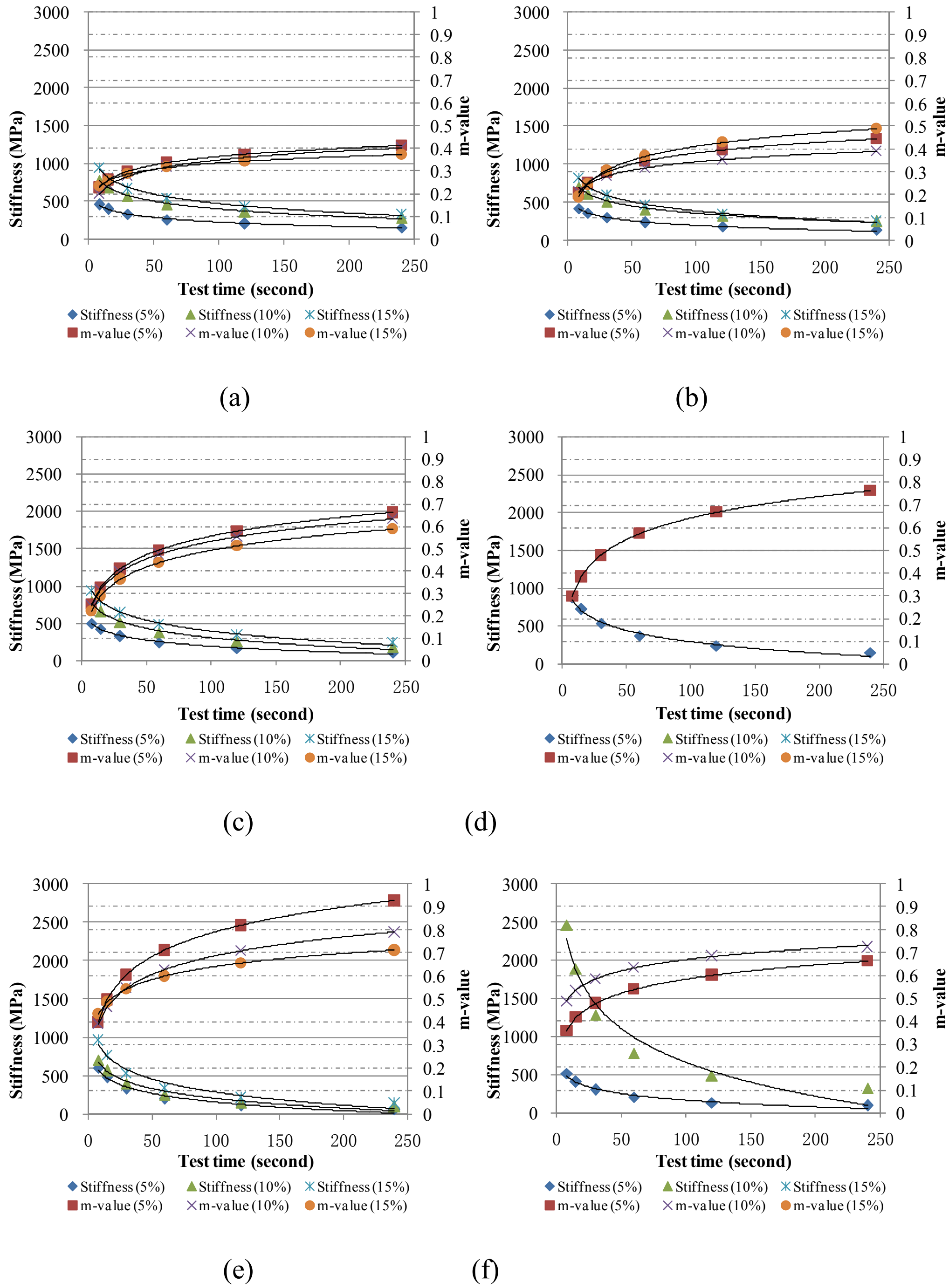
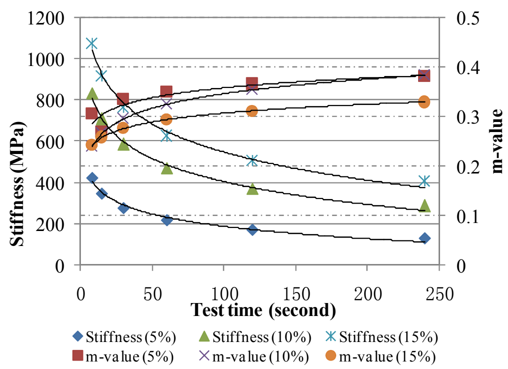


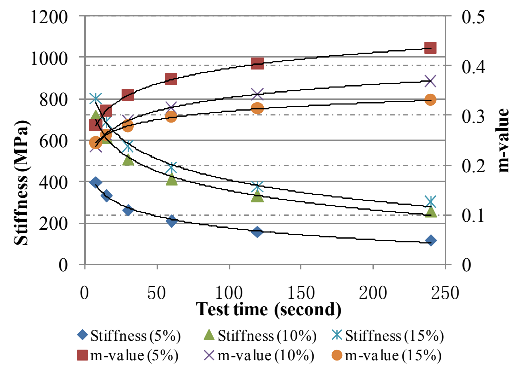
Figure 14-6: Stiffness and m-values of burned RAP sources A-F modified with RTFO binder PG 76-22 at -18ºC

15 Appendix F

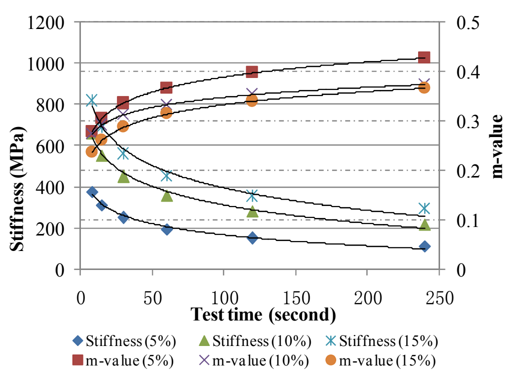
BBR Data: Burned RAP + PAV Binder @ -12 °C and -18 °C



(j)



(b)



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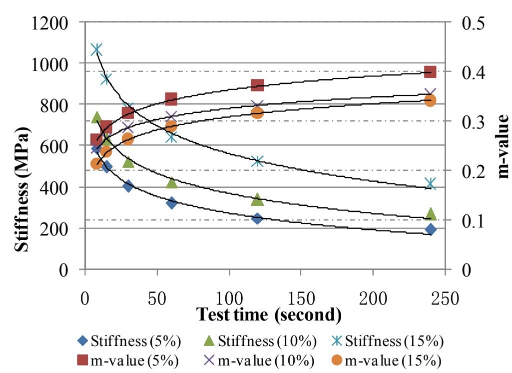
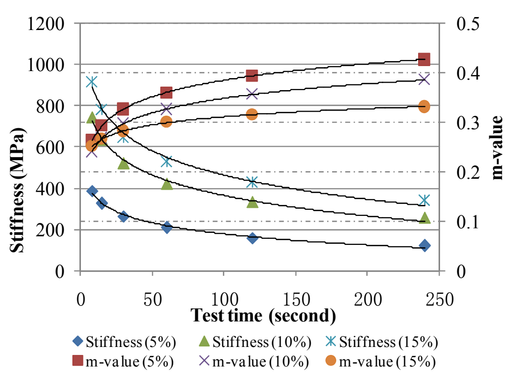
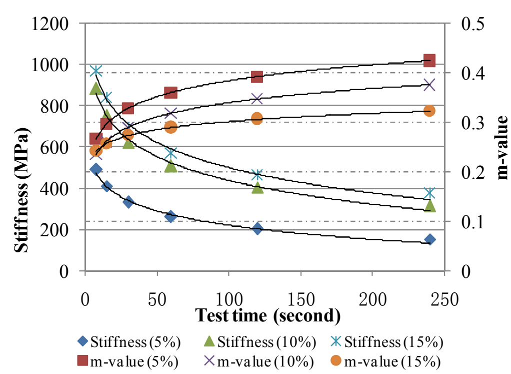


(d)



(e)



(f)

Figure 15-1: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 58-28 at -12ºC

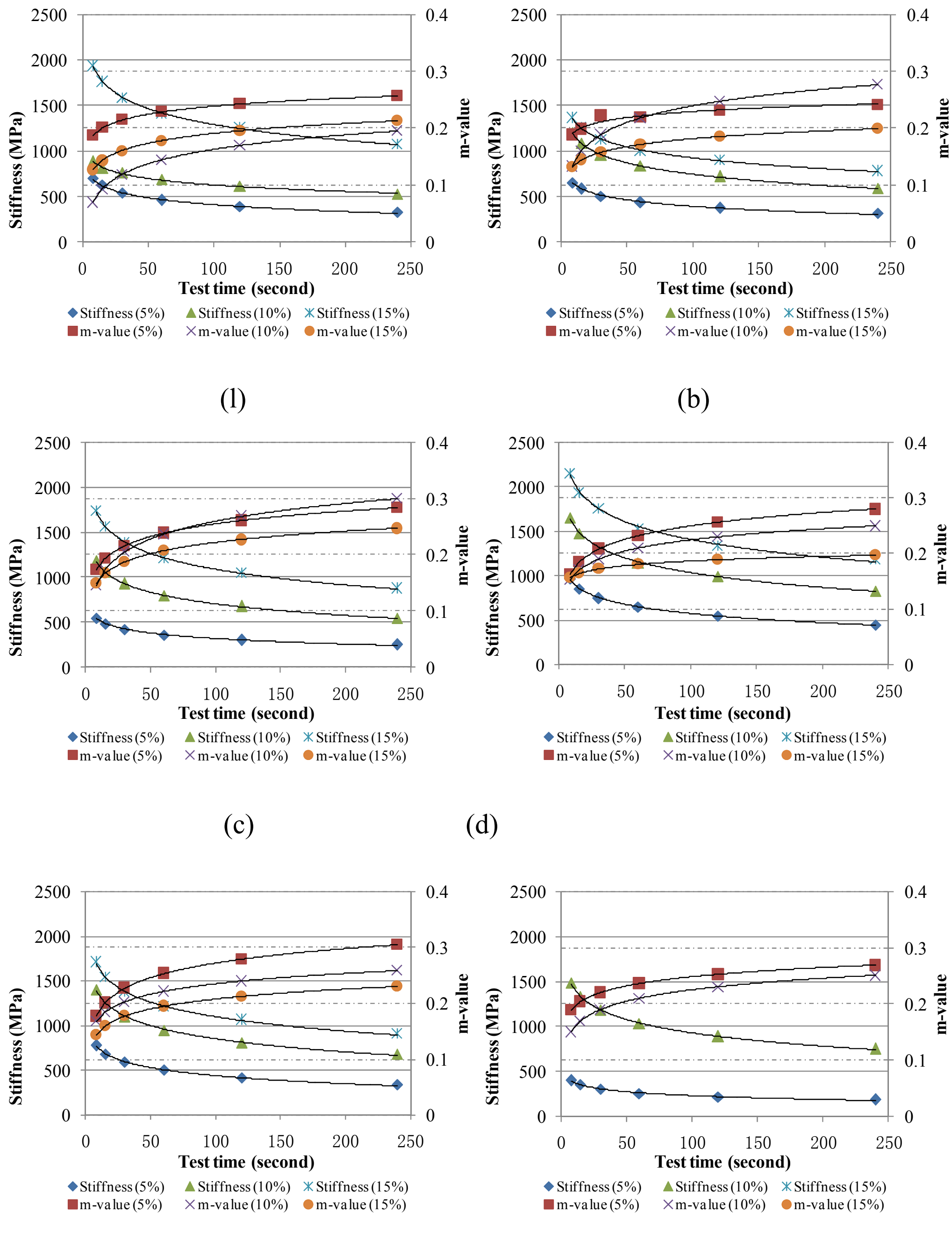
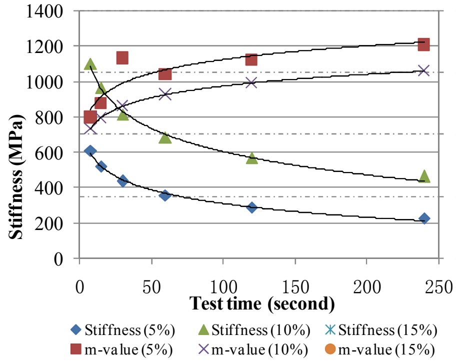
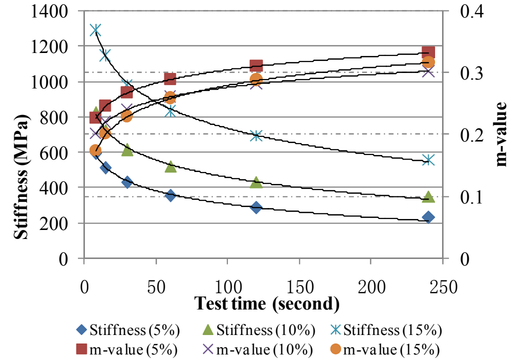
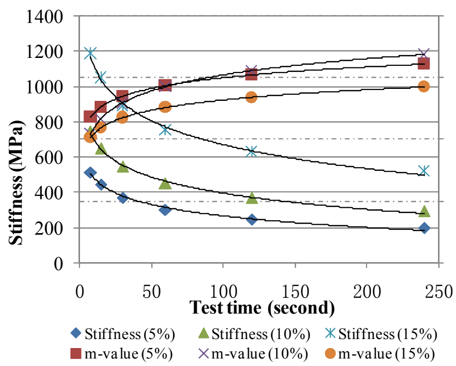


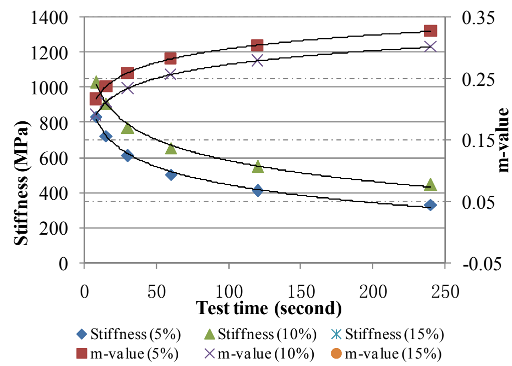
Figure 15-2: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 64-22 at -12ºC



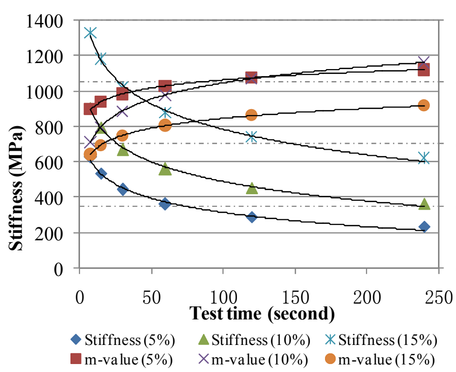


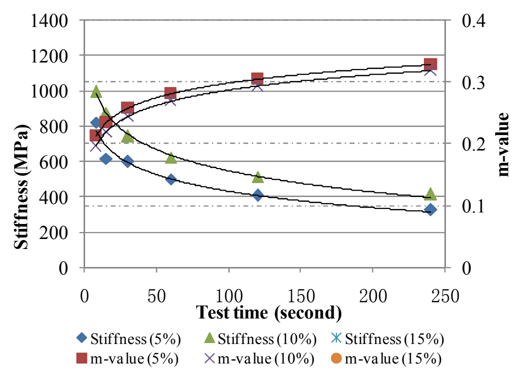
(j) (b)





(c) (d)





(e) (f)

Figure 15-3: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 76-22 at -12ºC

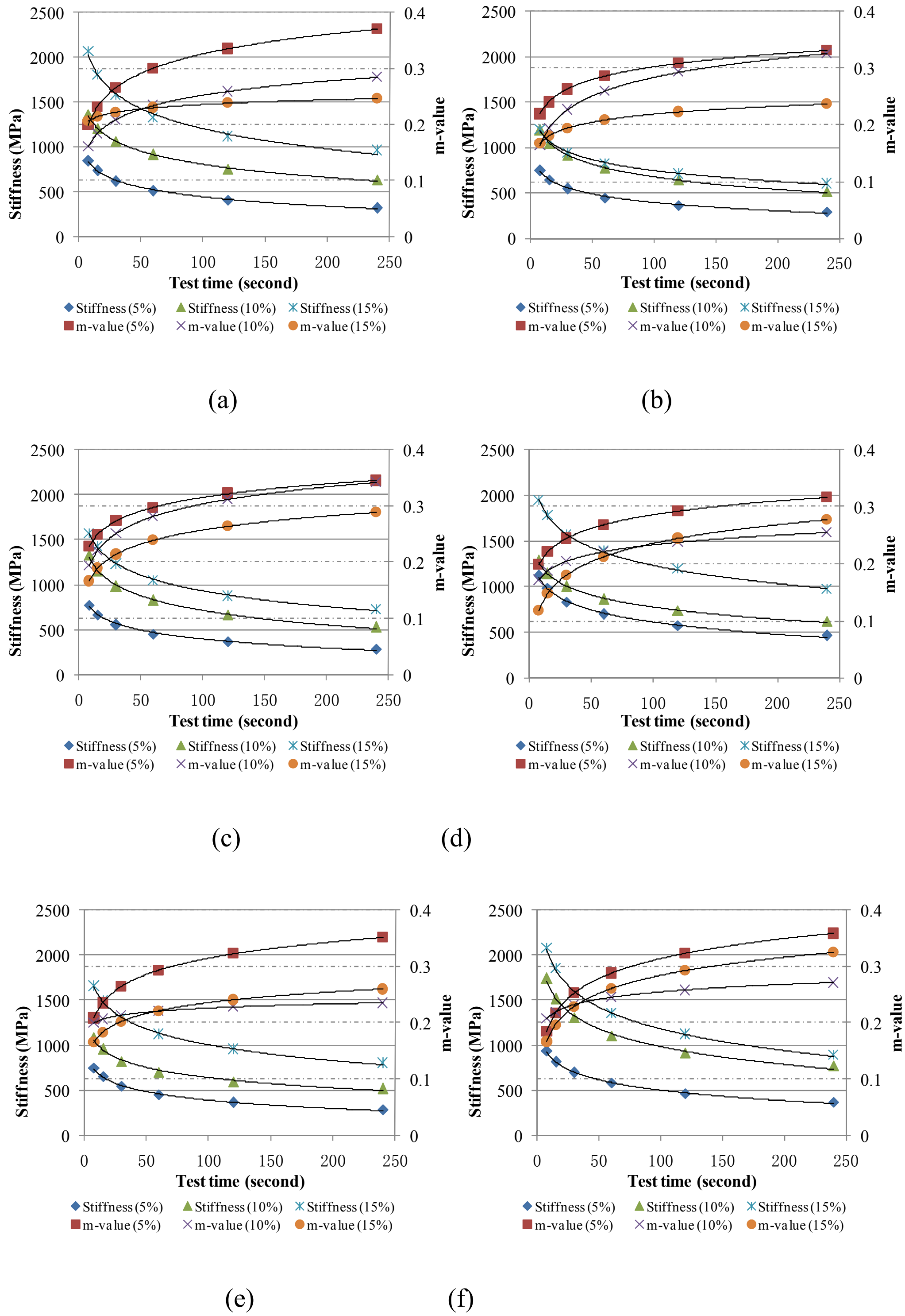


Figure 15-4: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 58-28 at -18ºC

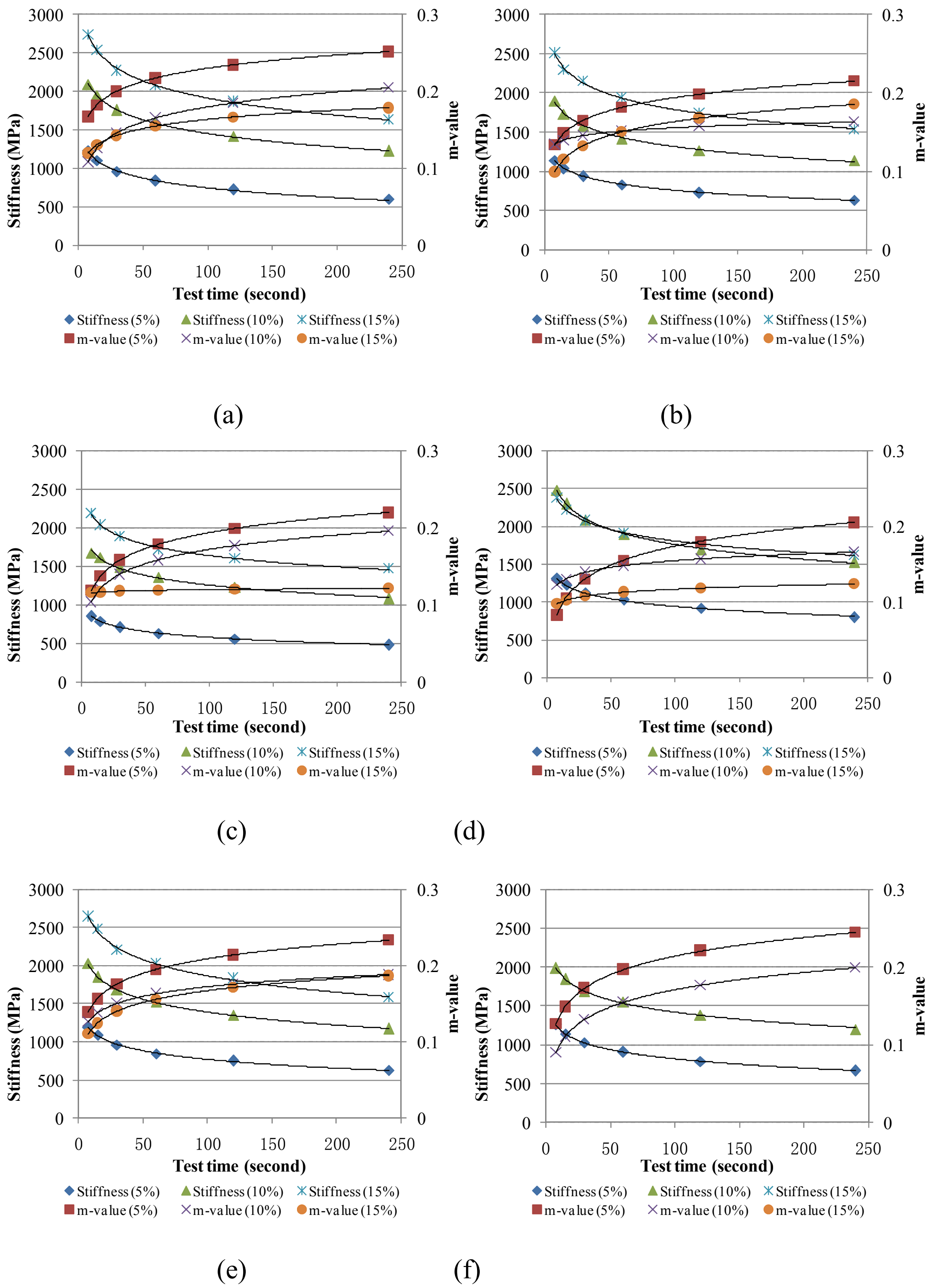


Figure 15-5: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 64-22 at -18ºC

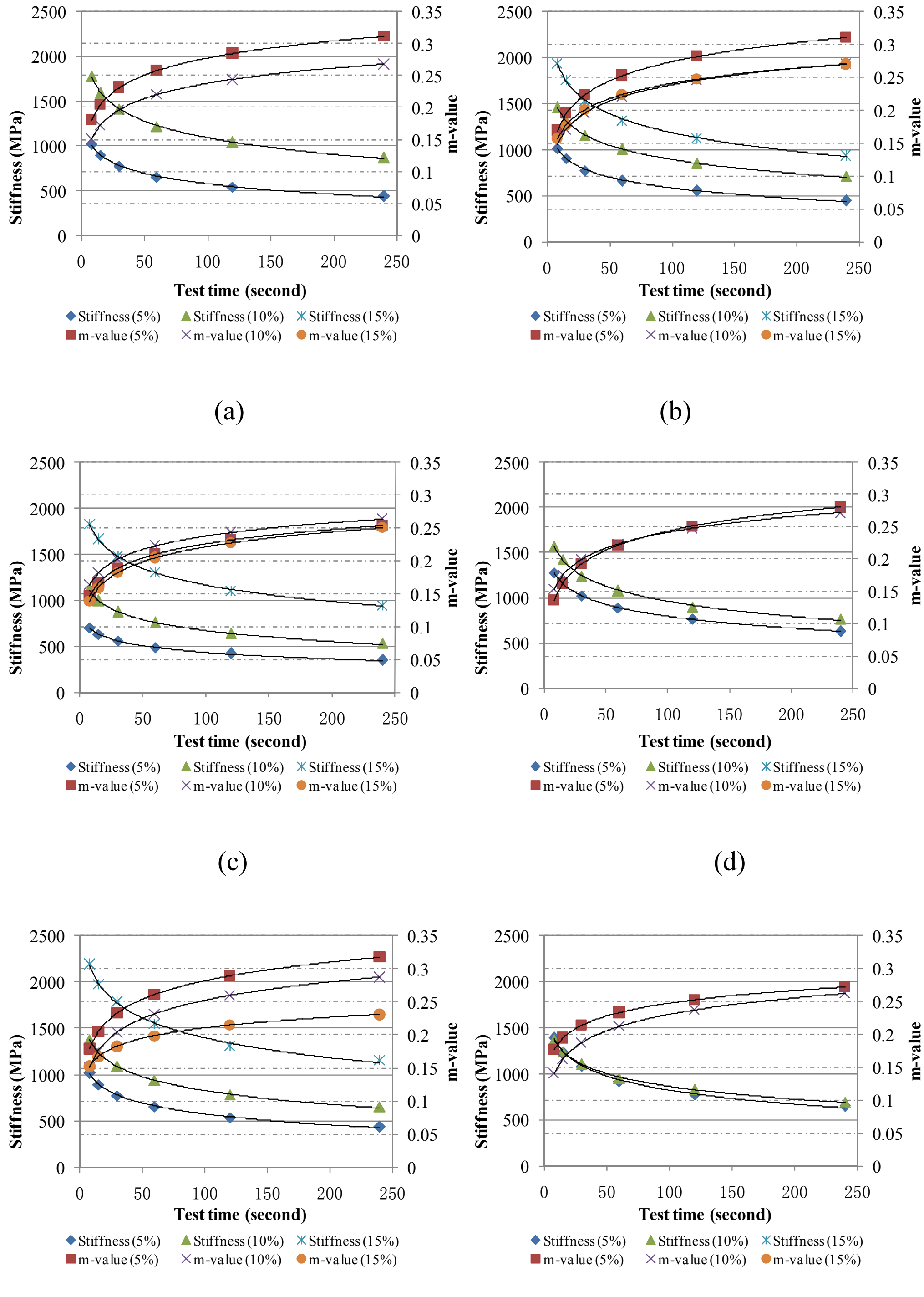
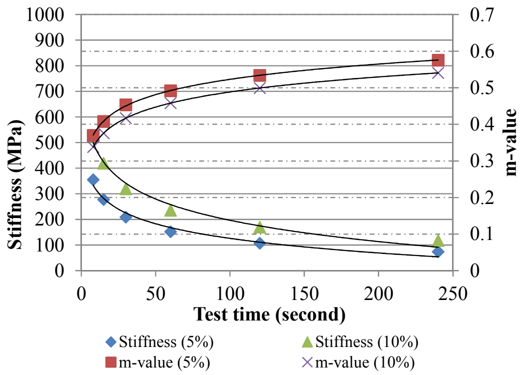


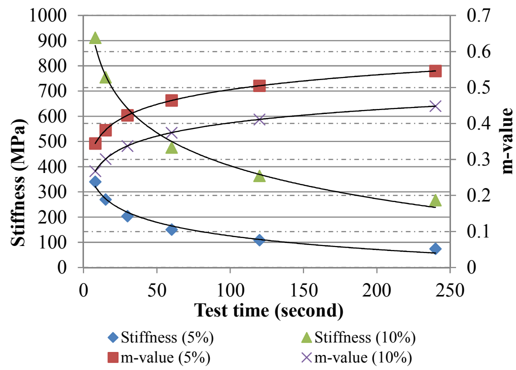
Figure 15-6: Stiffness and m-values of burned RAP sources A-F modified with PAV binder PG 76-22 at -18ºC

16 Appendix G

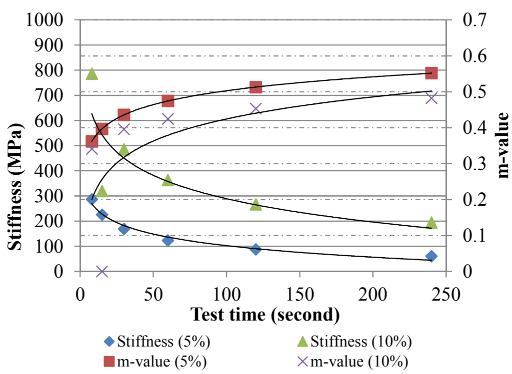
BBR Data: RAP after 1 Year + Various Binders @ -12 °C and -18 °C



(a)

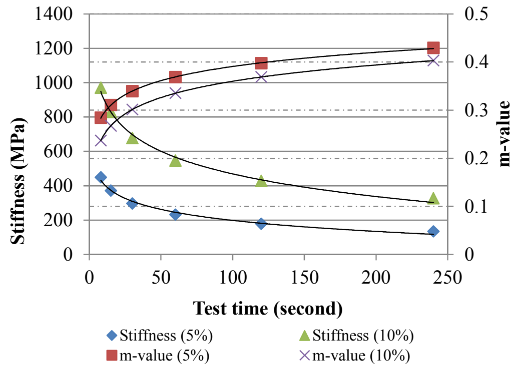


(b)

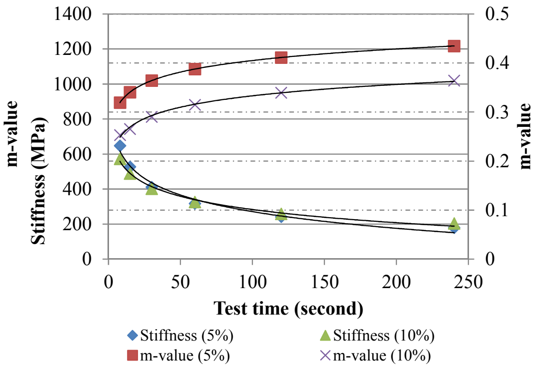


(c)

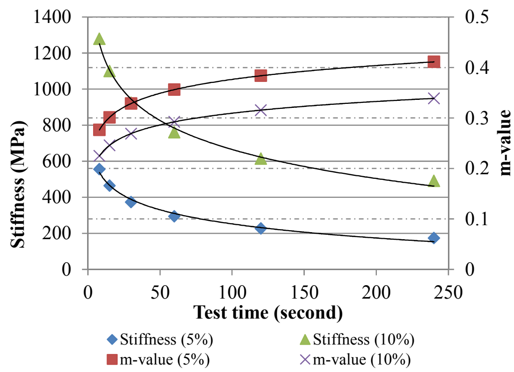
Figure 16-1: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 58-28 at -12ºC



(m)

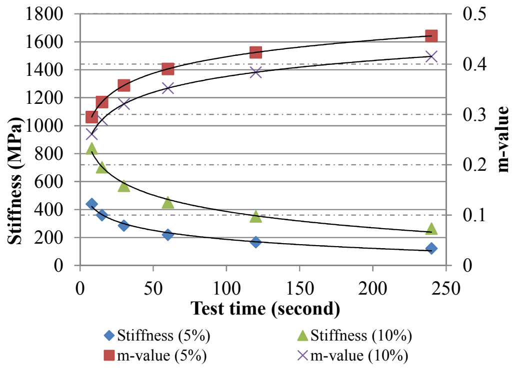


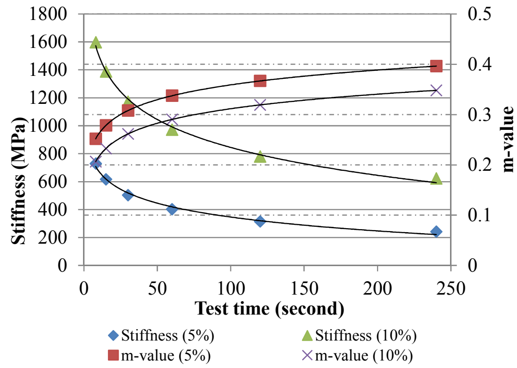
(b)



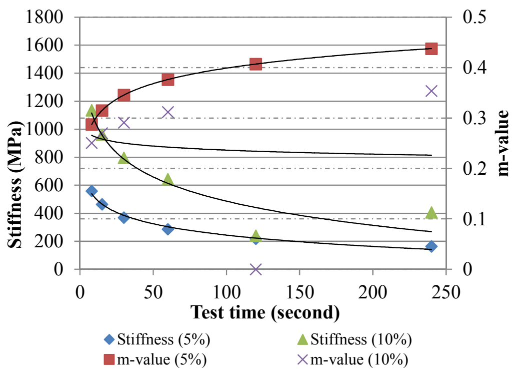
(c)

Figure 16-2: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 64-22 at -12ºC



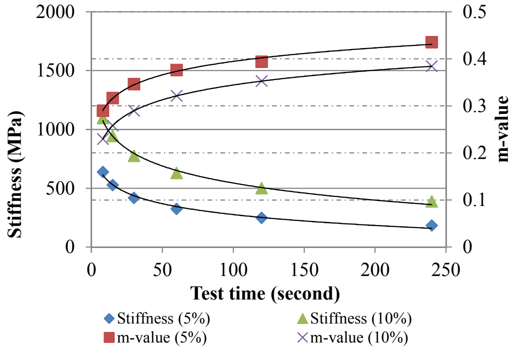


(b) (b)

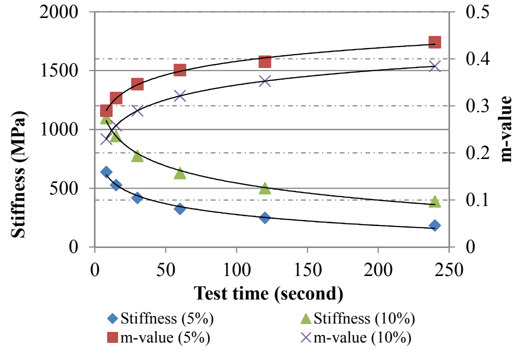


(c)

Figure 16-3: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 76-22 at -12ºC



(a)



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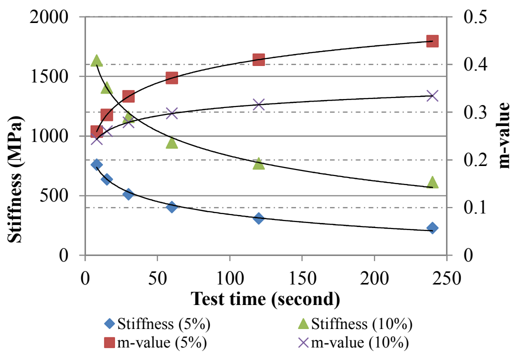
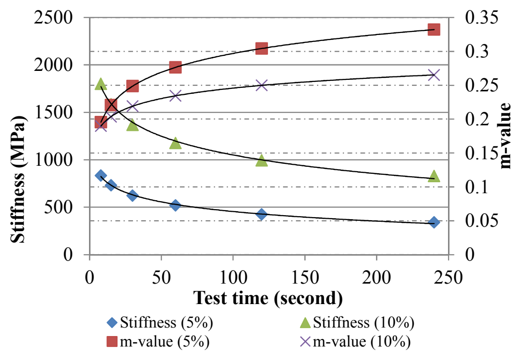
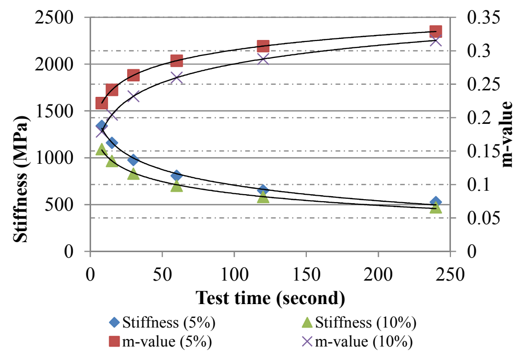


(c)

Figure 16-4: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 58-28 at -18ºC



(n)



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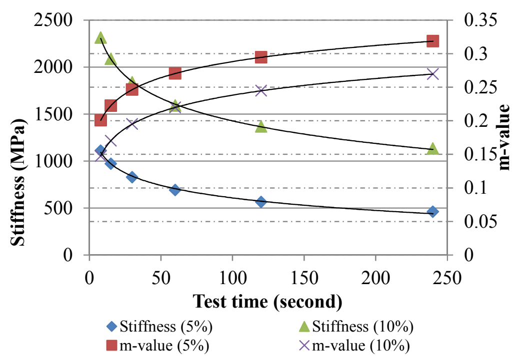
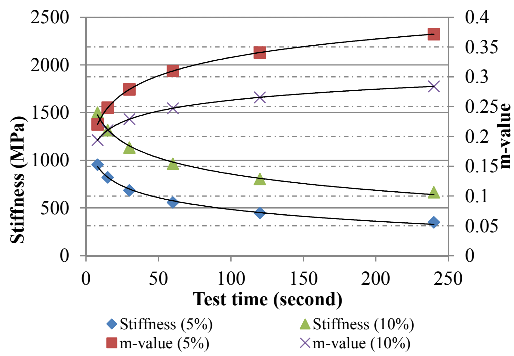
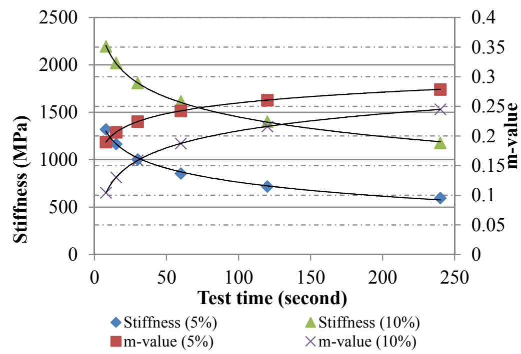


(c)

Figure 16-5: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 64-22 at -18ºC



(a)



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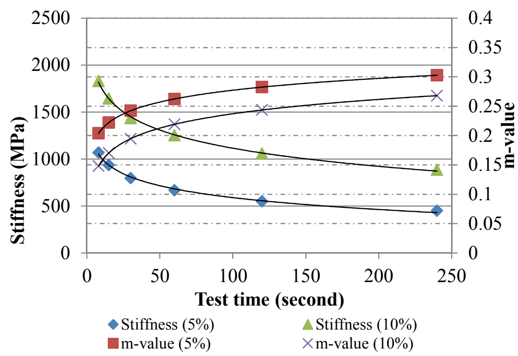
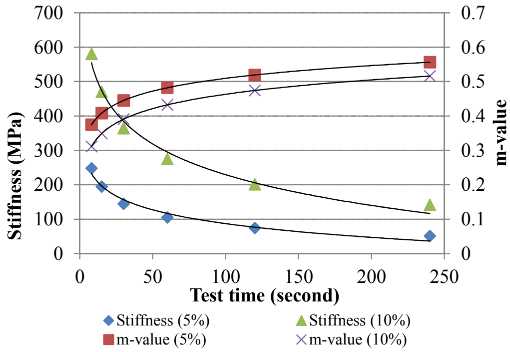
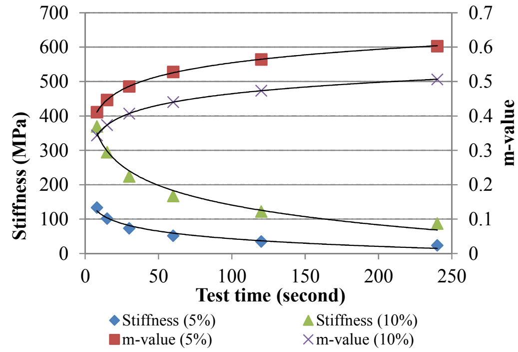


(c)

Figure 16-6: Stiffness and m-values of RAP sources C, D, and F modified with virgin binder PG 76-22 at -18ºC



(a)



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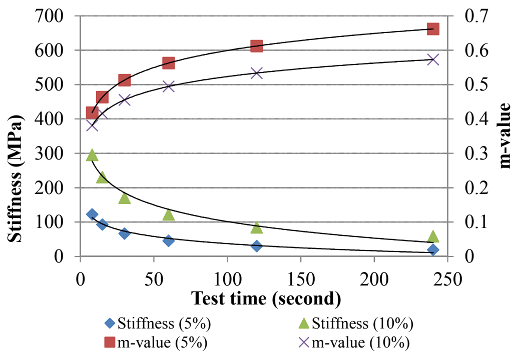
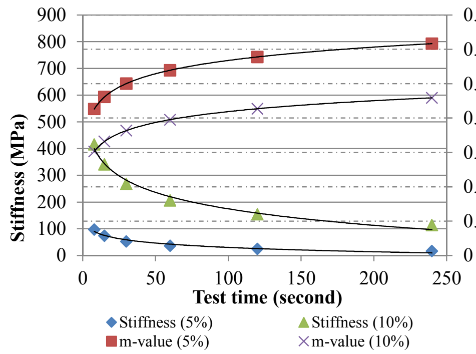
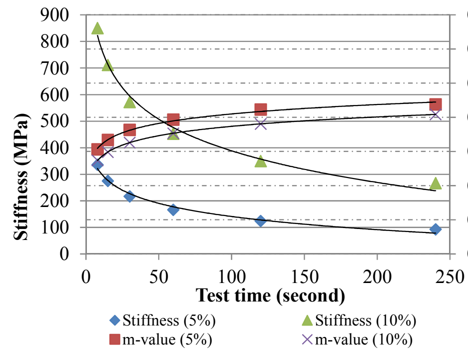


(c)

Figure 16-7: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 58-28 at -6^{o}C



(a)



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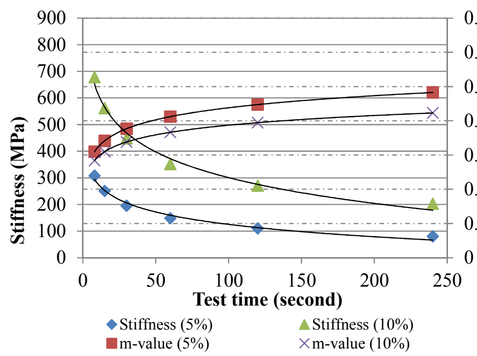
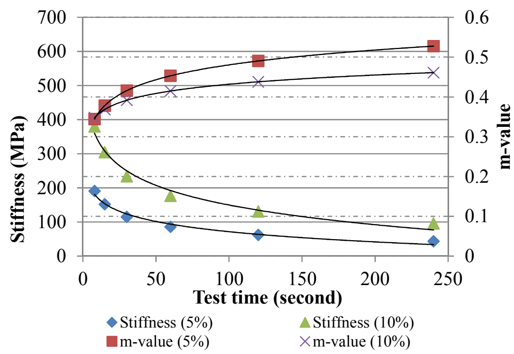
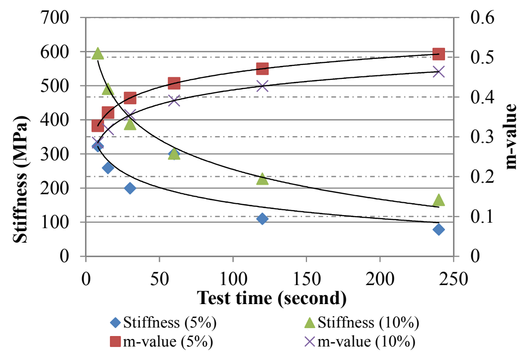


(c)

Figure 16-8: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 64-22 at -6ºC



(a)



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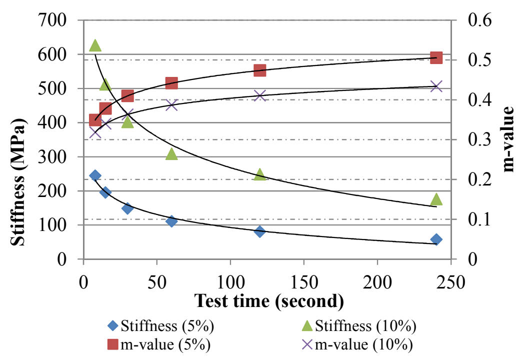
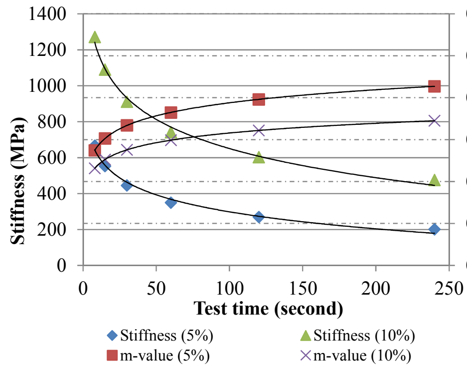
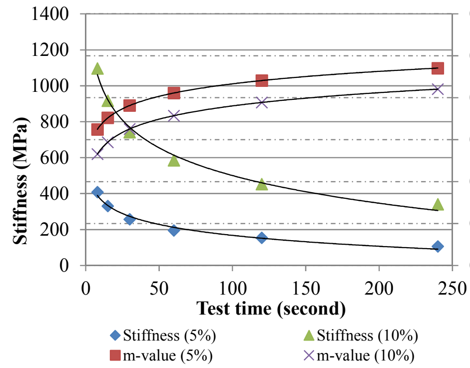


(c)

Figure 16-9: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 76-22 at -6°C



(a)



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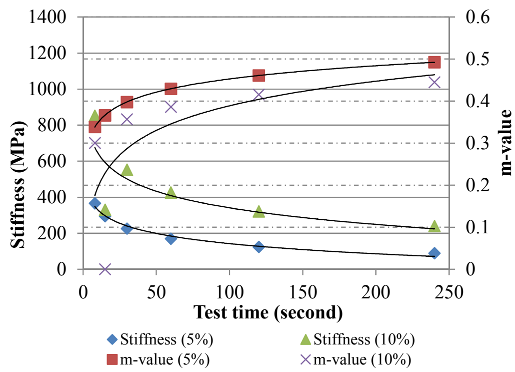
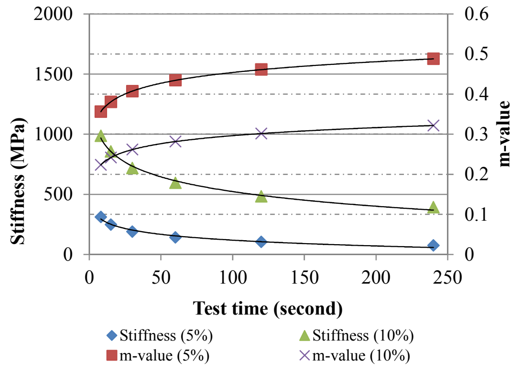
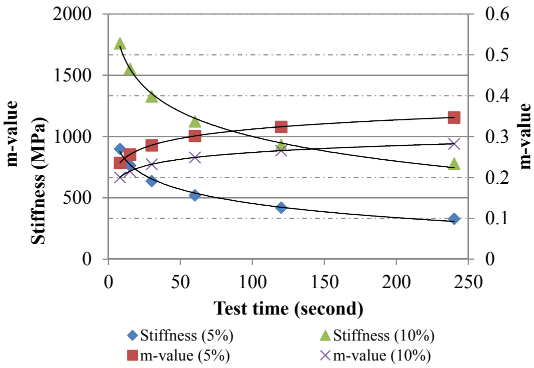


(c)

Figure 16-10: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 58-28 at -12ºC



(a)



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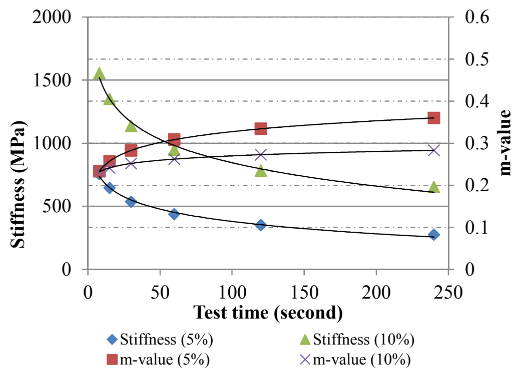
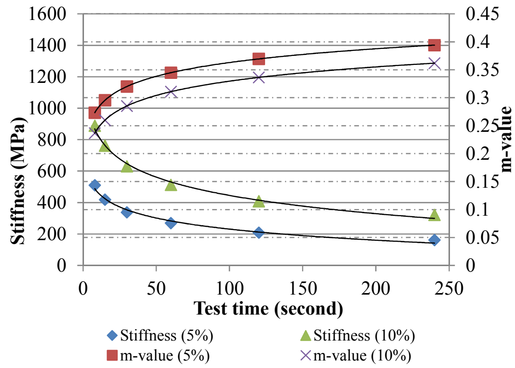
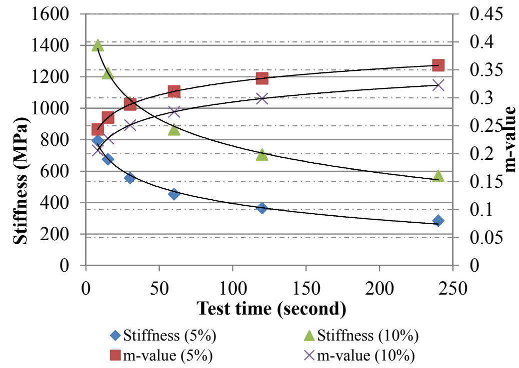


(c)

Figure 16-11: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 64-22 at -12ºC



(a)



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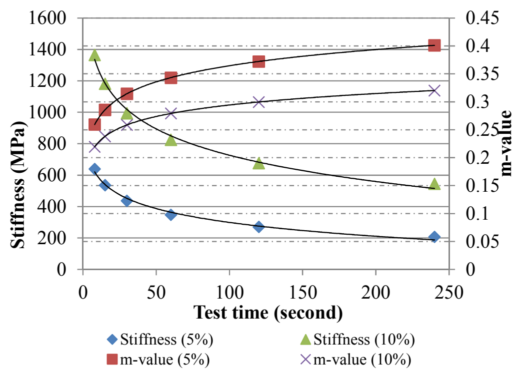
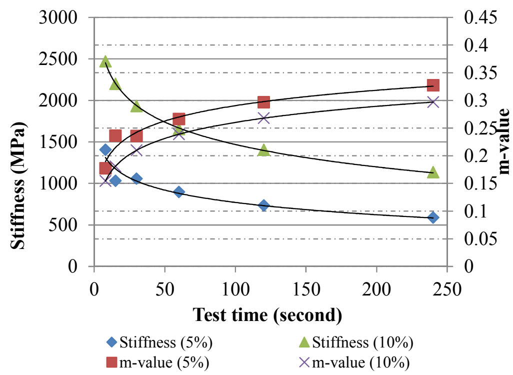
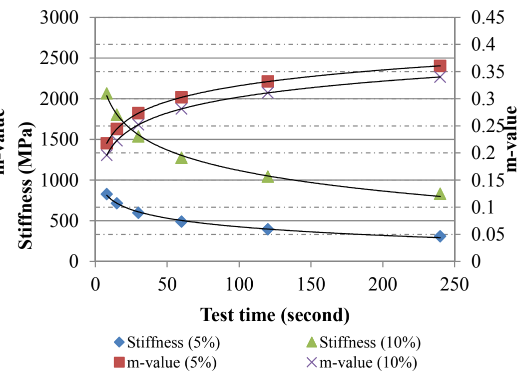


(c)

Figure 16-12: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 76-22 at -12ºC



(a)



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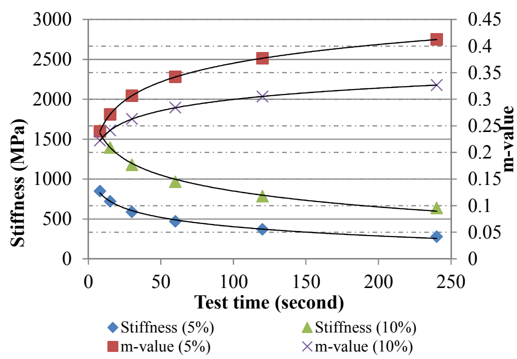
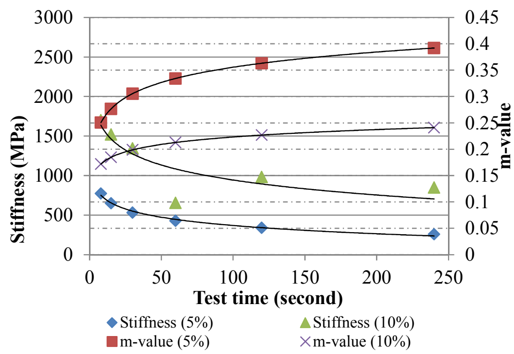
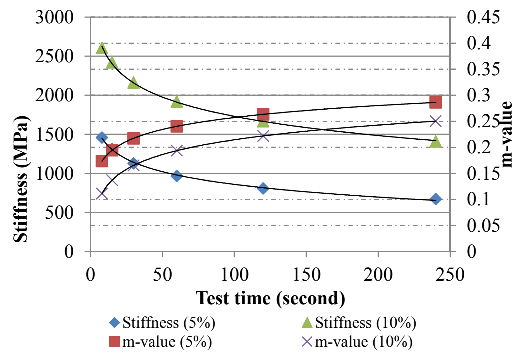


(c)

Figure 16-13: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 58-28 at -18ºC



(a)



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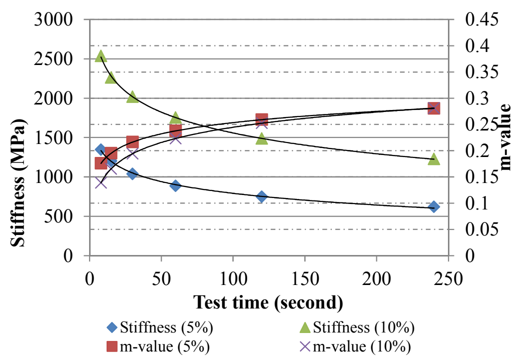
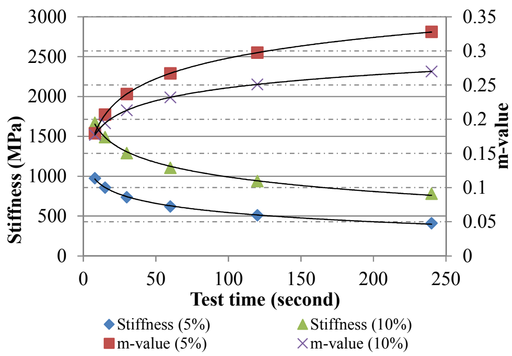
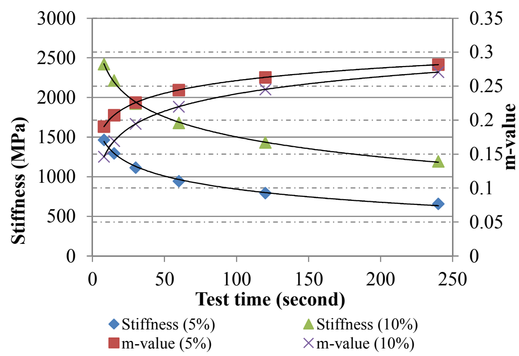


(c)

Figure 16-14: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 64-22 at -18ºC



(a)



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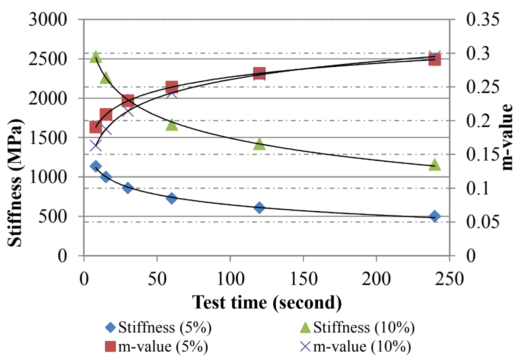
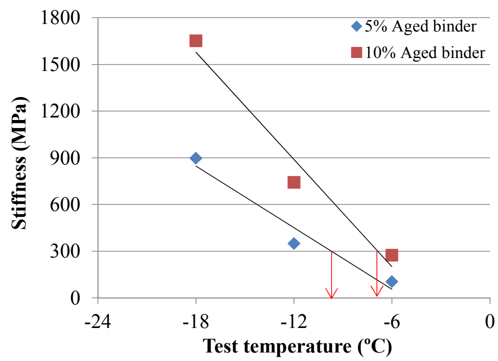


(c)

Figure 16-15: Stiffness and m-values of RAP sources C, D, and F modified with RTFO binder PG 76-22 at -18°C



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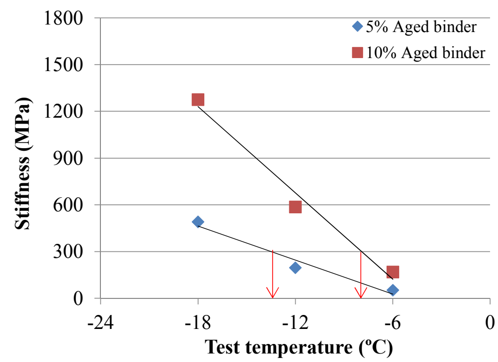

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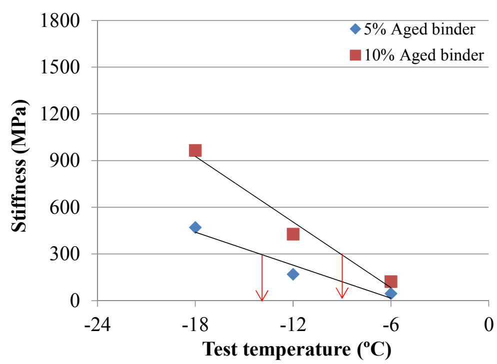
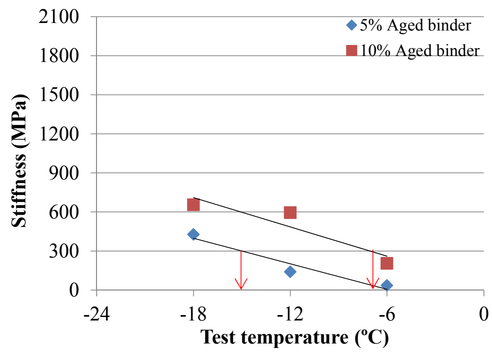
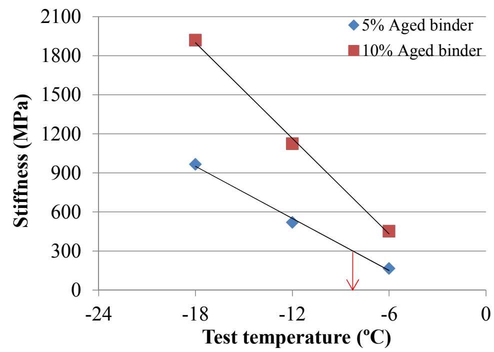


(c)

Figure 16-16: Low temperature determinations of RAP sources C, D, and F modified with RTFO binder PG 58-28 in terms of stiffness



(a)



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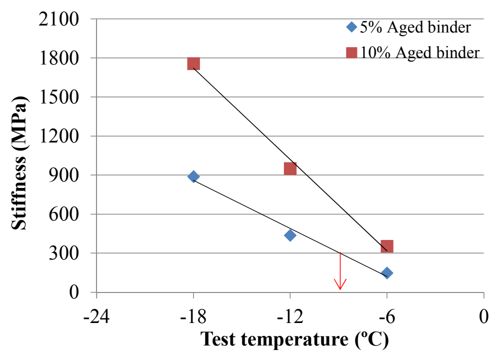
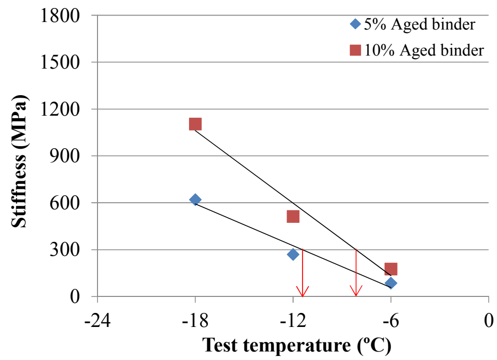
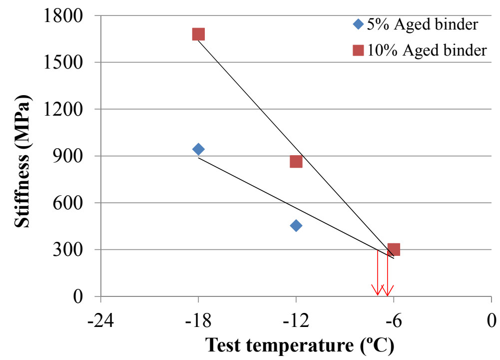


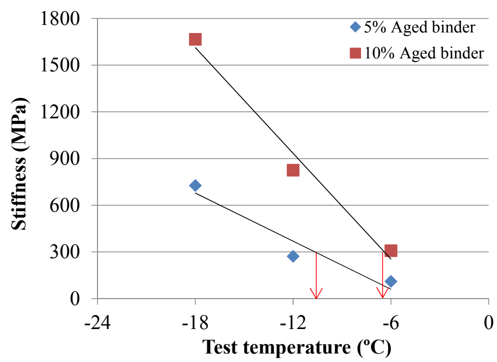
(c)

Figure 16-17: Low temperature determinations of RAP sources C, D, and F modified with RTFO binder PG 64-22 in terms of stiffness



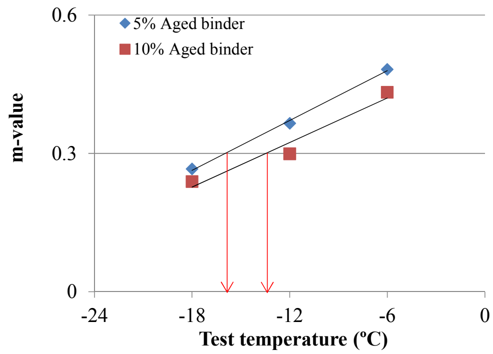


(b) (b)



(c)

Figure 16-18: Low temperature determinations of RAP sources C, D, and F modified with RTFO binder PG 76-22 in terms of stiffness



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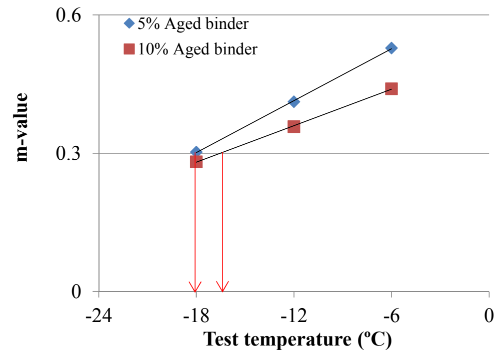

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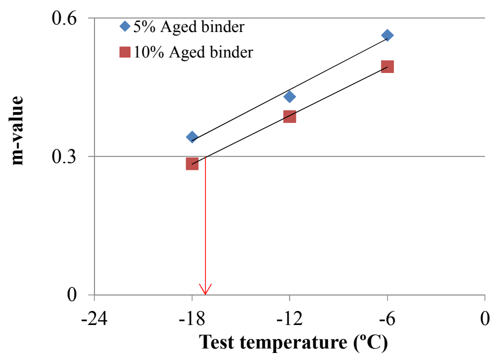
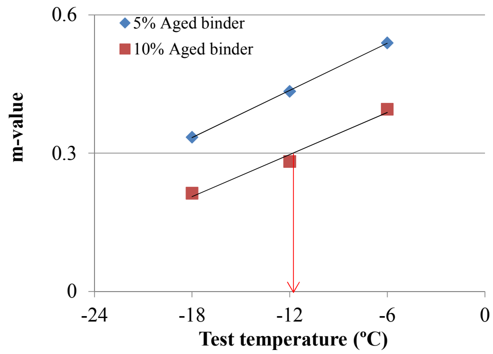
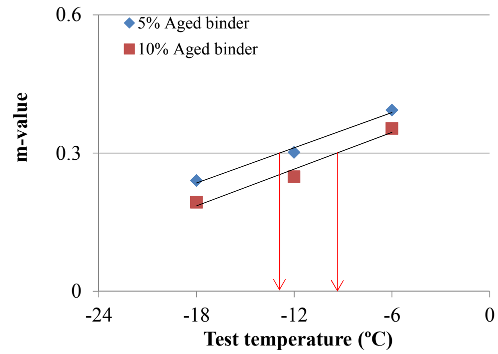


(c)

Figure 16-19: Low temperature determinations of RAP sources C, D, and F modified with RTFO binder PG 58-28 in terms of m-value



(b)



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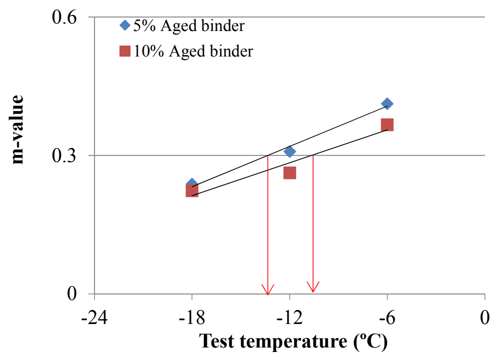
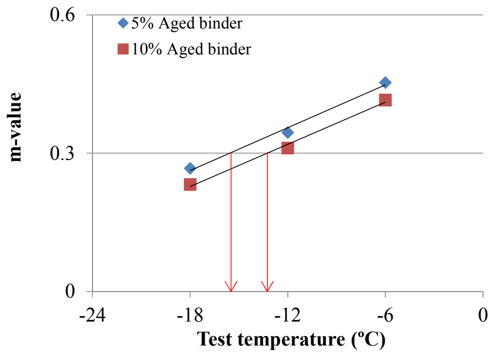
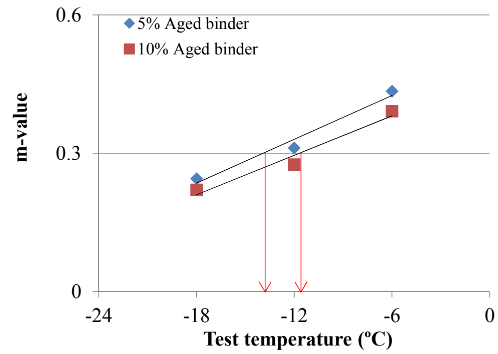


(c)

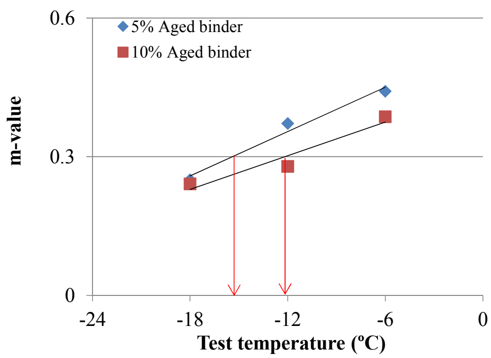
Figure 16-20: Low temperature determinations of RAP sources C, D, and F modified with RTFO binder PG 64-22 in terms of m-value



(b)

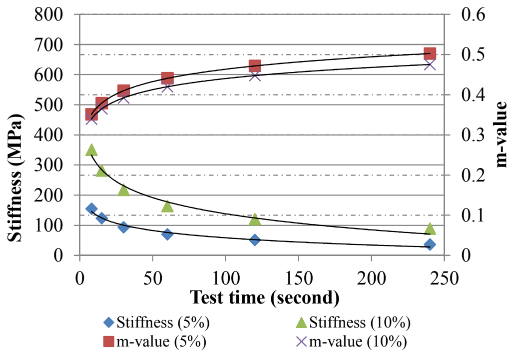


(b)

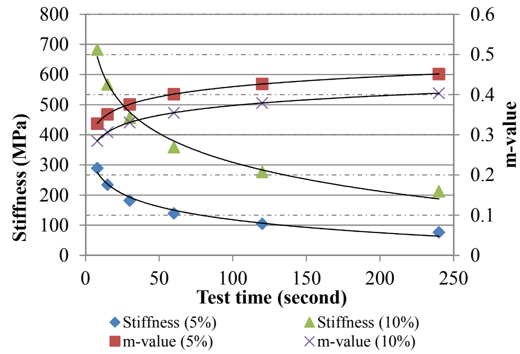


(c)

Figure 16-21: Low temperature determinations of RAP sources C, D, and F modified with RTFO binder PG 76-22 in terms of m-value



(a)



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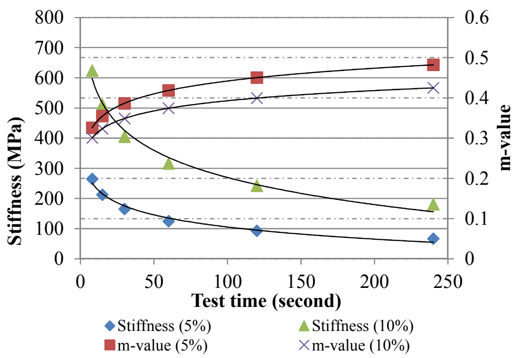
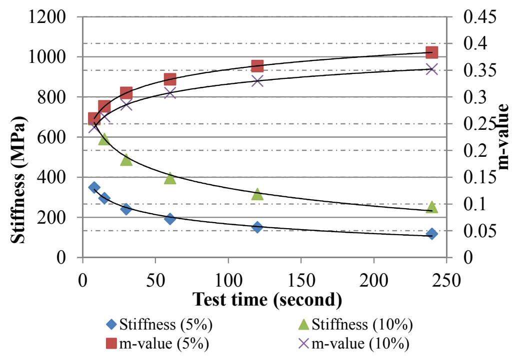
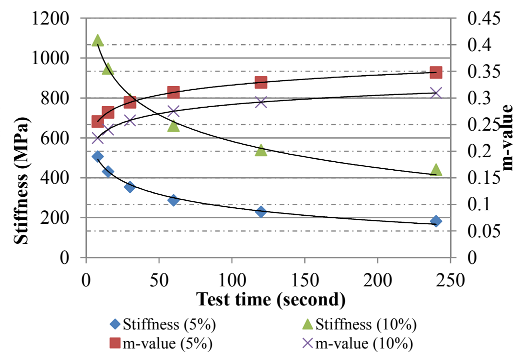


(c)

Figure 16-22: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 58-28 at -6ºC



(a)



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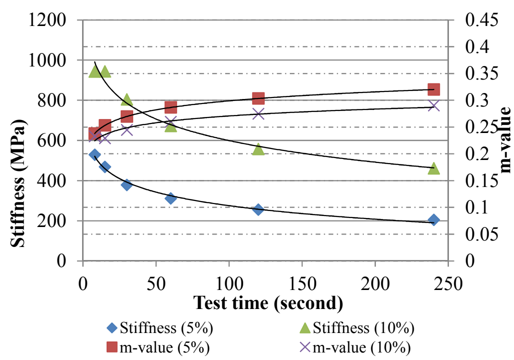
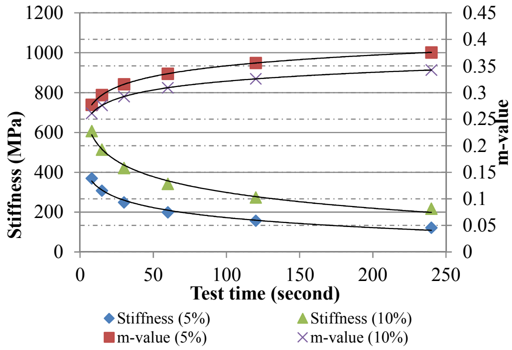
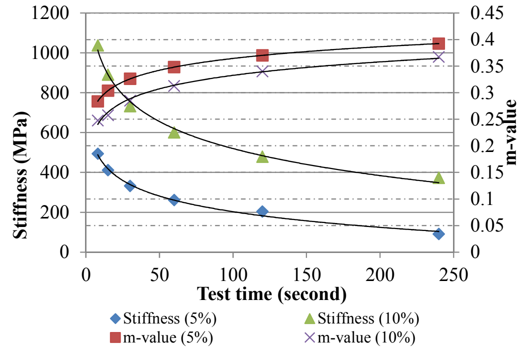


(c)

Figure 16-23: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 64-22 at -6°C



(a)



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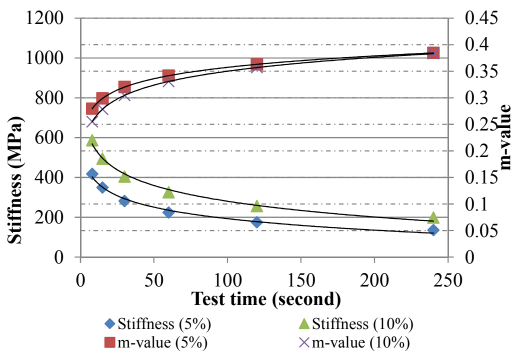
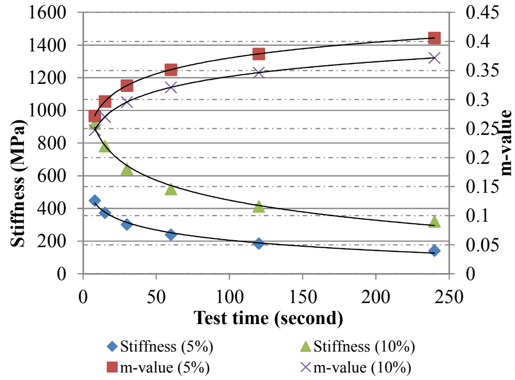
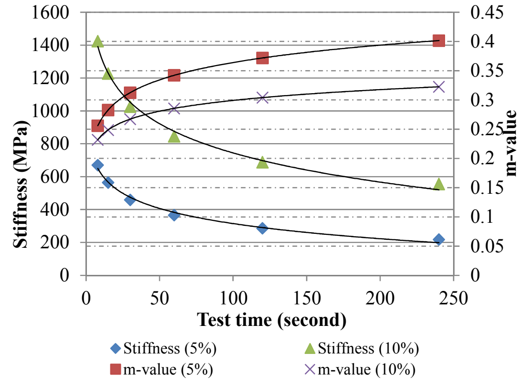


(c)

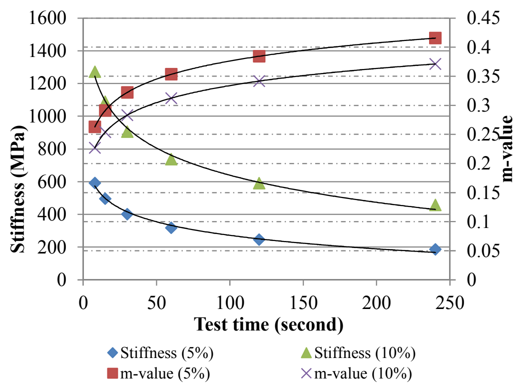
Figure 16-24: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 76-22 at -6^{o}C



(a)

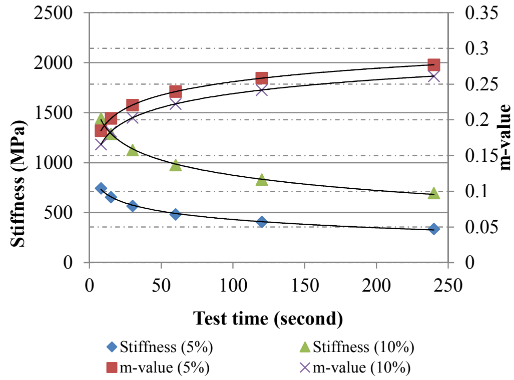


(b)

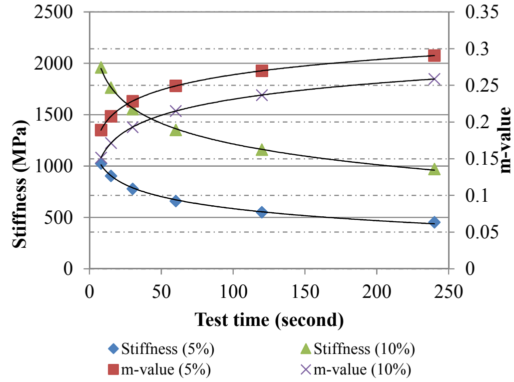


(c)

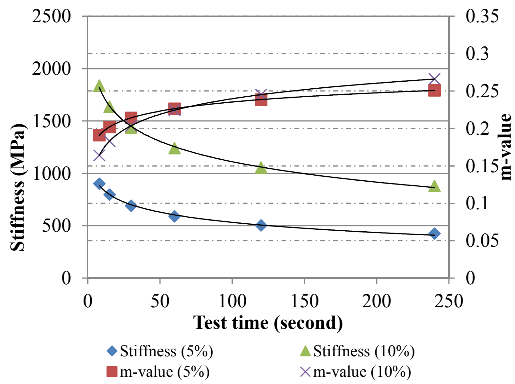
Figure 16-25: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 58-28 at -12ºC



(a)

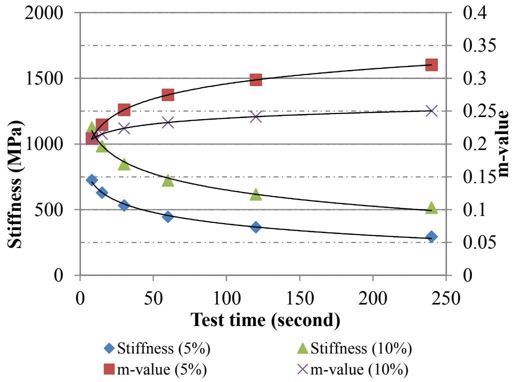


(b)

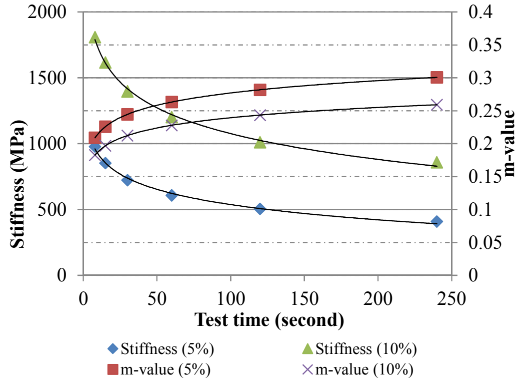


(c)

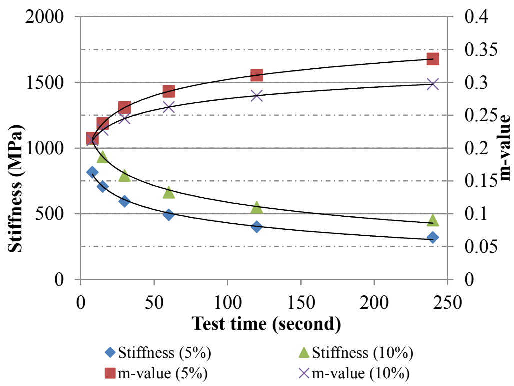
Figure 16-26: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 64-22 at -12ºC



(a)

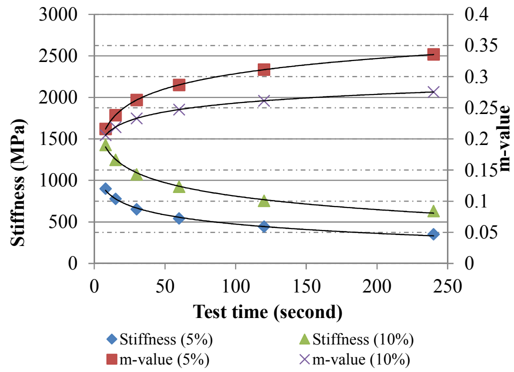


(b)

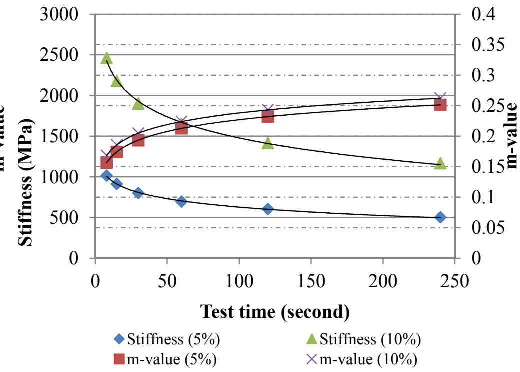


(c)

Figure 16-27: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 76-22 at -12ºC



(a)



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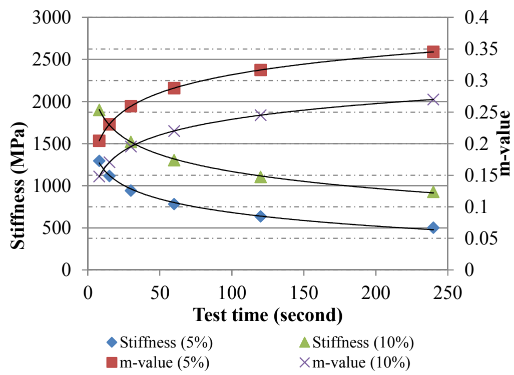
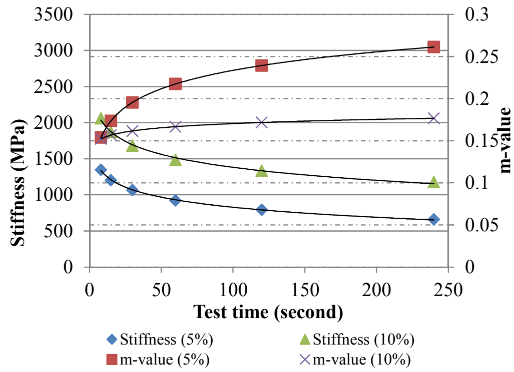
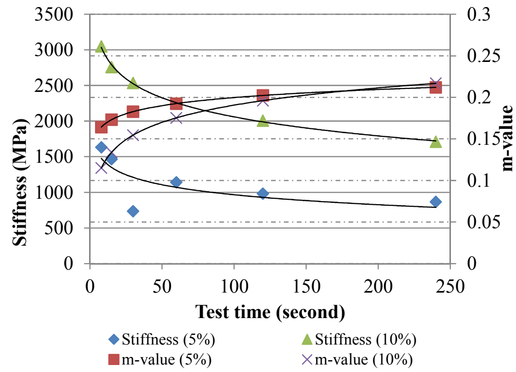


(c)

Figure 16-28: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 58-28 at -18ºC



(a)



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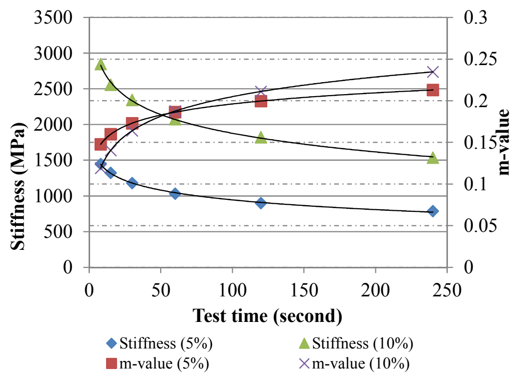
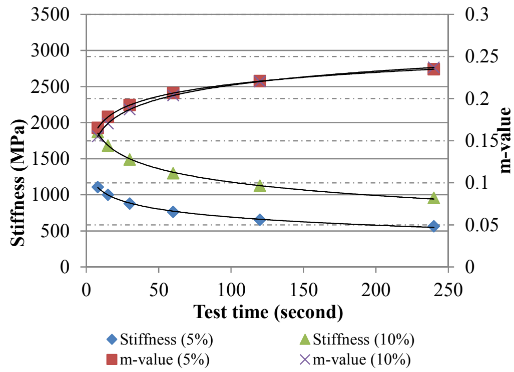
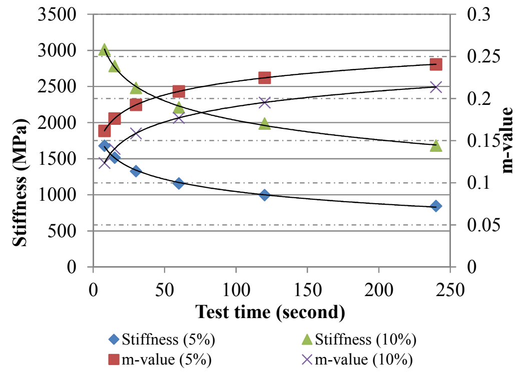


(c)

Figure 16-29: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 64-22 at -18ºC



(a)



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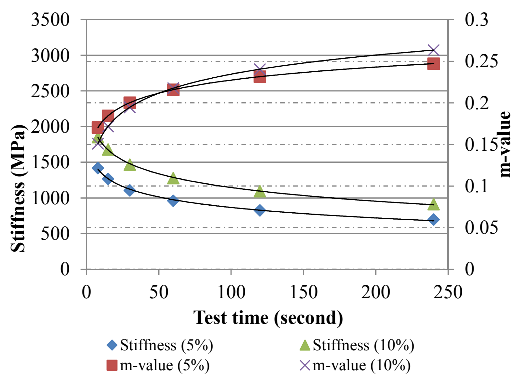
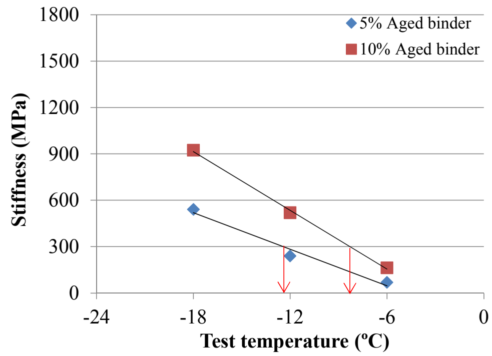
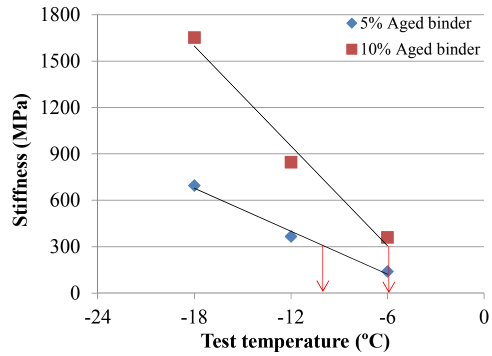


(c)

Figure 16-30: Stiffness and m-values of RAP sources C, D, and F modified with PAV binder PG 76-22 at -18ºC



(a)



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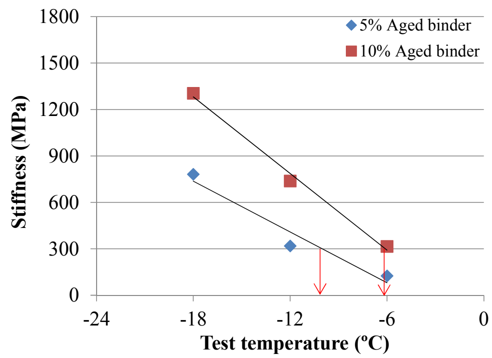


(c)

Figure 16-31: Low temperature determinations of RAP sources C, D, and F modified with PAV binder PG 58-28 in terms of stiffness

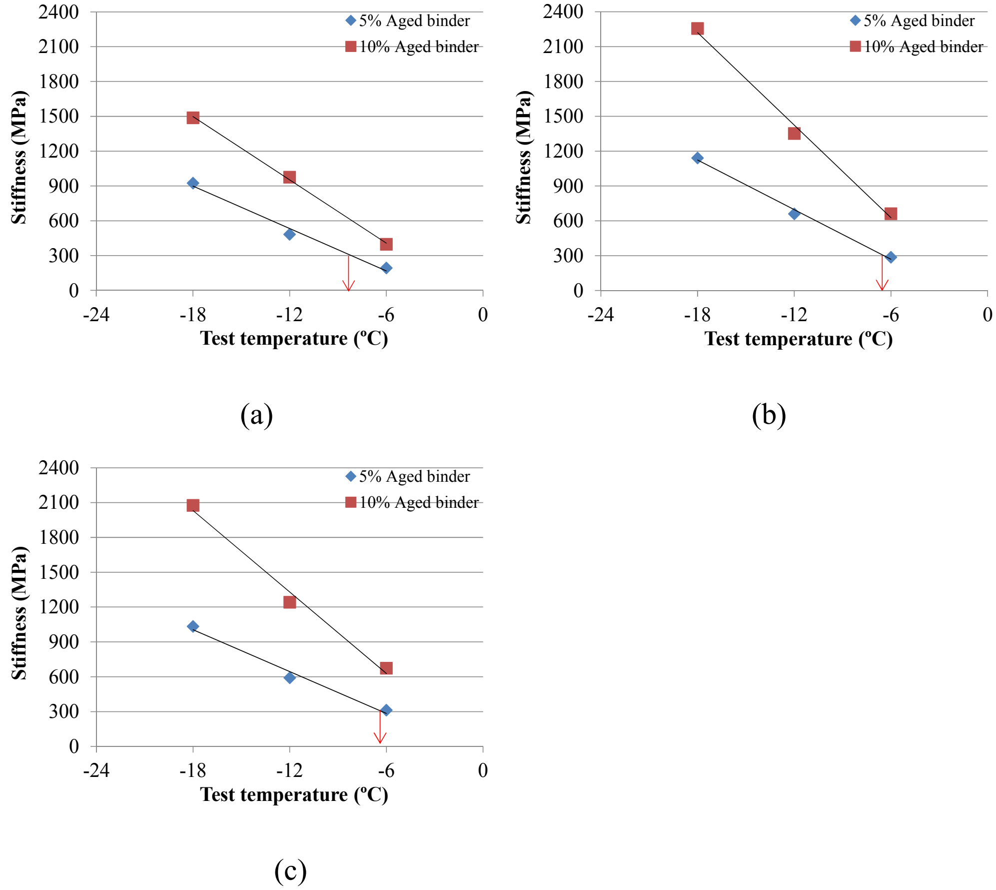
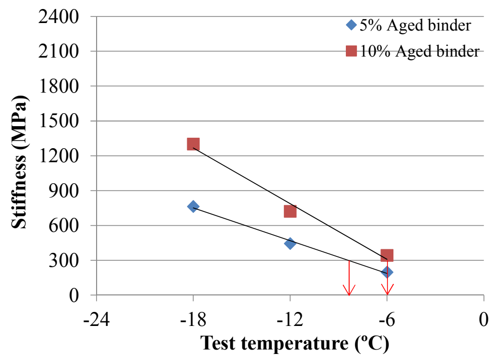
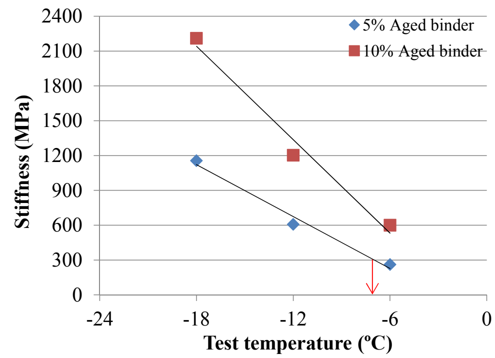


Figure 16-32: Low temperature determinations of RAP sources C, D, and F modified with PAV binder PG 64-22 in terms of stiffness



(a)



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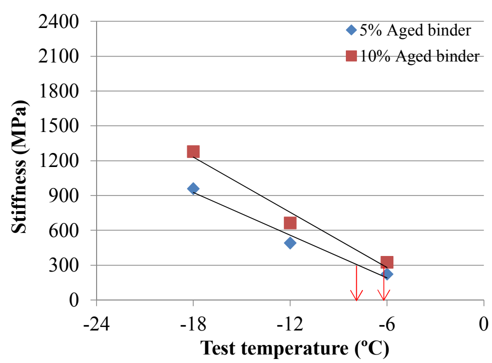
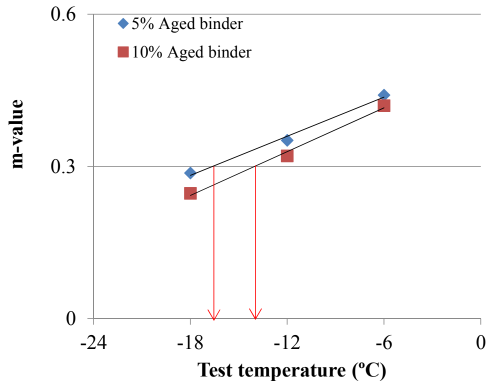
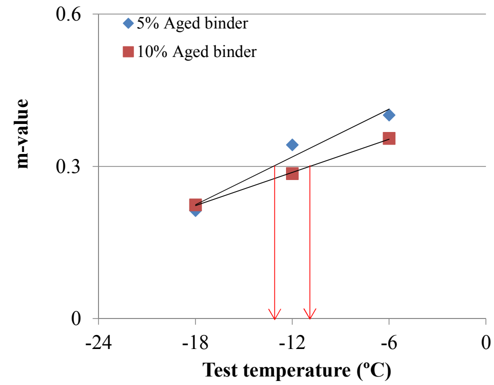


(c)

Figure 16-33: Low temperature determinations of RAP sources C, D, and F modified with PAV binder PG 76-22 in terms of stiffness



(a)



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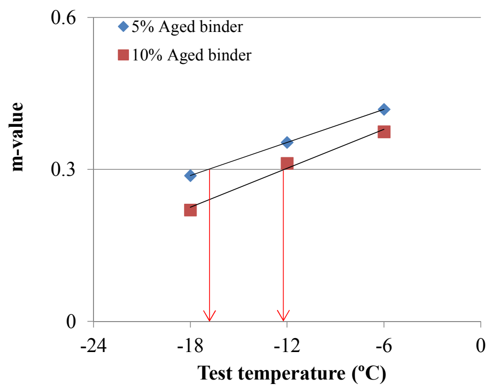


(c)

Figure 16-34: Low temperature determinations of RAP sources C, D, and F modified with PAV binder PG 58-28 in terms of m-value

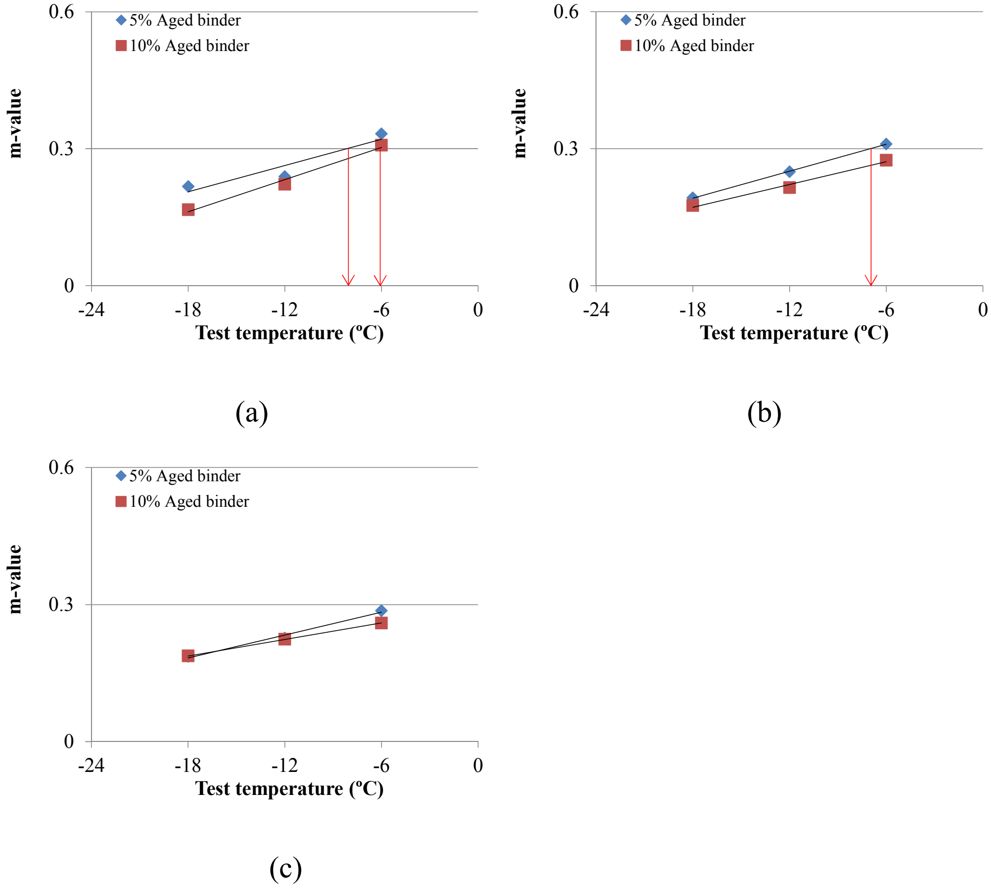
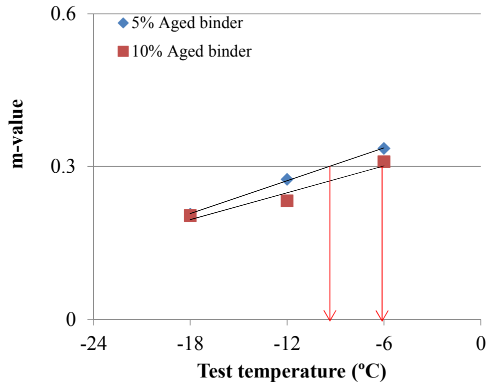
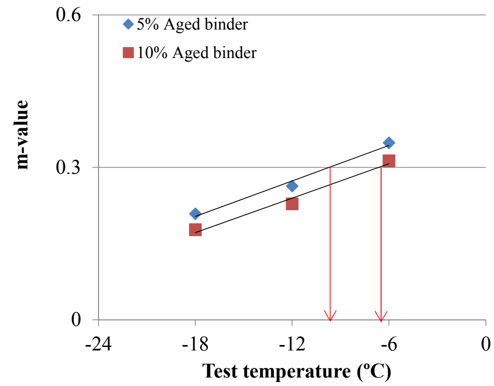


Figure 16-35: Low temperature determinations of RAP sources C, D, and F modified with PAV binder PG 64-22 in terms of m-value



(a)



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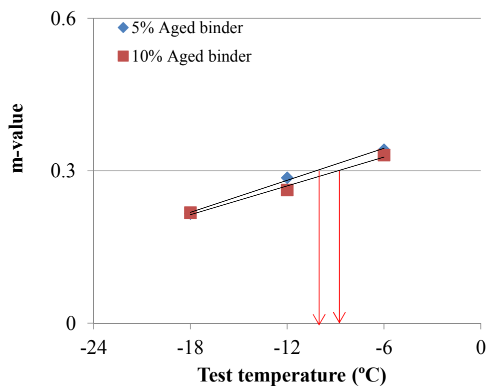
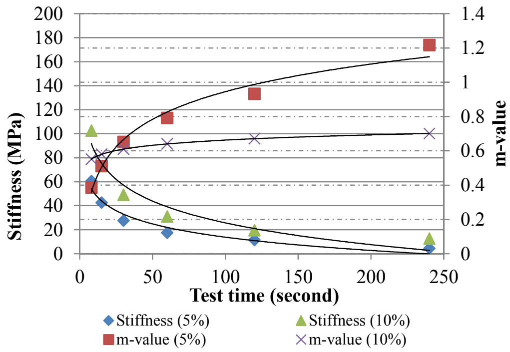


(c)

Figure 16-36: Low temperature determinations of RAP sources C, D, and F modified with PAV binder PG 76-22 in terms of m-value

17 Appendix H

BBR Data: Burned RAP after 1 Year + Various Binders @ -12 °C and -18 °C



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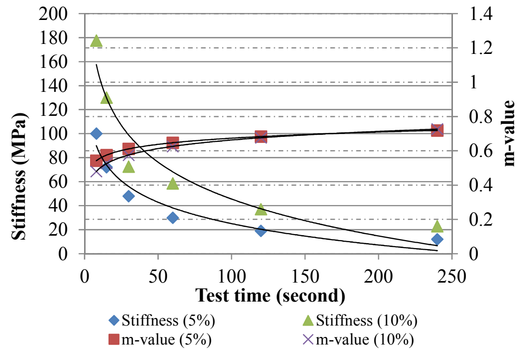

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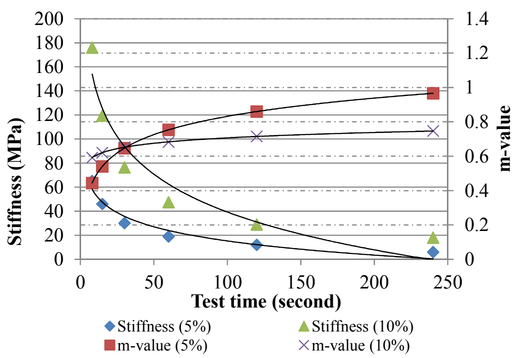
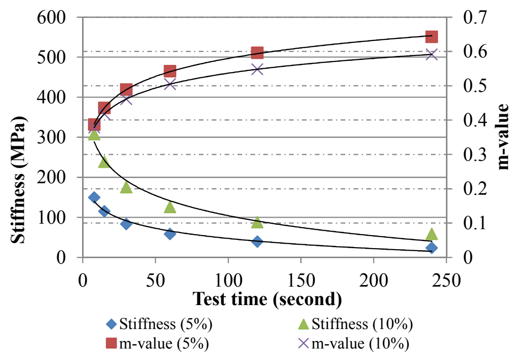
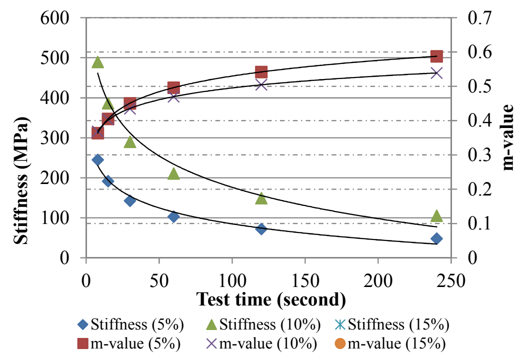


(c)

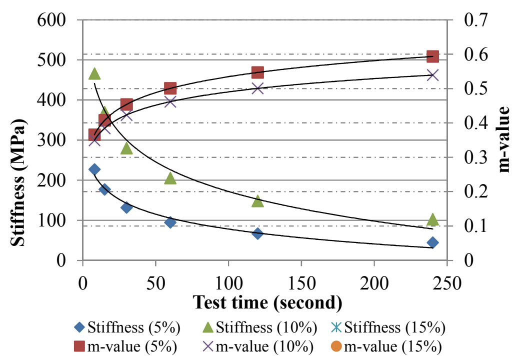
Figure 17-1: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 58-28 at -6ºC



(o)

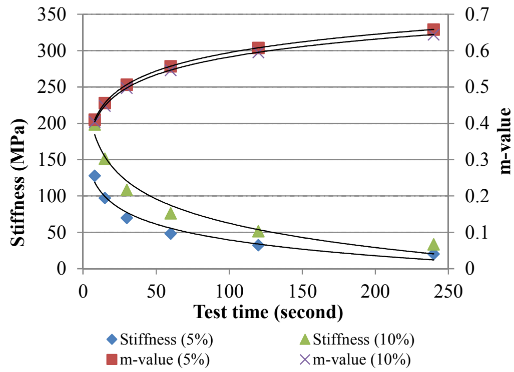


(b)



(c)

Figure 17-2: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 64-22 at -6°C



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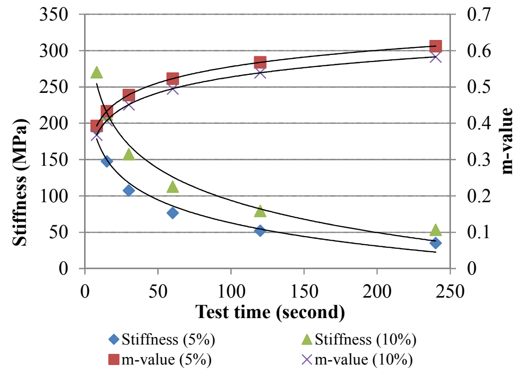

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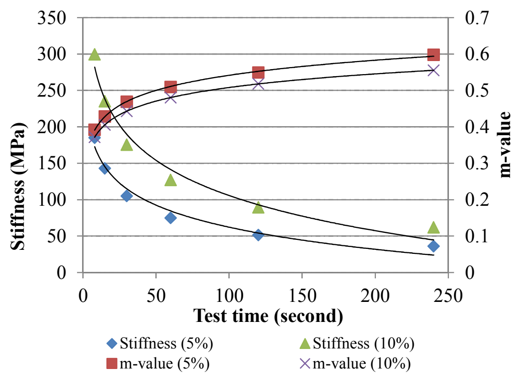


(c)

Figure 17-3: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 76-22 at -6ºC

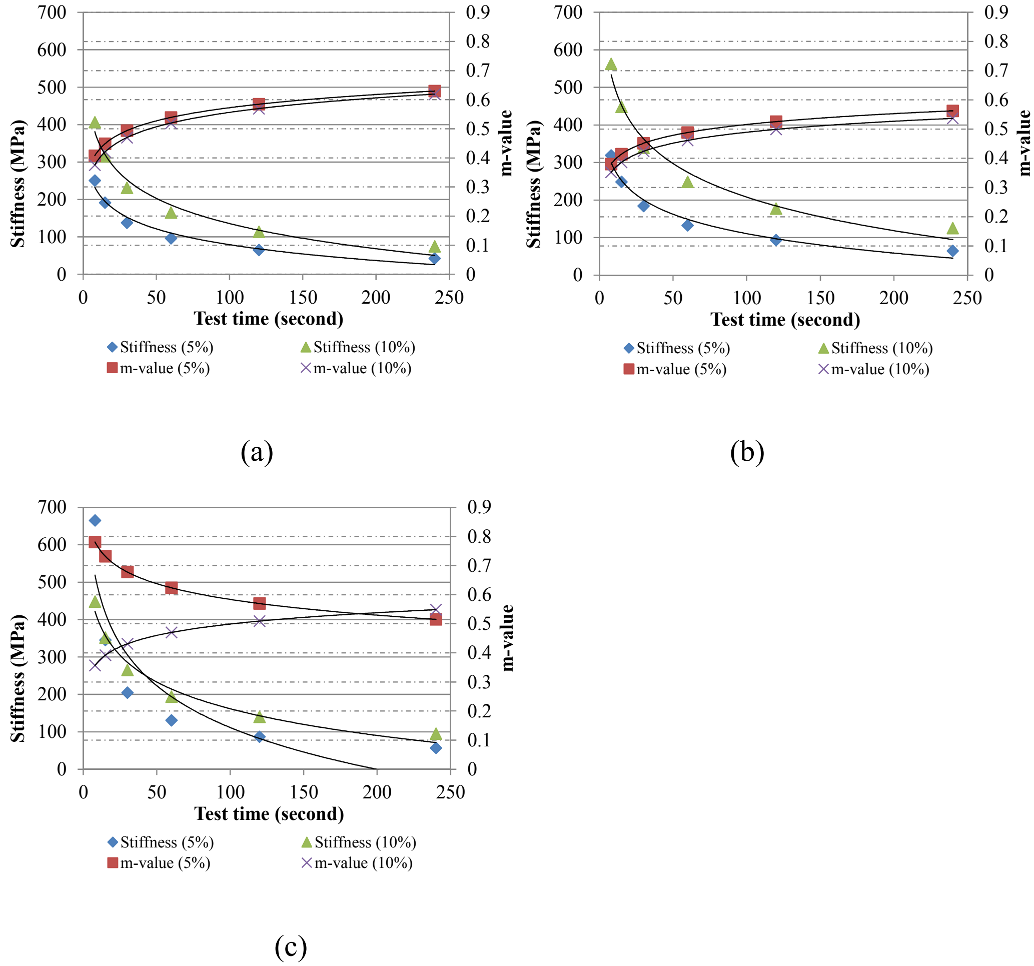
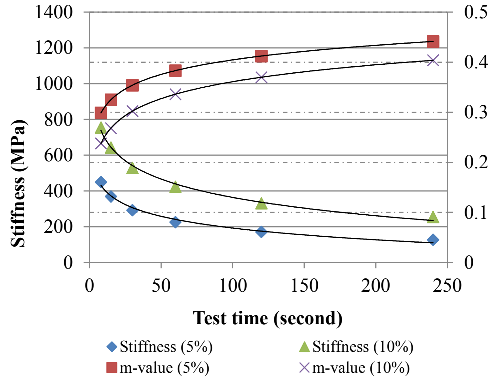
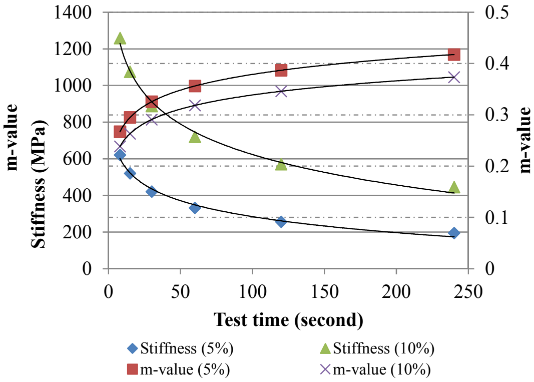


Figure 17-4: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 58-28 at -12ºC



(a)



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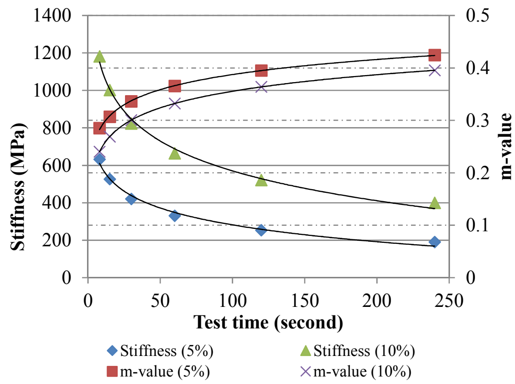
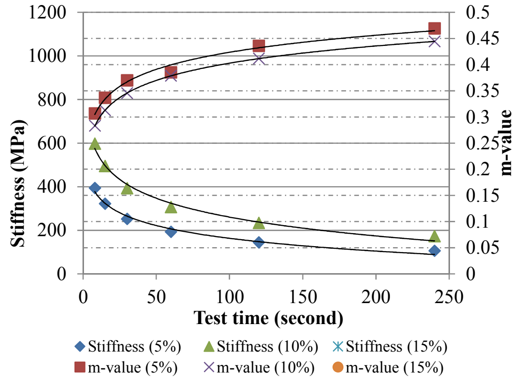
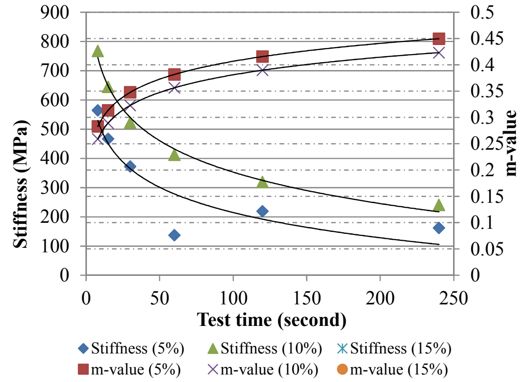


(c)

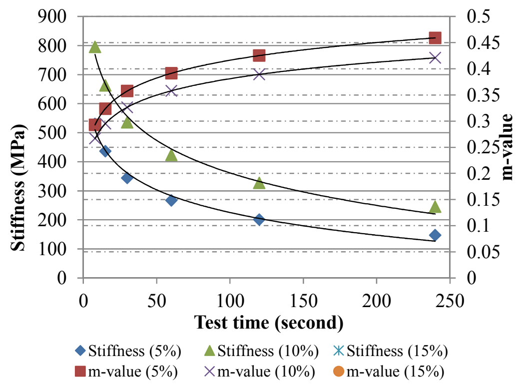
Figure 17-5: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 64-22 at -12ºC



(a)



(b)



(c)

Figure 17-6: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 76-22 at -12°C

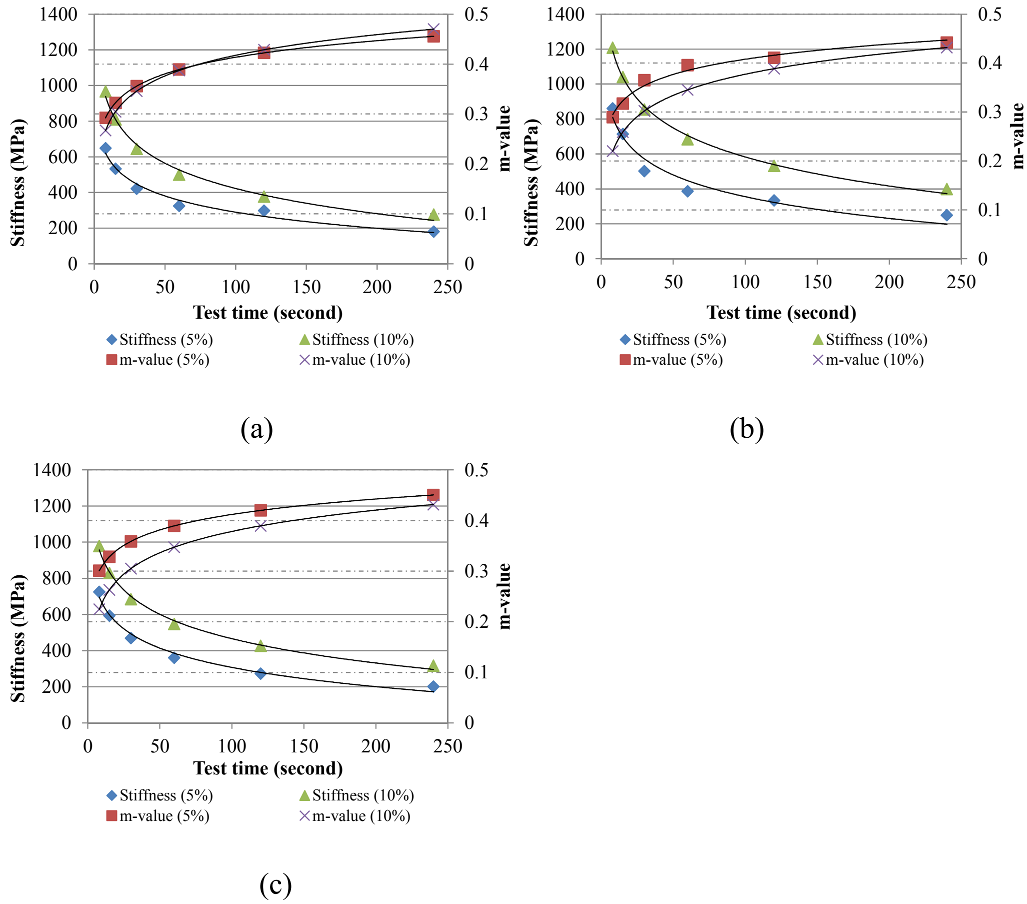
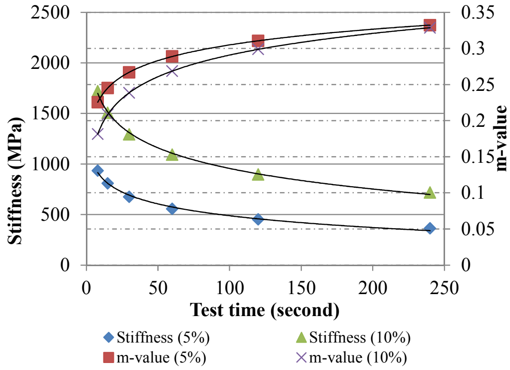
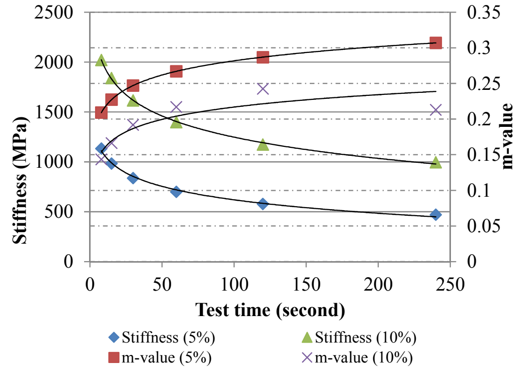


Figure 17-7: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 58-28 at -18ºC



(a)



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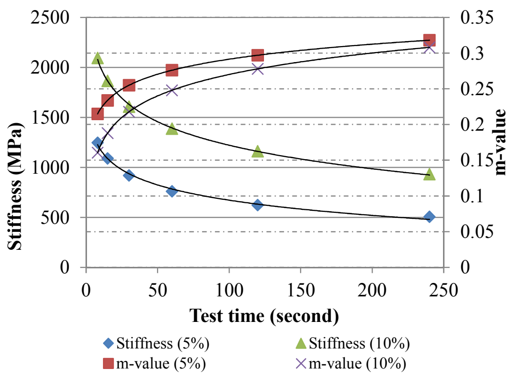
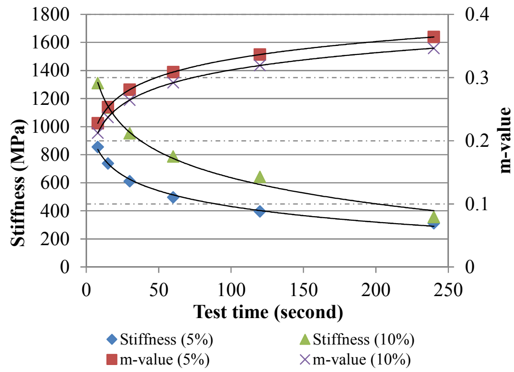
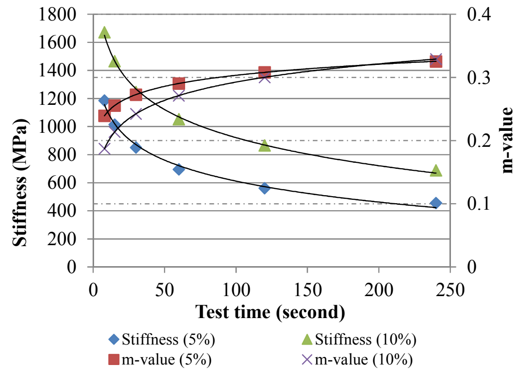


(c)

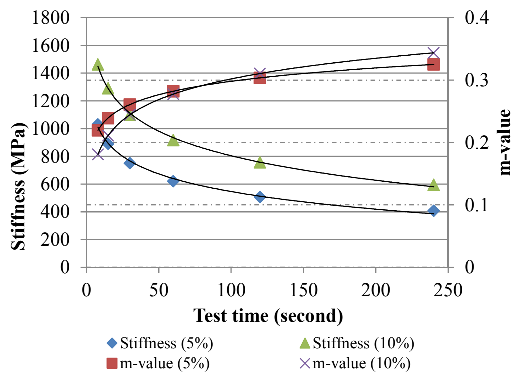
Figure 17-8: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 64-22 at -18ºC



(a)

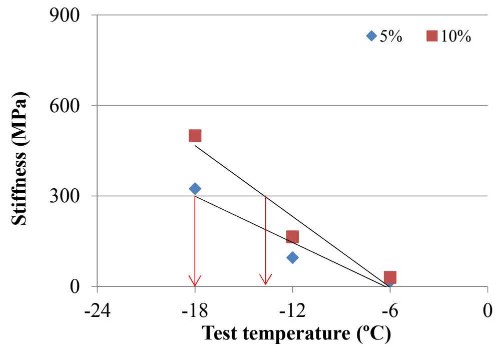


(b)

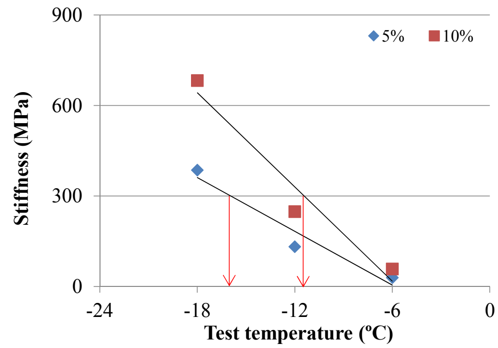


(c)

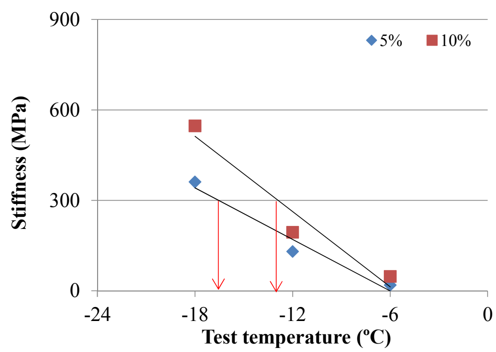
Figure 17-9: Stiffness and m-values of burned RAP sources C, D, and F modified with virgin binder PG 76-22 at -18^{o}C



(a)

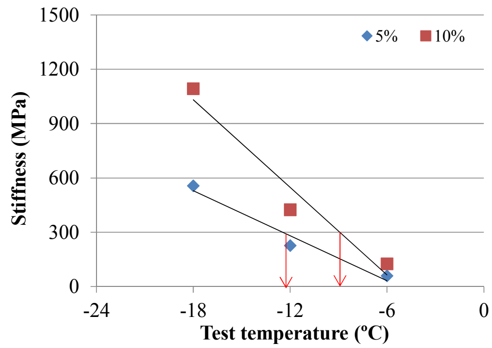


(b)

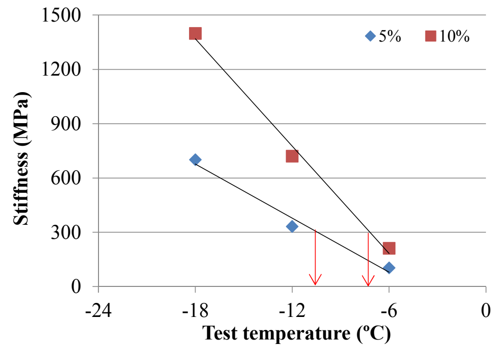


(c)

Figure 17-10: Low temperature determinations of burned RAP sources C, D, and F modified with virgin binder PG 58-28 in terms of stiffness



c.



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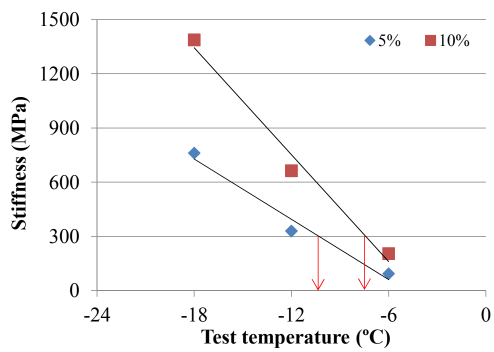
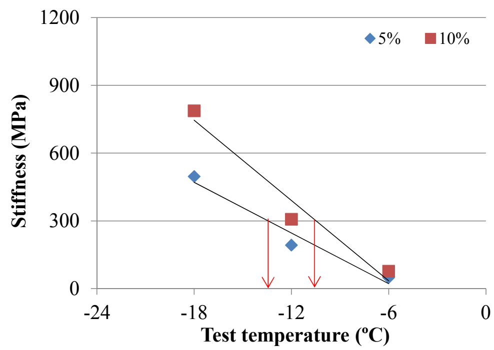
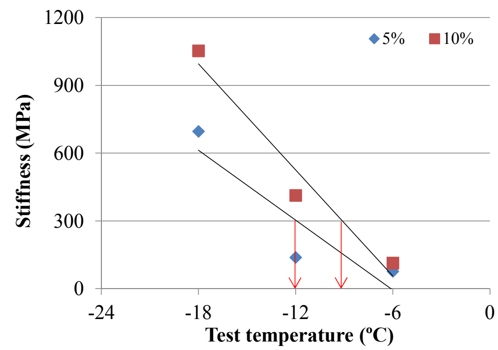


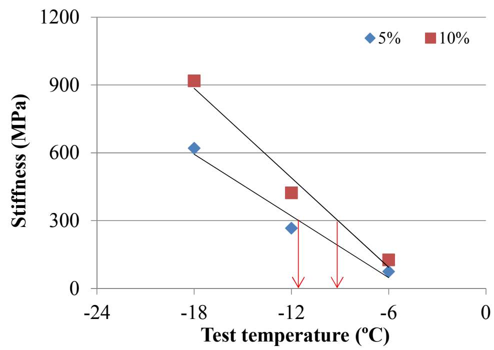
(c)

Figure 17-11: Low temperature determinations of burned RAP sources C, D, and F modified with virgin binder PG 64-22 in terms of stiffness



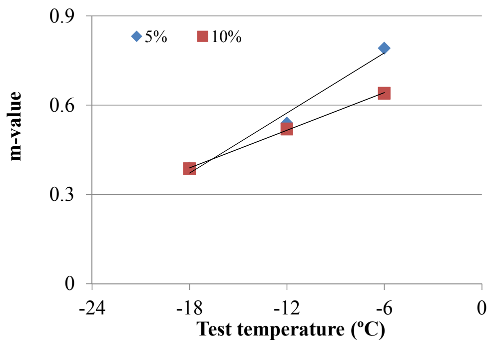


(c)   (b)



(c)

Figure 17-12: Low temperature determinations of burned RAP sources C, D, and F modified with virgin binder PG 76-22 in terms of stiffness



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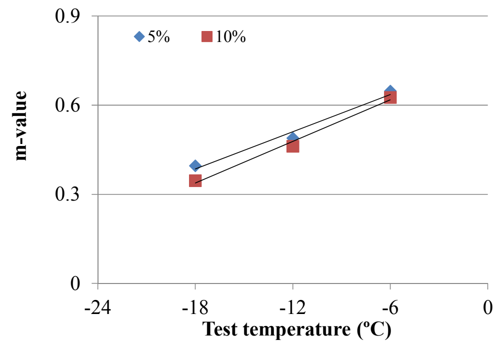

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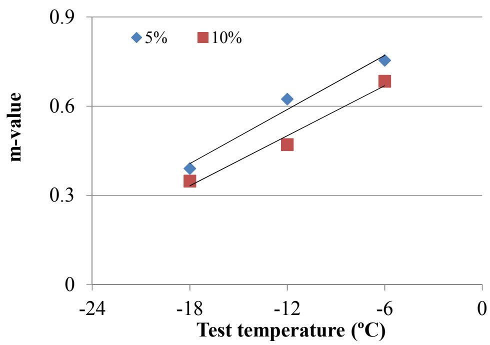
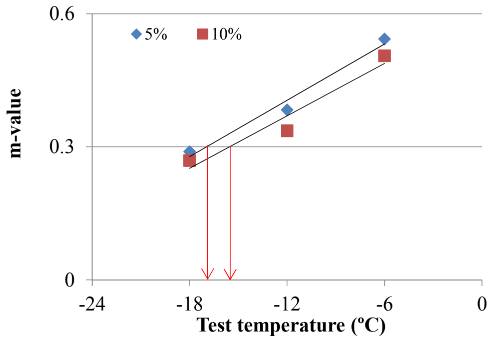


(c)

Figure 17-13: Low temperature determinations of burned RAP sources C, D, and F modified with virgin binder PG 58-28 in terms of m-value



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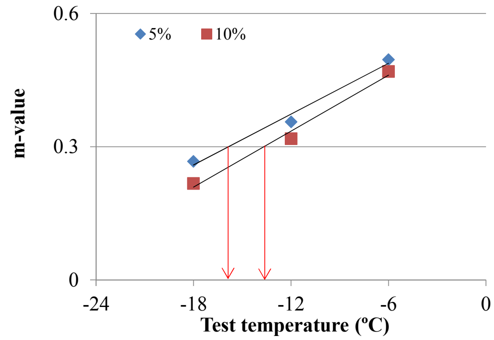

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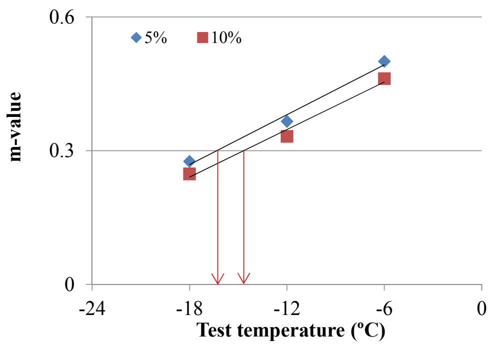
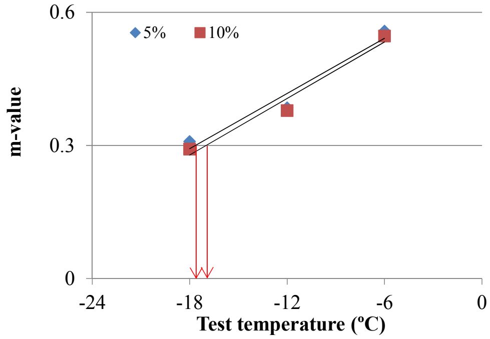
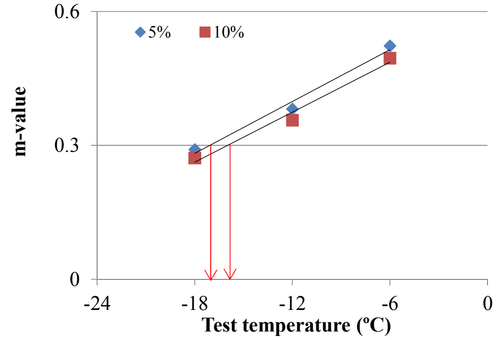


(c)

Figure 17-14: Low temperature determinations of burned RAP sources C, D, and F modified with virgin binder PG 64-22 in terms of m-value



(c)



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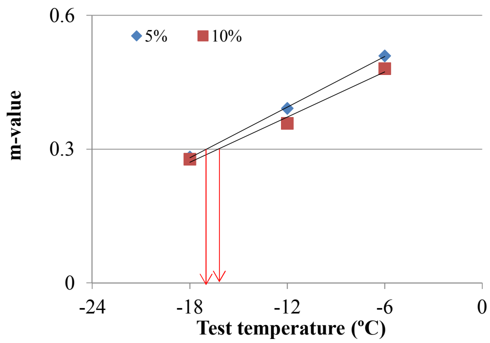


(c)

Figure 17-15: Low temperature determinations of burned RAP sources C, D, and F modified with virgin binder PG 76-22 in terms of m-value

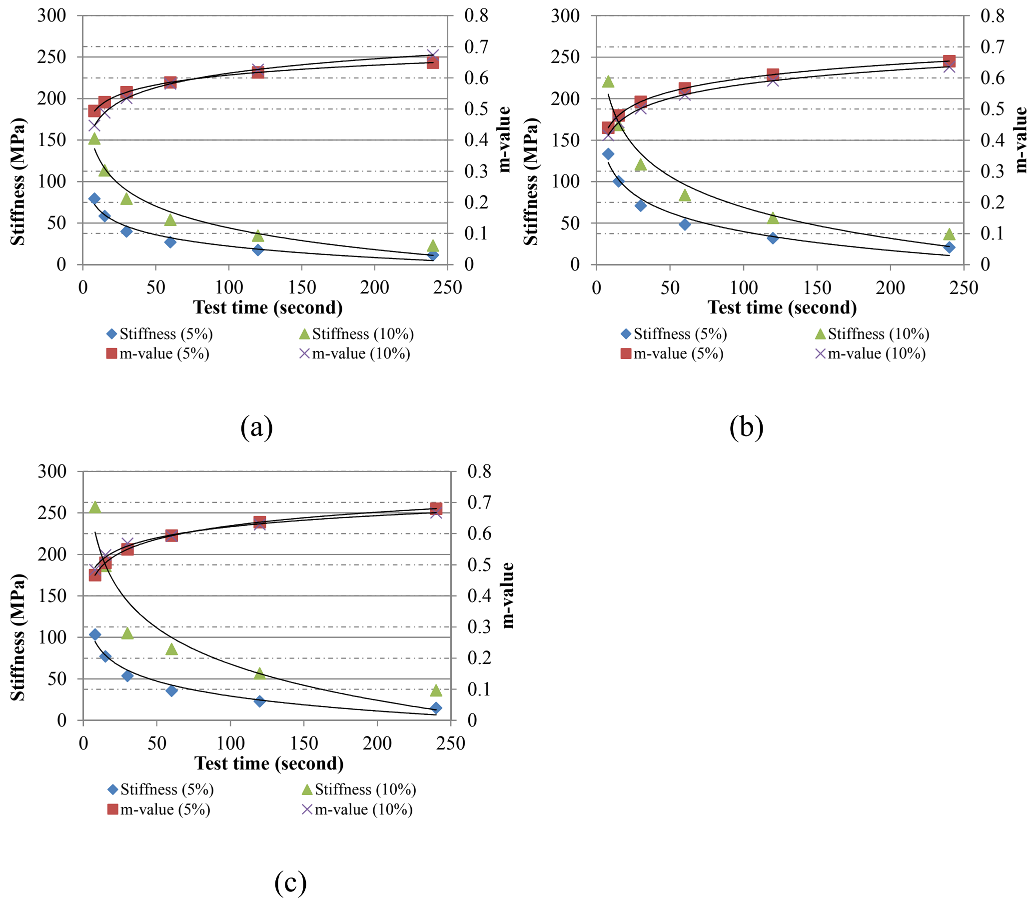
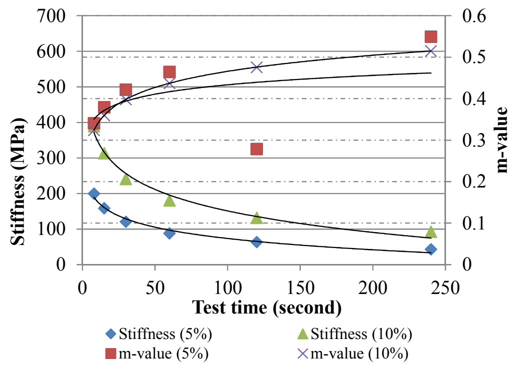
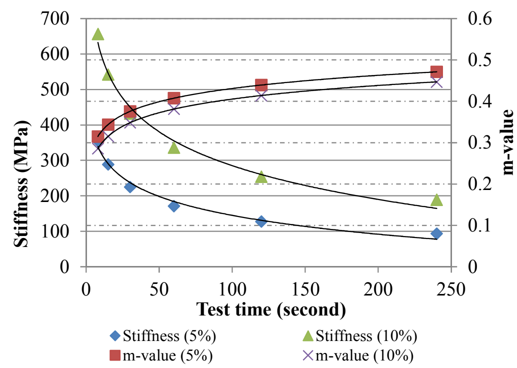


Figure 17-16: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 58-28 at -6°C



(a)



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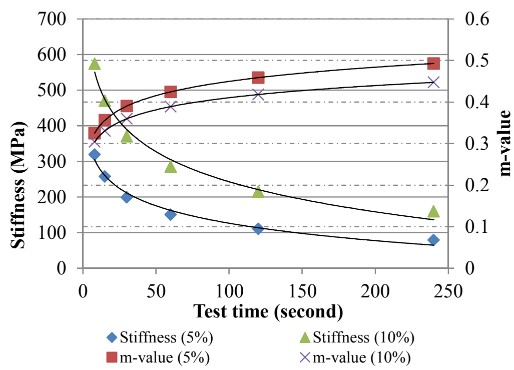
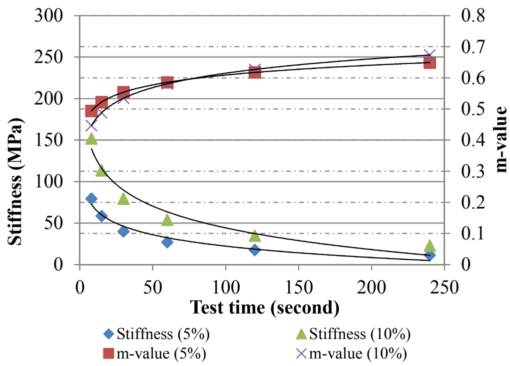
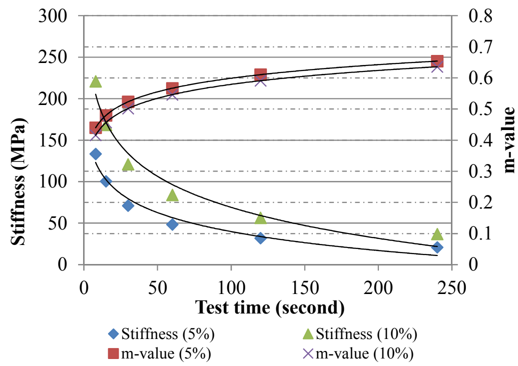


(c)

Figure 17-17: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 64-22 at -6°C



(a)



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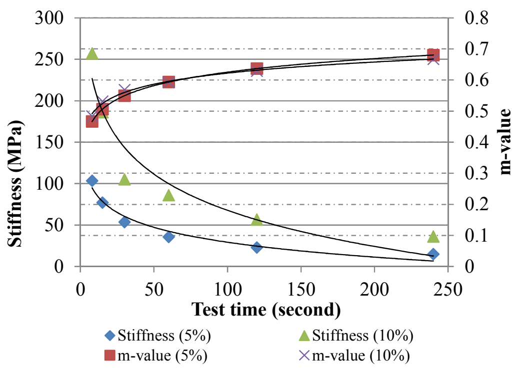
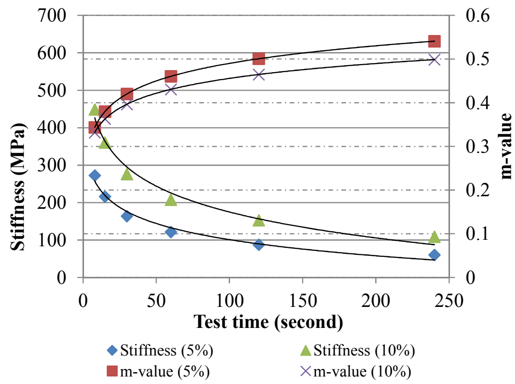
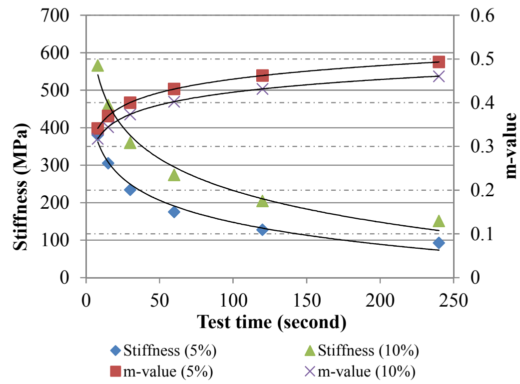


(c)

Figure 17-18: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 76-22 at -6°C



(a)



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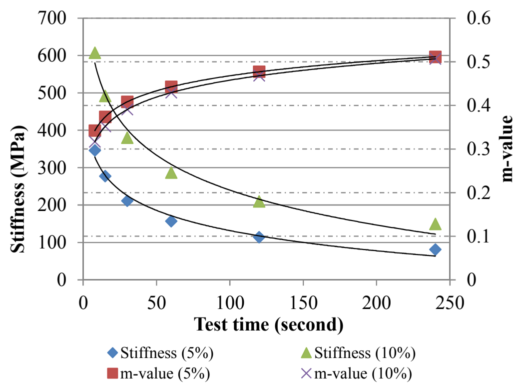
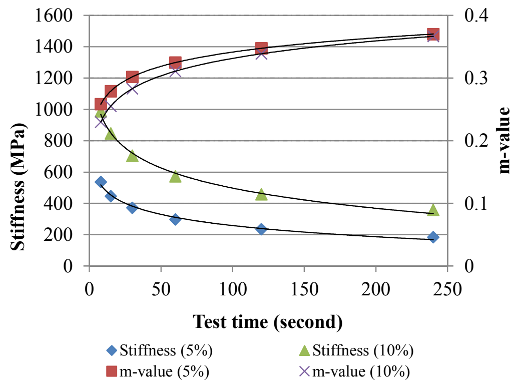
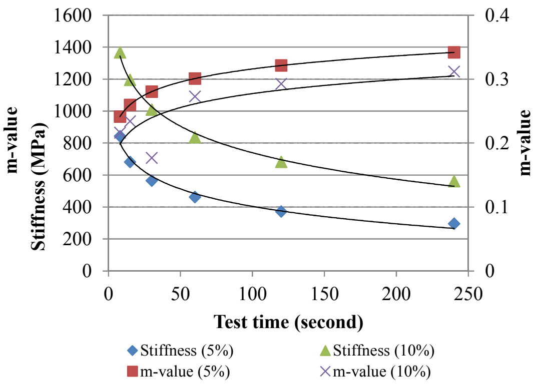


(c)

Figure 17-19: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 58-28 at -12ºC



(a)



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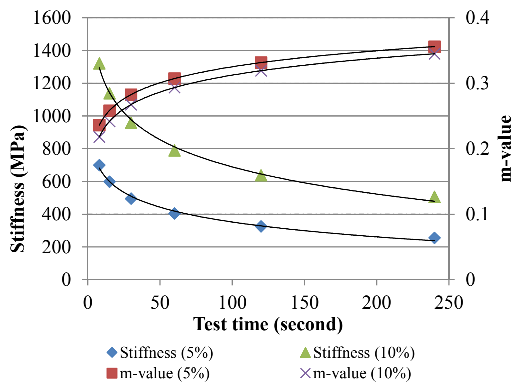
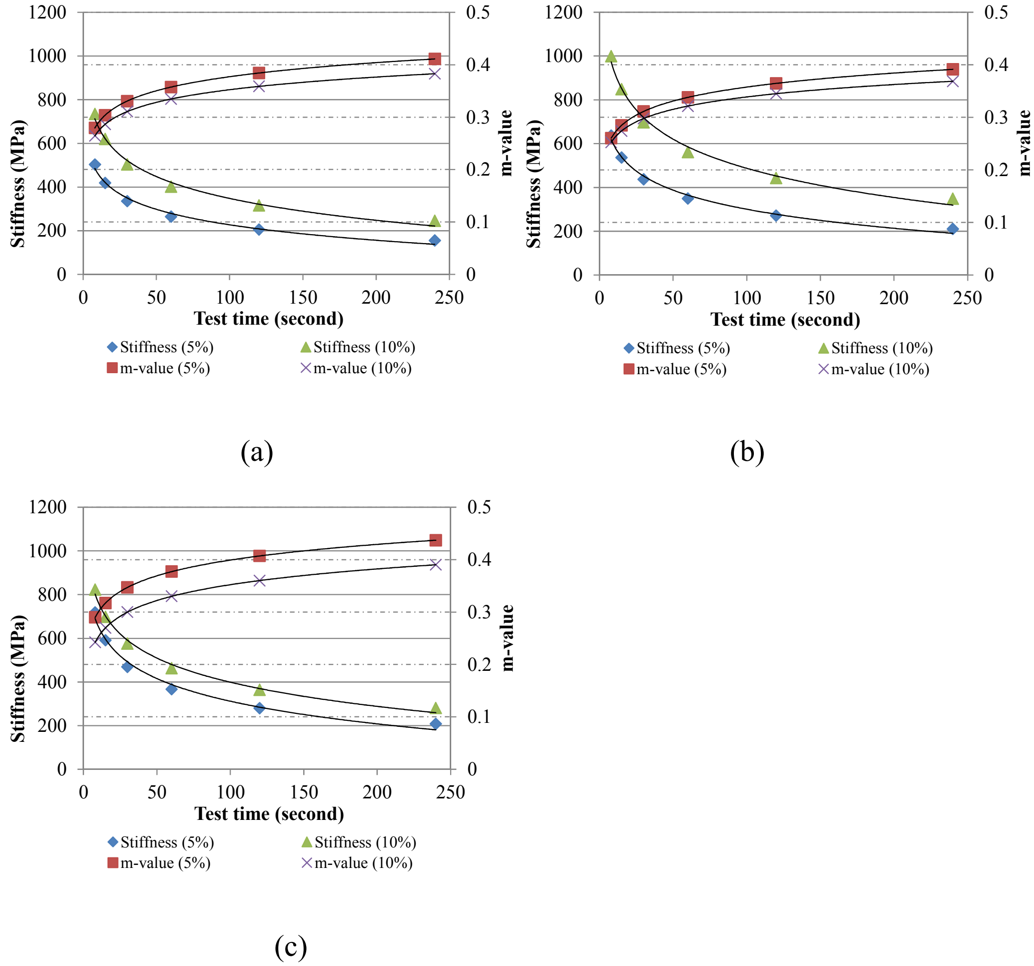


(c)

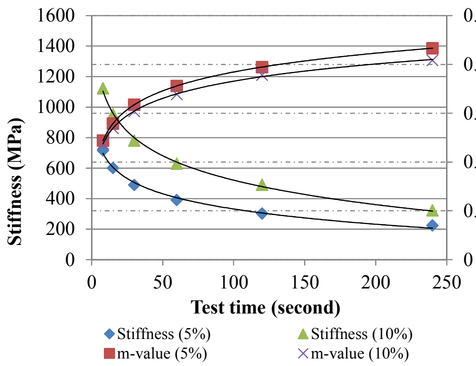
Figure 17-20: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 64-22 at -12ºC



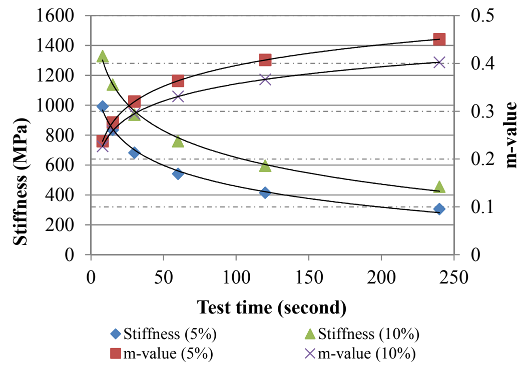
(a) (b)

(c)

Figure 17-21: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 76-22 at -12ºC



(a)



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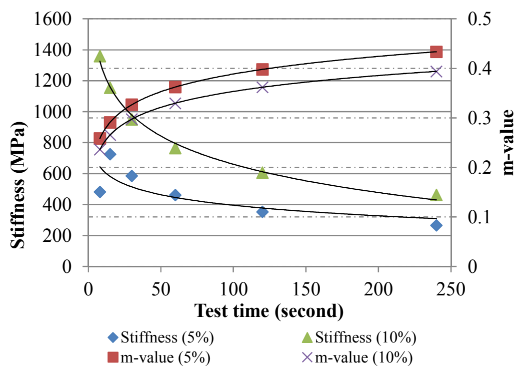
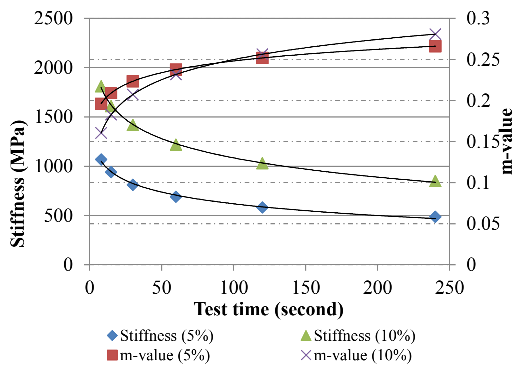
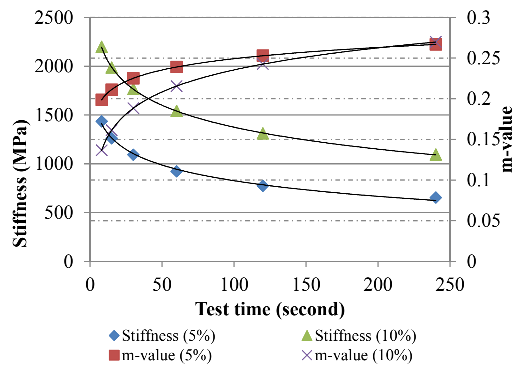


(c)

Figure 17-22: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 58-28 at -18ºC



(a)



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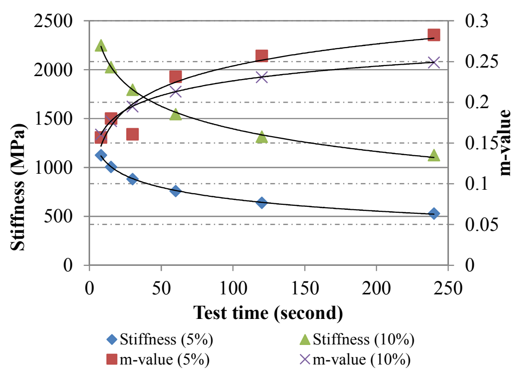


(c)

Figure 17-23: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 64-22 at -18°C

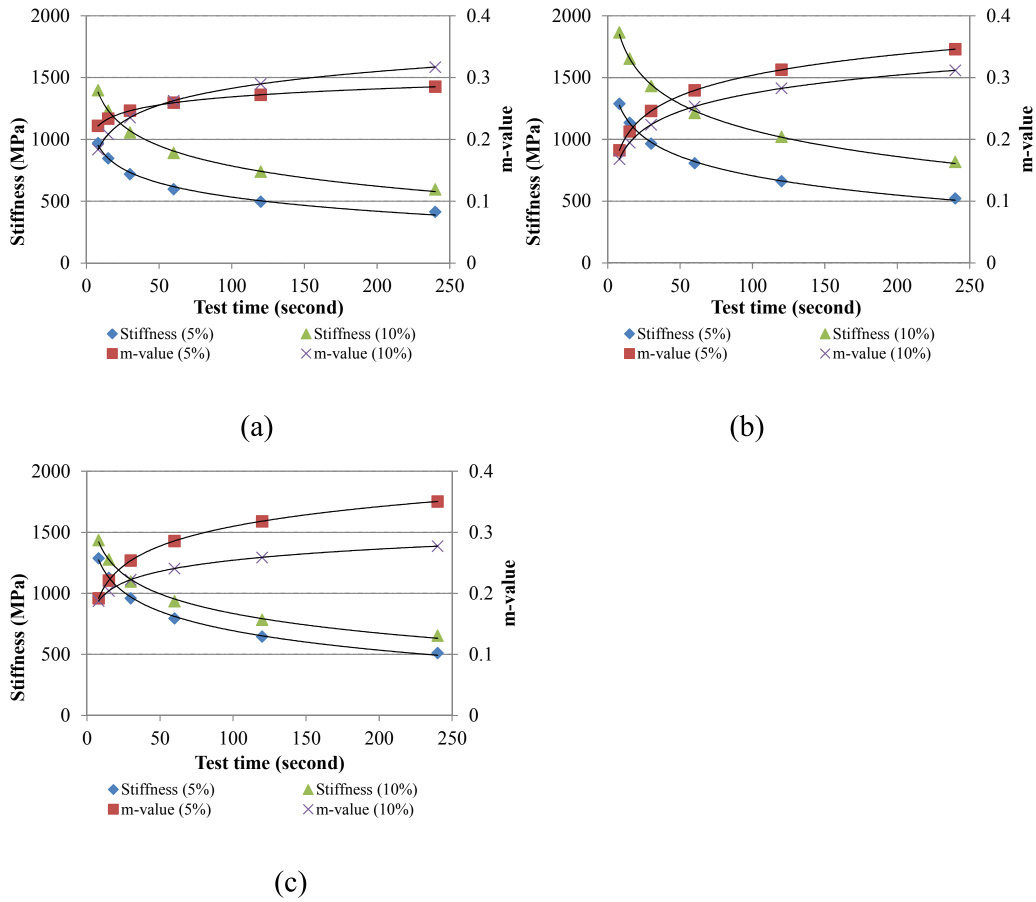
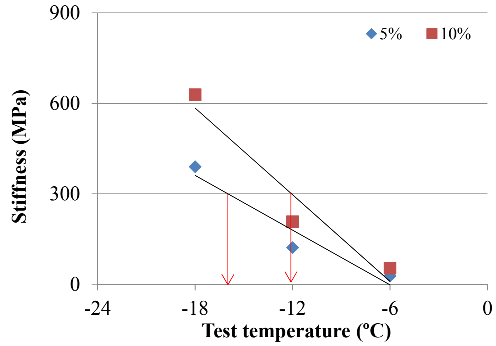
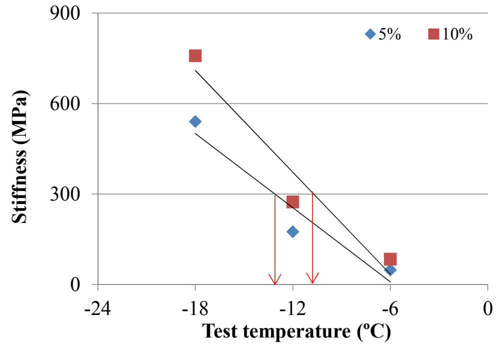


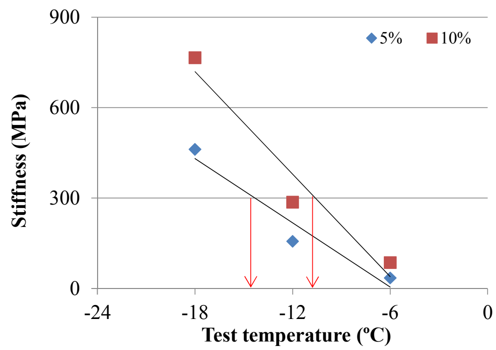
Figure 17-24: Stiffness and m-values of burned RAP sources C, D, and F modified with RTFO binder PG 76-22 at -18ºC



(a)



(b)



(c)

Figure 17-25: Low temperature determinations of burned RAP sources C, D, and F modified with RTFO binder PG 58-28 in terms of stiffness

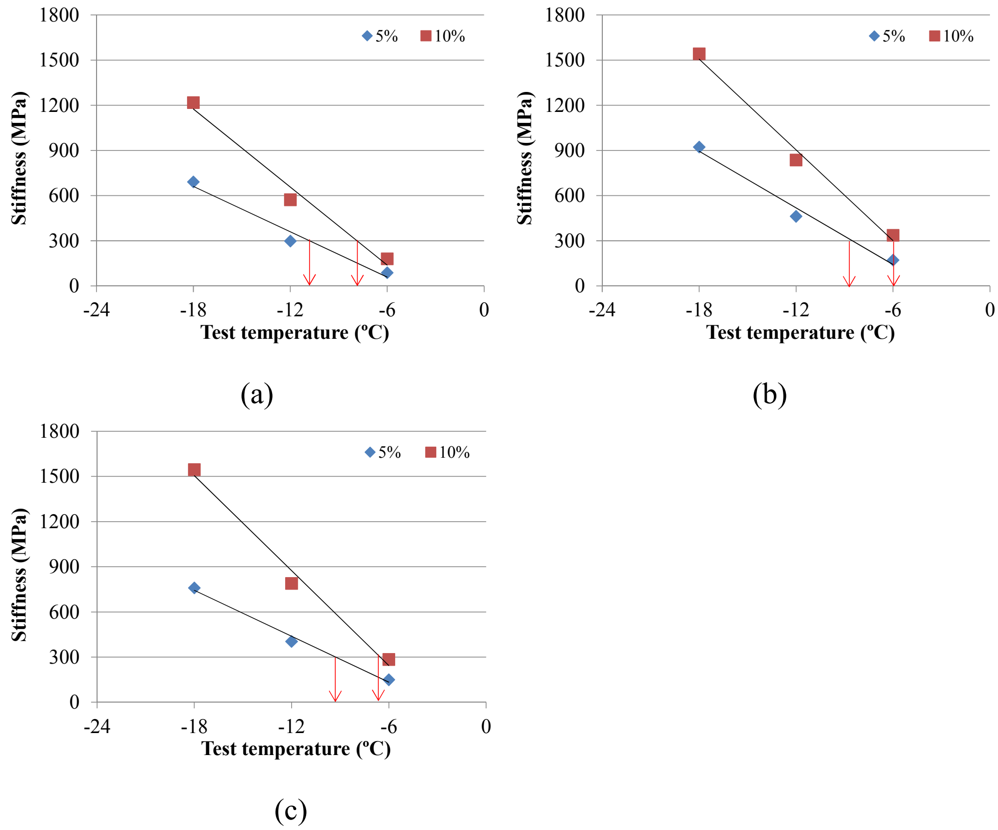


Figure 17-26: Low temperature determinations of burned RAP sources C, D, and F modified with RTFO binder PG 64-22 in terms of stiffness

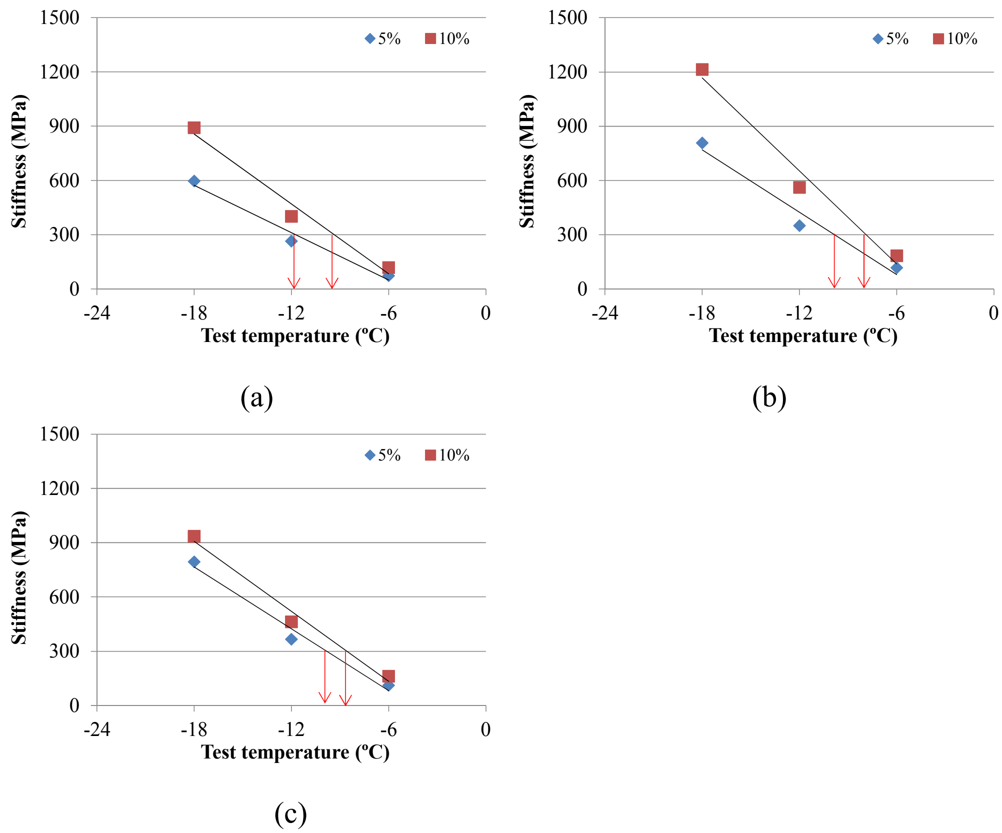
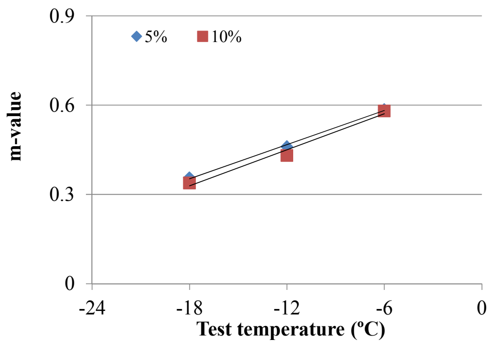
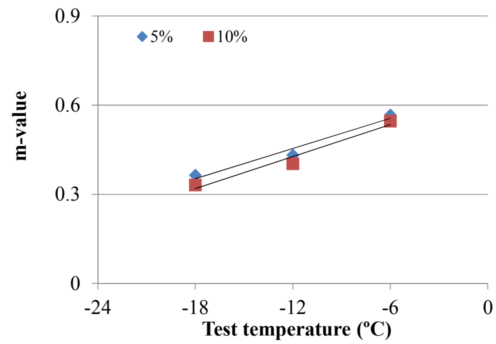


Figure 17-27: Low temperature determinations of burned RAP sources C, D, and F modified with RTFO binder PG 76-22 in terms of stiffness



(a)



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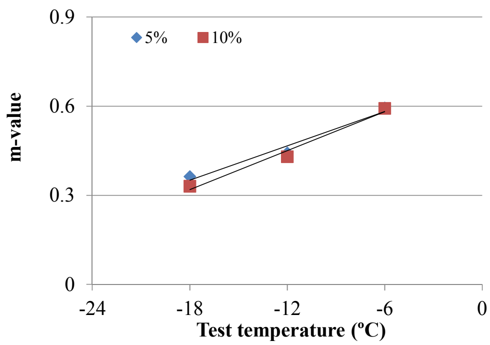


(c)

Figure 17-28: Low temperature determinations of burned RAP sources C, D, and F modified with RTFO binder PG 58-28 in terms of m-value

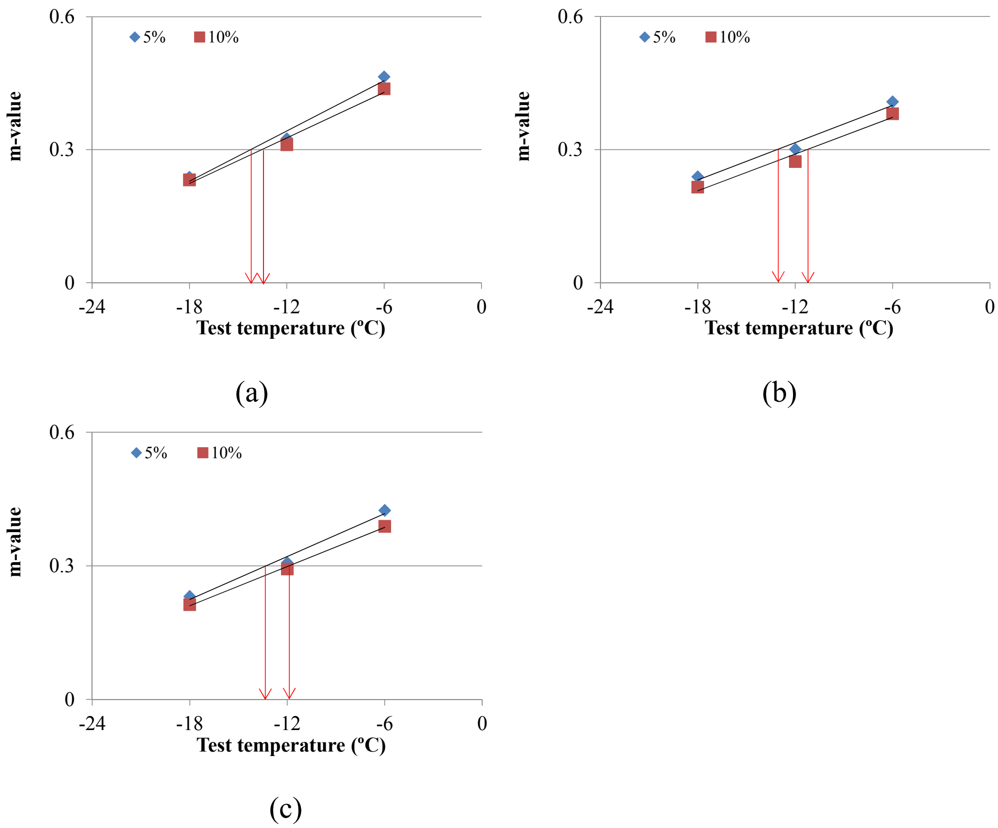
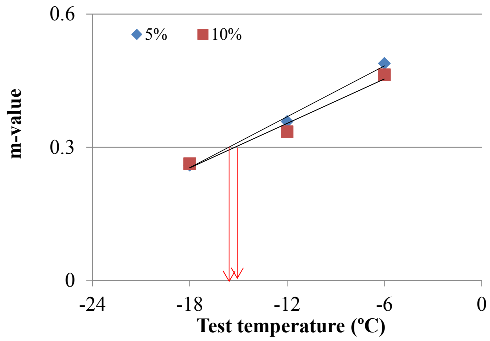
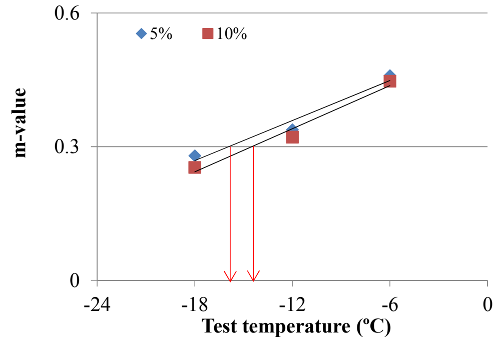


Figure 17-29: Low temperature determinations of burned RAP sources C, D, and F modified with RTFO binder PG 64-22 in terms of m-value



(a)



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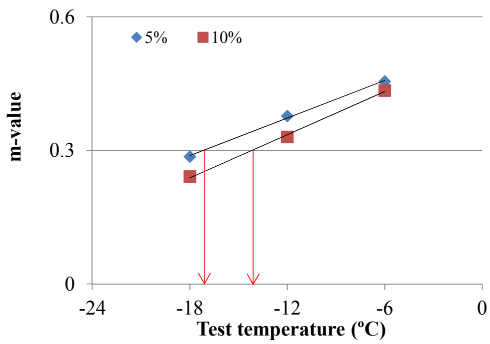
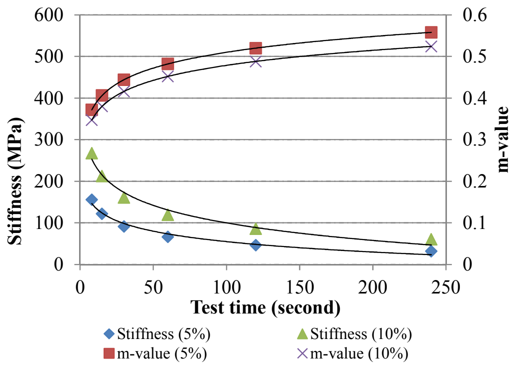
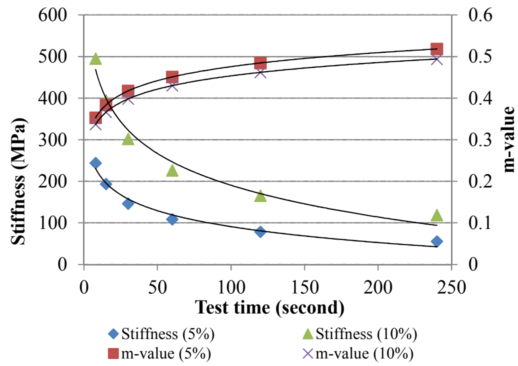


(c)

Figure 17-30: Low temperature determinations of burned RAP sources C, D, and F modified with RTFO binder PG 76-22 in terms of m-value



(a)



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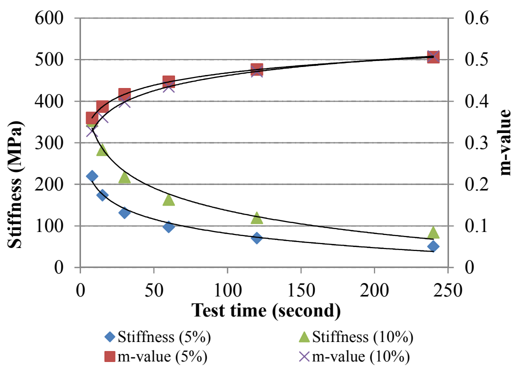


(c)

Figure 17-31: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 58-28 at -6ºC

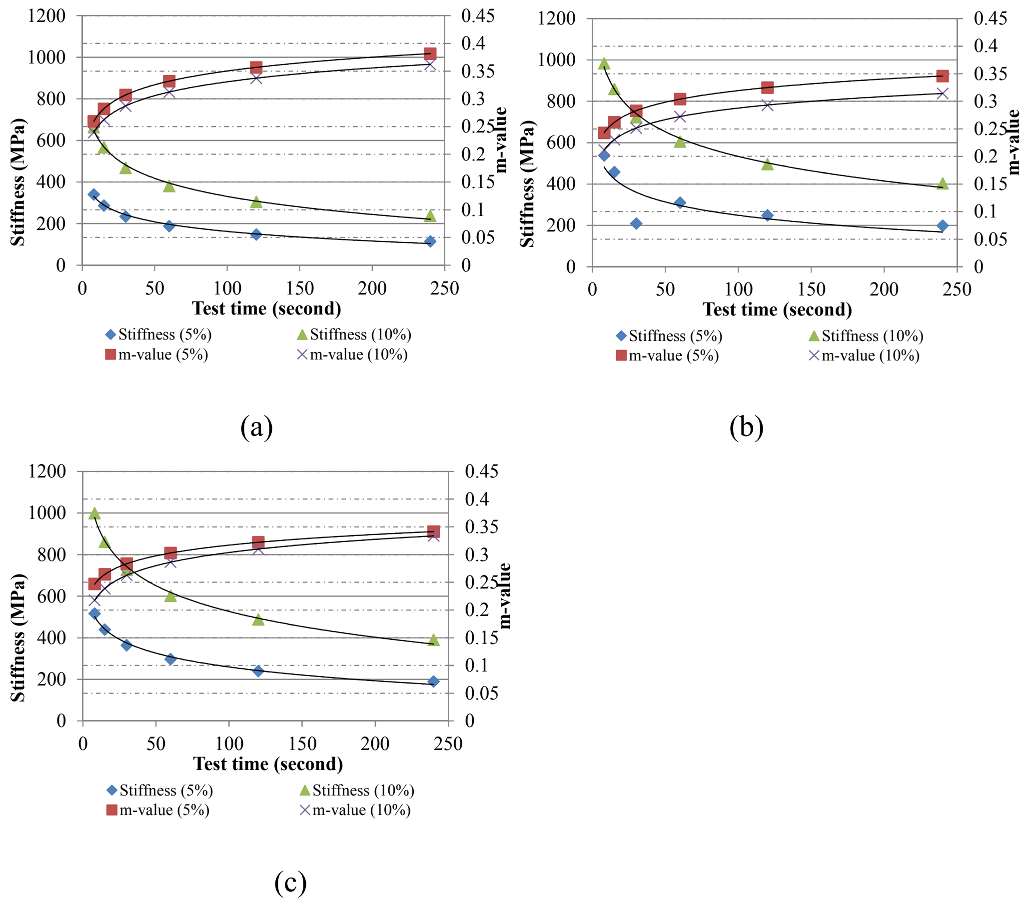
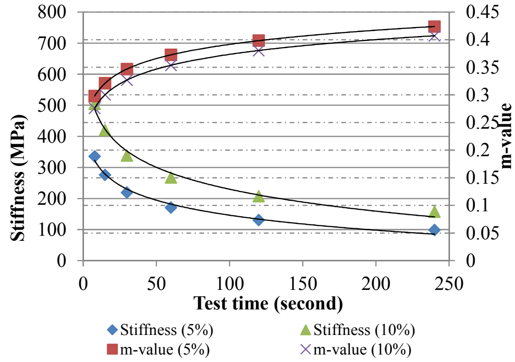
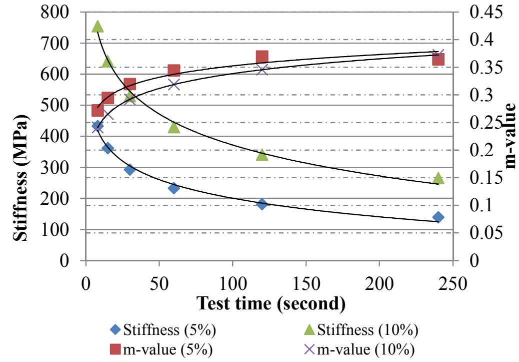


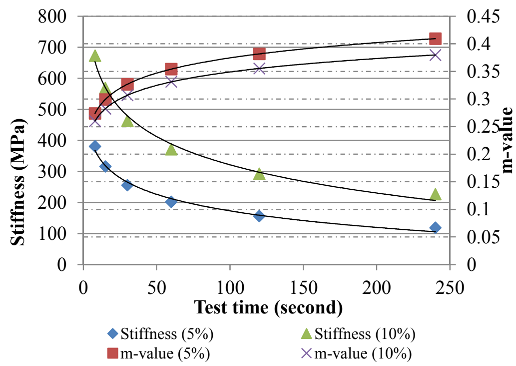
Figure 17-32: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 64-22 at -6ºC



(a)

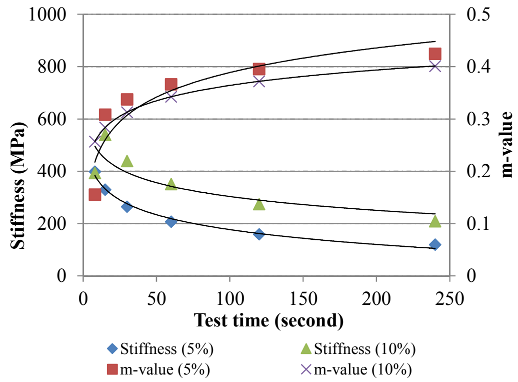


(b)

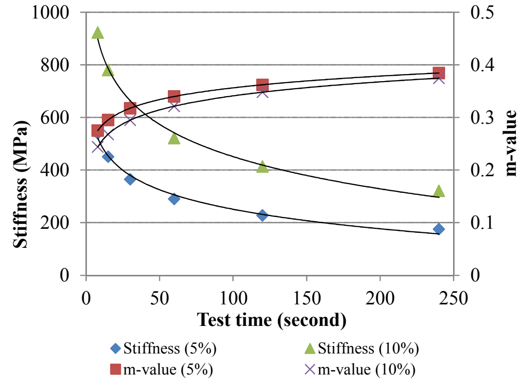


(c)

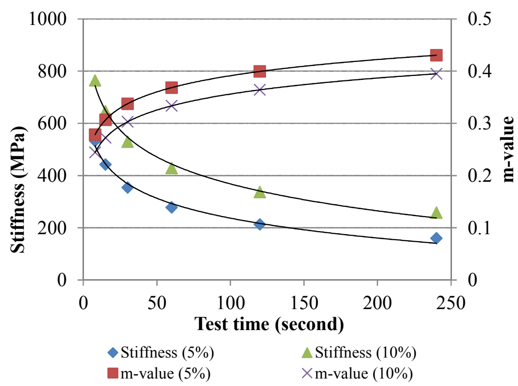
Figure 17-33: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 76-22 at -6°C



(a)



(b)



(c)

Figure 17-34: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 58-28 at -12ºC

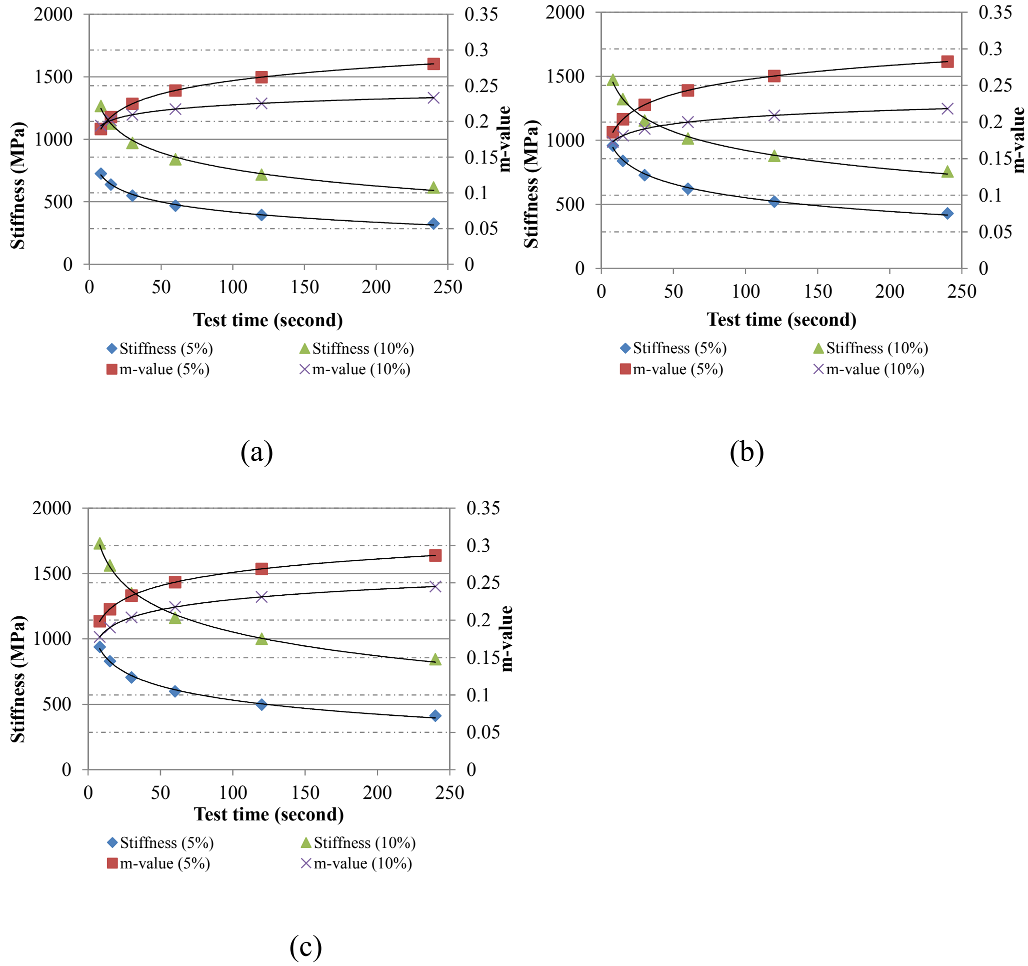
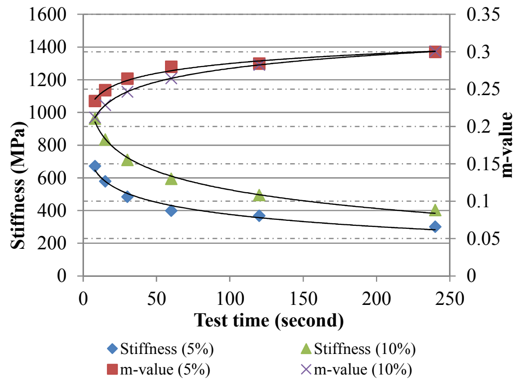
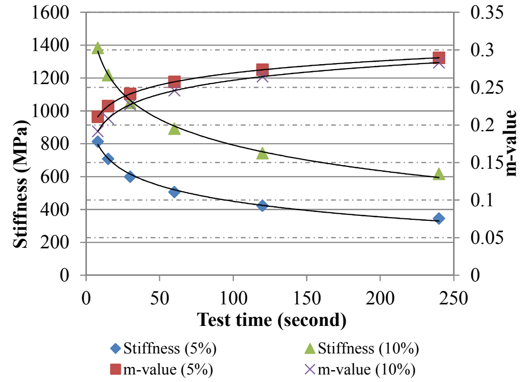


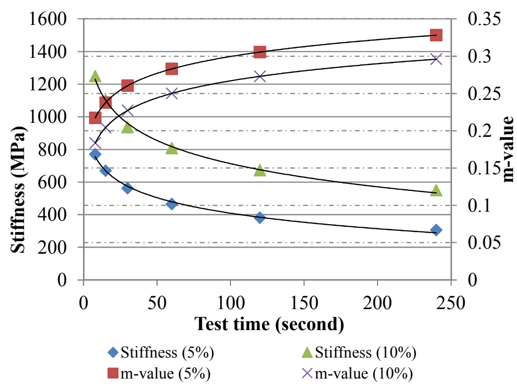
Figure 17-35: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 64-22 at -12ºC



(a)

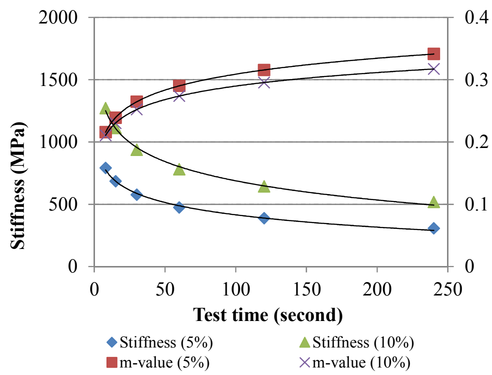


(b)

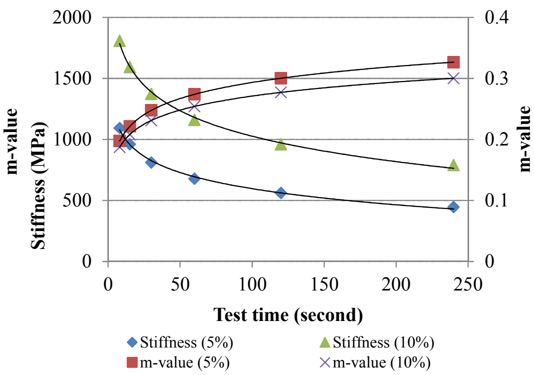


(c)

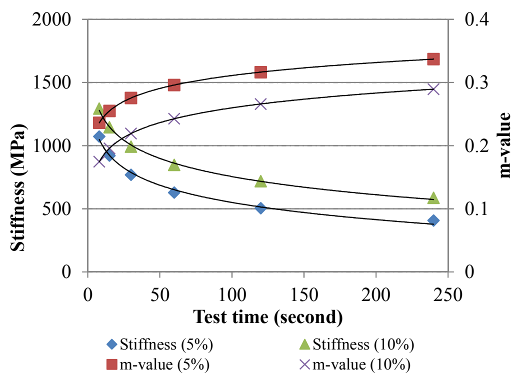
Figure 17-36: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 76-22 at -12ºC



(a)

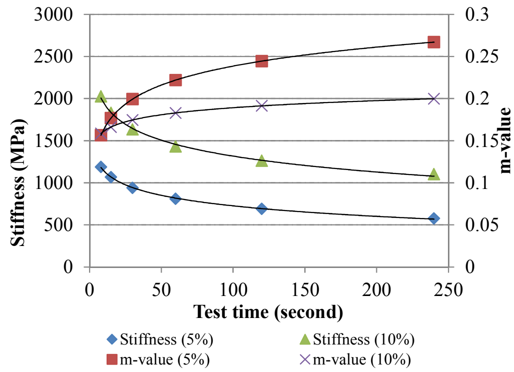


(b)

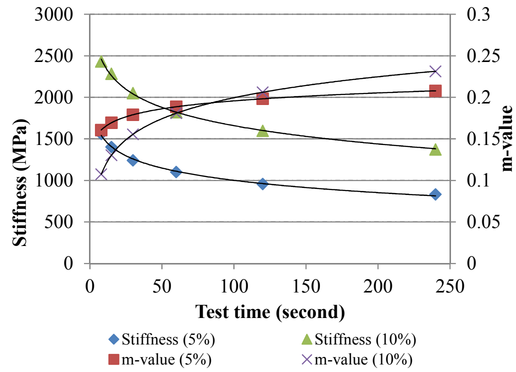


(c)

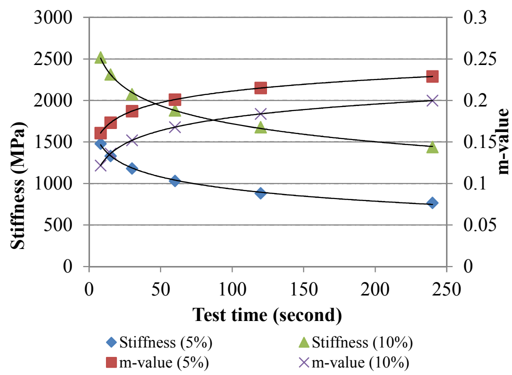
Figure 17-37: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 58-28 at -18ºC



(a)

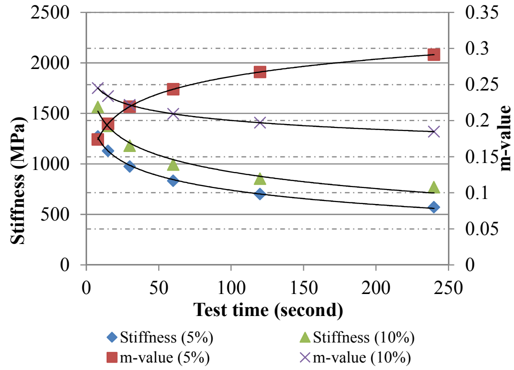


(b)

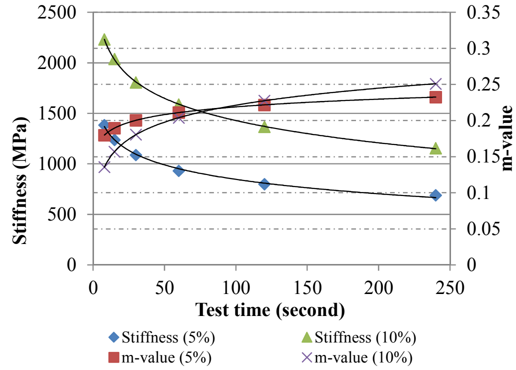


(c)

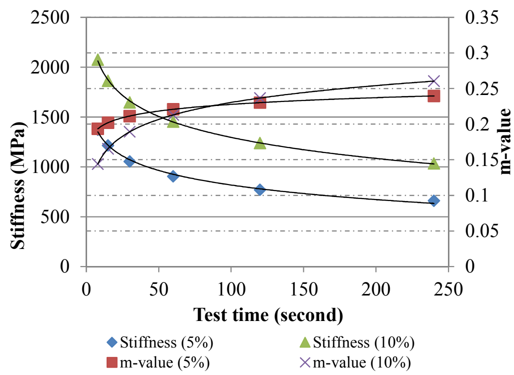
Figure 17-38: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 64-22 at -18ºC



(a)

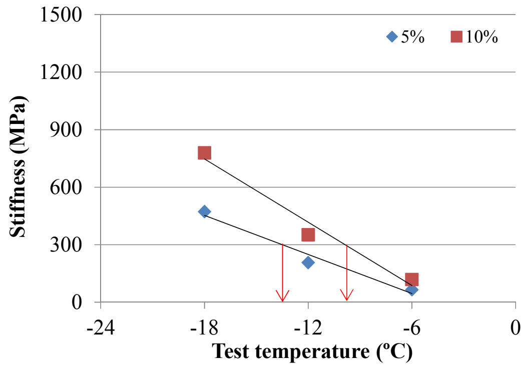


(b)

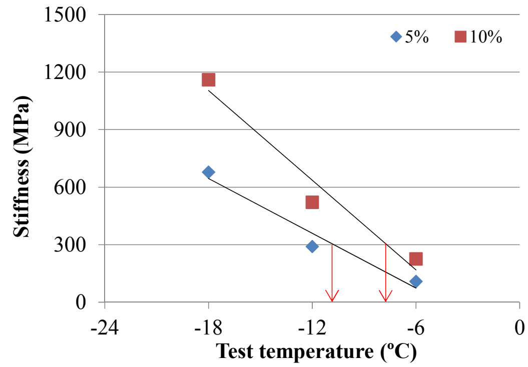


(c)

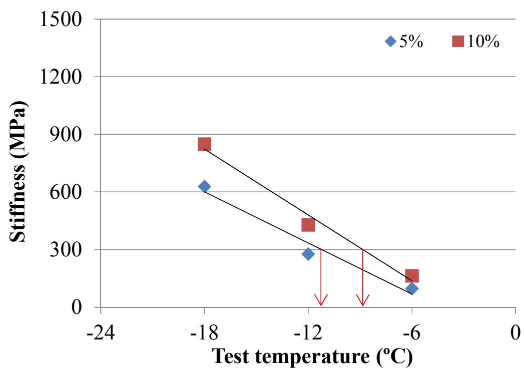
Figure 17-39: Stiffness and m-values of burned RAP sources C, D, and F modified with PAV binder PG 76-22 at -18ºC



(a)

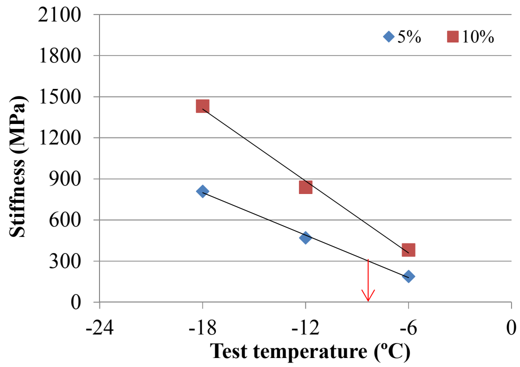


(b)

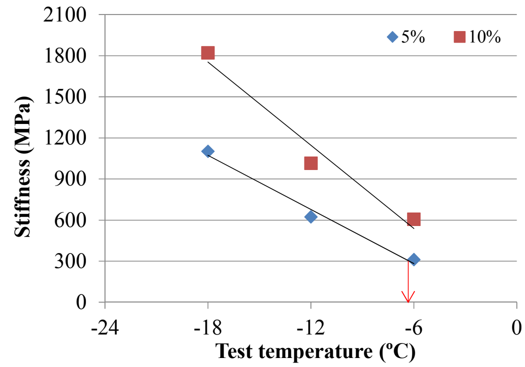


(c)

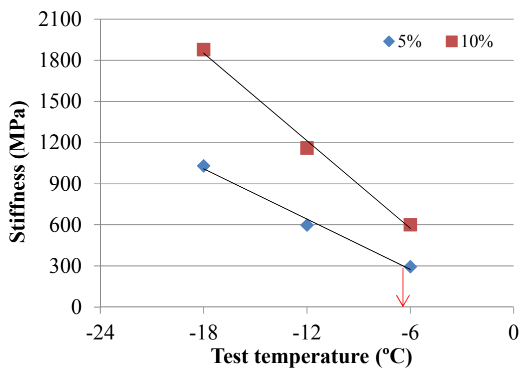
Figure 17-40: Low temperature determinations of burned RAP sources C, D, and F modified with PAV binder PG 58-28 in terms of stiffness



(a)

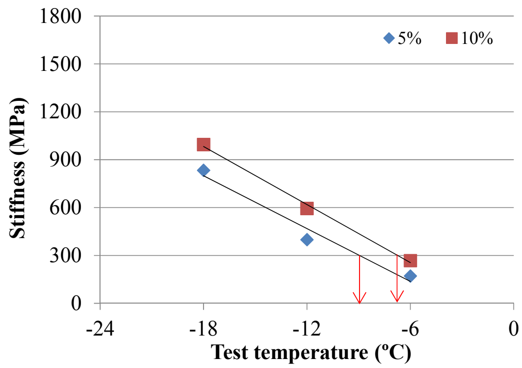


(b)

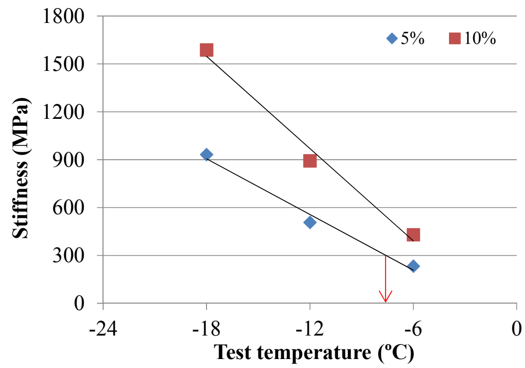


(c)

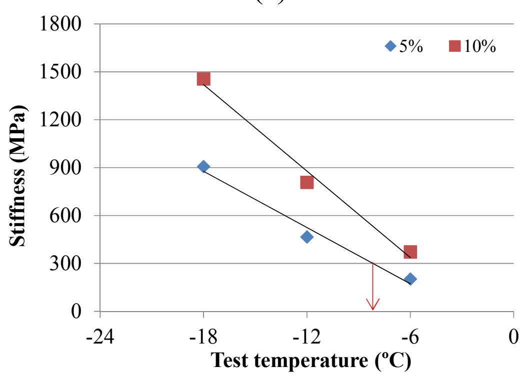
Figure 17-41: Low temperature determinations of burned RAP sources C, D, and F modified with PAV binder PG 64-22 in terms of stiffness



(a)

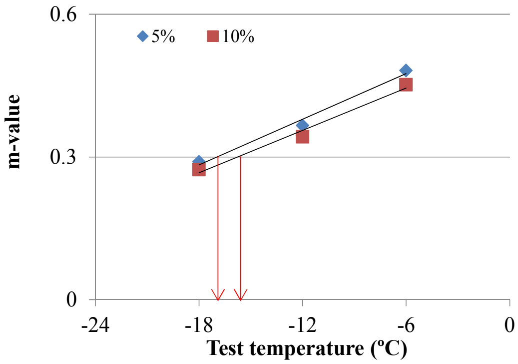


(b)

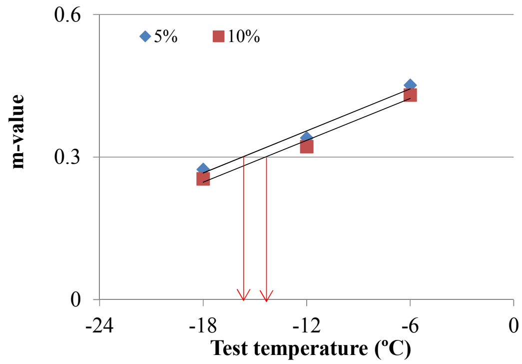


(c)

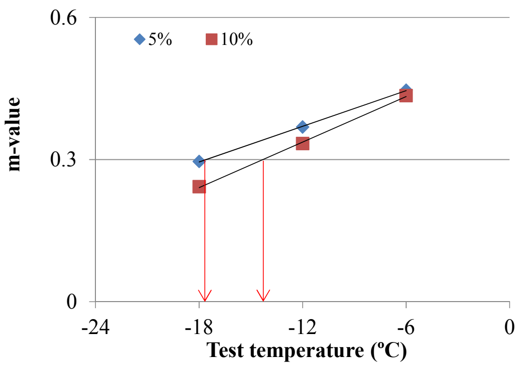
Figure 17-42: Low temperature determinations of burned RAP sources C, D, and F modified with PAV binder PG 76-22 in terms of stiffness



(a)

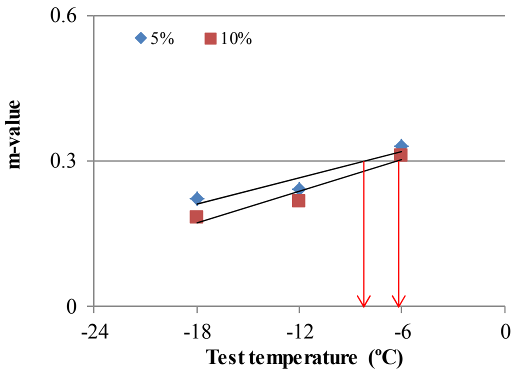


(b)

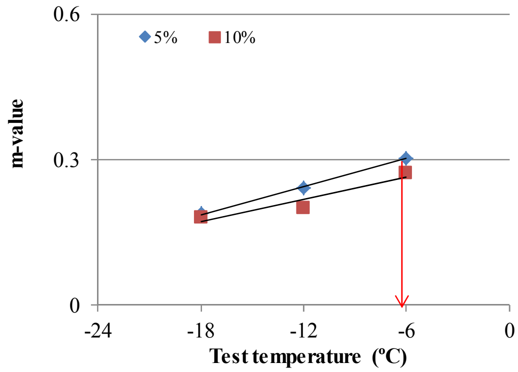


(c)

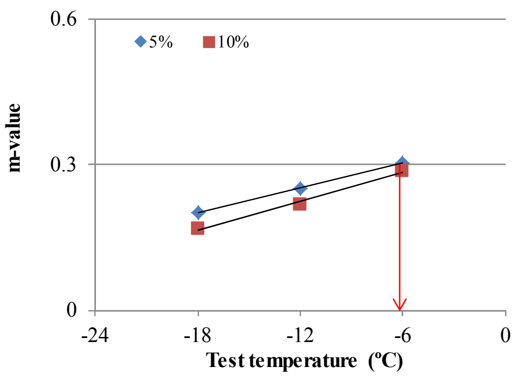
Figure 17-43: Low temperature determinations of burned RAP sources C, D, and F modified with PAV binder PG 58-28 in terms of m-value



(a)

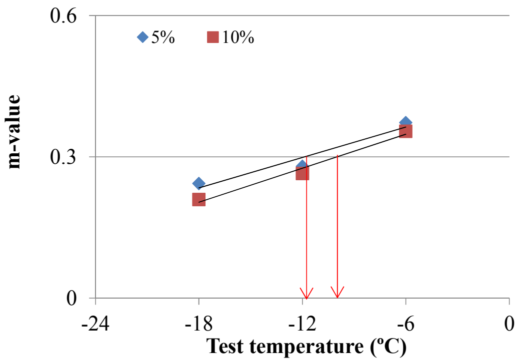


(b)

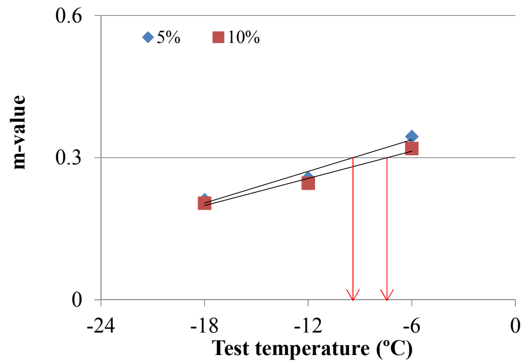


(c)

Figure 17-44: Low temperature determinations of burned RAP sources C, D, and F modified with PAV binder PG 64-22 in terms of m-value



(a)



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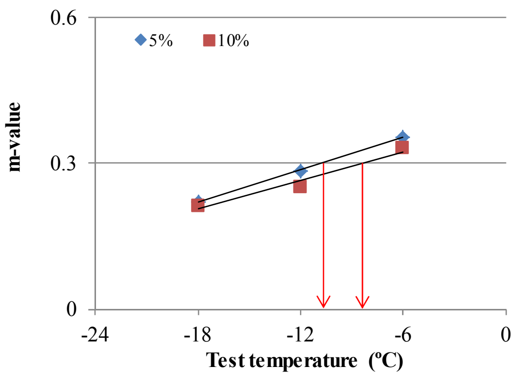


(c)

Figure 17-45: Low temperature determinations of burned RAP sources C, D, and F modified with PAV binder PG 76-22 in terms of m-value

18 Appendix I

BBR Data: Extracted RAP Binders + Various Binder @ -12 °C and -18 °C

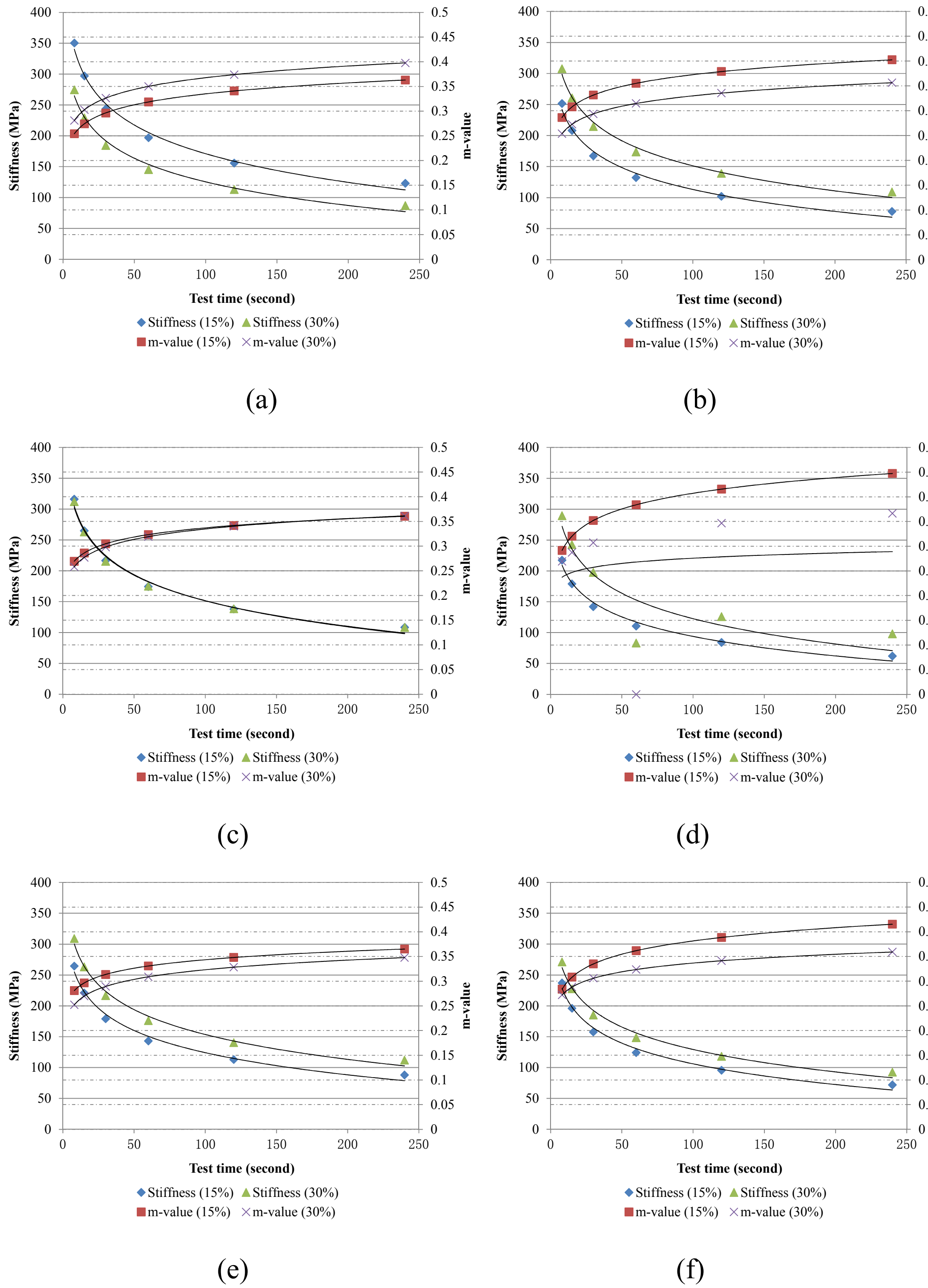


Figure 18-1: Stiffness and m-values of extracted aged binders A-F modified with binder PG 58-28 at -12ºC

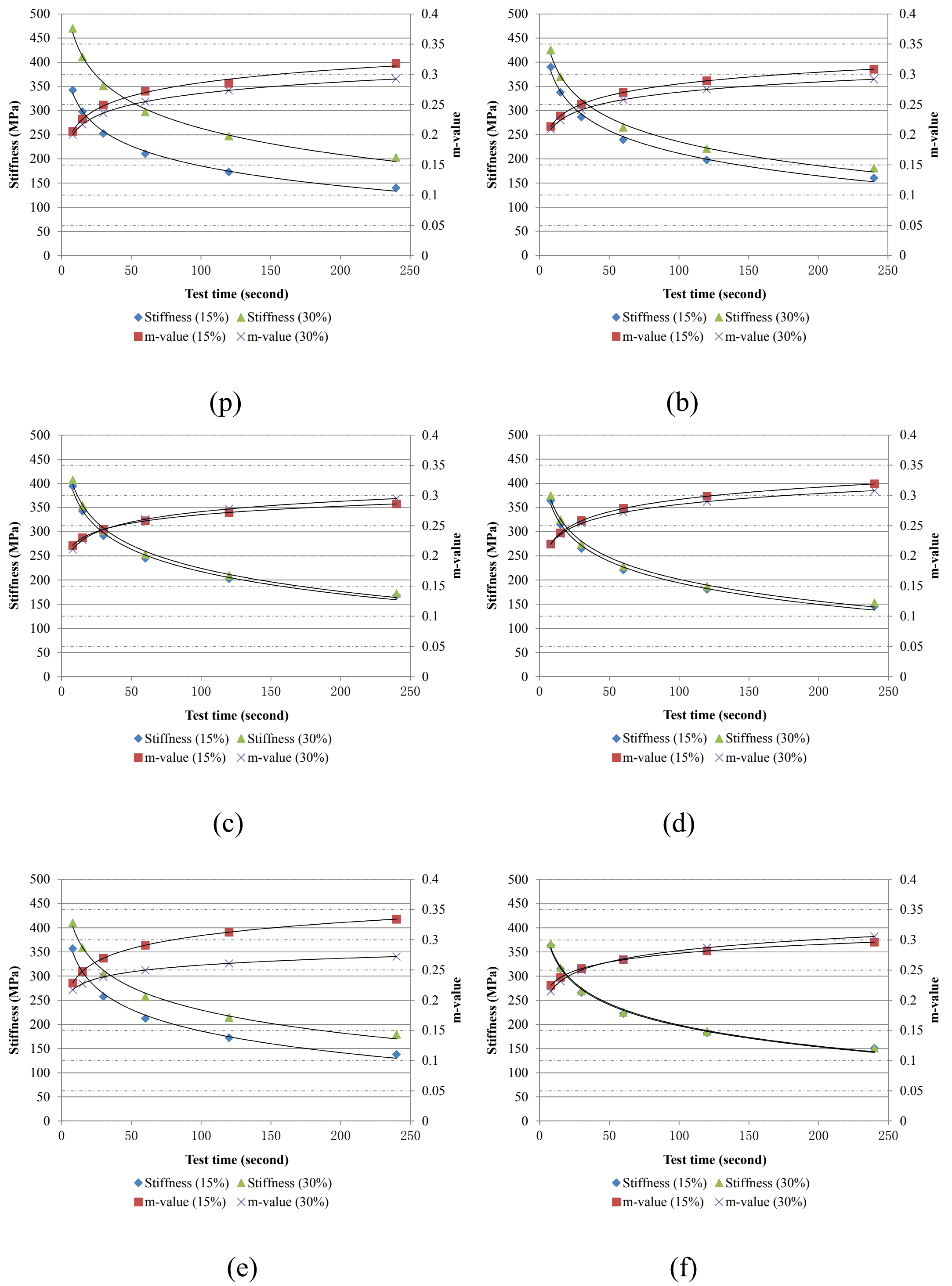
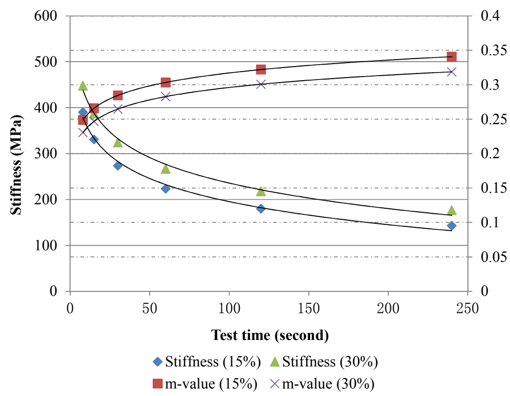
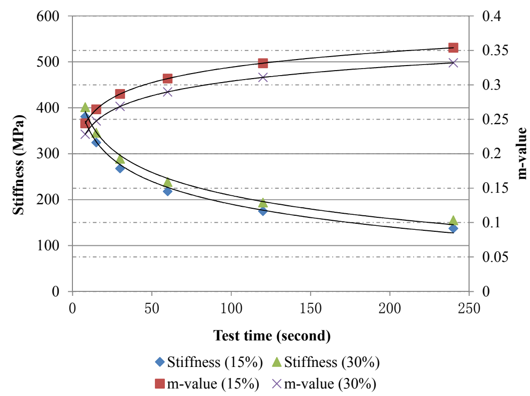
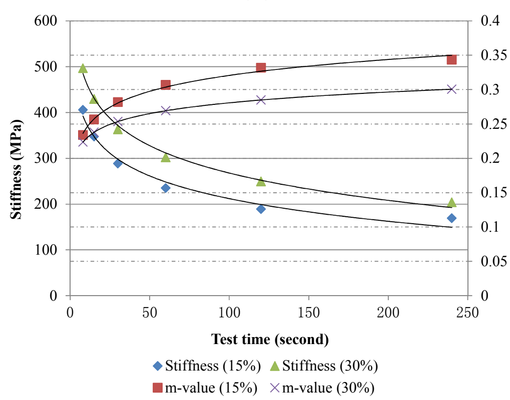


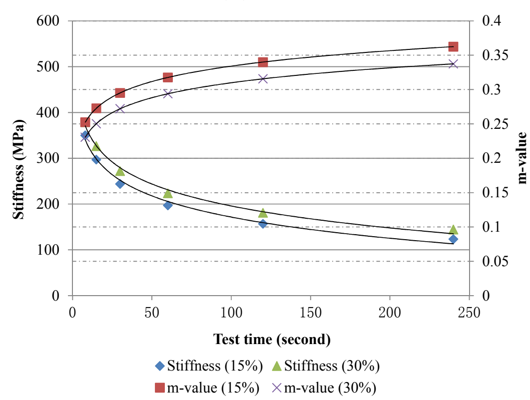
Figure 18-2: Stiffness and m-values of extracted aged binders A-F modified with binder PG 64-22 at -12ºC



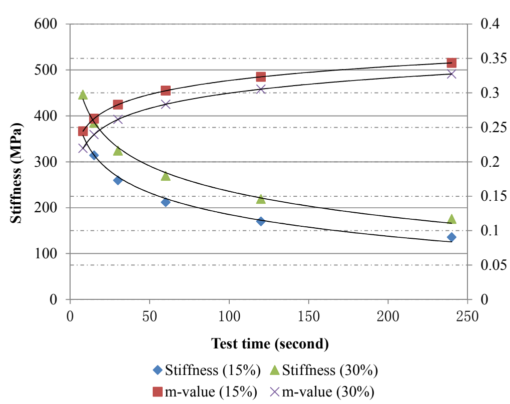


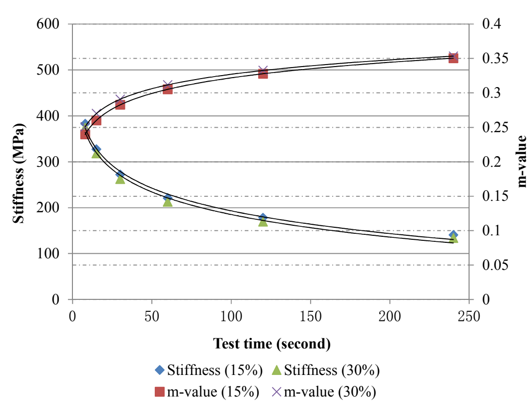
(b) (b)





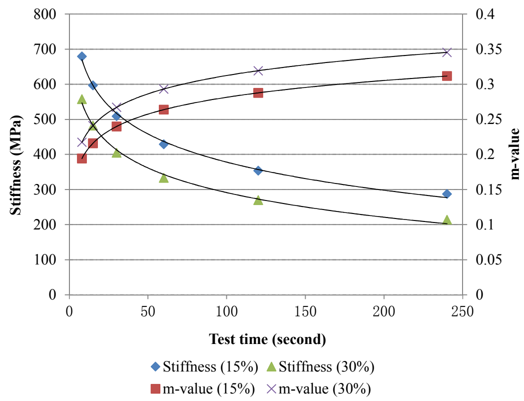
(c) (d)



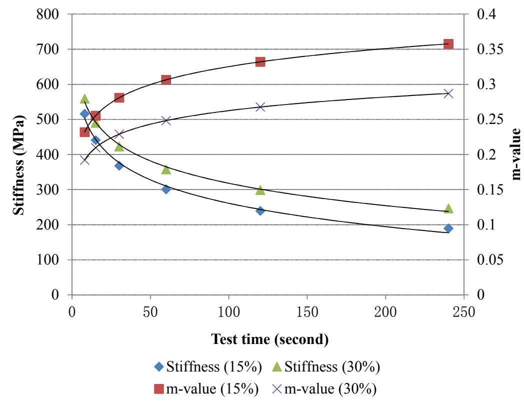


(e) (f)

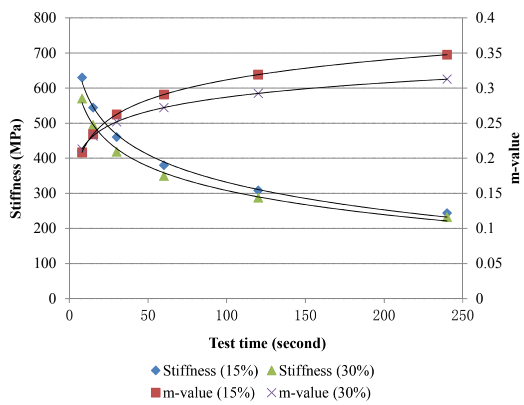
Figure 18-3: Stiffness and m-values of extracted aged binders A-F modified with binder PG 76-22 at -12ºC



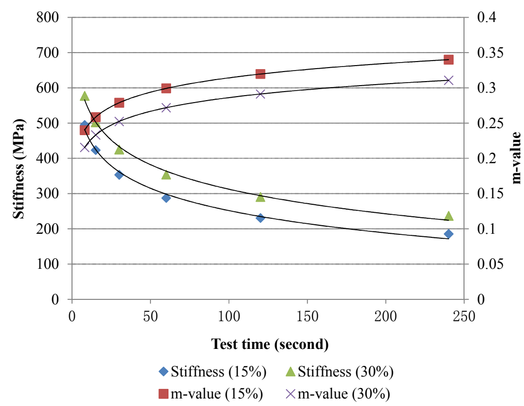
(a)



(b)



(c)



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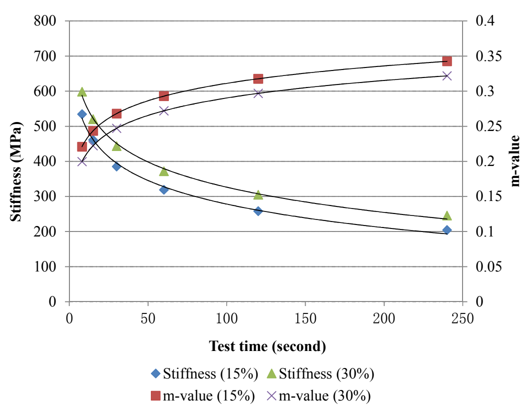
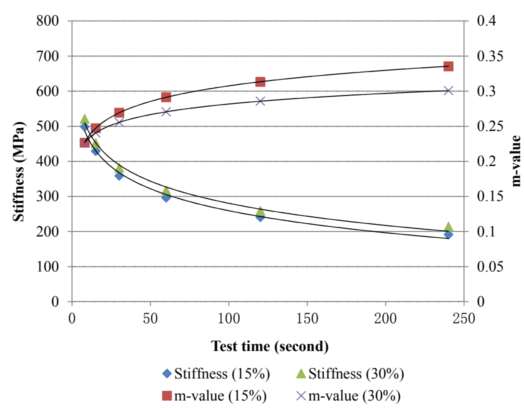


(e)



(f)

Figure 18-4: Stiffness and m-values of extracted aged binders A-F modified with binder PG 58-28 at -18ºC

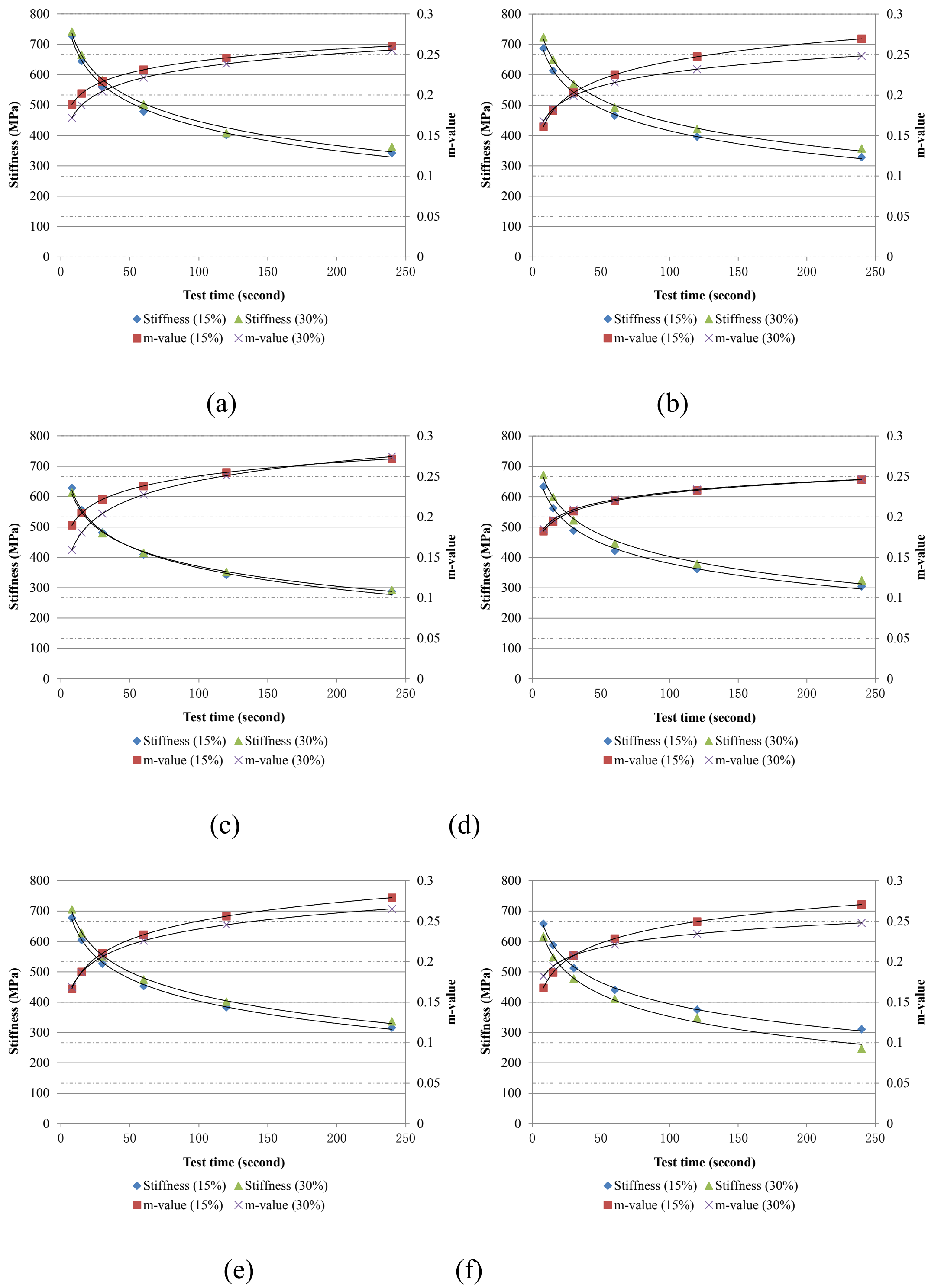


Figure 18-5: Stiffness and m-values of extracted aged binders A-F modified with binder PG 64-22 at -18^{o}C

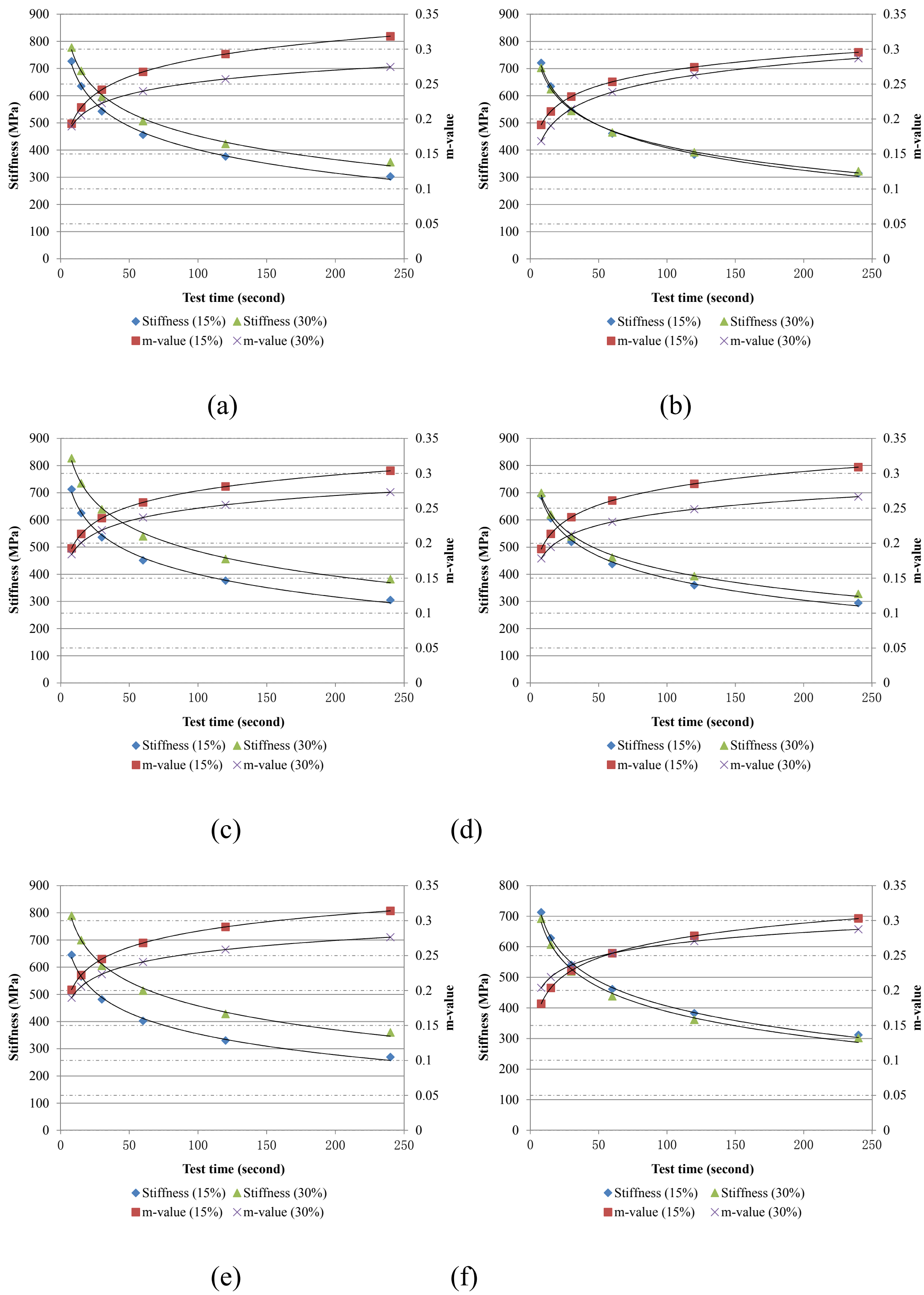


Figure 18-6: Stiffness and m-values of extracted aged binders A-F modified with binder PG 76-22 at -18ºC

19 Appendix J

BBR Data: BBR Comparisons

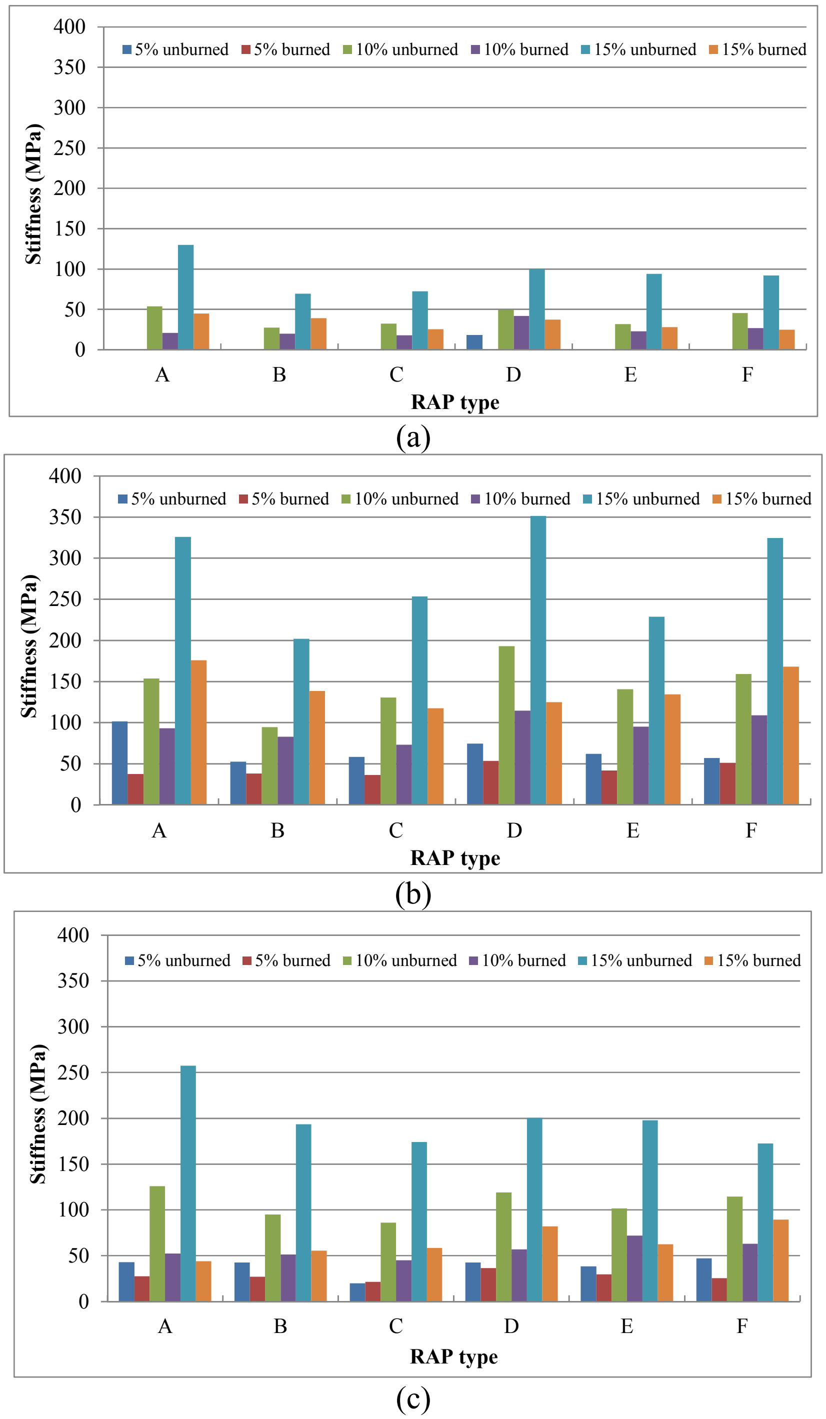
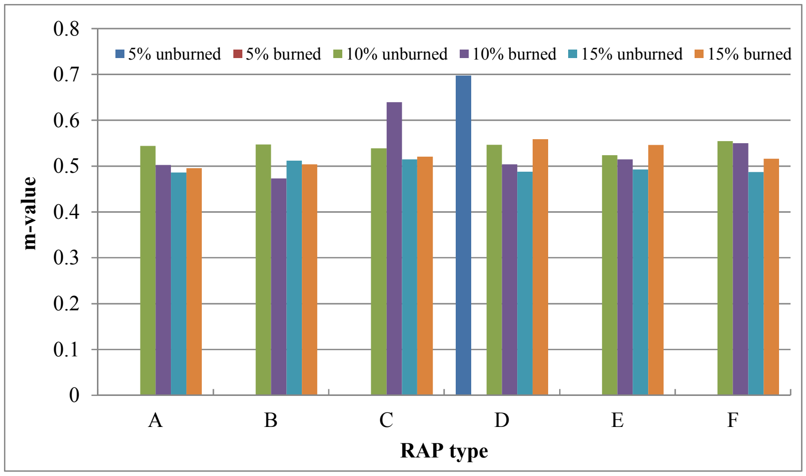
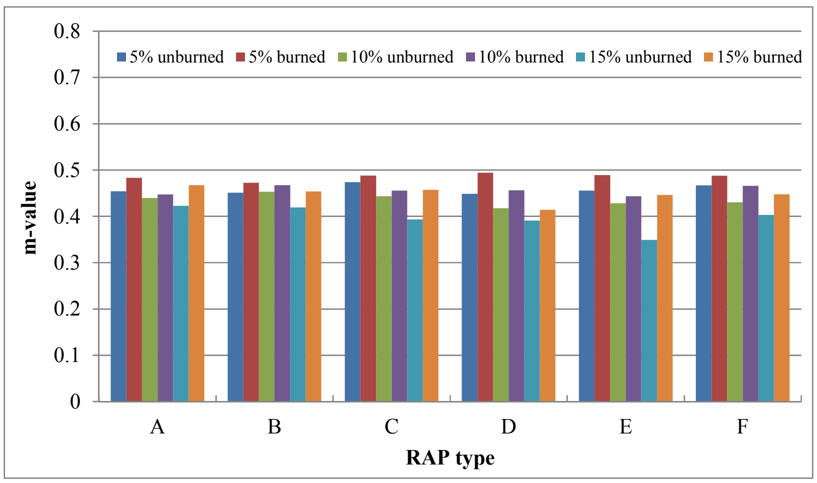


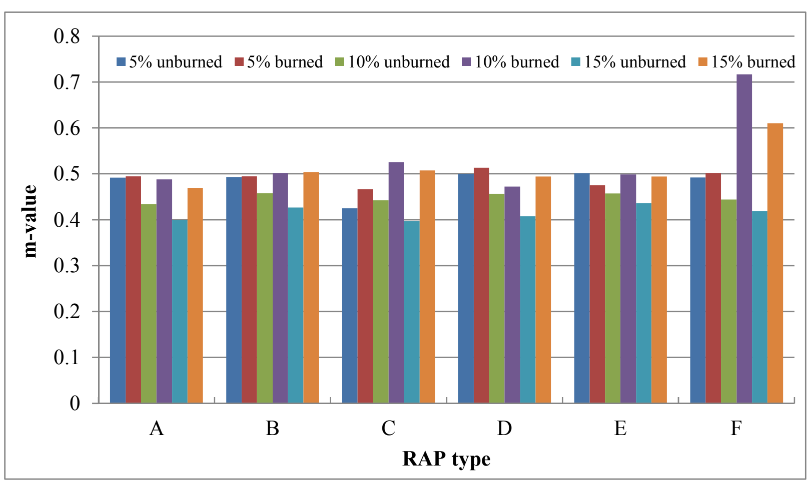
Figure 19-1: Stiffness comparisons of RAP sources A-F modified with virgin binders at -6ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

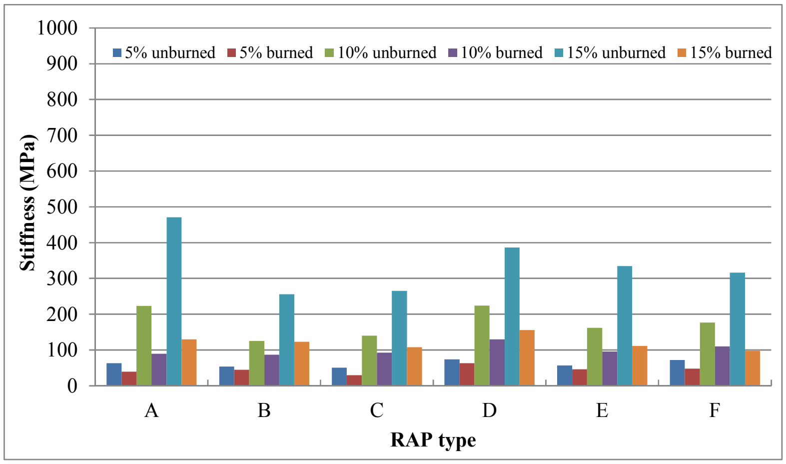


(b)

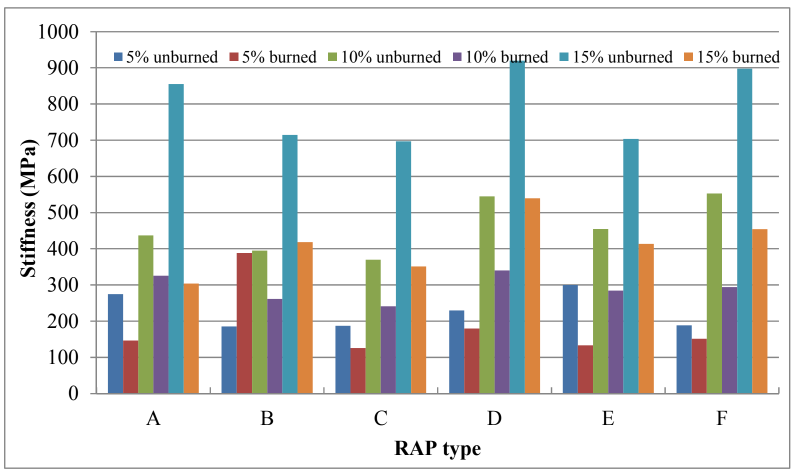


(c)

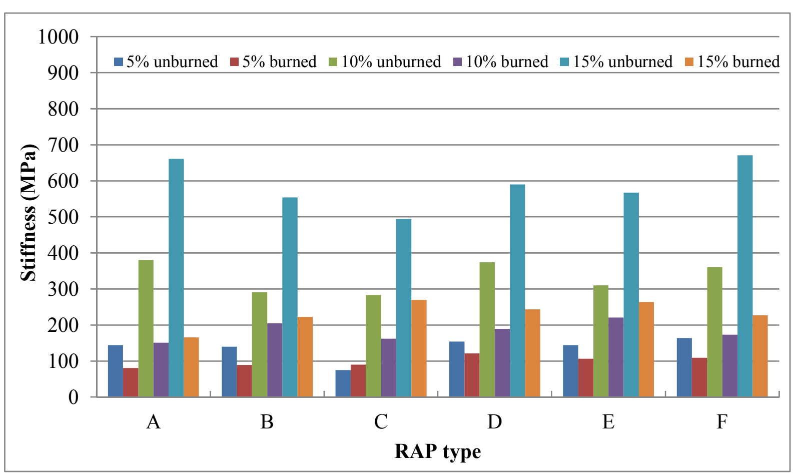
Figure 19-2: m-value comparisons of RAP sources A-F modified with virgin binders at -6^{o}C, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

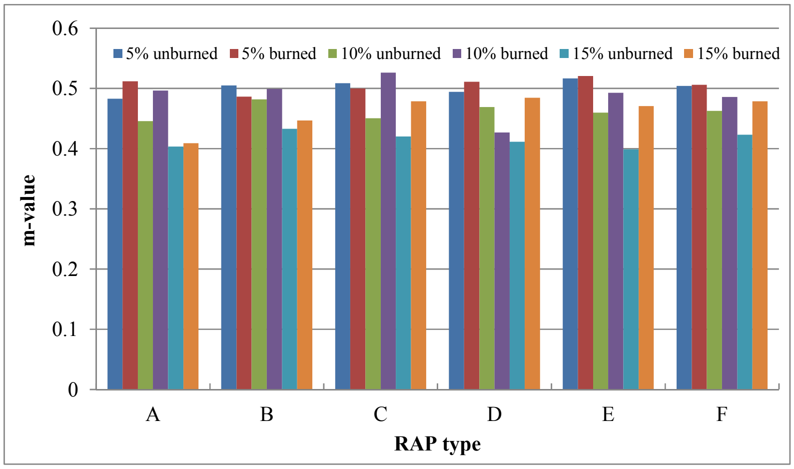


(b)

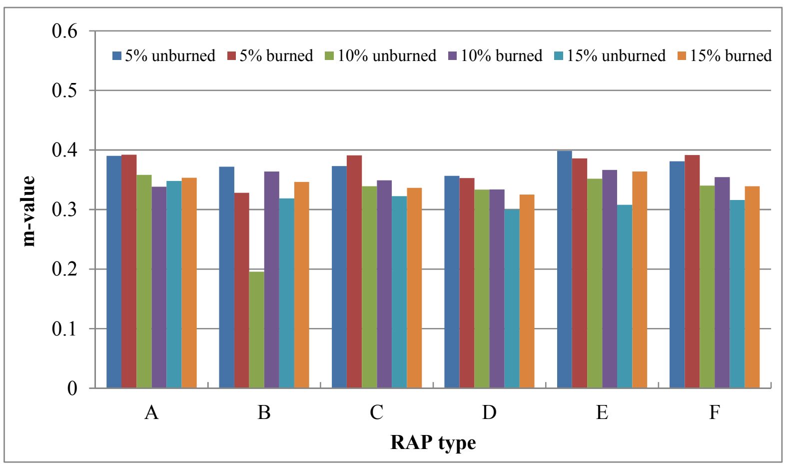


(c)

Figure 19-3: Stiffness comparisons of RAP sources A-F modified with virgin binders at -12ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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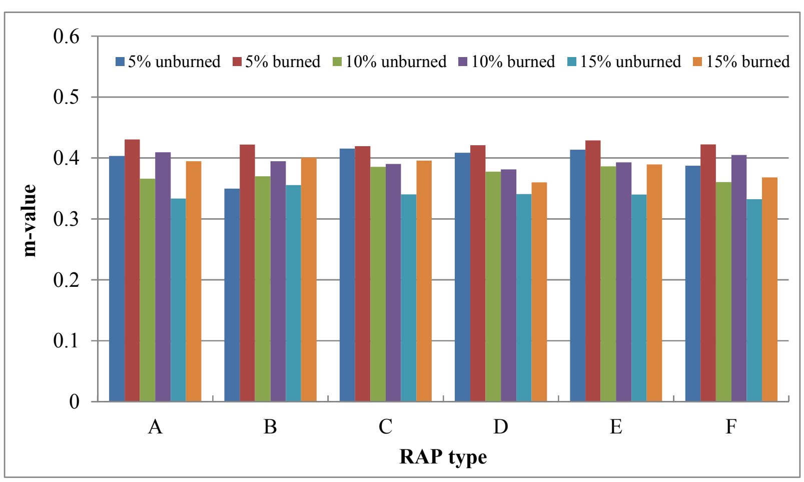
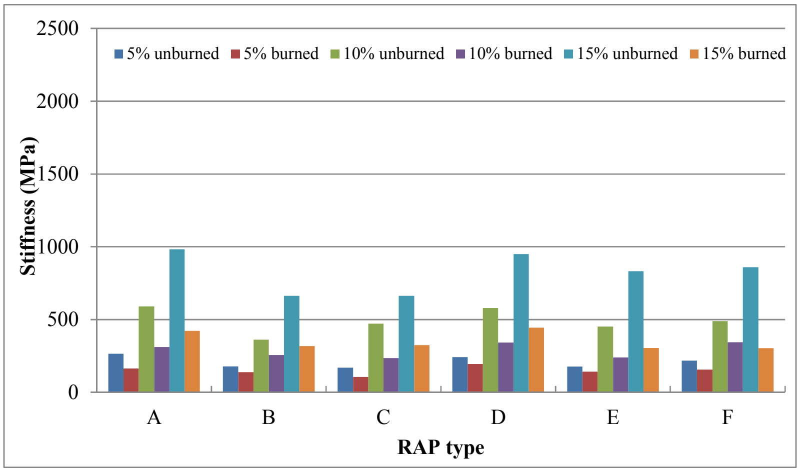
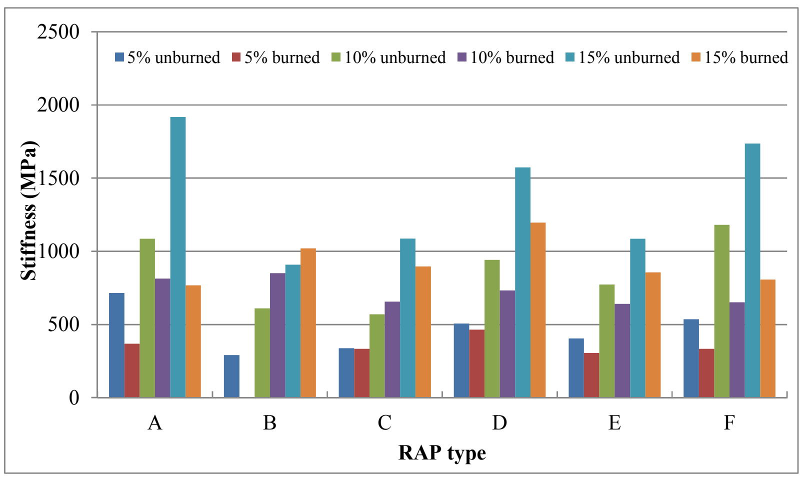


(c)

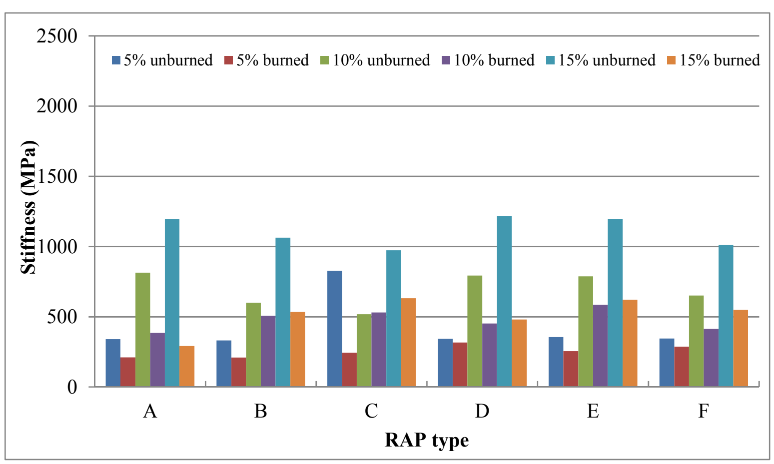
Figure 19-4: m-value comparisons of RAP sources A-F modified with virgin binders at -12ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

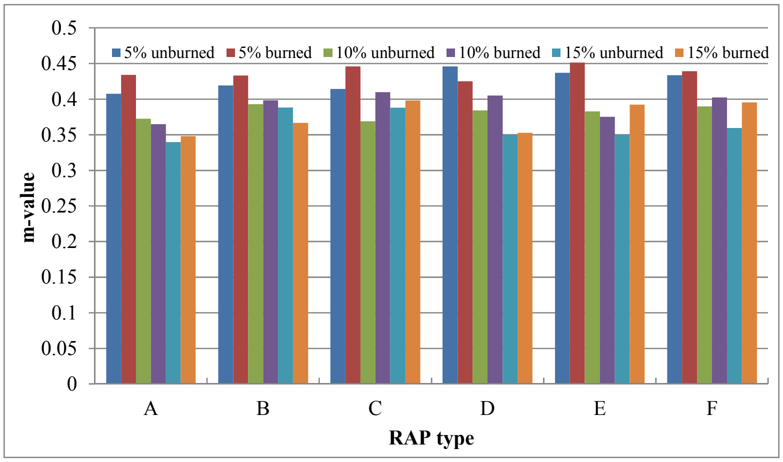


(b)

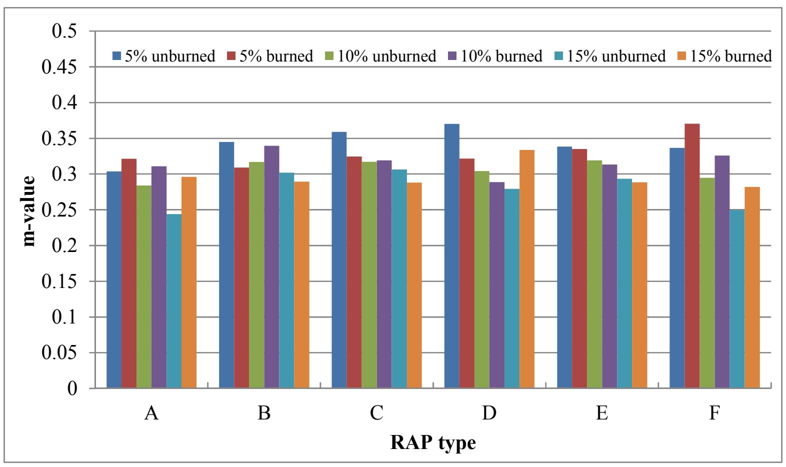


(c)

Figure 19-5: Stiffness comparisons of RAP sources A-F modified with virgin binder at -18ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



(b)

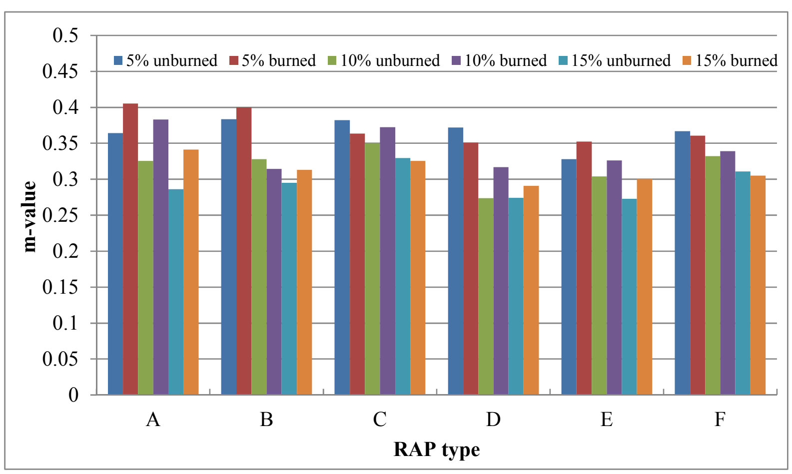
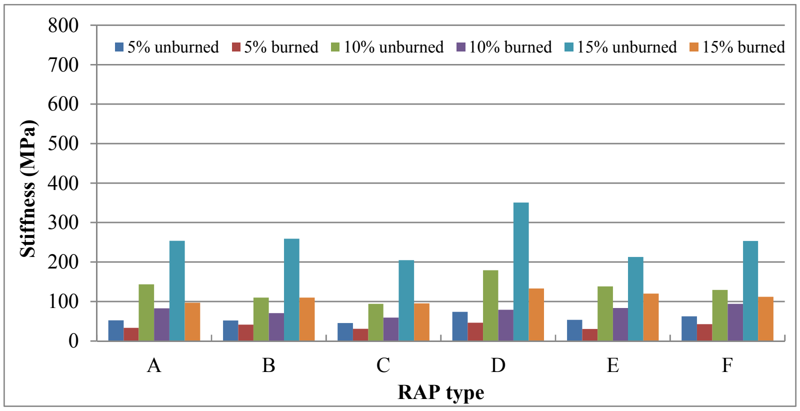
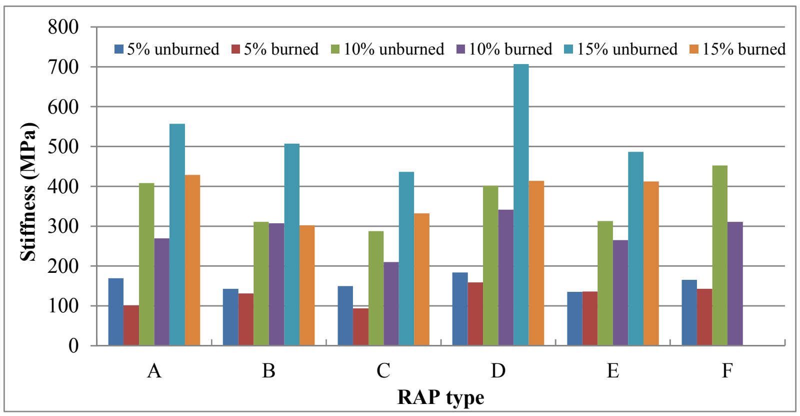


Figure 19-6: m-value comparisons of RAP sources A-F modified with virgin binders at -18ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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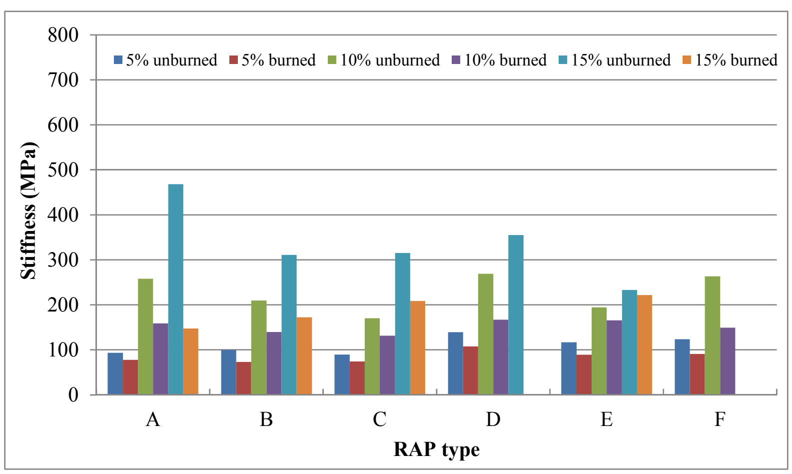
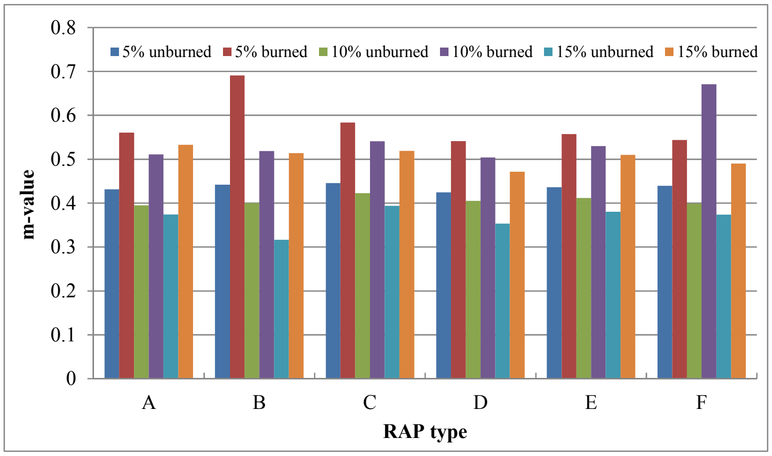
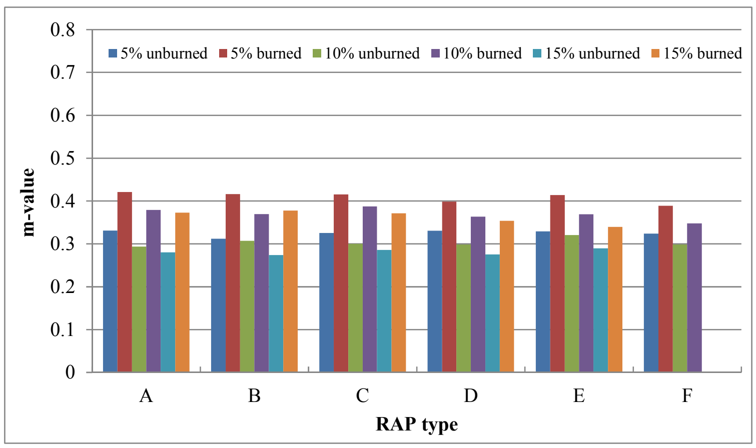


(c)

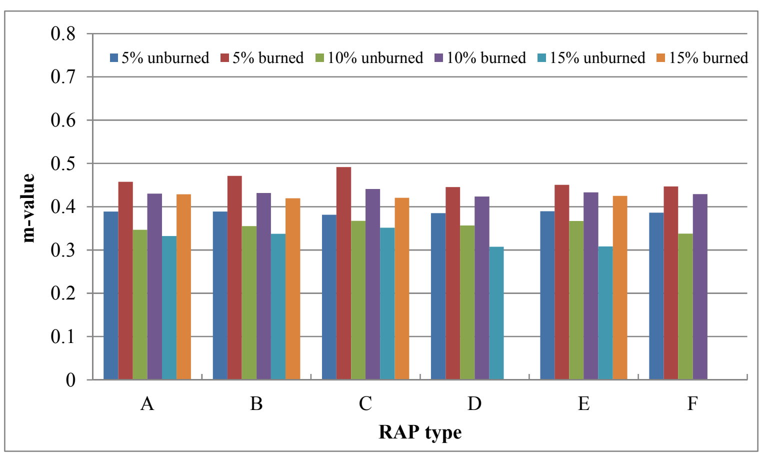
Figure 19-7: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -6ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

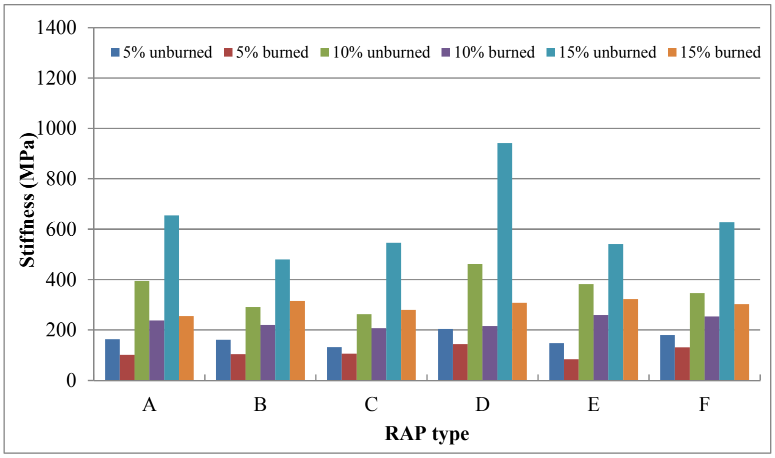


(b)

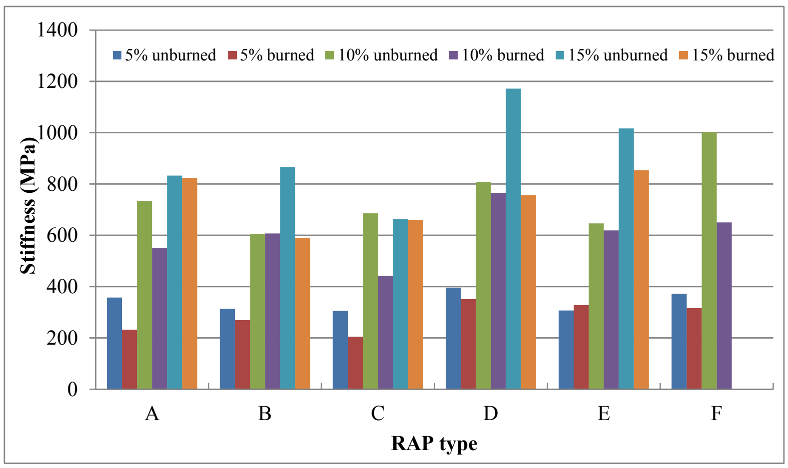


(c)

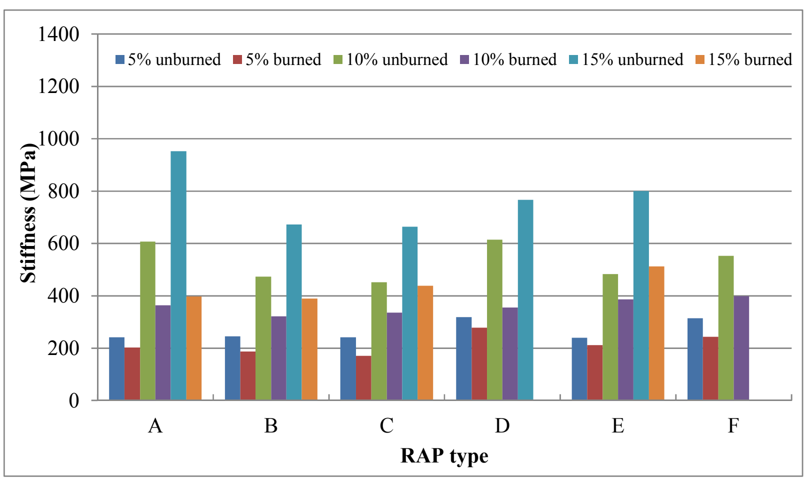
Figure 19-8: m-value comparisons of RAP sources A-F modified with RTFO binders at -6ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

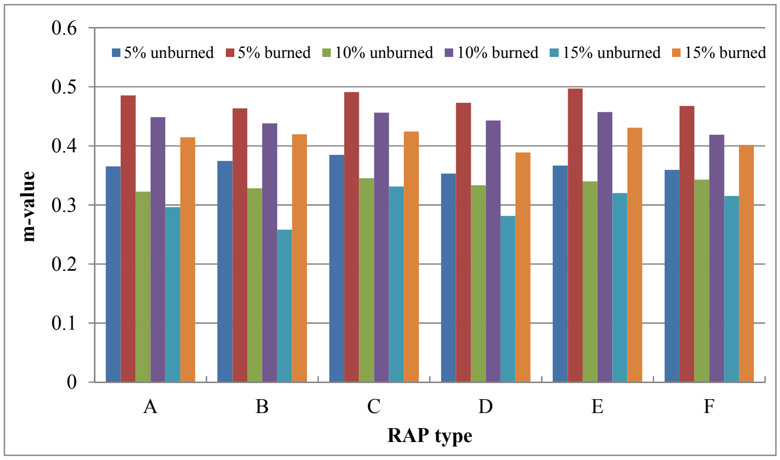


(b)

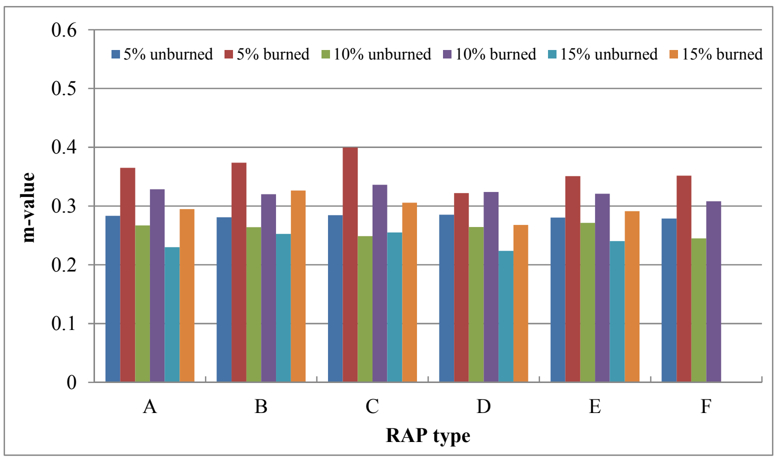


(c)

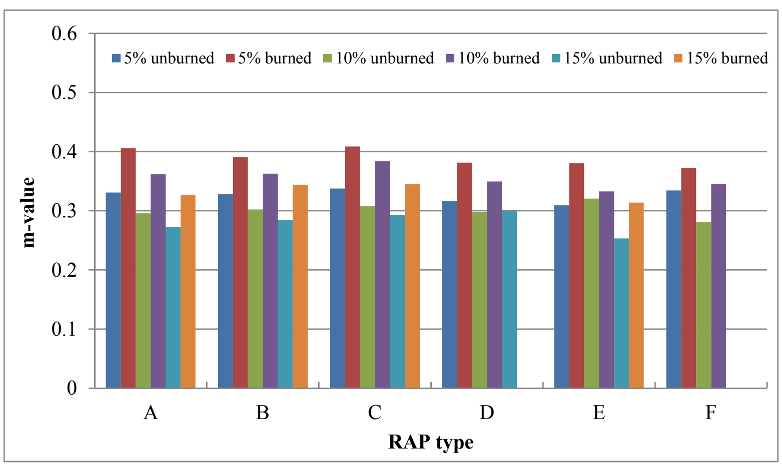
Figure 19-9: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -12ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

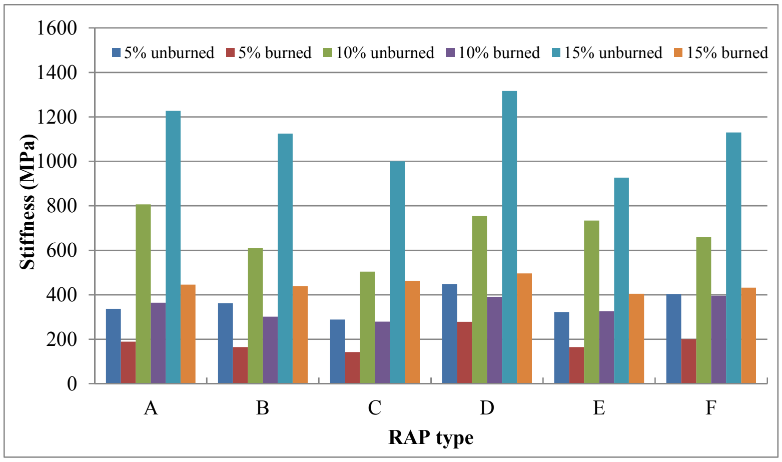


(b)

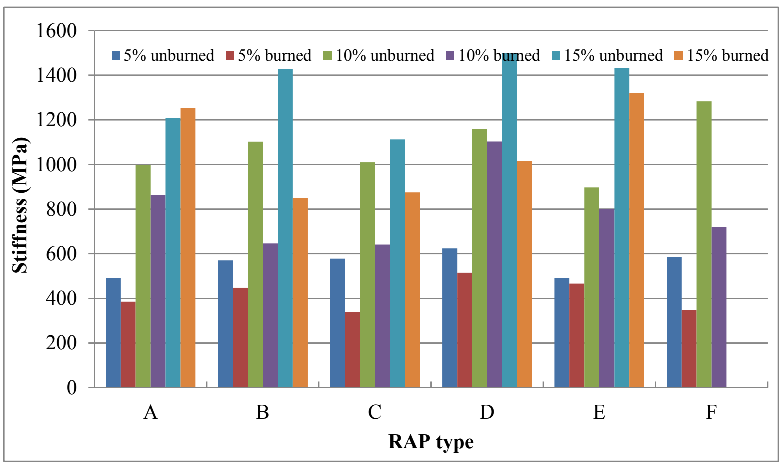


(c)

Figure 19-10: m-value comparisons of RAP sources A-F modified with RTFO binders at -12°C, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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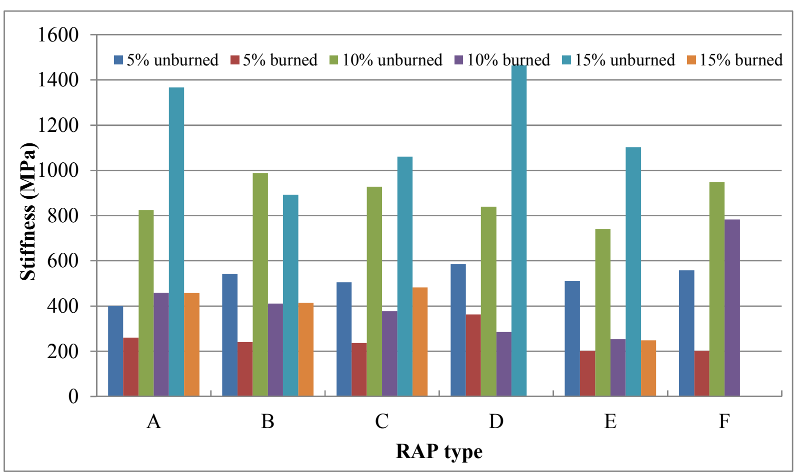
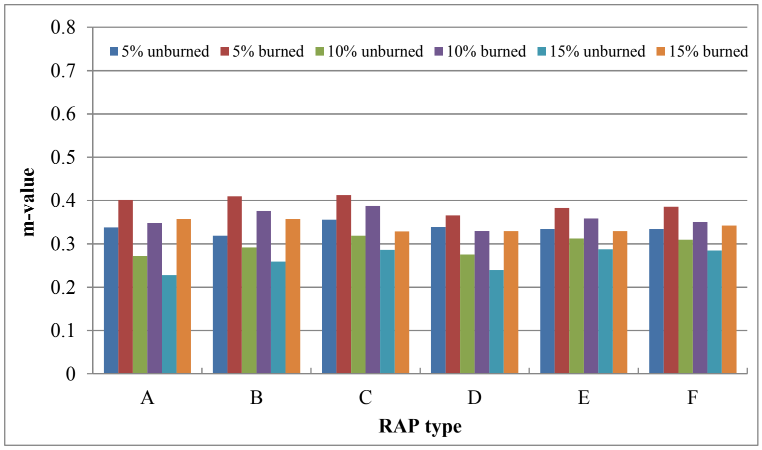
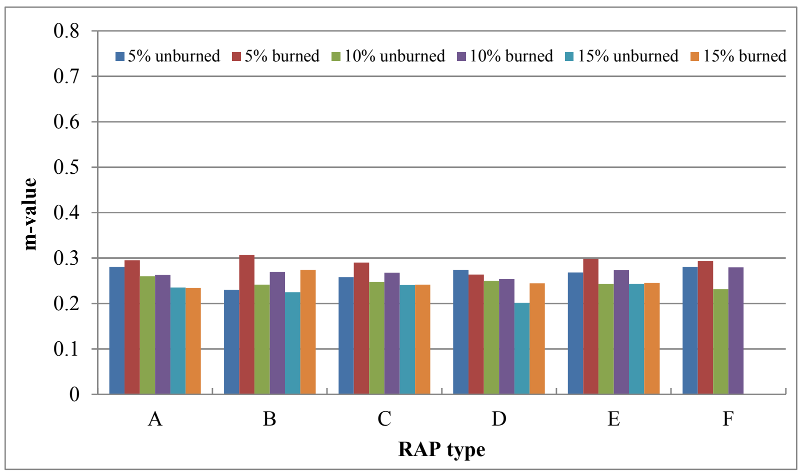


(c)

Figure 19-11: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -18ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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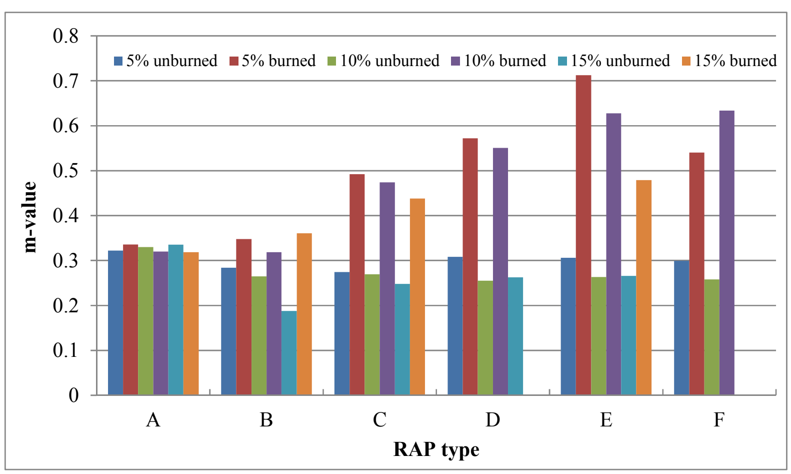
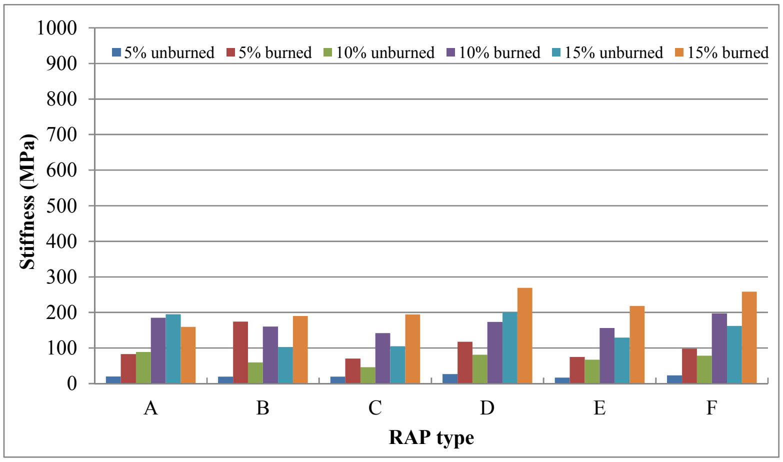
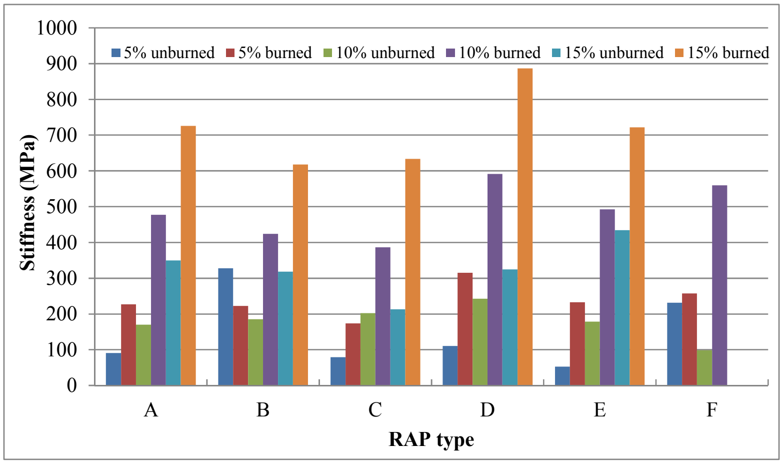


(c)

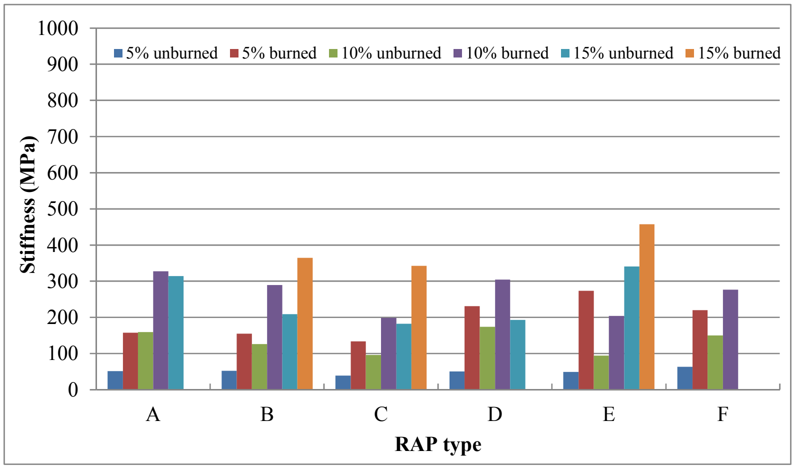
Figure 19-12: m-value comparisons of RAP sources A-F modified with RTFO binders at -18ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

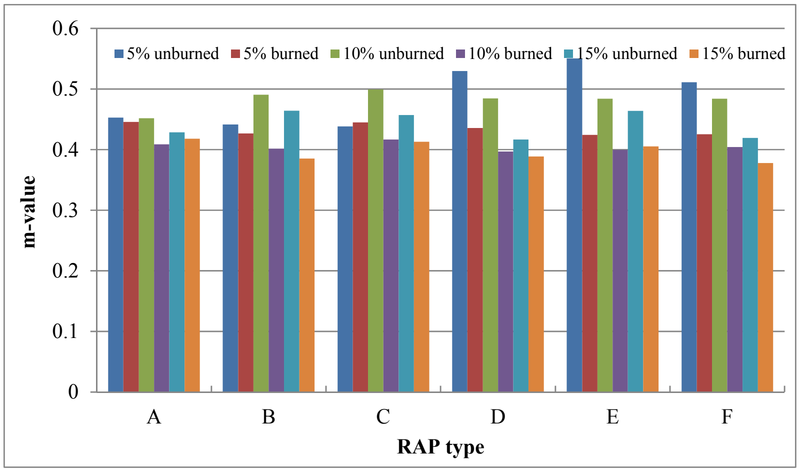


(b)

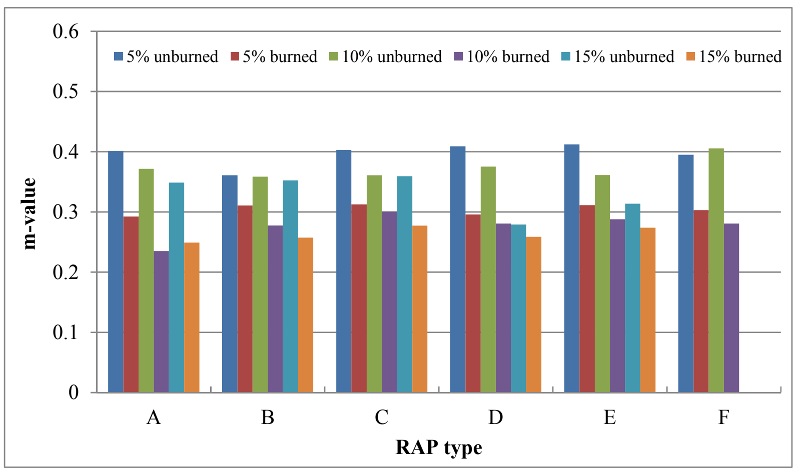


(c)

Figure 19-13: Stiffness comparisons of RAP sources A-F modified with PAV binders at -6ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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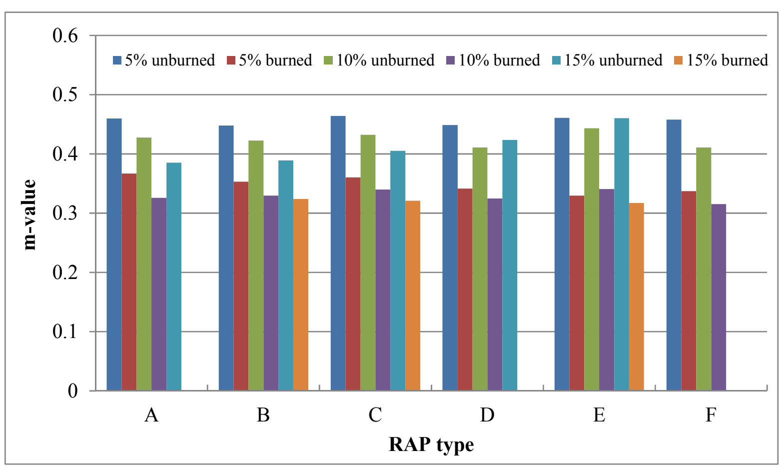
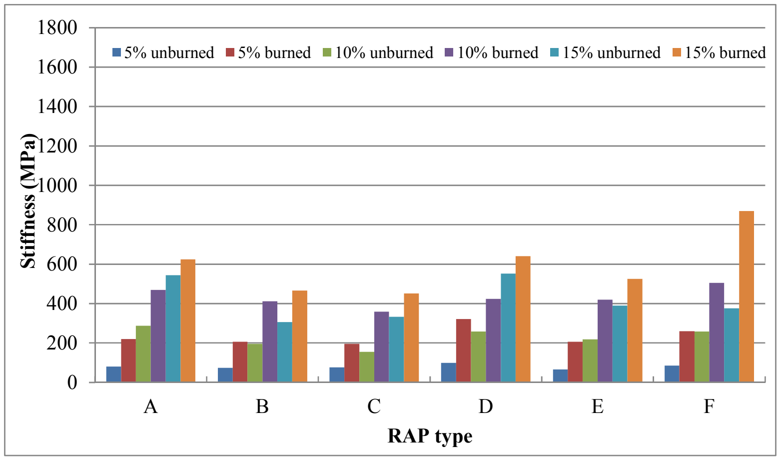
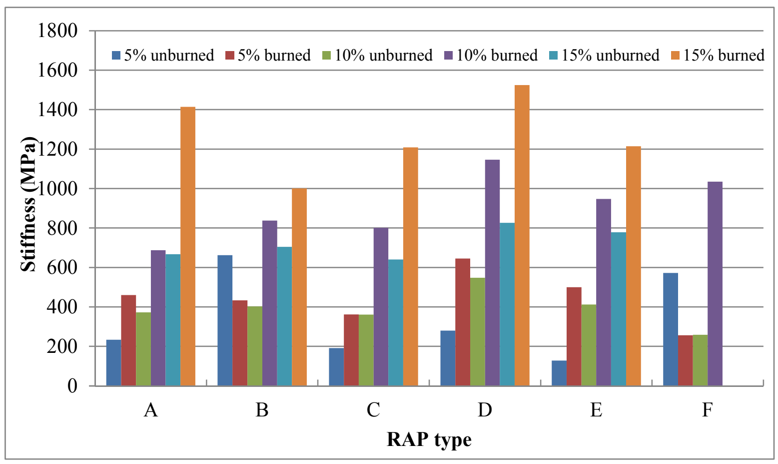


(c)

Figure 19-14: m-value comparisons of RAP sources A-F modified with PAV binders at -6ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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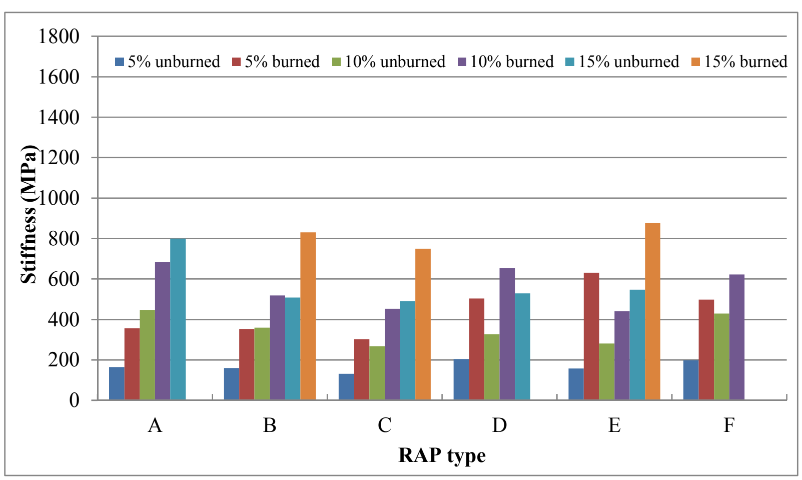
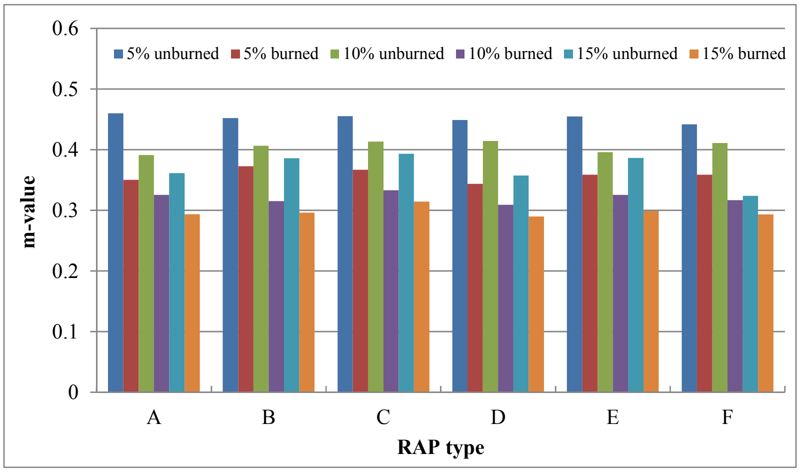
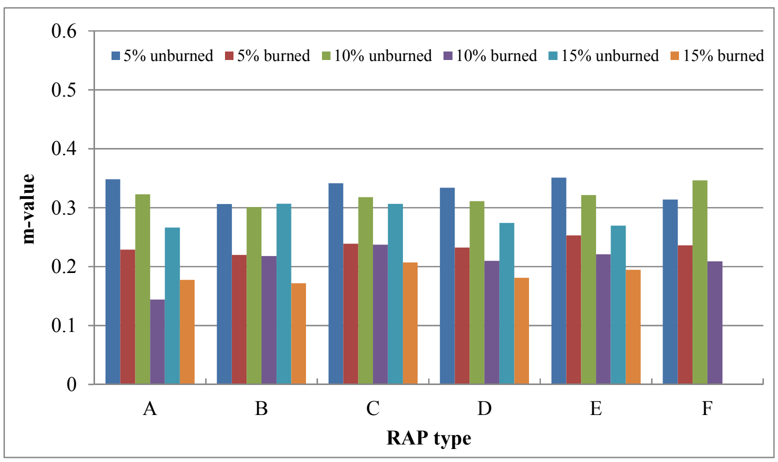


(c)

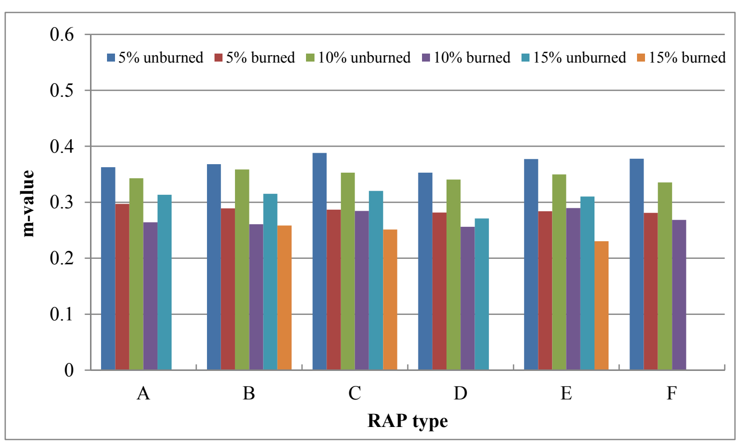
Figure 19-15: Stiffness comparisons of RAP sources A-F modified with PAV binders at -12ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

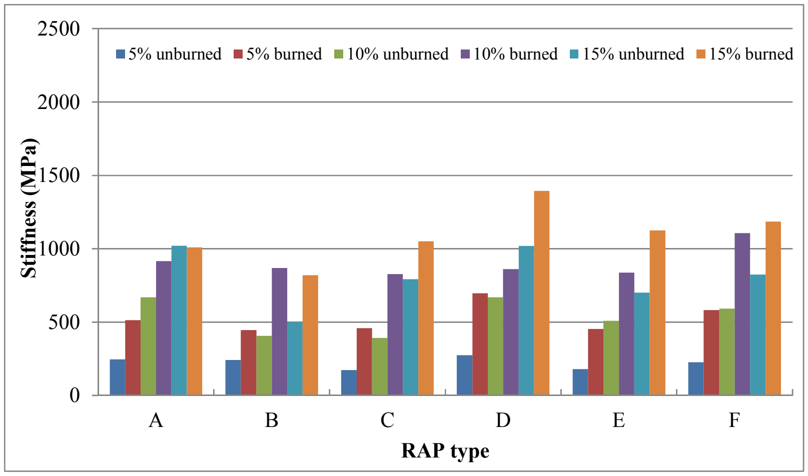


(b)

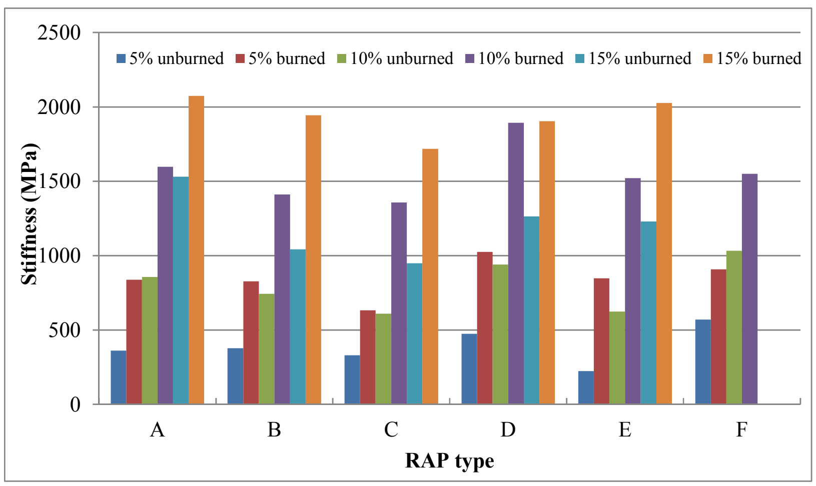


(c)

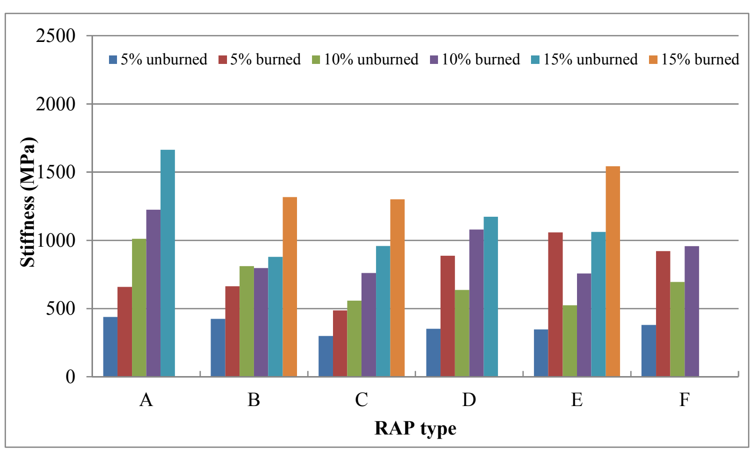
Figure 19-16: m-value comparisons of RAP sources A-F modified with PAV binders at -12ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

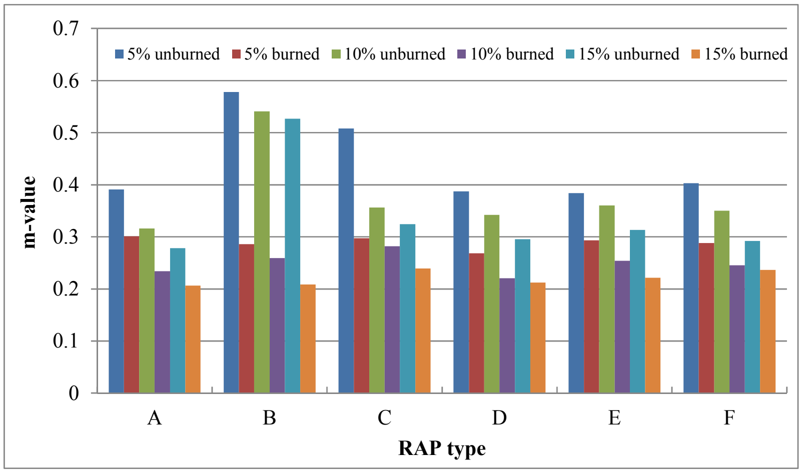


(b)

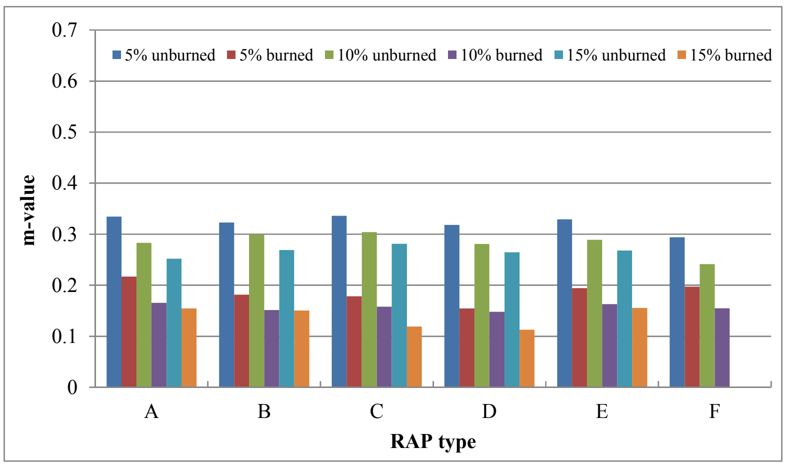


(c)

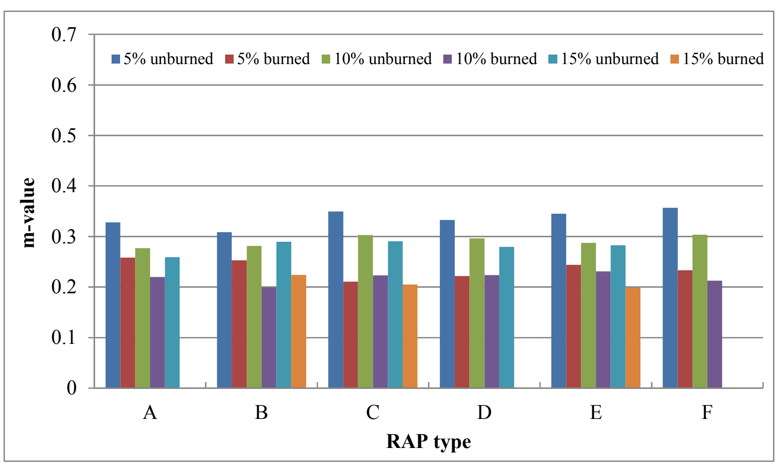
Figure 19-17: Stiffness comparisons of RAP sources A-F modified with PAV binders at -18ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

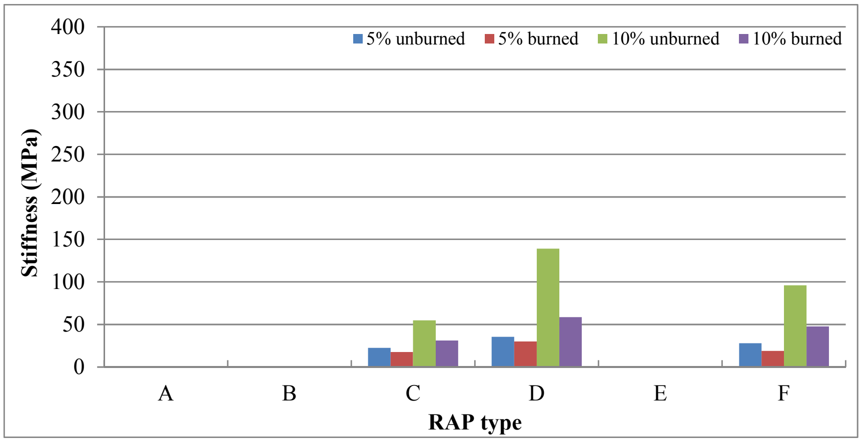


(b)

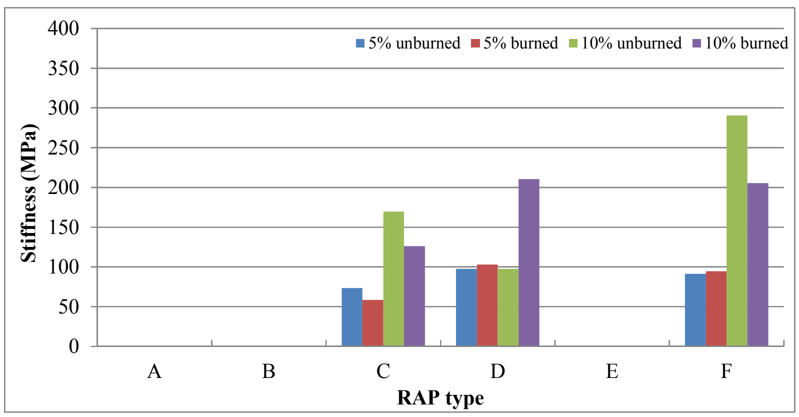


(c)

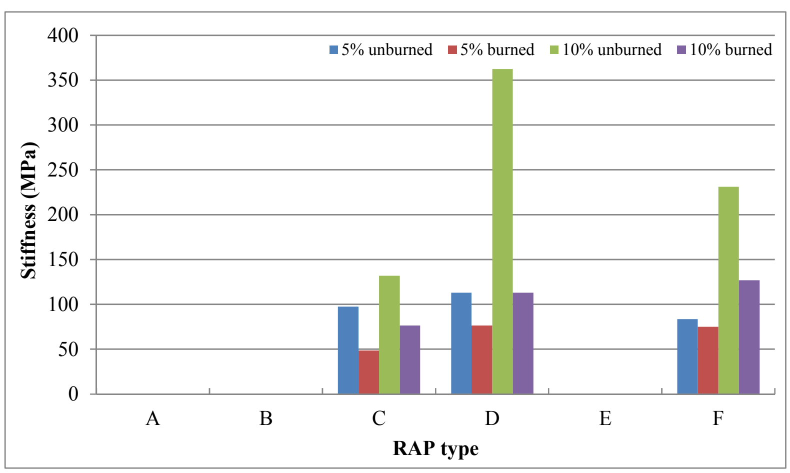
Figure 19-18: m-value comparisons of RAP sources A-F modified with PAV binders at -18ºC, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



(b)



(c)

Figure 19-19: Stiffness comparisons of RAP sources A-F modified with virgin binders at -6ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

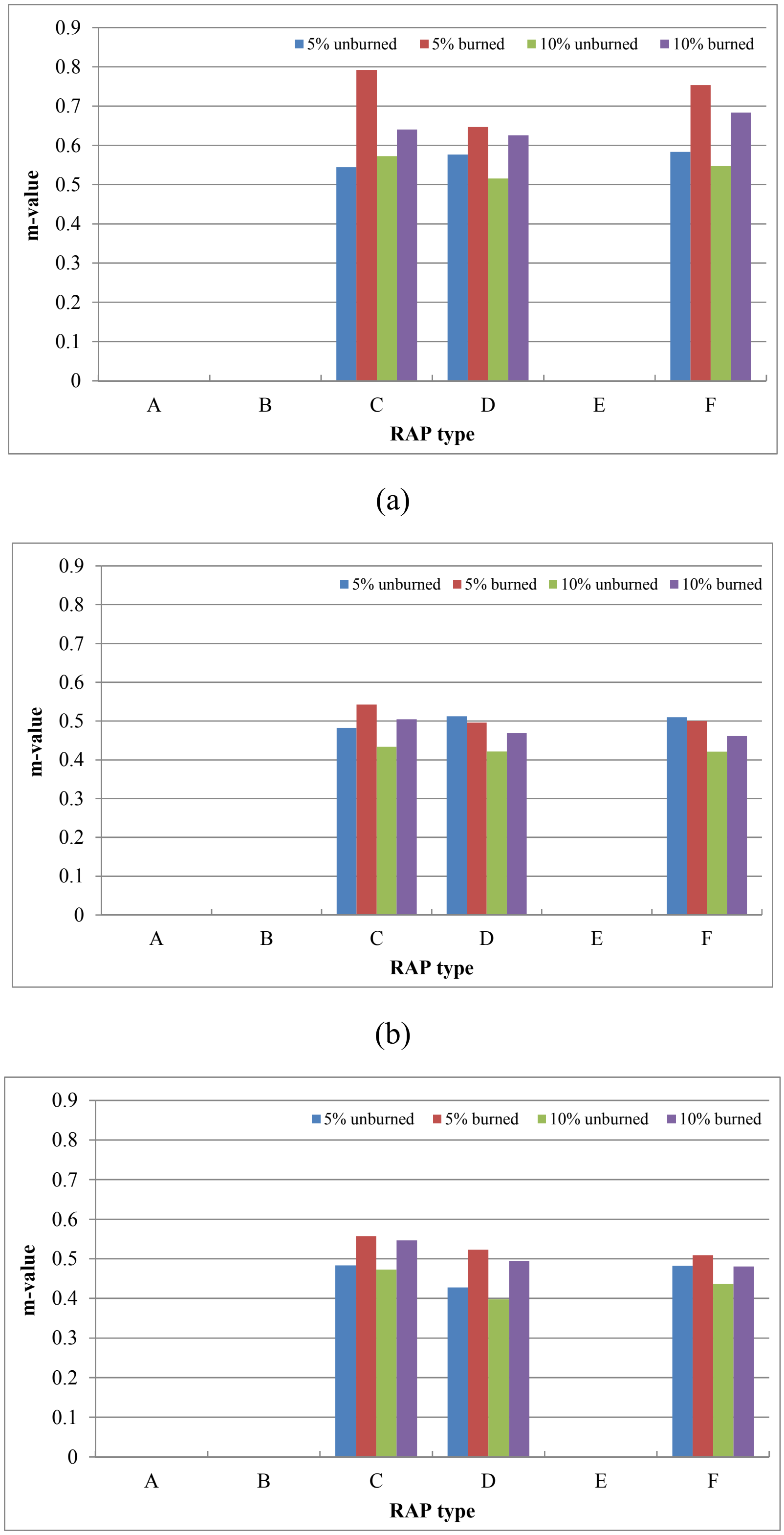
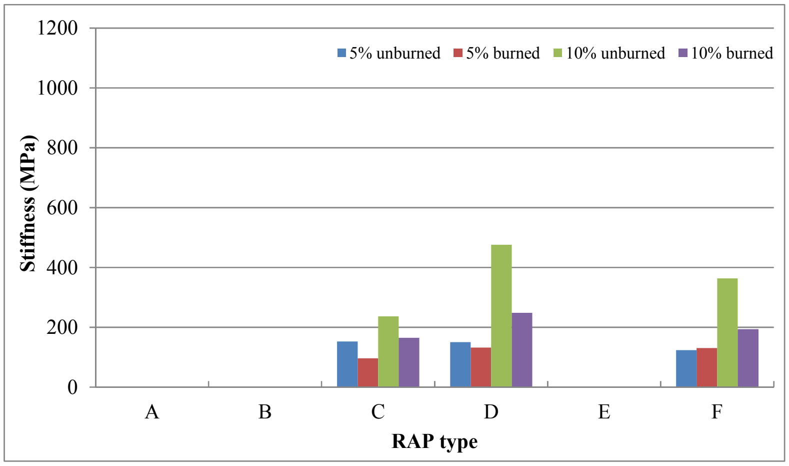
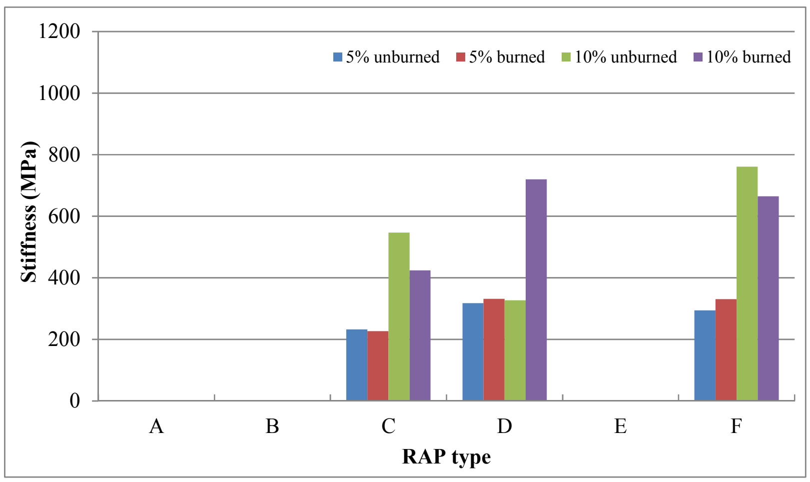


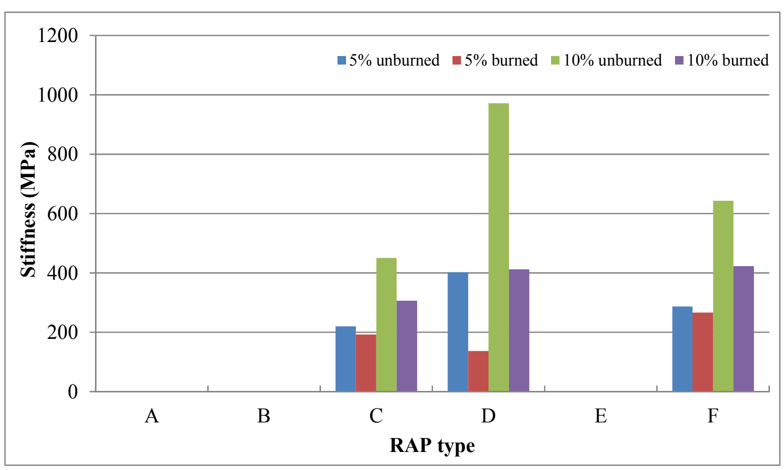
Figure 19-20: m-value comparisons of RAP sources A-F modified with virgin binders at -6ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

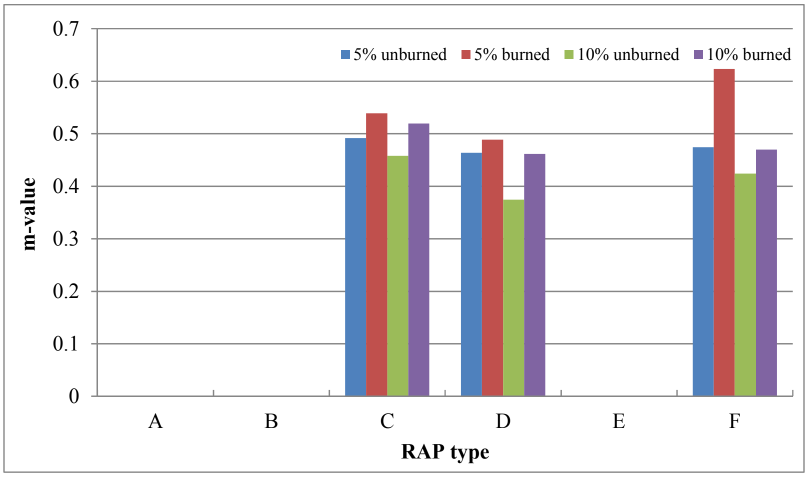


(b)

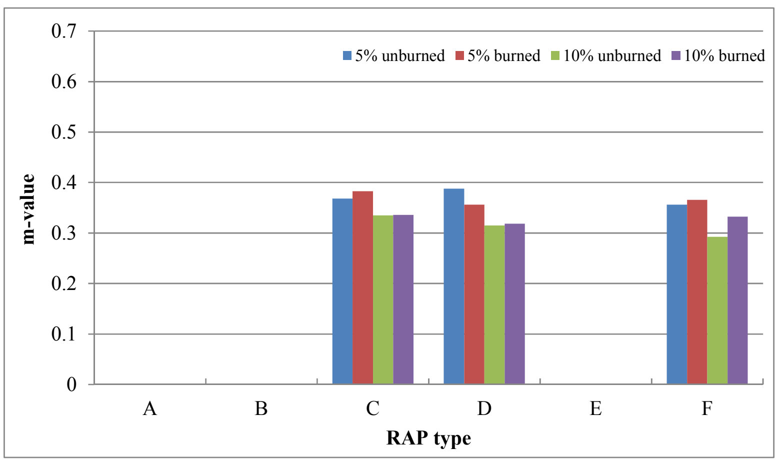


(c)

Figure 19-21: Stiffness comparisons of RAP sources A-F modified with virgin binders at -12ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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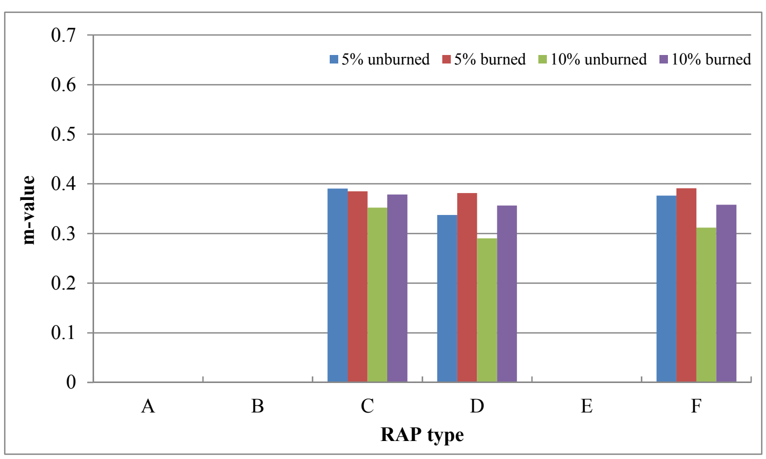
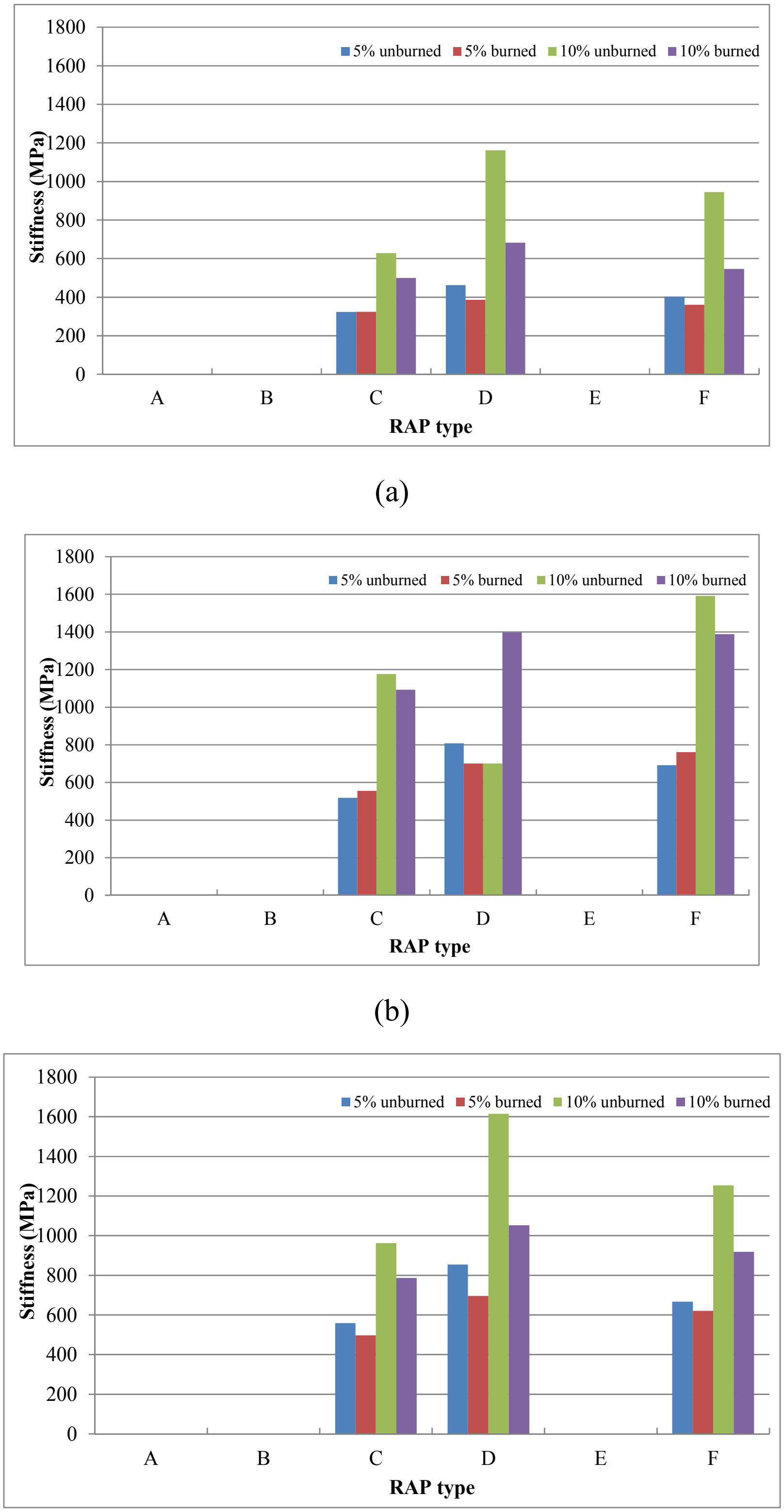


(c)

Figure 19-22: m-value comparisons of RAP sources A-F modified with virgin binders at -12ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

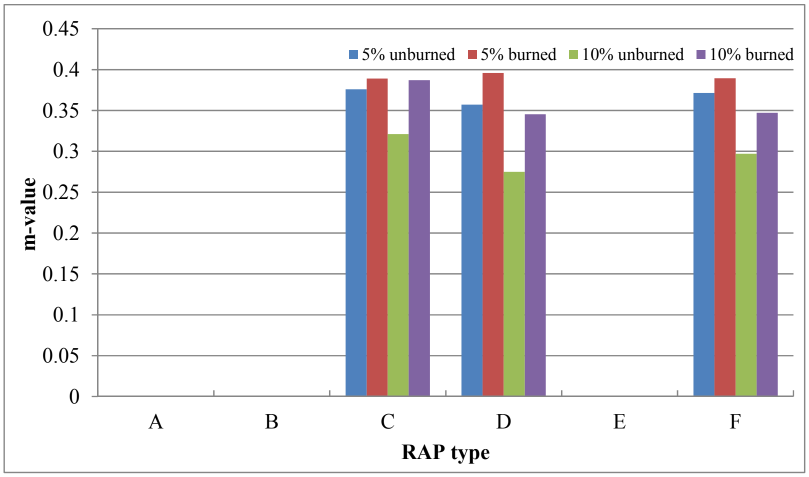


(a)

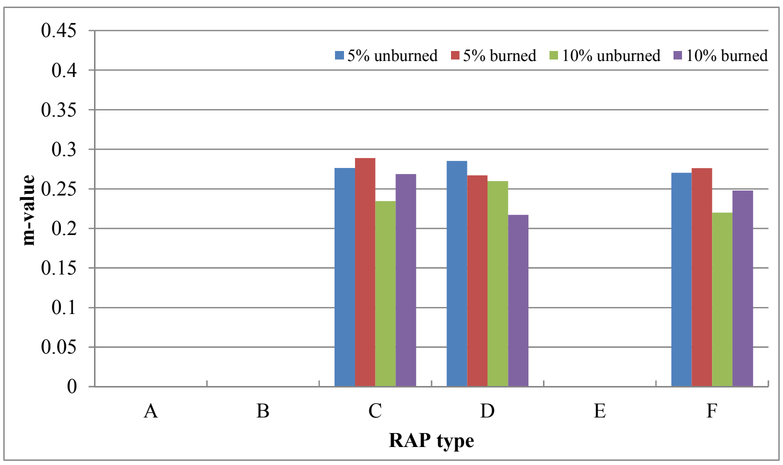
(b)

(c)

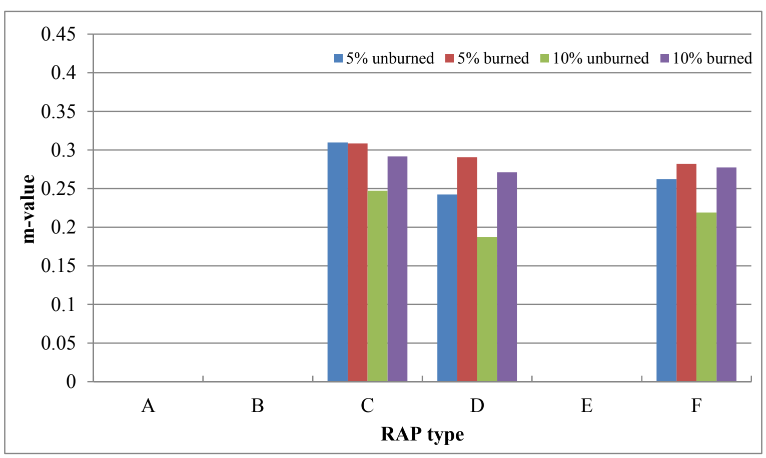
Figure 19-23: Stiffness comparisons of RAP sources A-F modified with virgin binders at -18ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

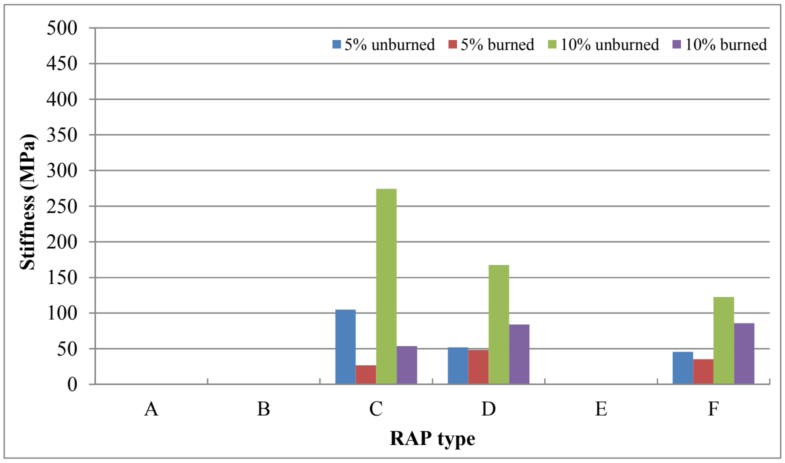


(b)

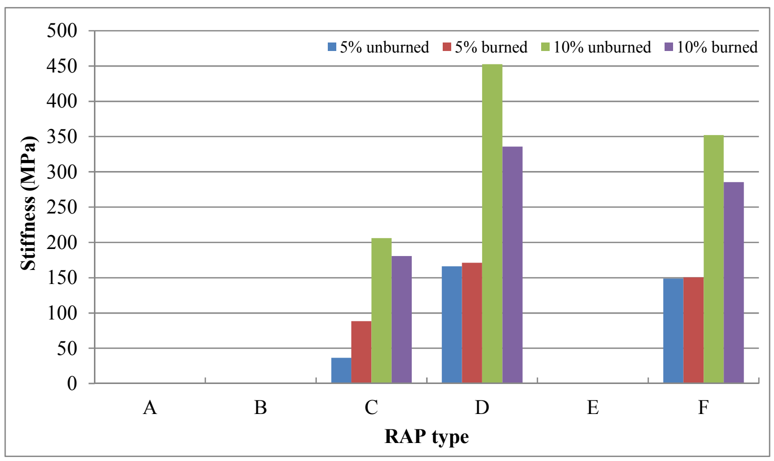


(c)

Figure 19-24: m-value comparisons of RAP sources A-F modified with virgin binders at -18ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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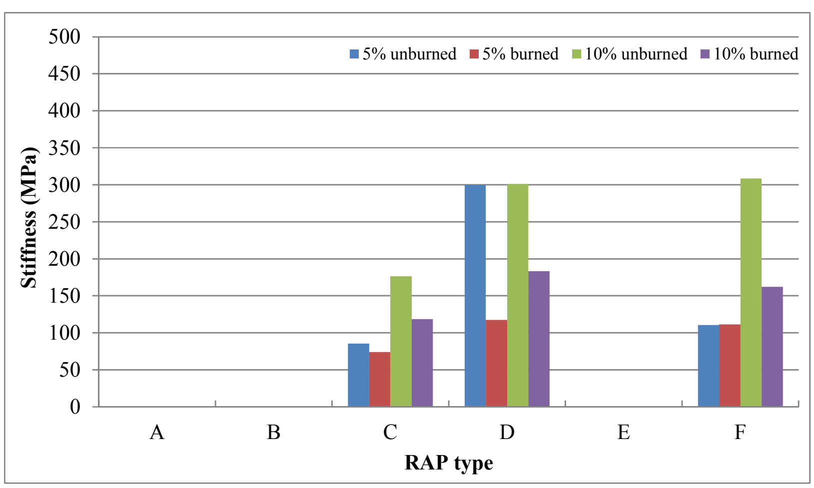
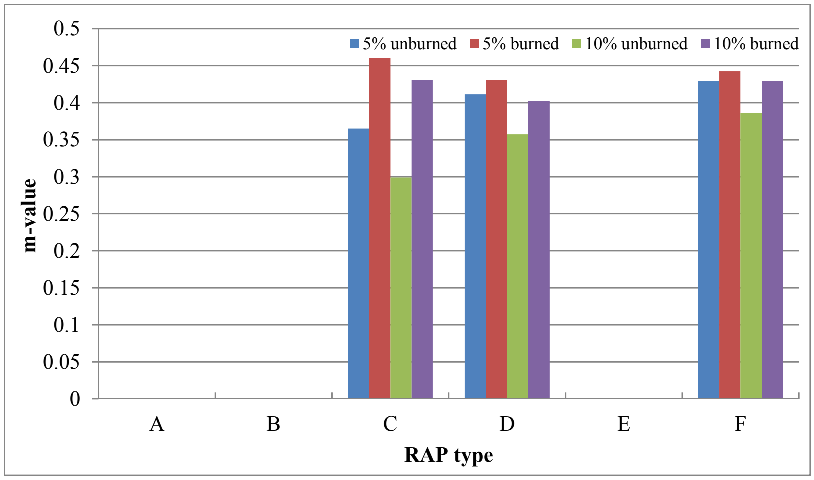
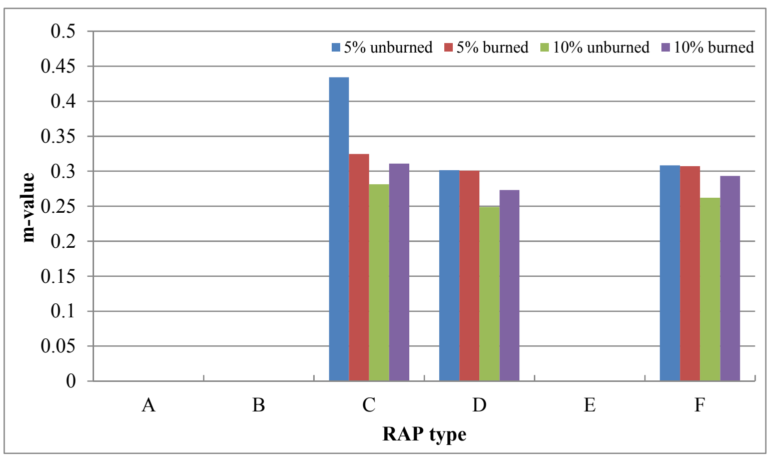


(c)

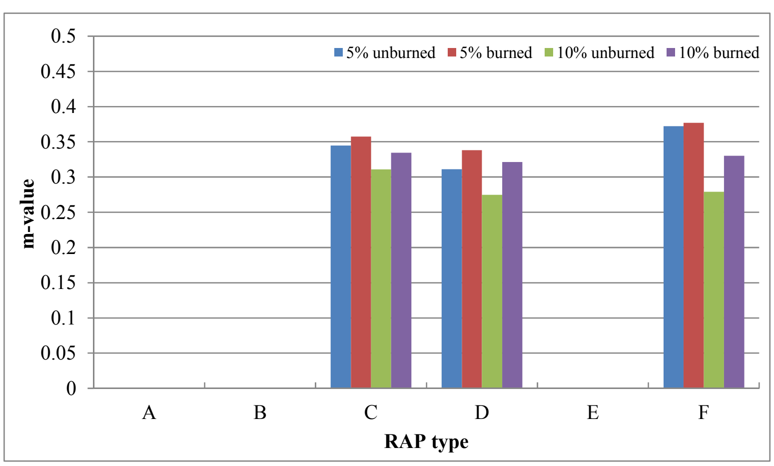
Figure 19-25: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -6ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

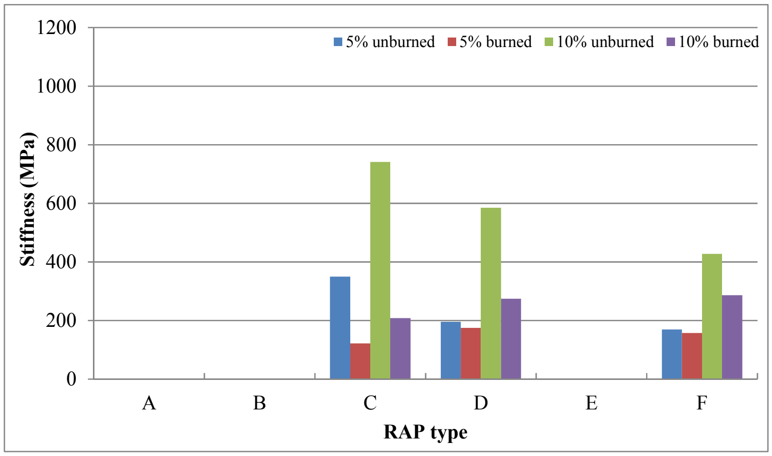


(b)

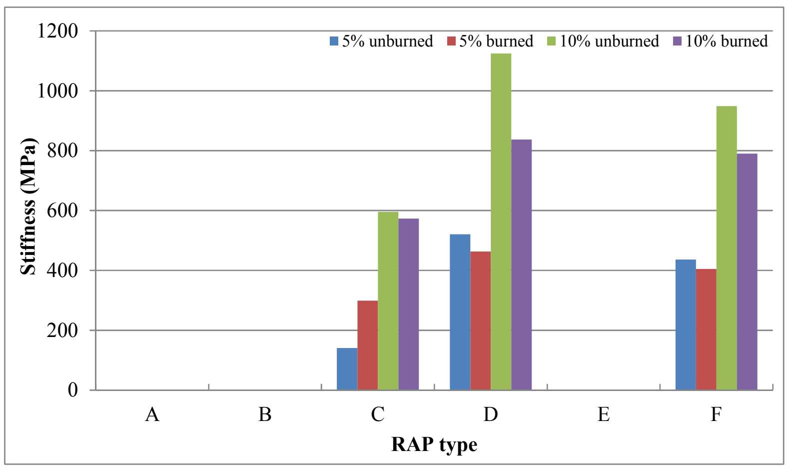


(c)

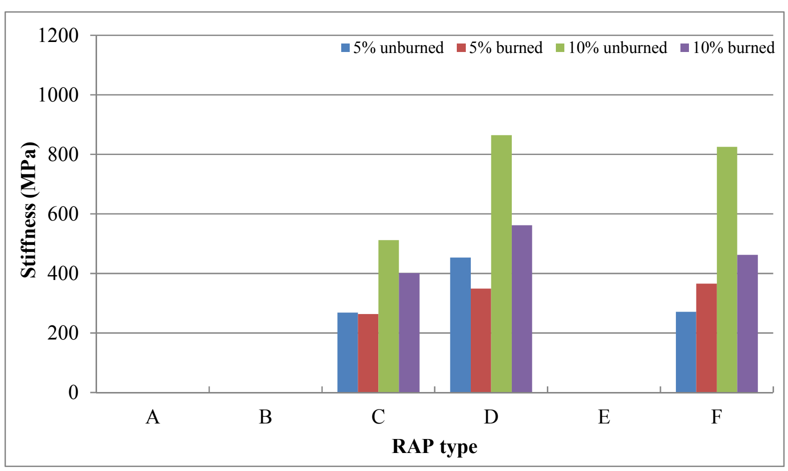
Figure 19-26: m-value comparisons of RAP sources A-F modified with RTFO binders at -6ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

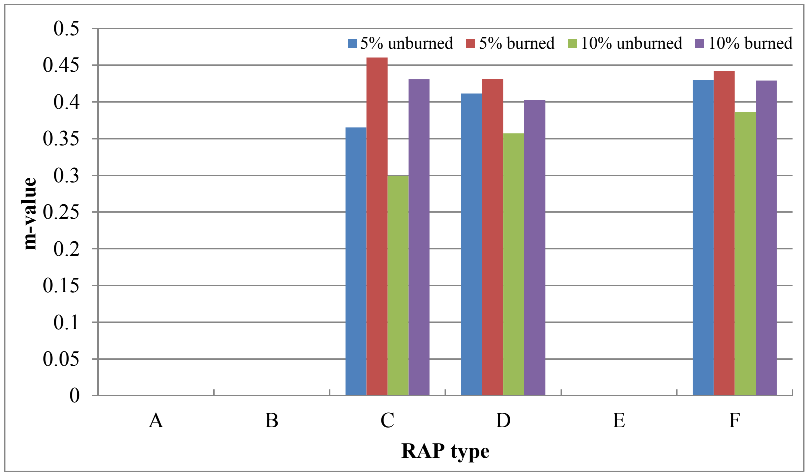


(b)

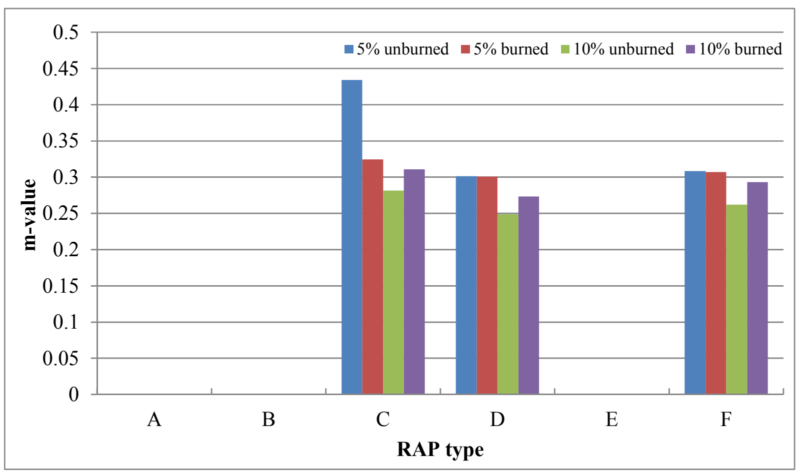


(c)

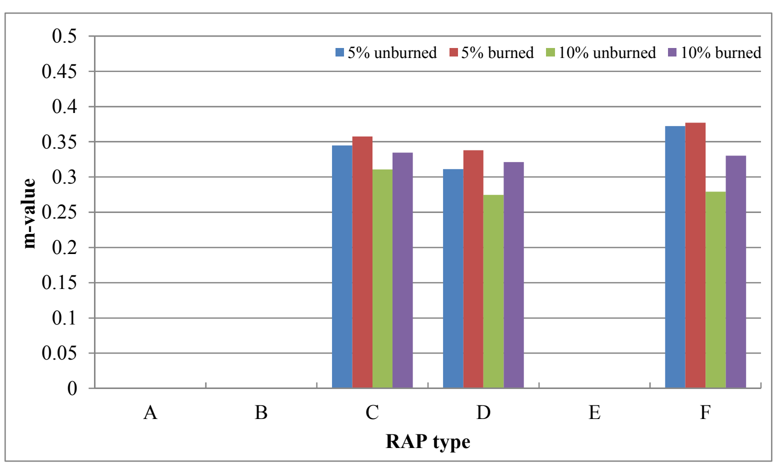
Figure 19-27: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -12ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

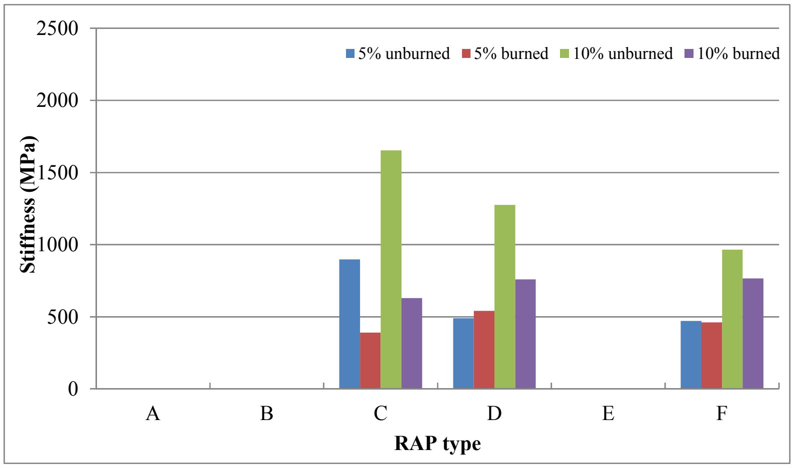


(b)

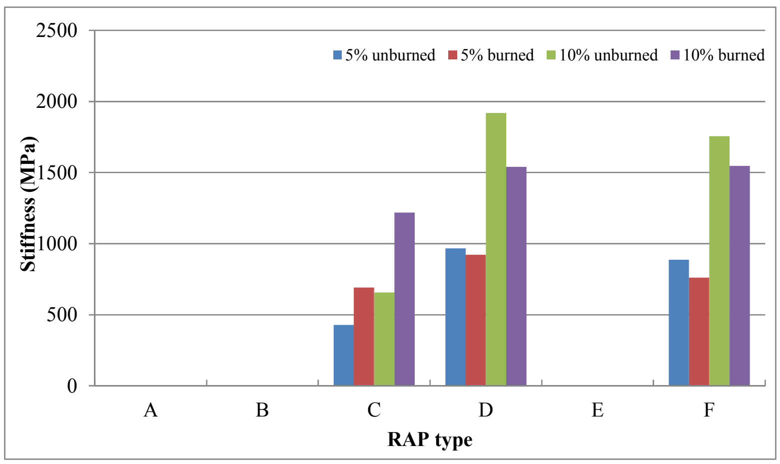


(c)

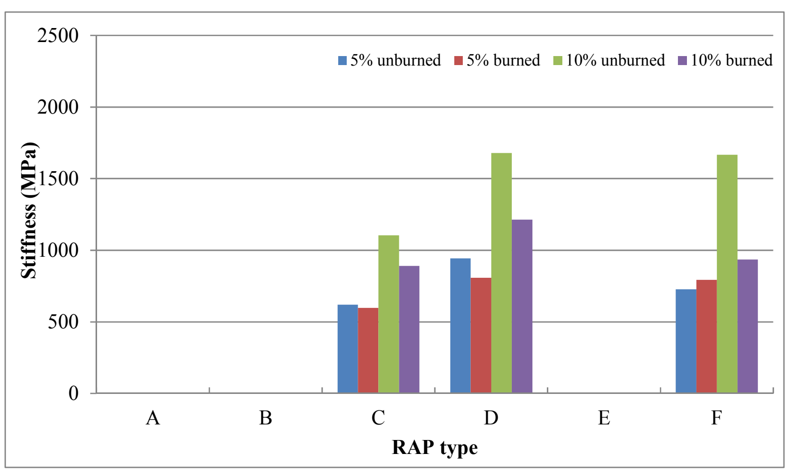
Figure 19-28: m-value comparisons of RAP sources A-F modified with RTFO binders at -12ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

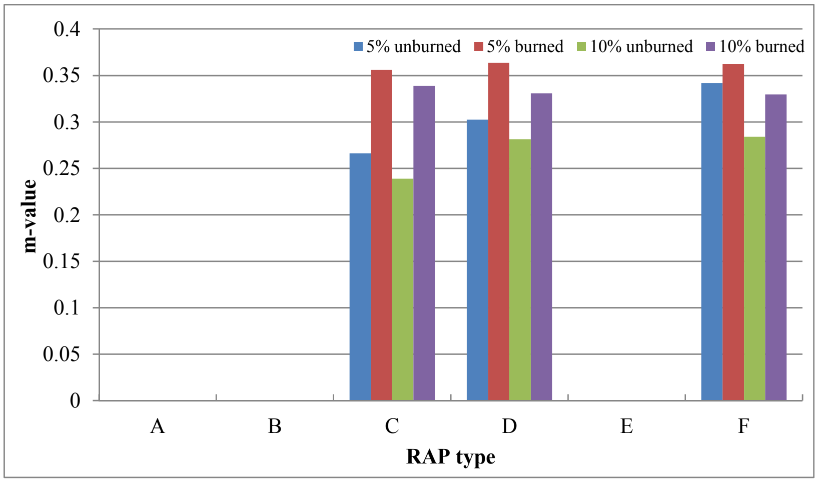


(b)

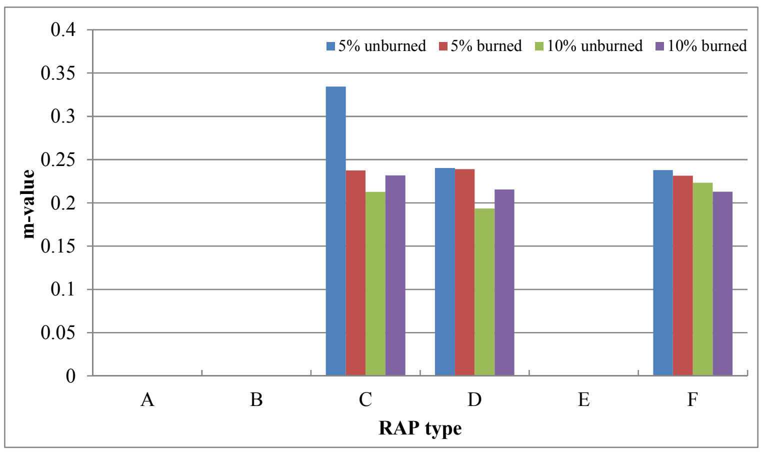


(c)

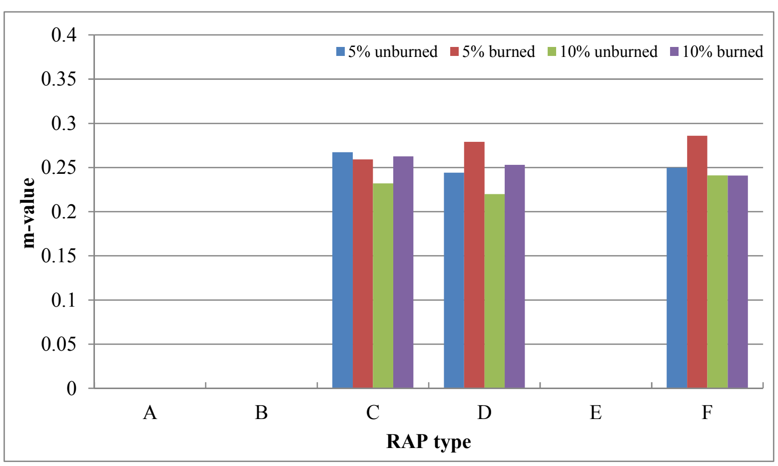
Figure 19-29: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -18^{o}C after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

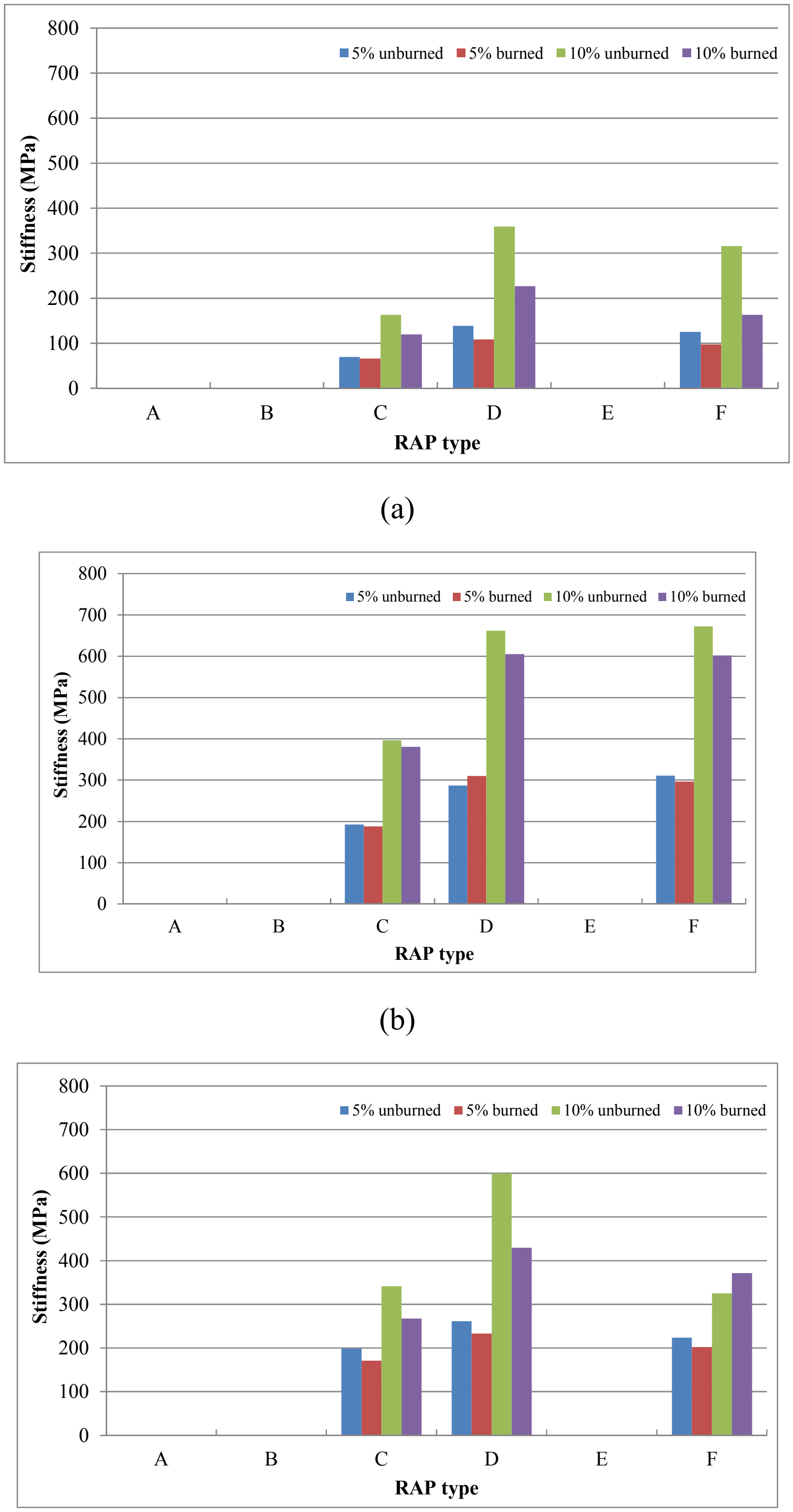


(b)



(c)

Figure 19-30: m-value comparisons of RAP sources A-F modified with RTFO binders at -18ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

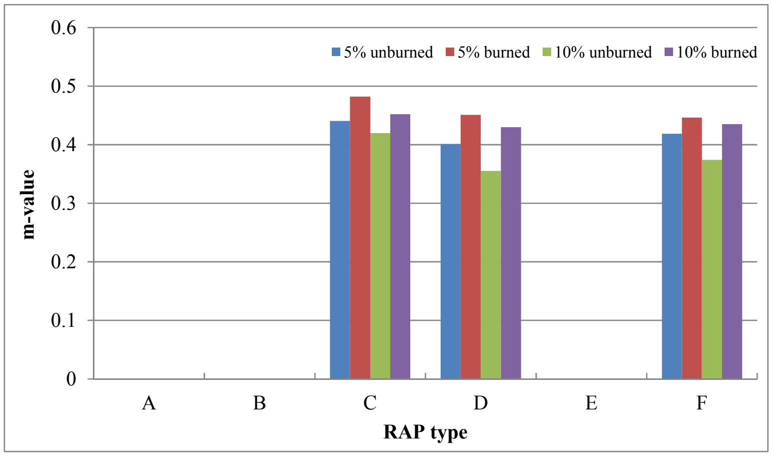


(a)

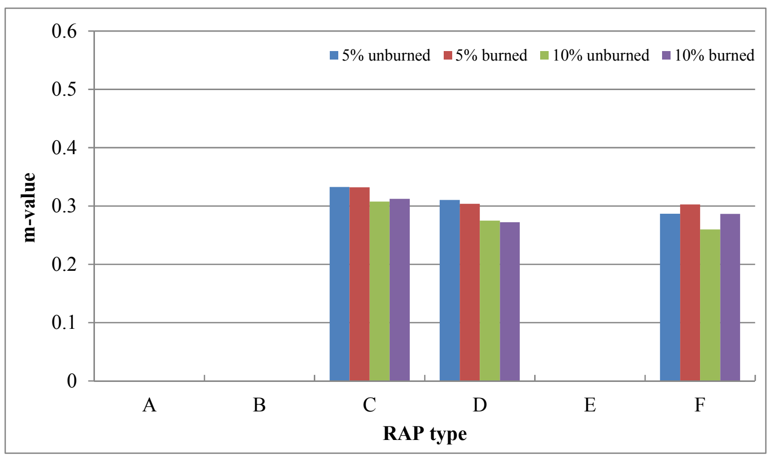
(b)

(c)

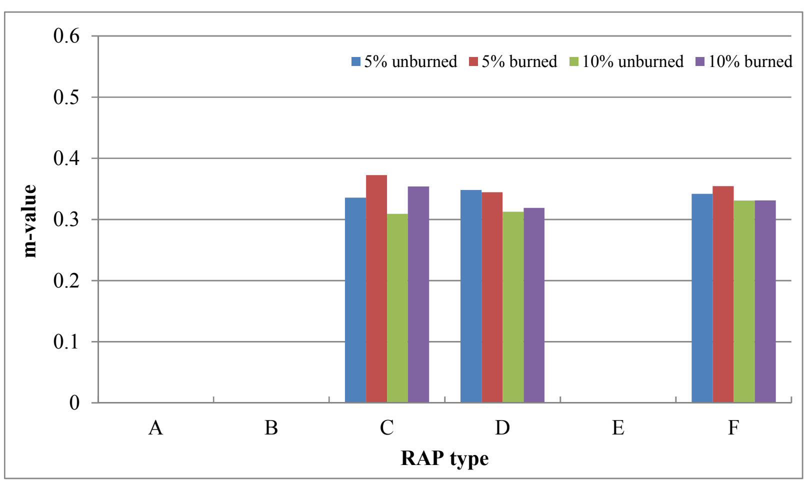
Figure 19-31: Stiffness comparisons of RAP sources A-F modified with PAV binders at -6ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

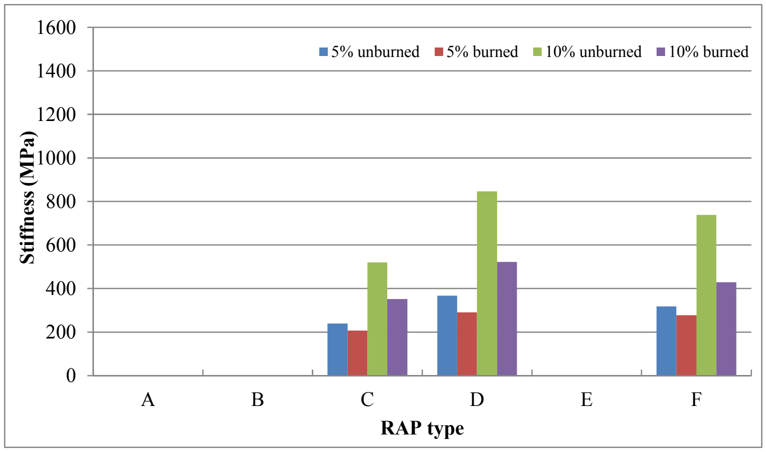


(b)



(c)

Figure 19-32: m-value comparisons of RAP sources A-F modified with PAV binders at -6ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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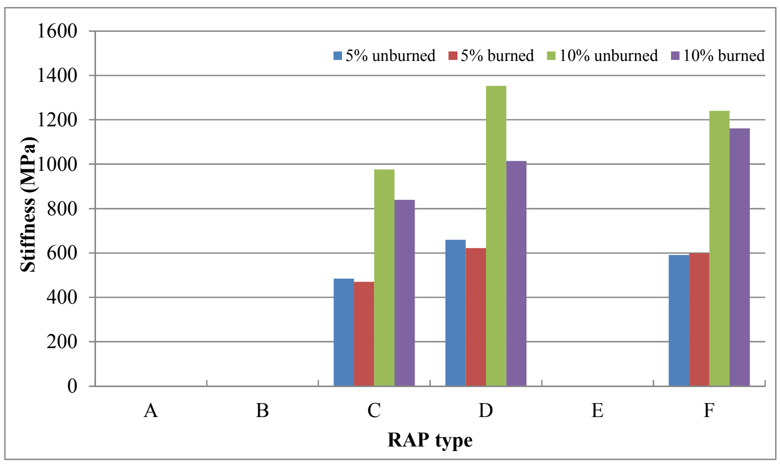

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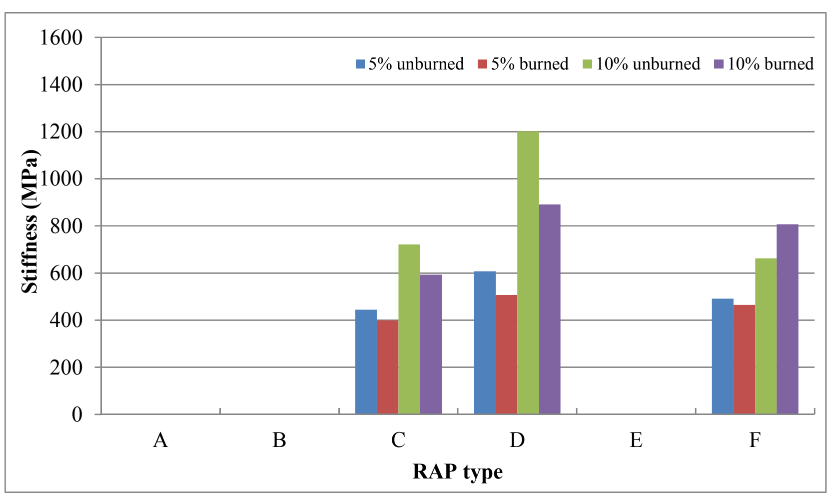
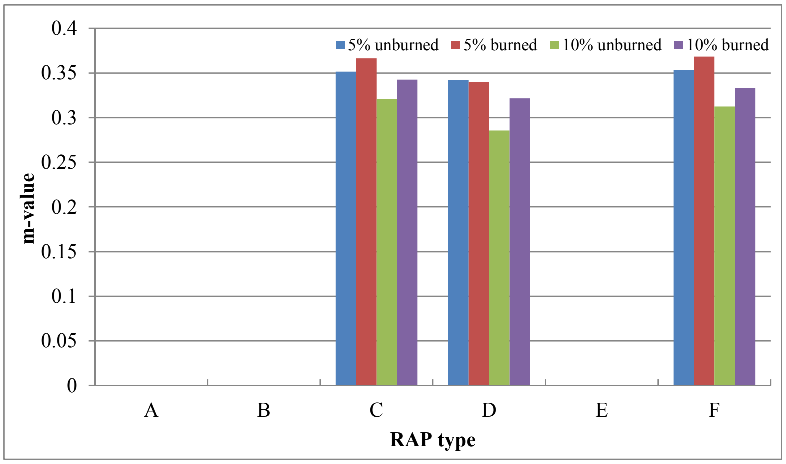
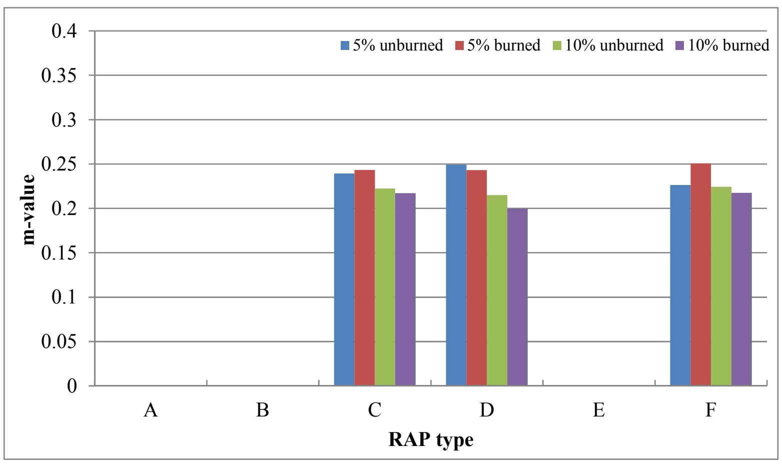


(c)

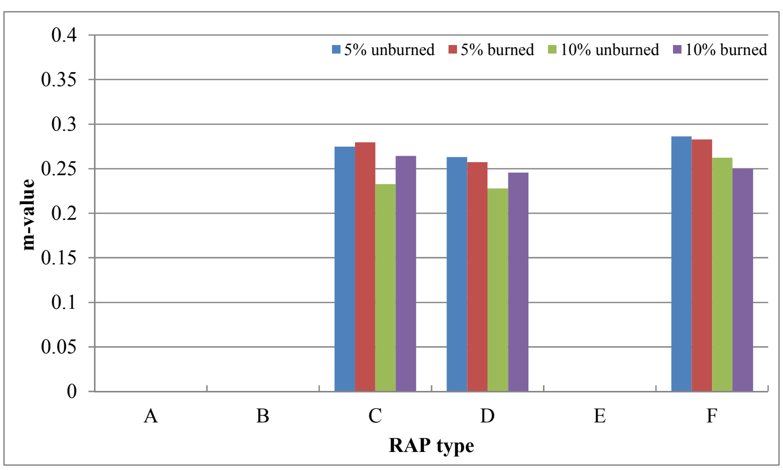
Figure 19-33: Stiffness comparisons of RAP sources A-F modified with PAV binders at -12ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

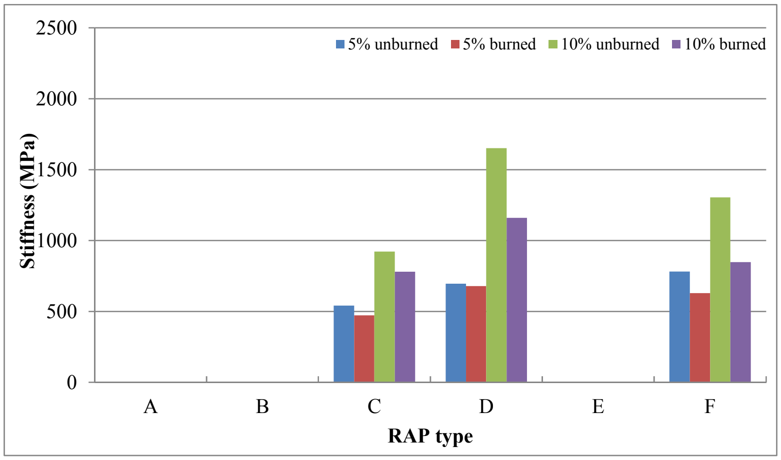


(b)



(c)

Figure 19-34: m-value comparisons of RAP sources A-F modified with PAV binders at -12ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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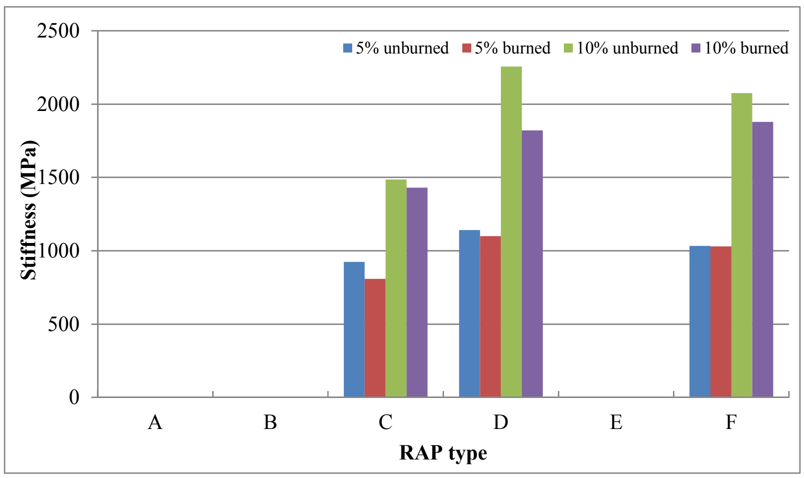
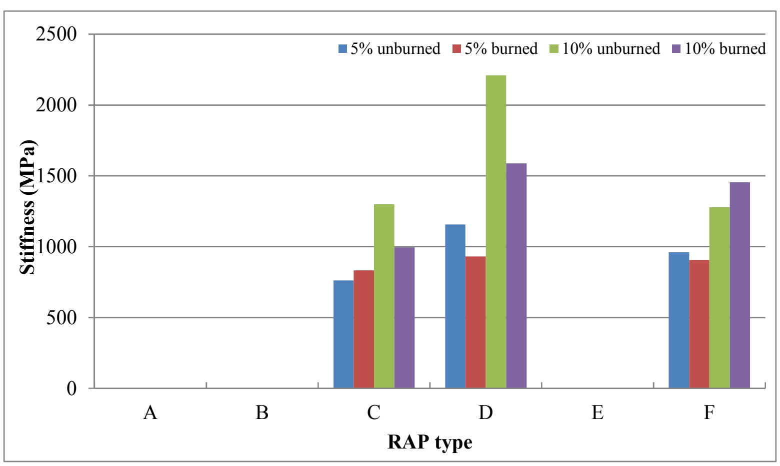
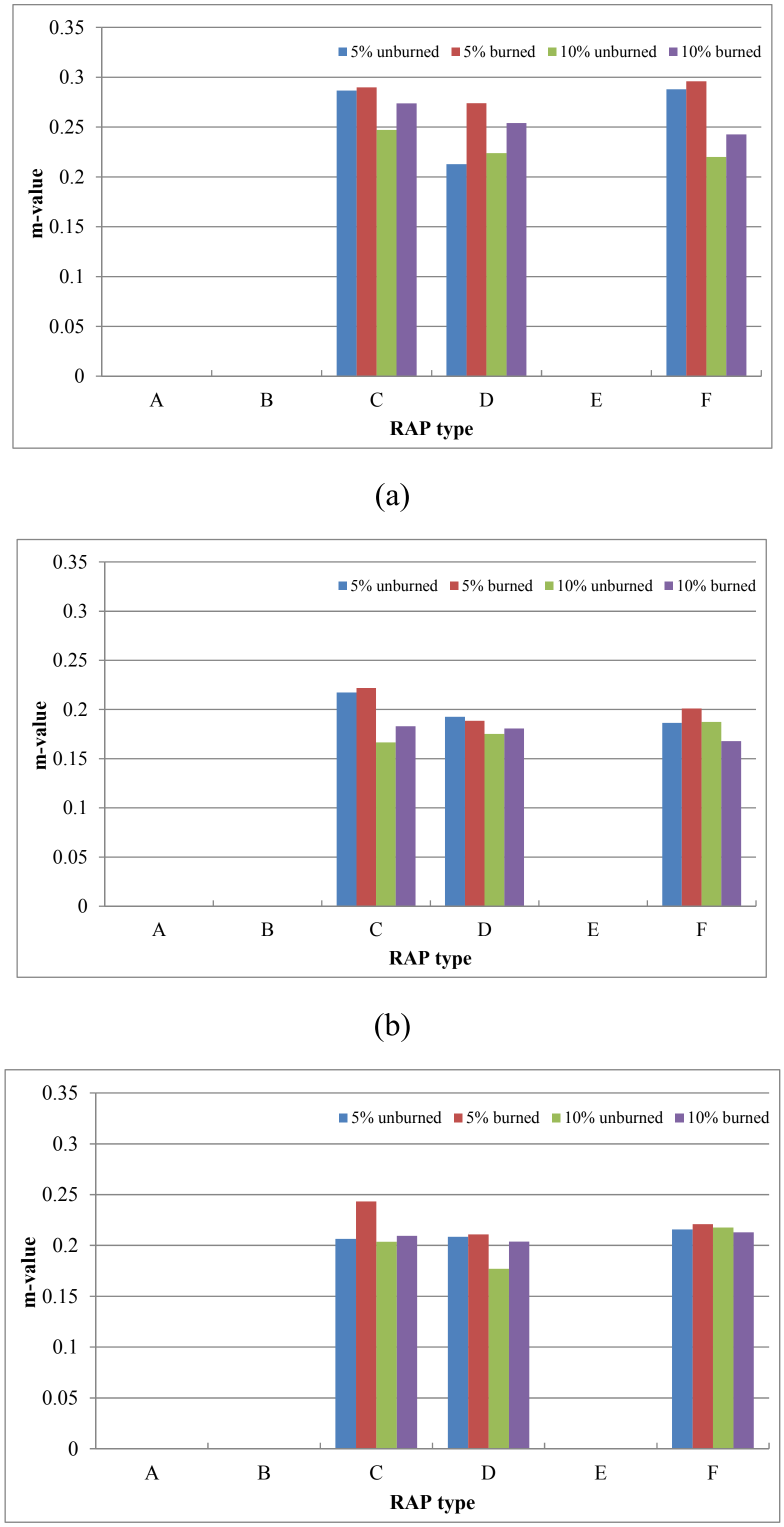


(b)



(c)

Figure 19-35: Stiffness comparisons of RAP sources A-F modified with PAV binders at -18ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

(b)

(c)

Figure 19-36: m-value comparisons of RAP sources A-F modified with PAV binders at -18ºC after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

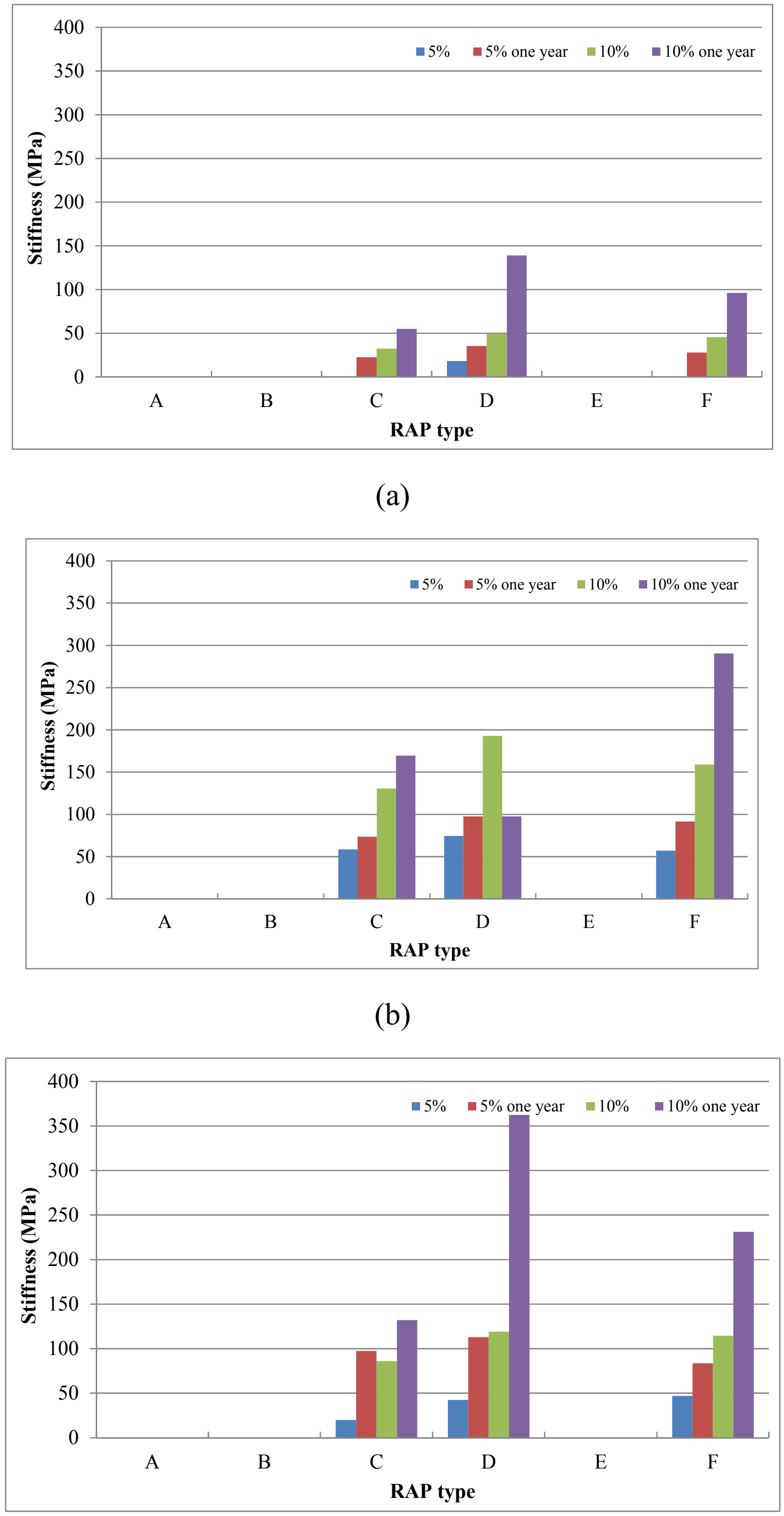
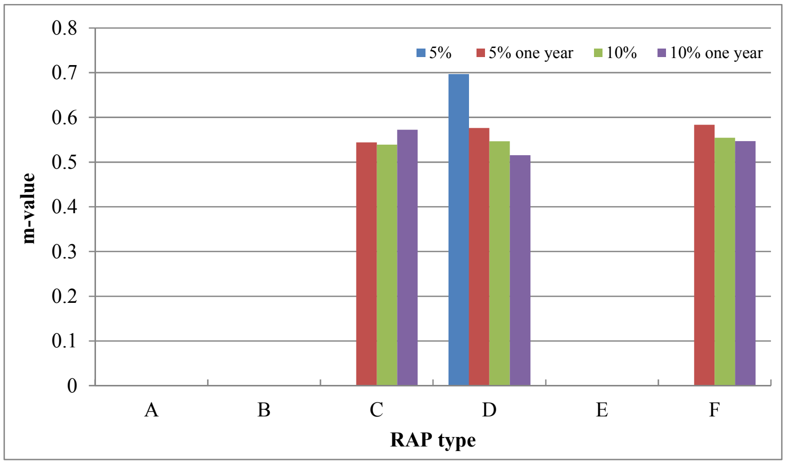
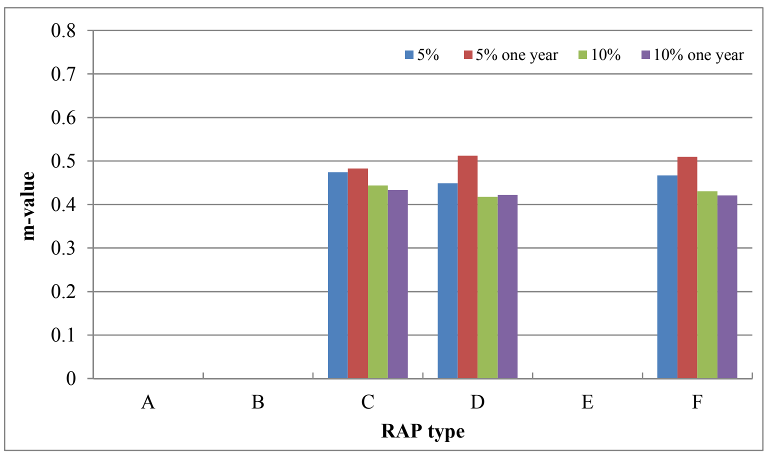


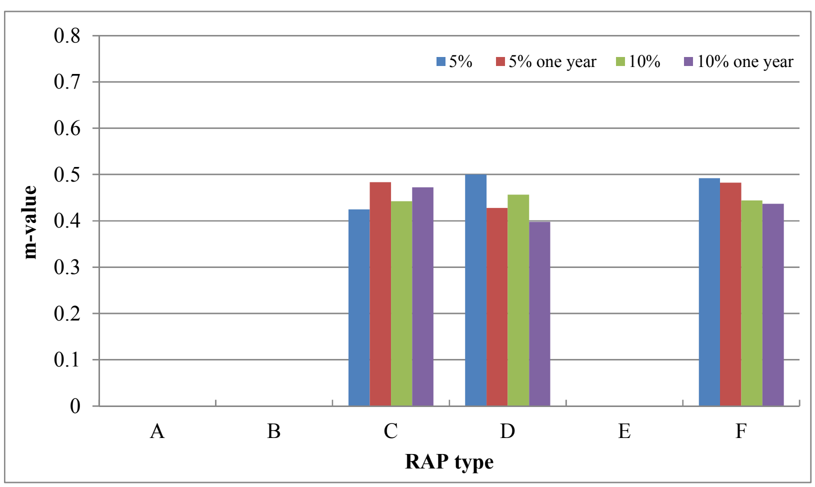
Figure 19-37: Stiffness comparisons of RAP sources A-F modified with virgin binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

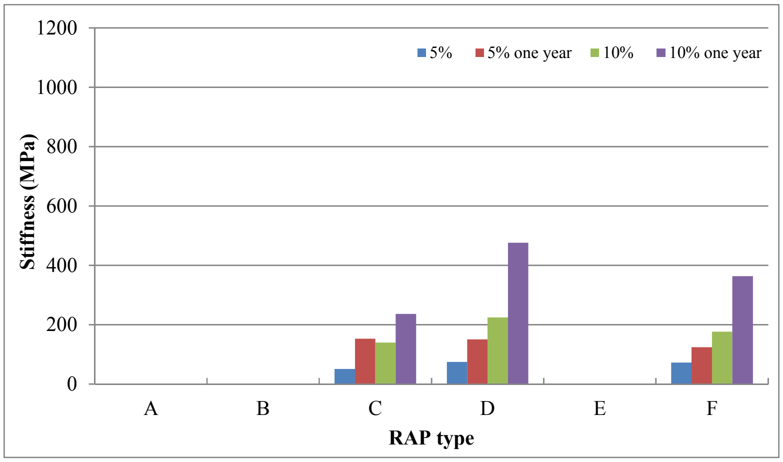


(b)

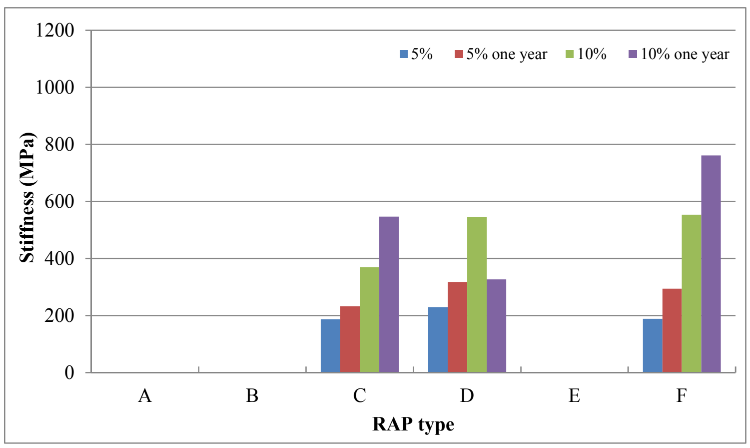


(c)

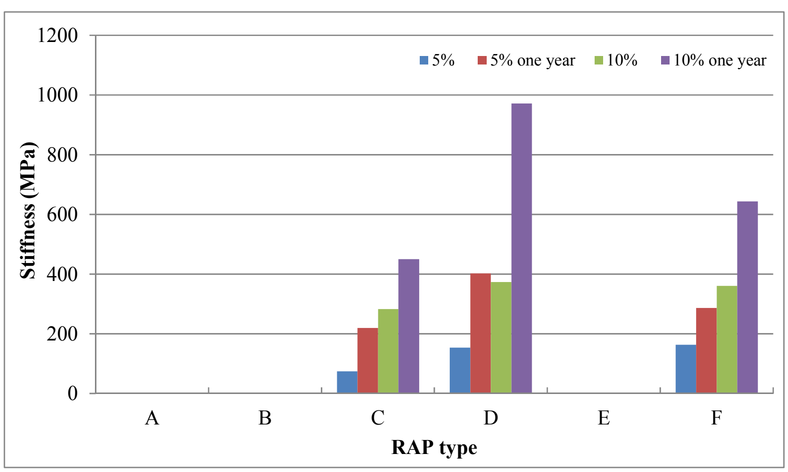
Figure 19-38: m-value comparisons of RAP sources A-F modified with virgin binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

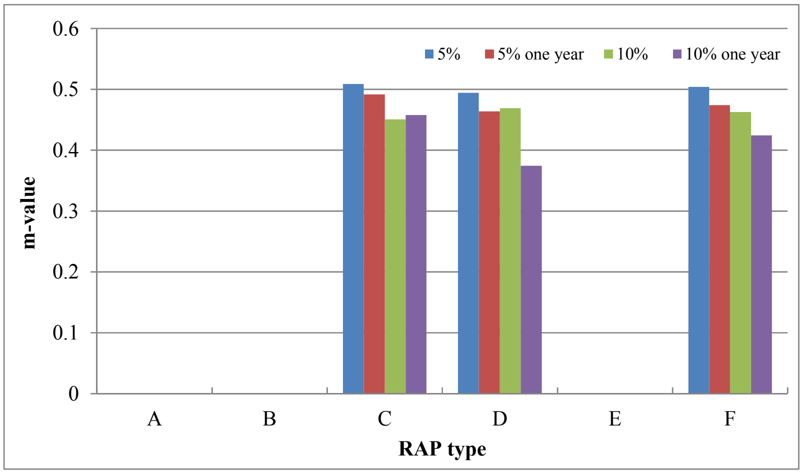


(b)

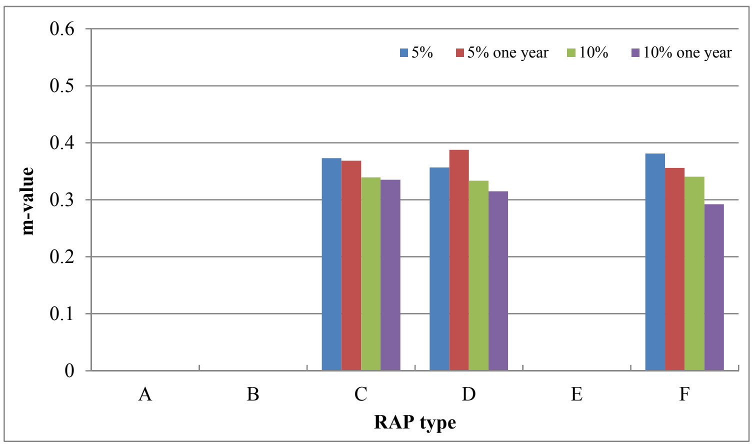


(c)

Figure 19-39: Stiffness comparisons of RAP sources A-F modified with virgin binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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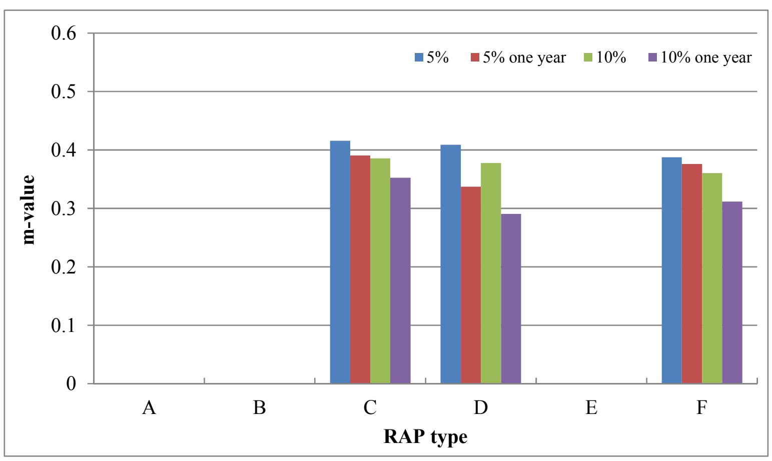
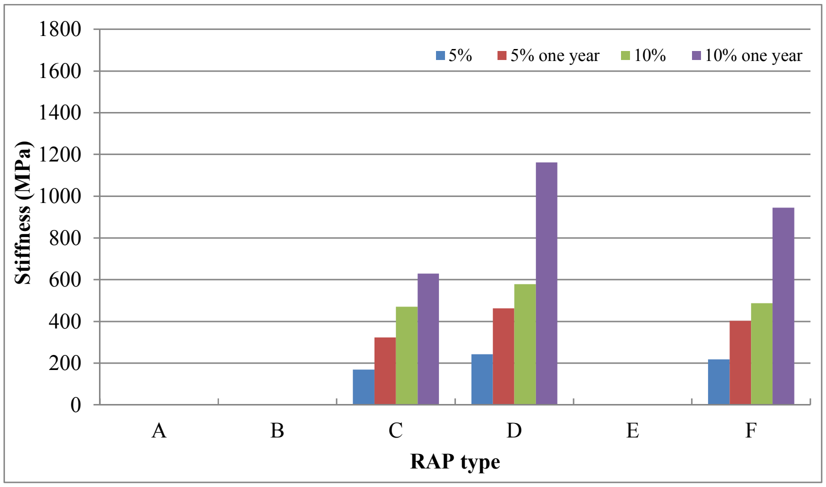
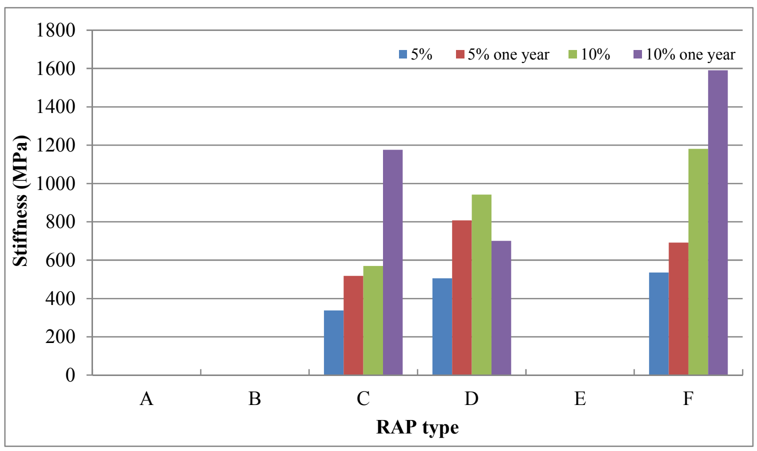


(c)

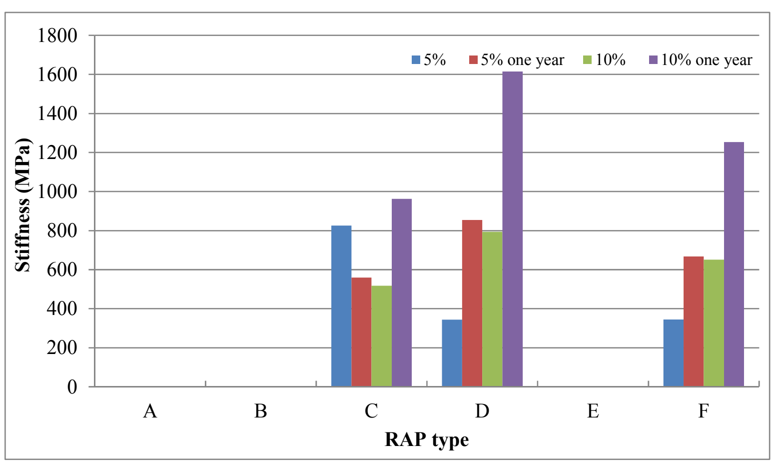
Figure 19-40: m-value comparisons of RAP sources A-F modified with virgin binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

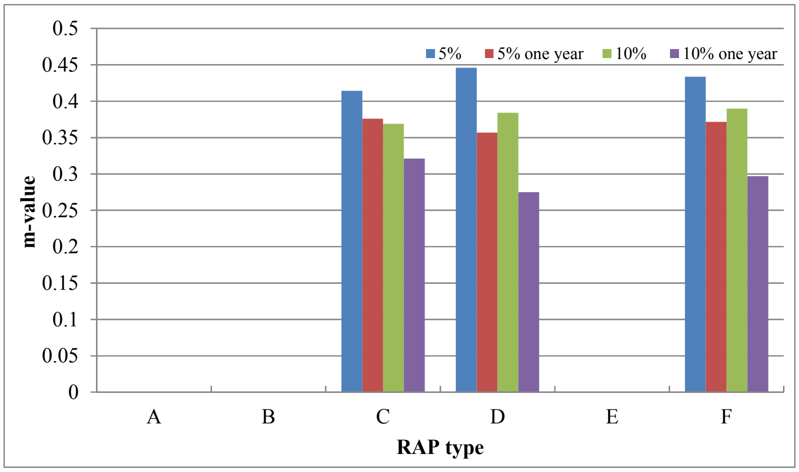


(b)

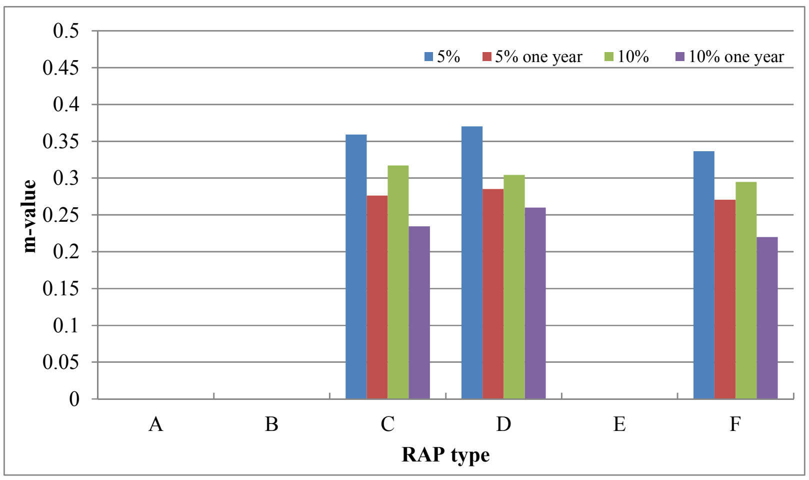


(c)

Figure 19-41: Stiffness comparisons of RAP sources A-F modified with virgin binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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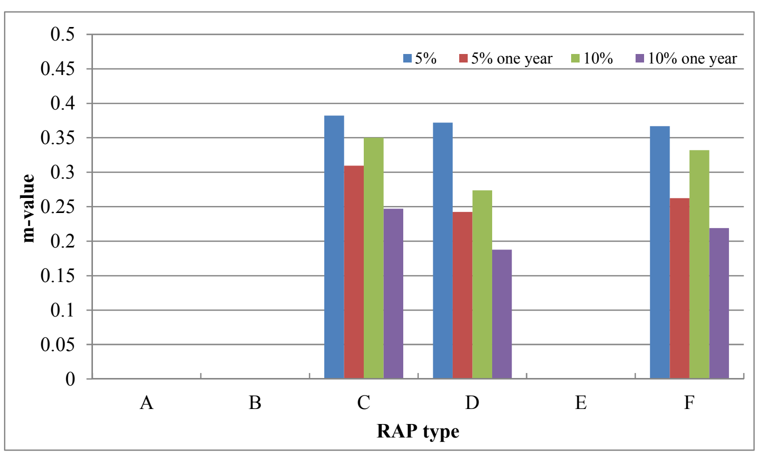
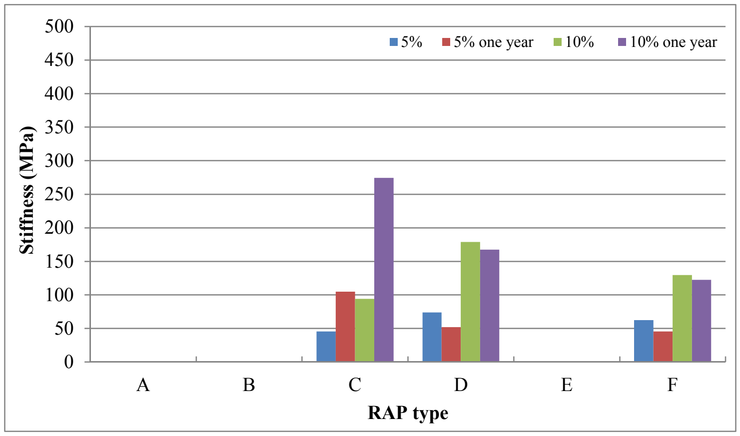


(c)

Figure 19-42: m-value comparisons of RAP sources A-F modified with virgin binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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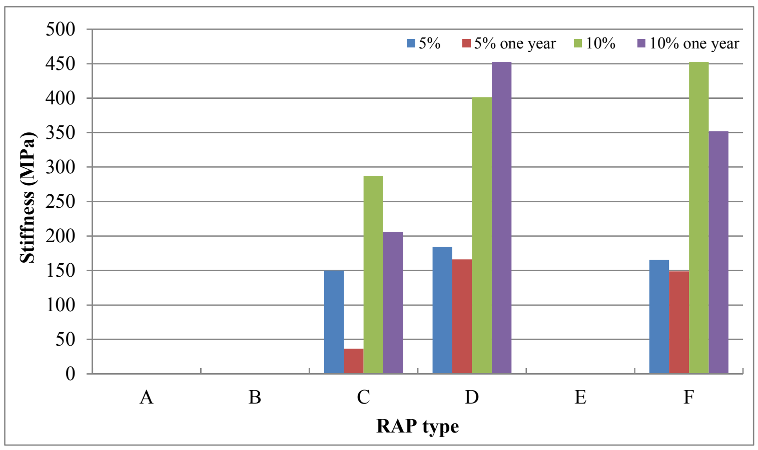

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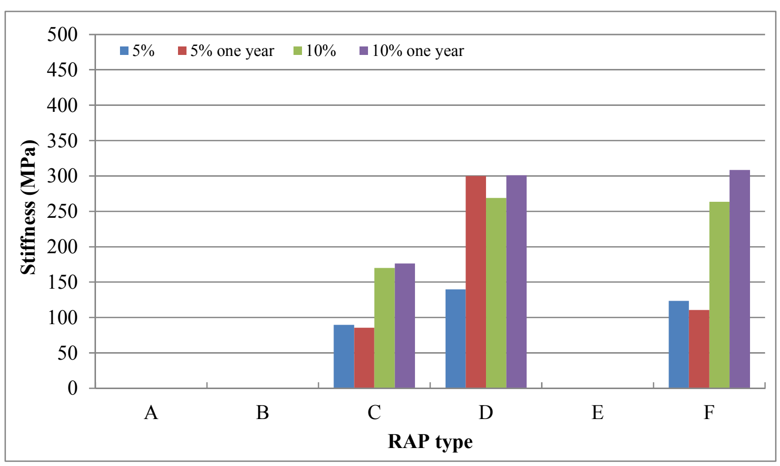
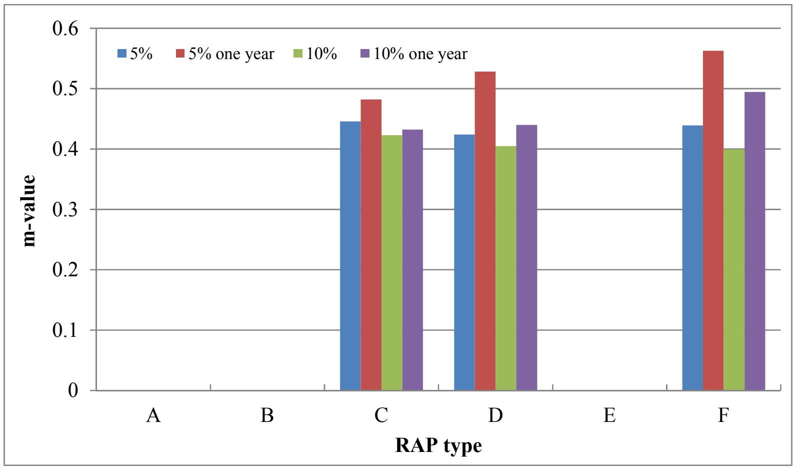
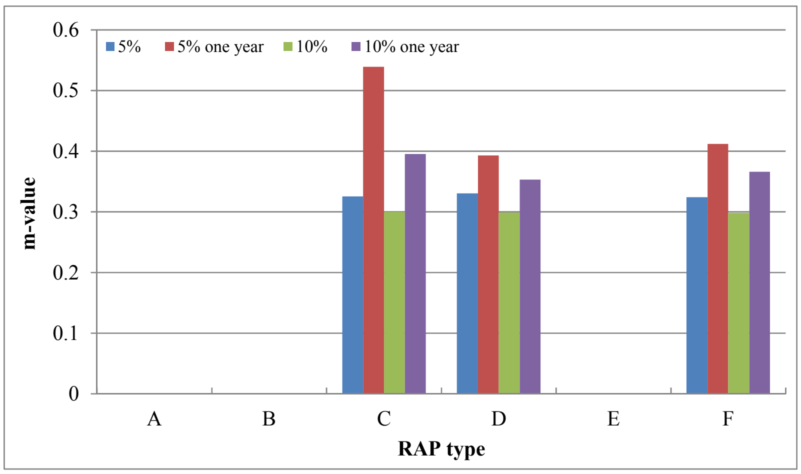


(c)

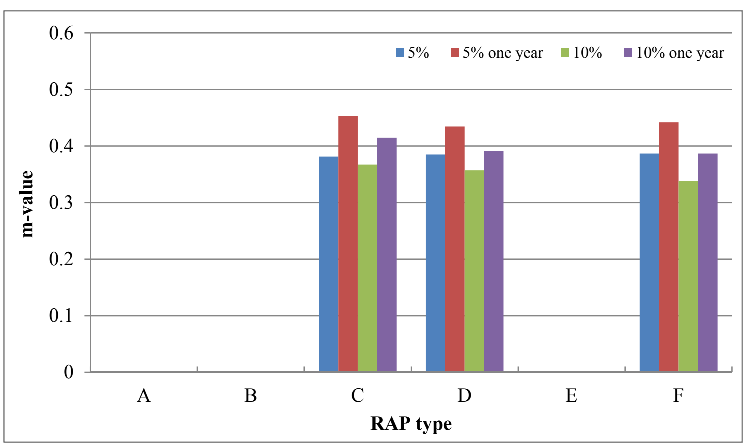
Figure 19-43: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

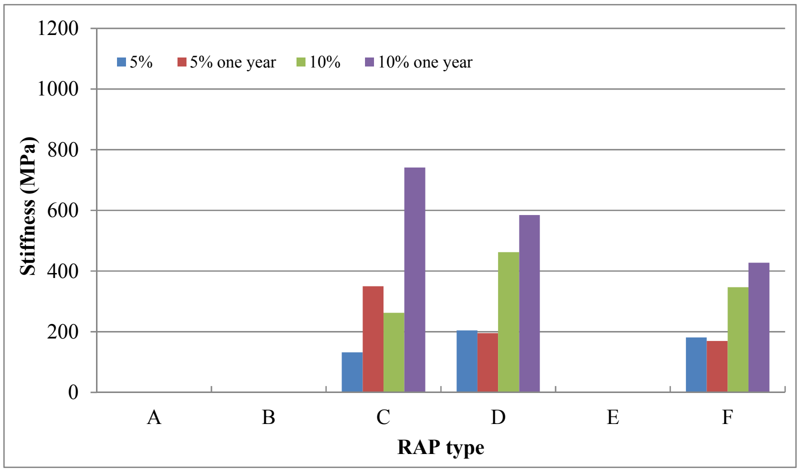


(b)

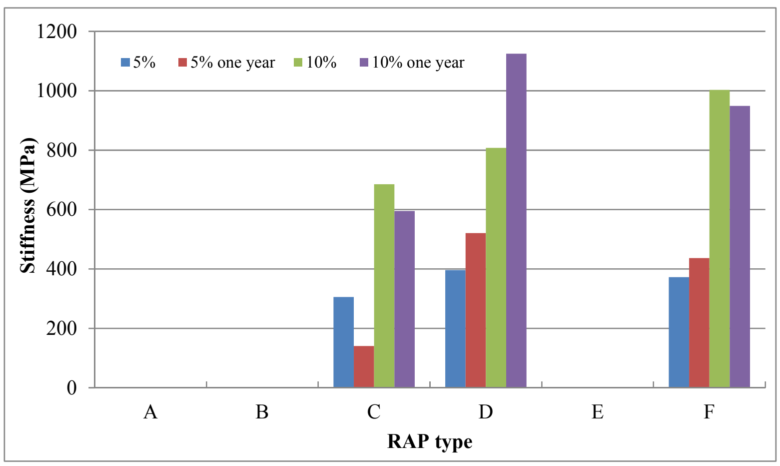


(c)

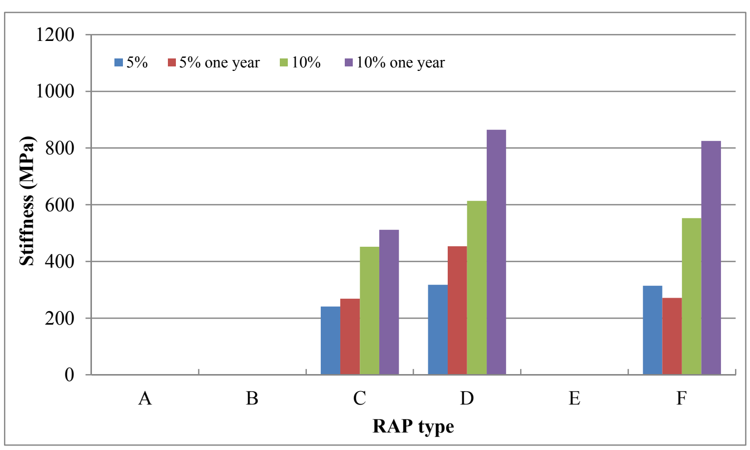
Figure 19-44: m-value comparisons of RAP sources A-F modified with RTFO binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

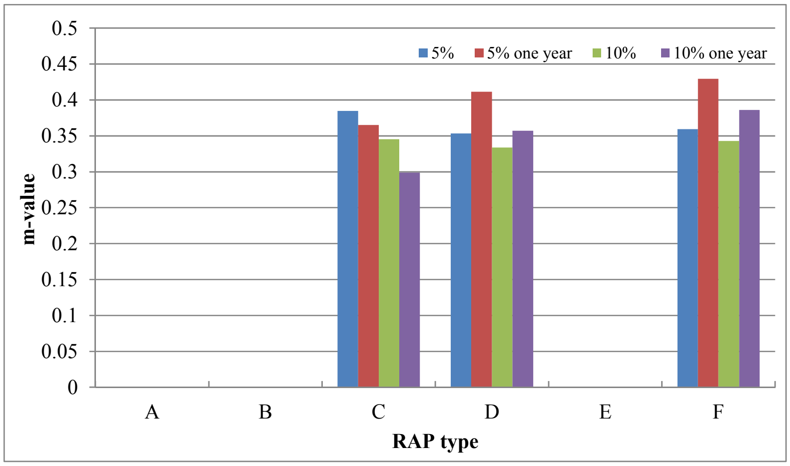


(b)

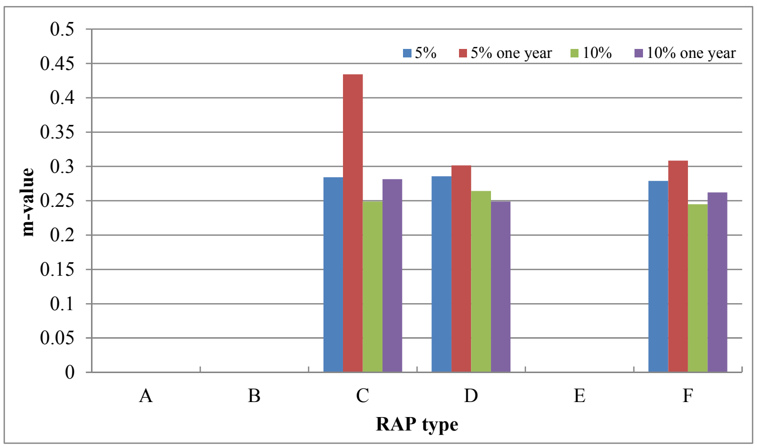


(c)

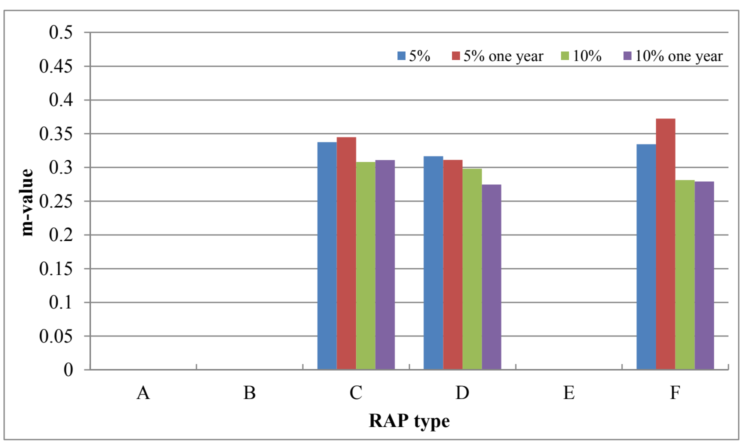
Figure 19-45: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

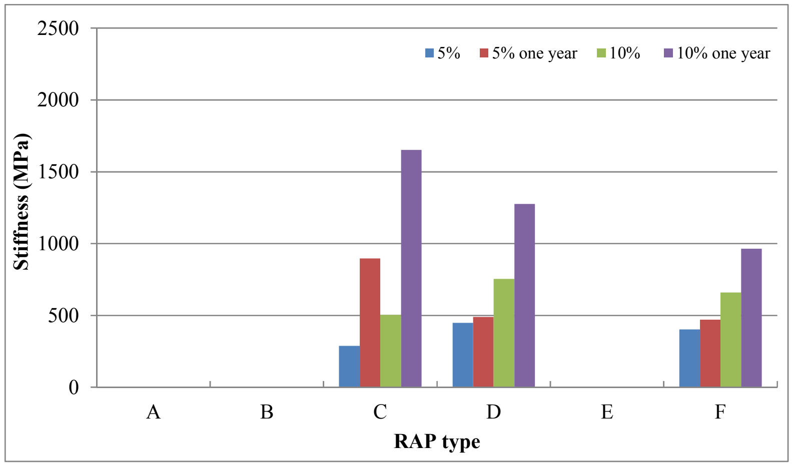


(b)

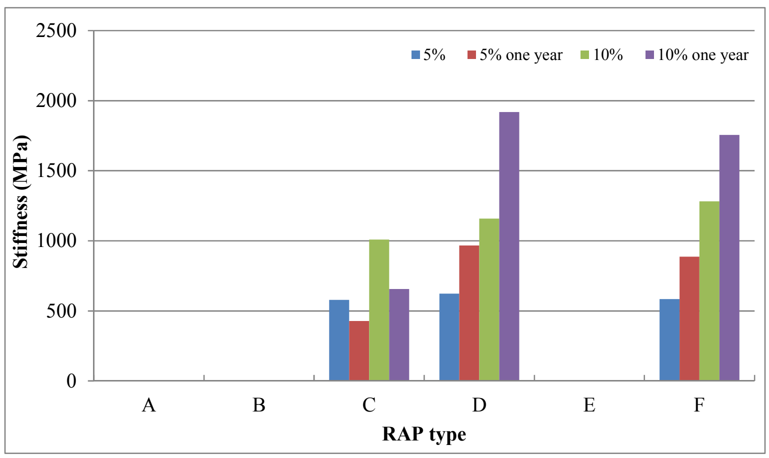


(c)

Figure 19-46: m-value comparisons of RAP sources A-F modified with RTFO binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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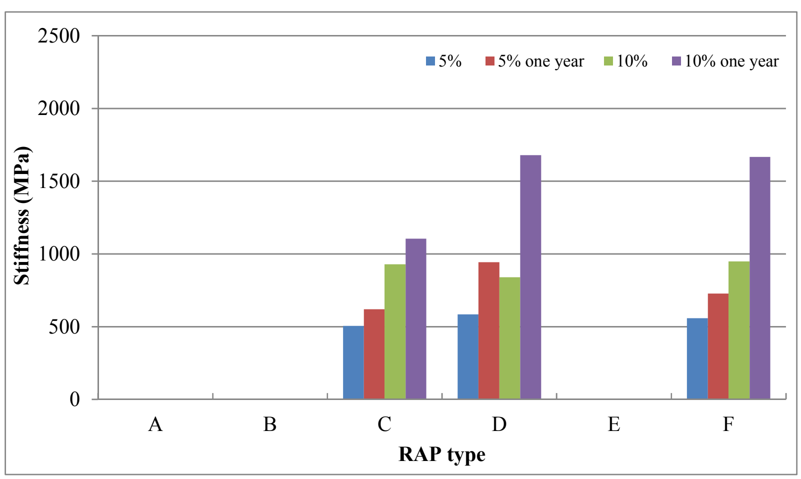
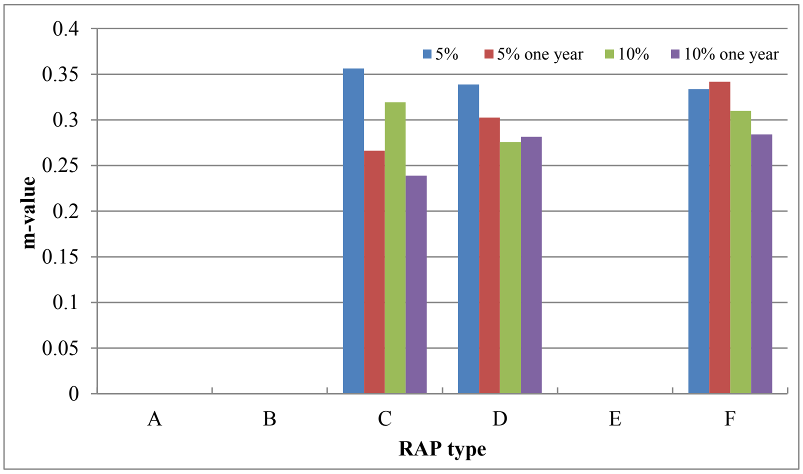
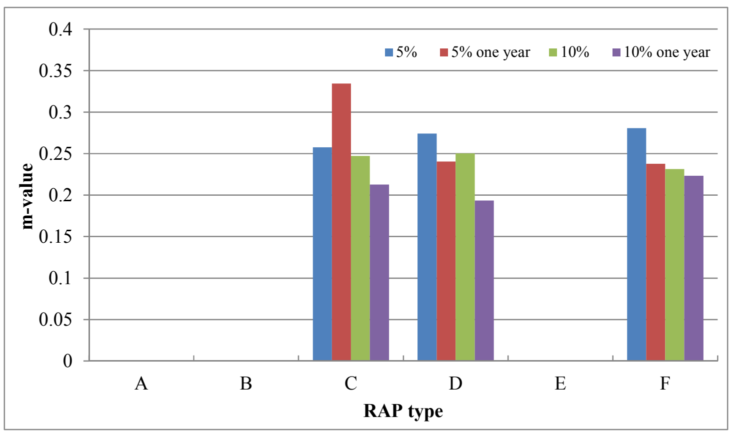


(c)

Figure 19-47: Stiffness comparisons of RAP sources A-F modified with RTFO binders at -18°C before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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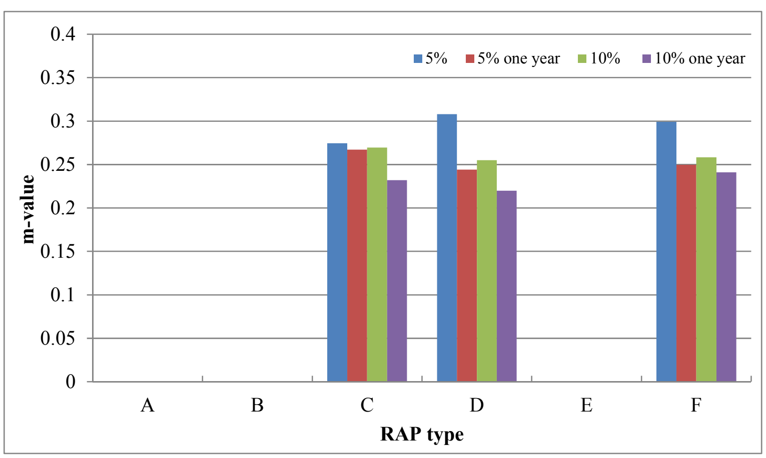
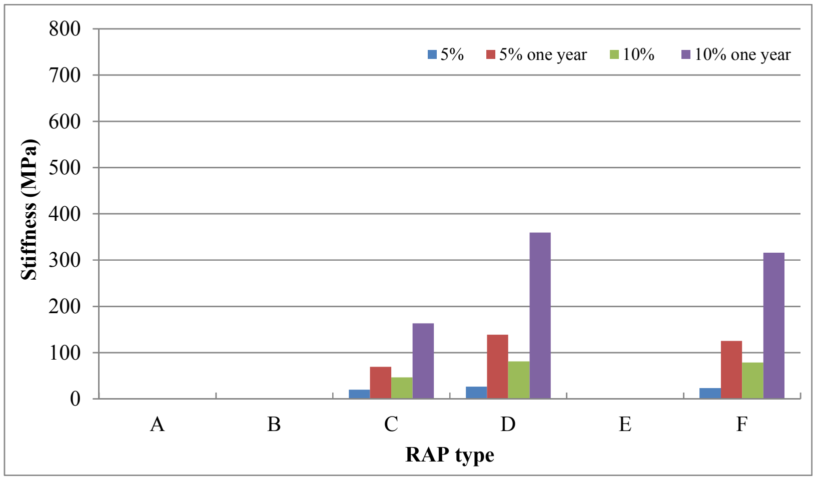
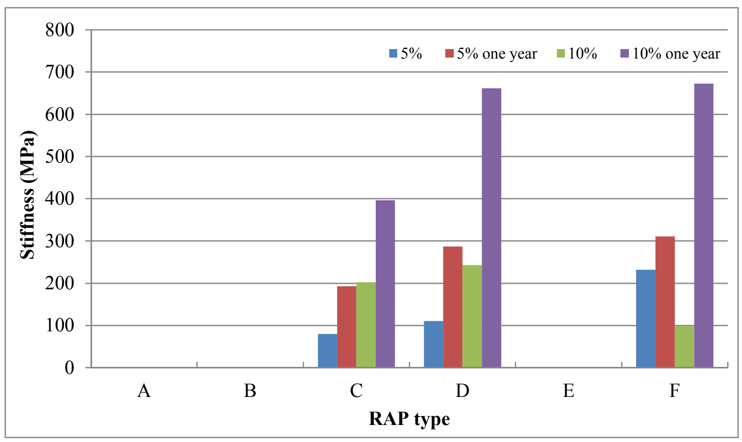


(c)

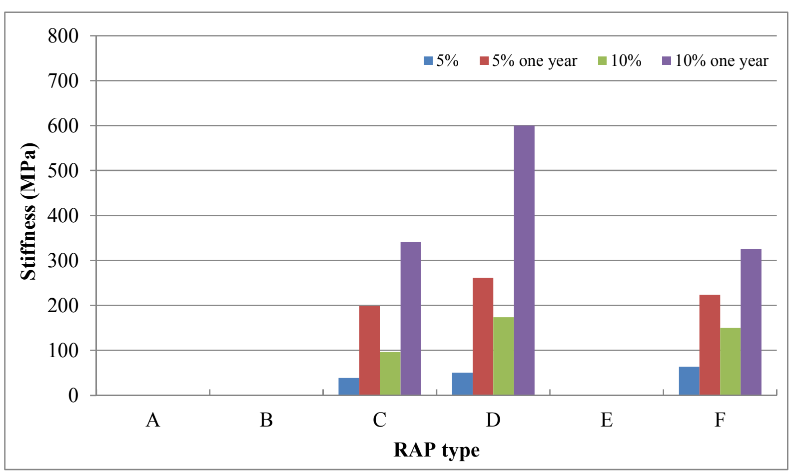
Figure 19-48: m-value comparisons of RAP sources A-F modified with RTFO binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

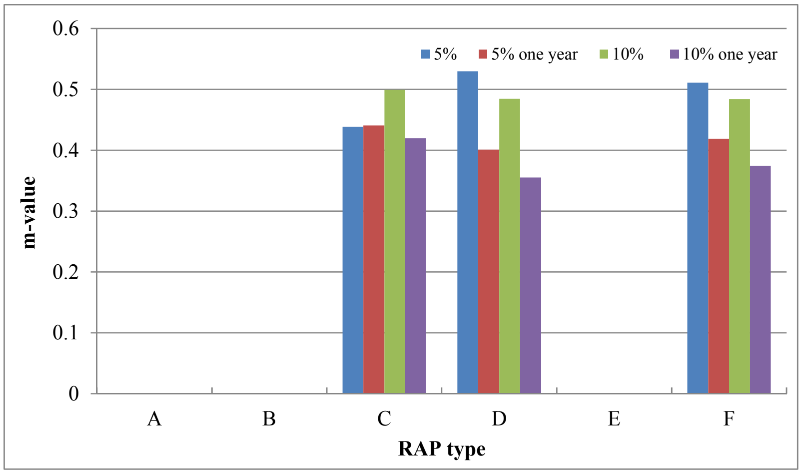


(b)

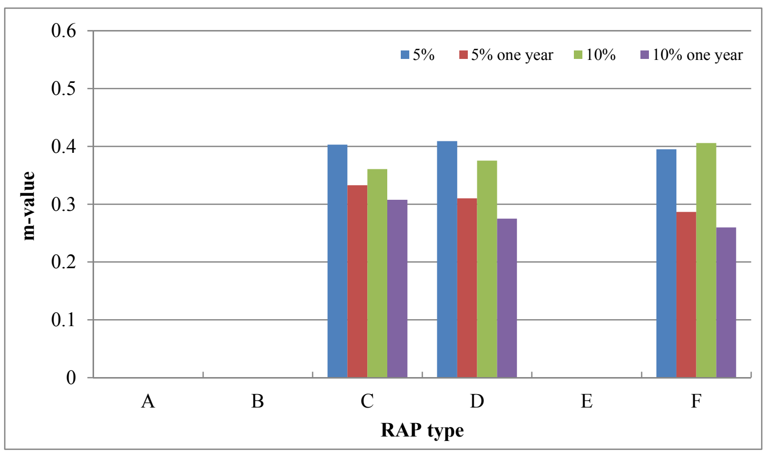


(c)

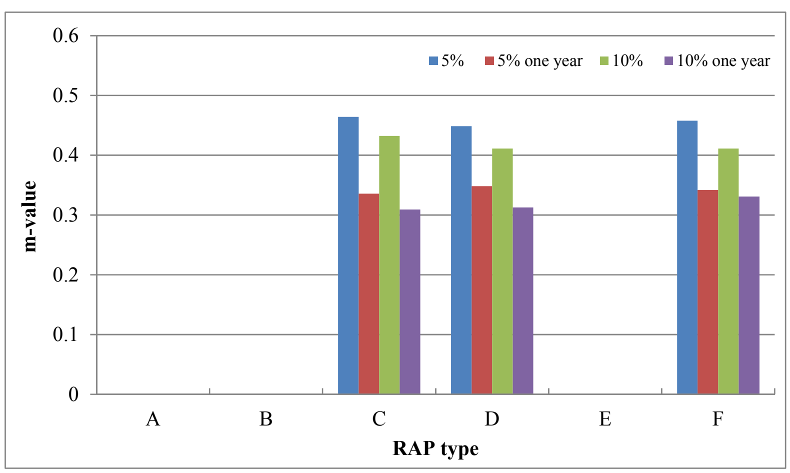
Figure 19-49: Stiffness comparisons of RAP sources A-F modified with PAV binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

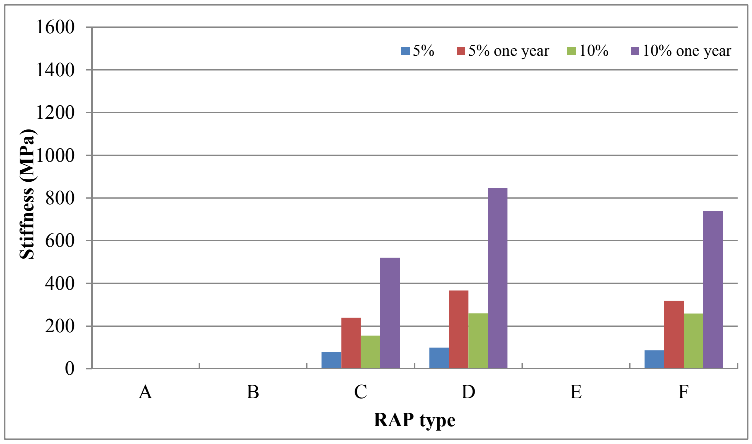


(b)

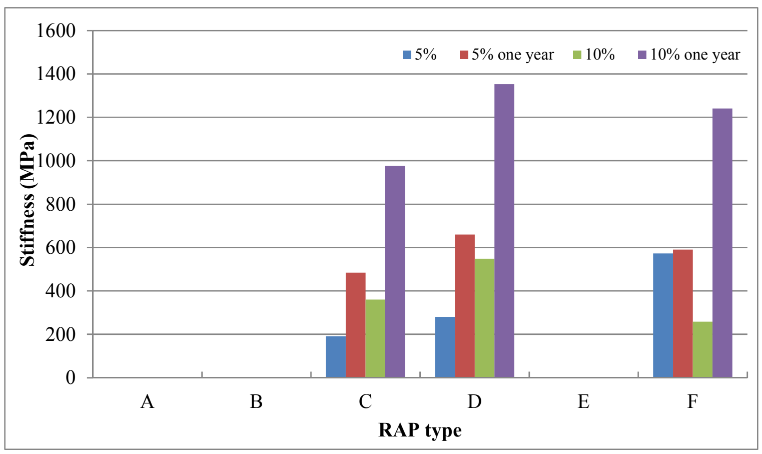


(c)

Figure 19-50: m-value comparisons of RAP sources A-F modified with PAV binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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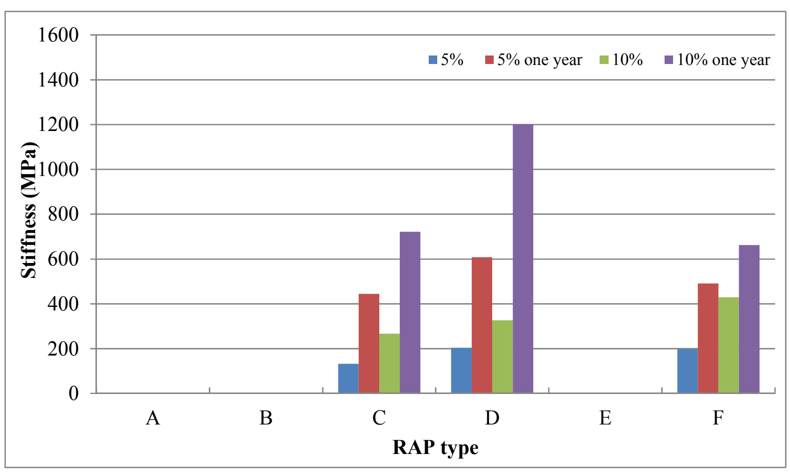
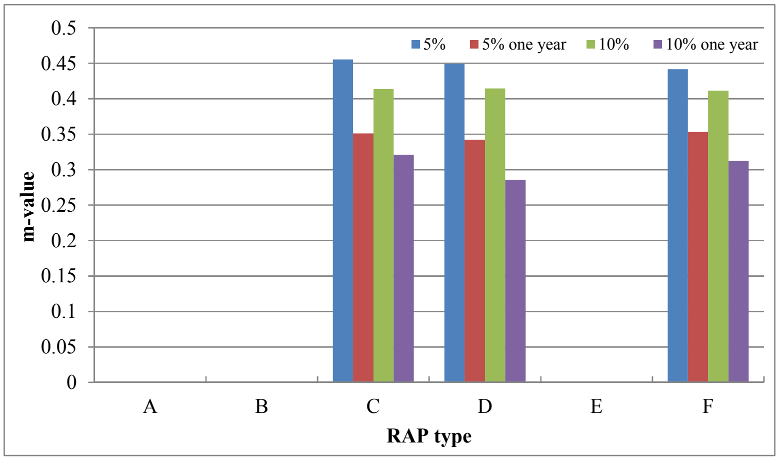
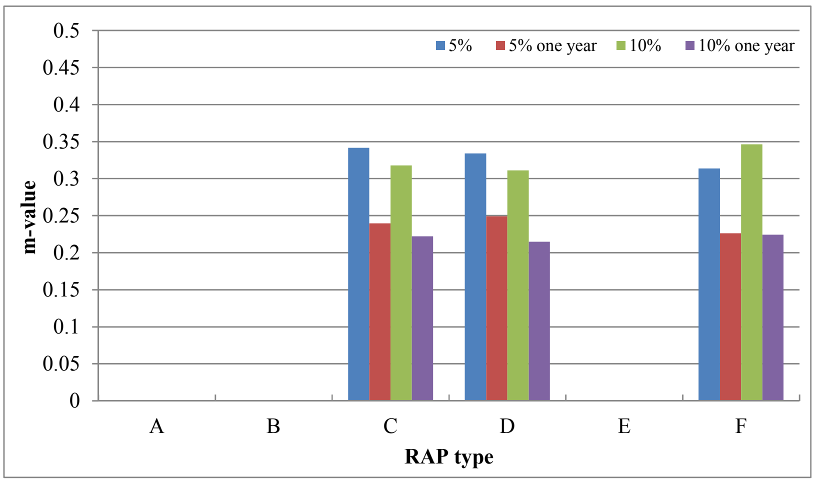


(c)

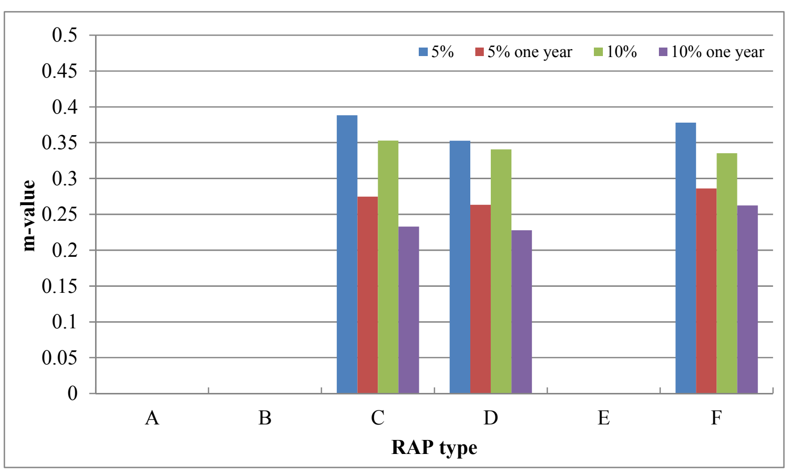
Figure 19-51: Stiffness comparisons of RAP sources A-F modified with PAV binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

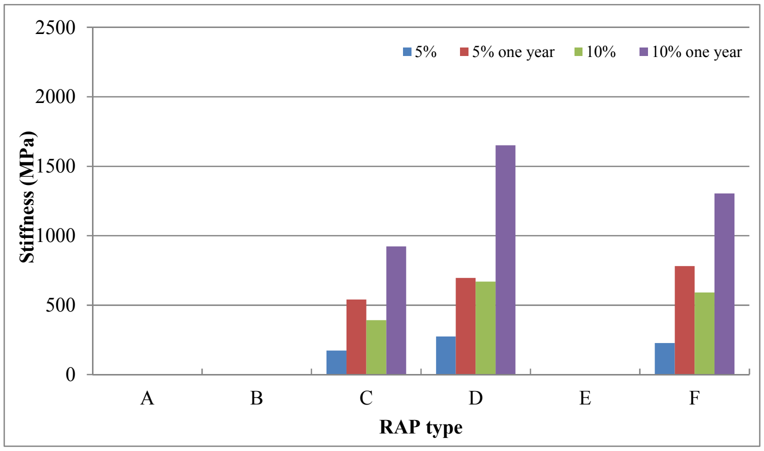


(b)

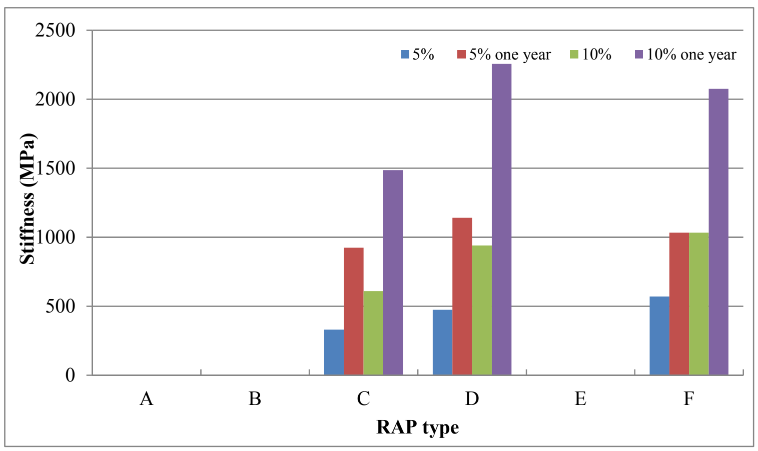


(c)

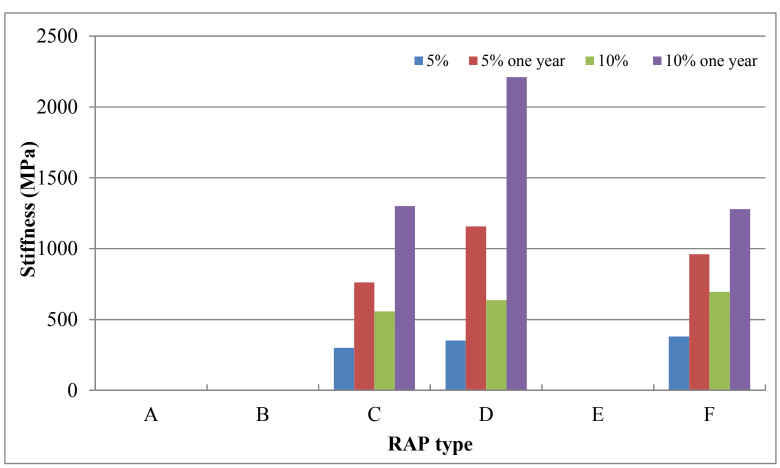
Figure 19-52: m-value comparisons of RAP sources A-F modified with PAV binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

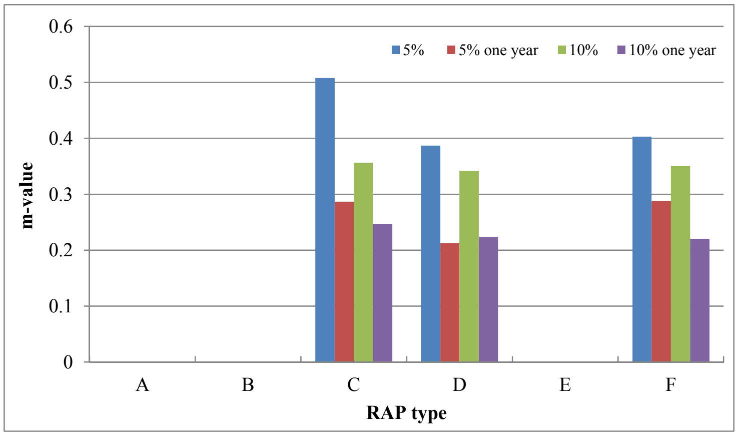


(b)

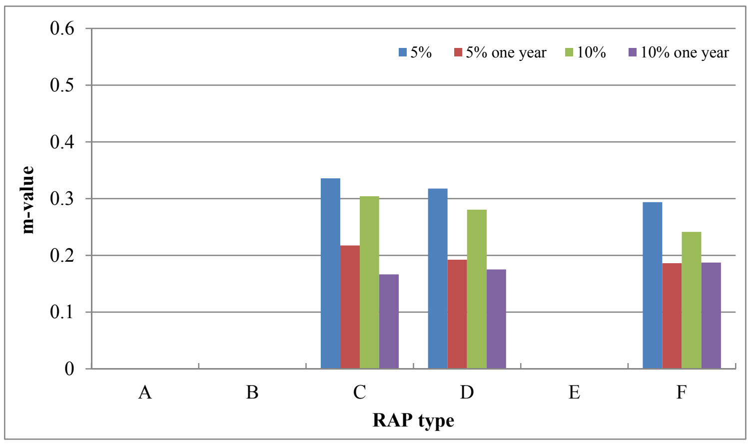


(c)

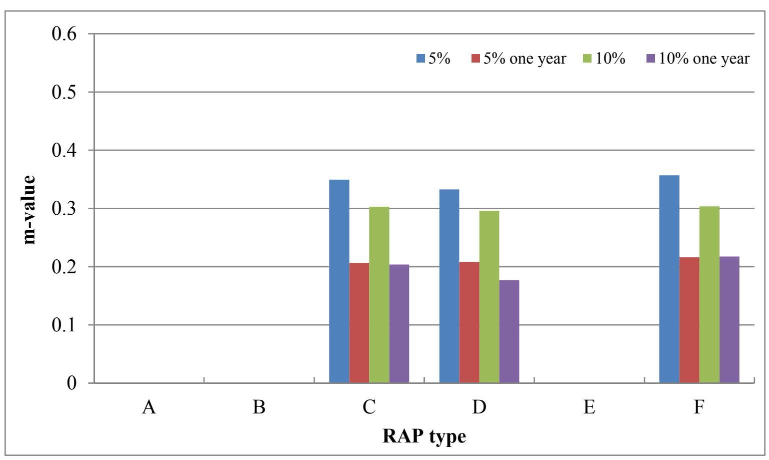
Figure 19-53: Stiffness comparisons of RAP sources A-F modified with PAV binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

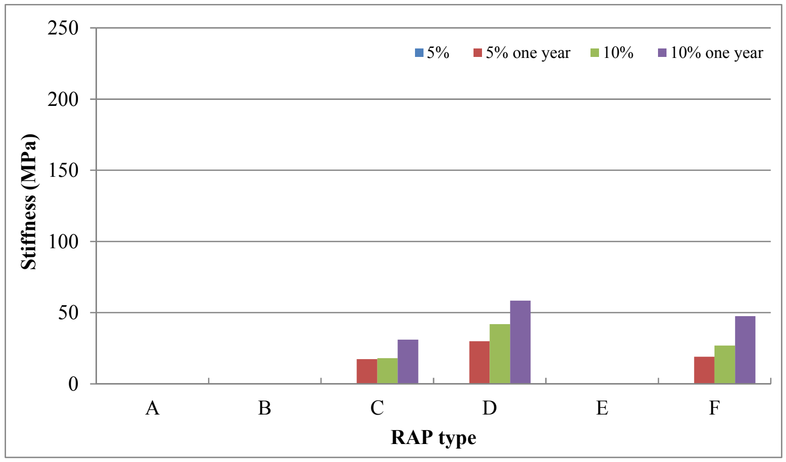


(b)



(c)

Figure 19-54: m-value comparisons of RAP sources A-F modified with PAV binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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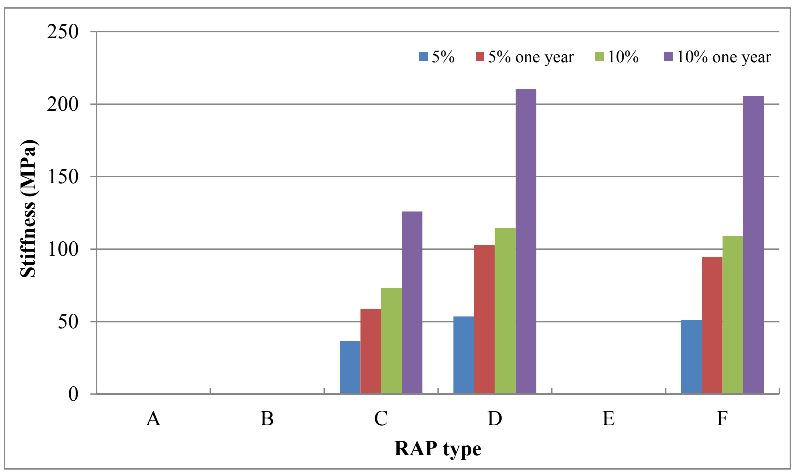

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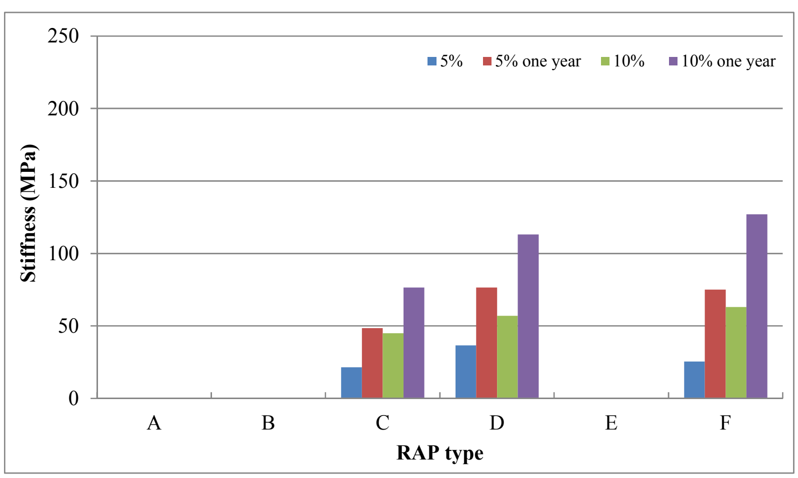
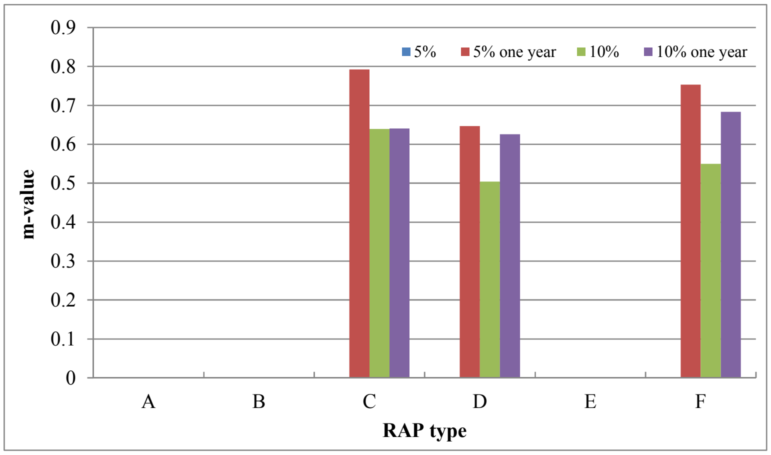


(c)

Figure 19-55: Stiffness comparisons of burned RAP sources A-F modified with virgin binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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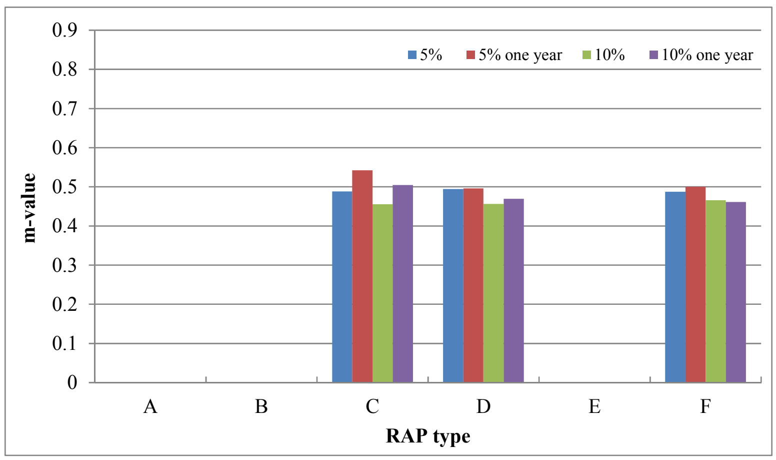

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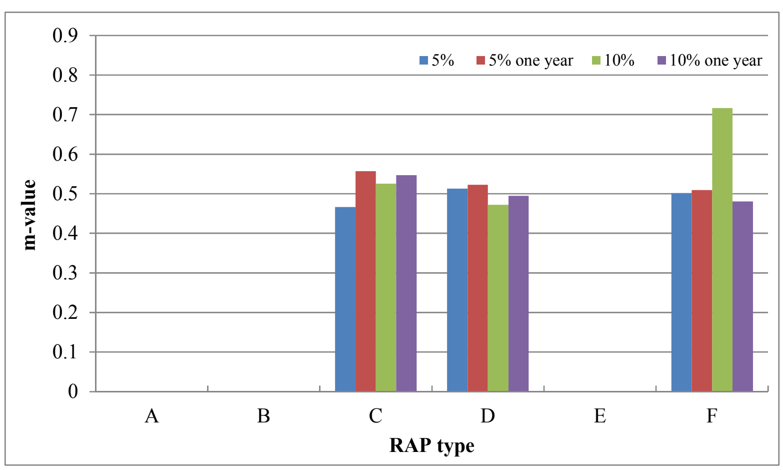
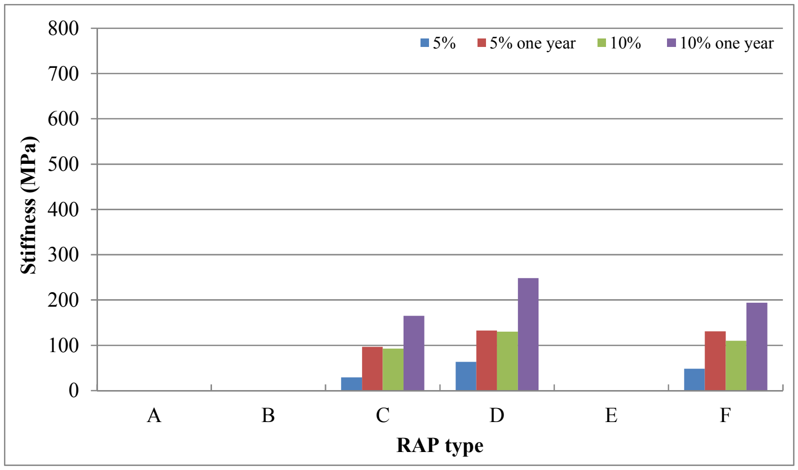


(c)

Figure 19-56: m-value comparisons of burned RAP sources A-F modified with virgin binders at -6°C before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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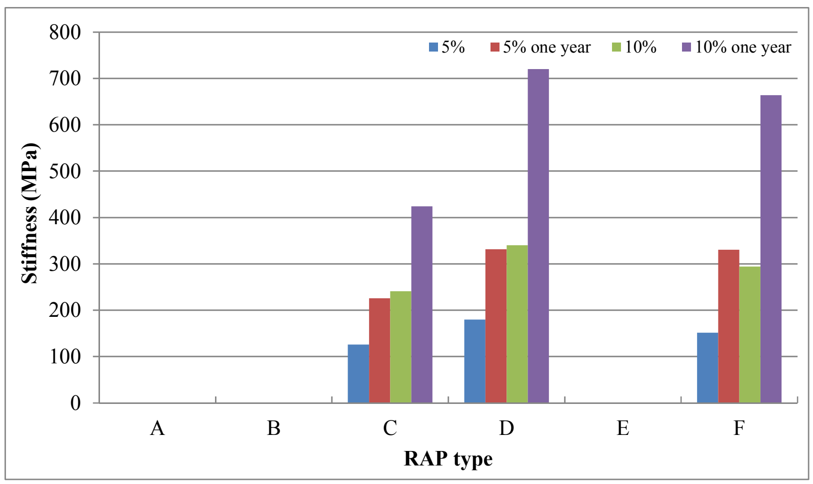
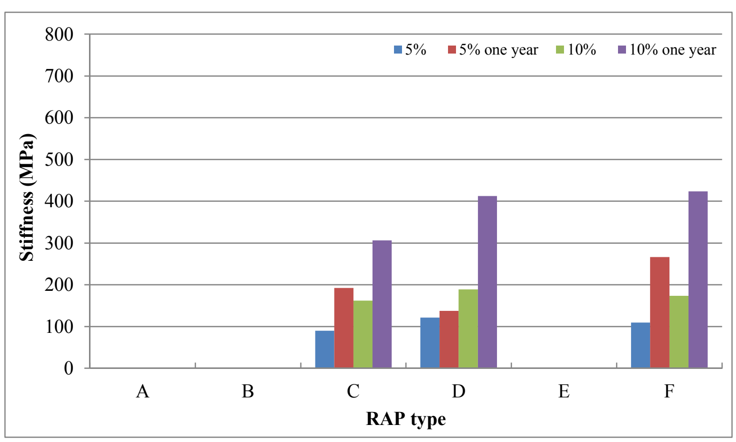
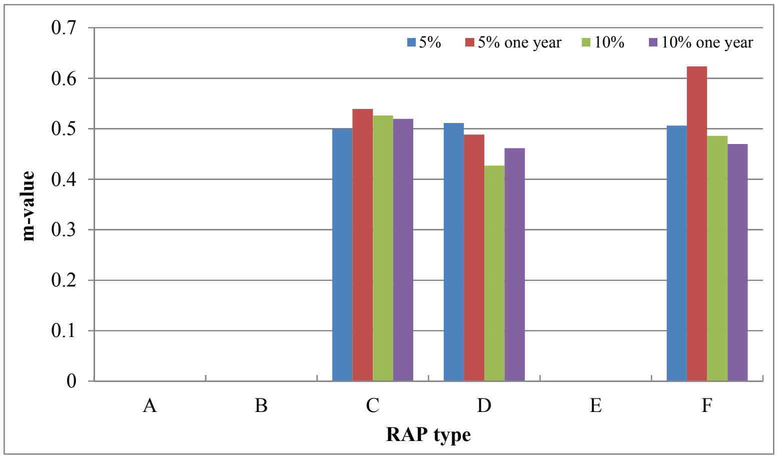


(b)

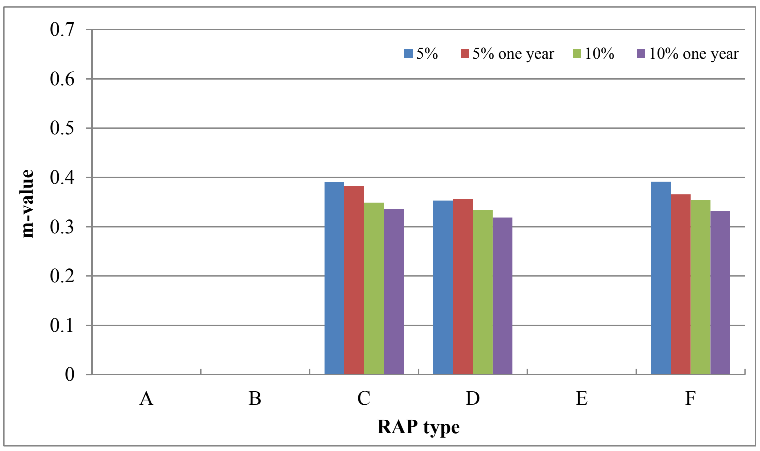


(c)

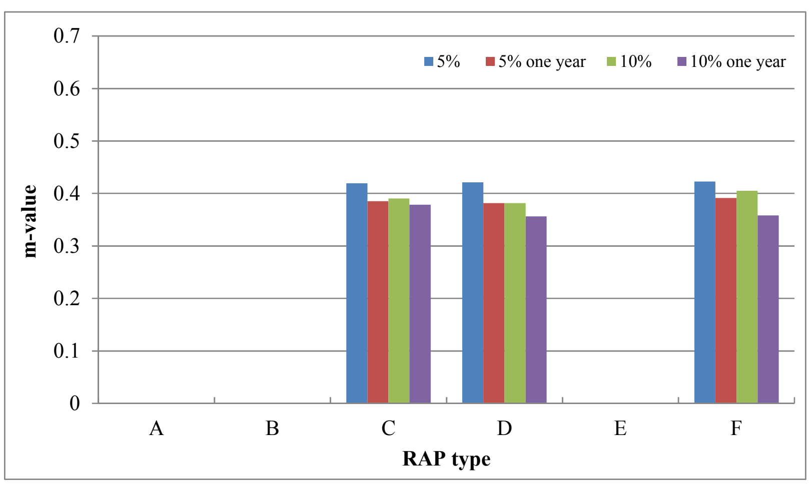
Figure 19-57: Stiffness comparisons of burned RAP sources A-F modified with virgin binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

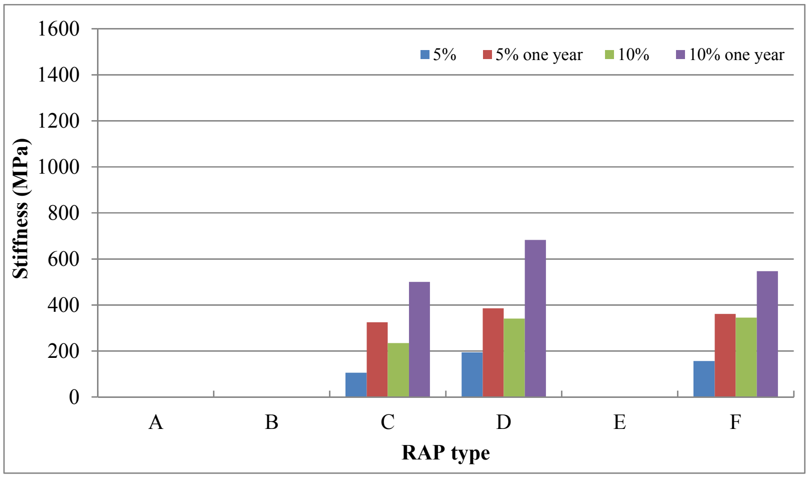


(b)

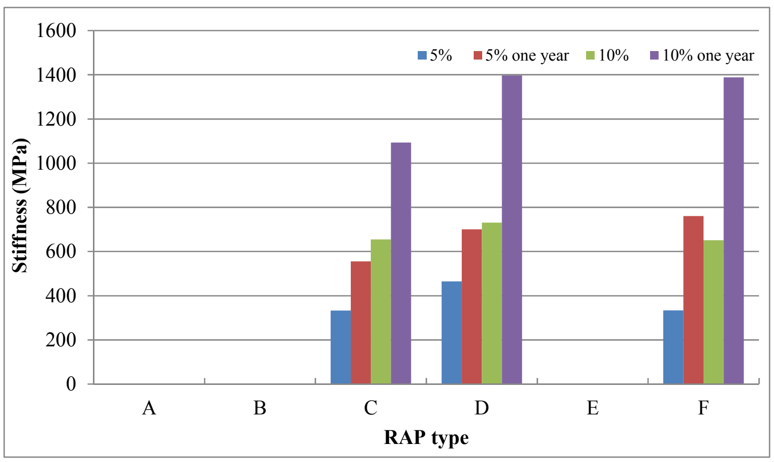


(c)

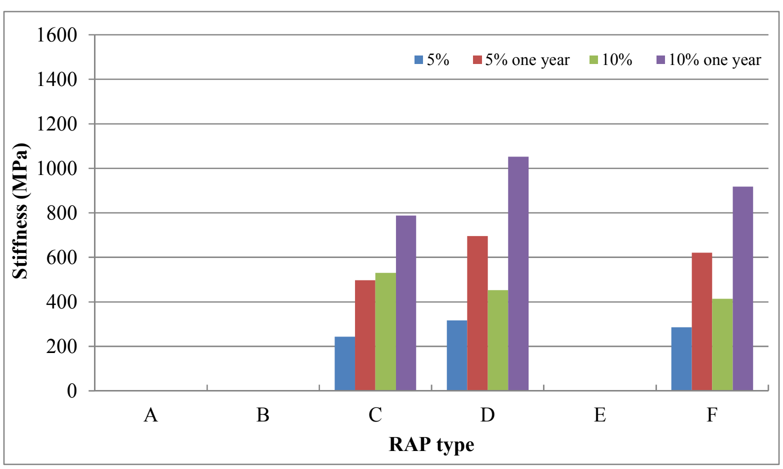
Figure 19-58: m-value comparisons of burned RAP sources A-F modified with virgin binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

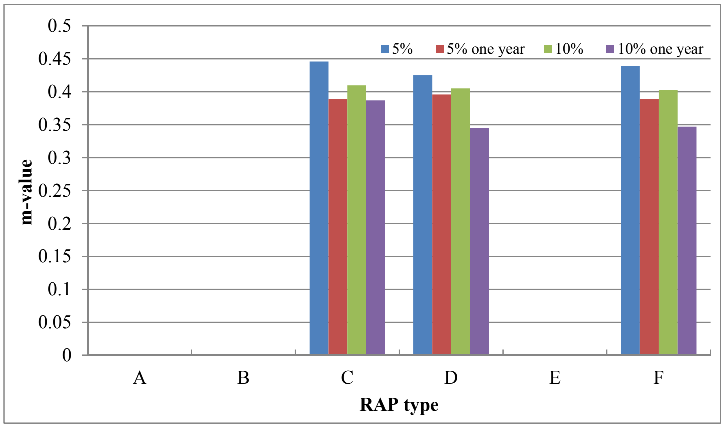


(b)

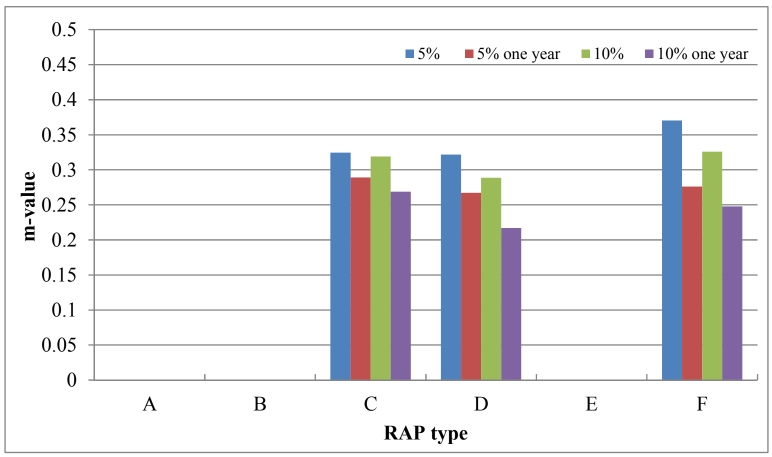


(c)

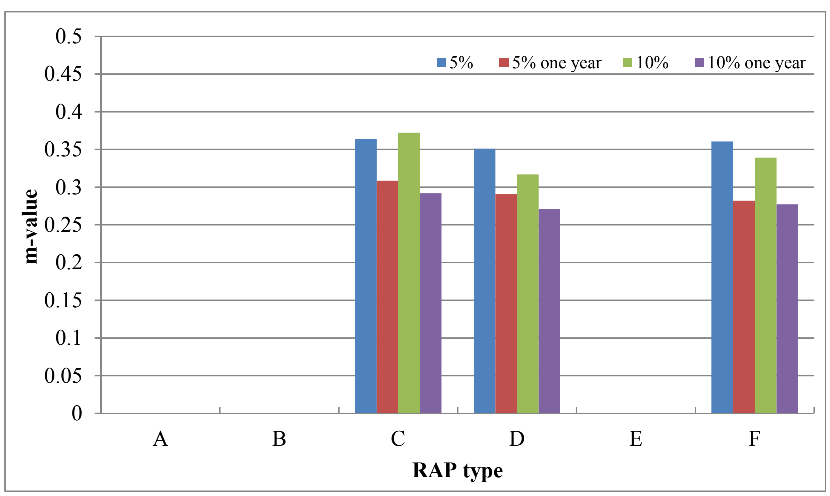
Figure 19-59: Stiffness comparisons of burned RAP sources A-F modified with virgin binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

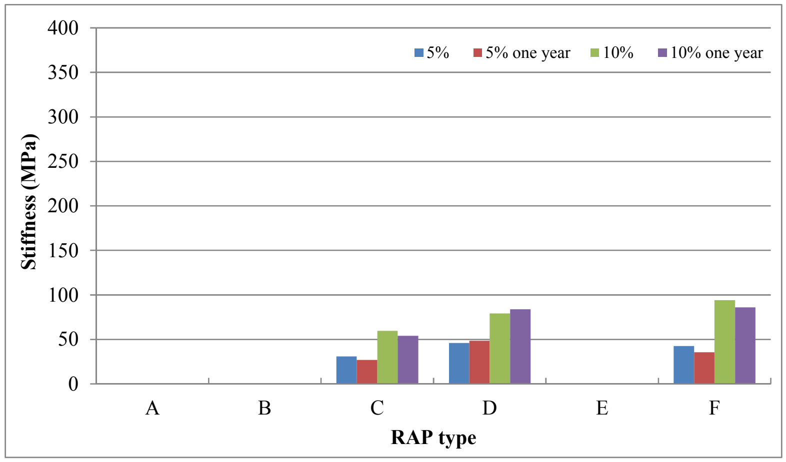


(b)

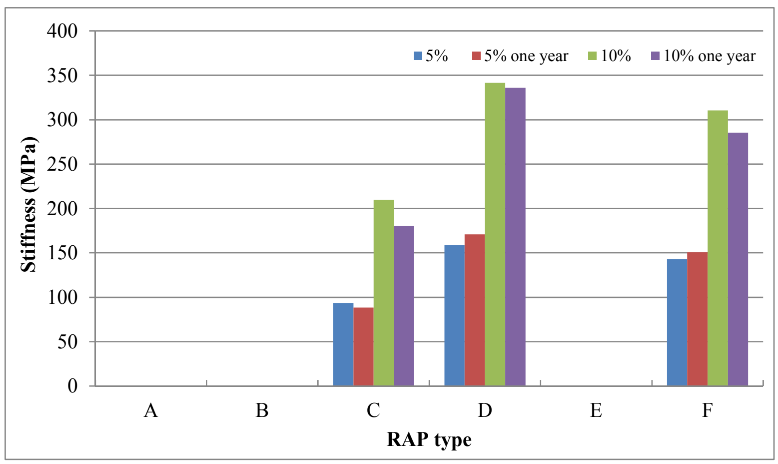


(c)

Figure 19-60: m-value comparisons of burned RAP sources A-F modified with virgin binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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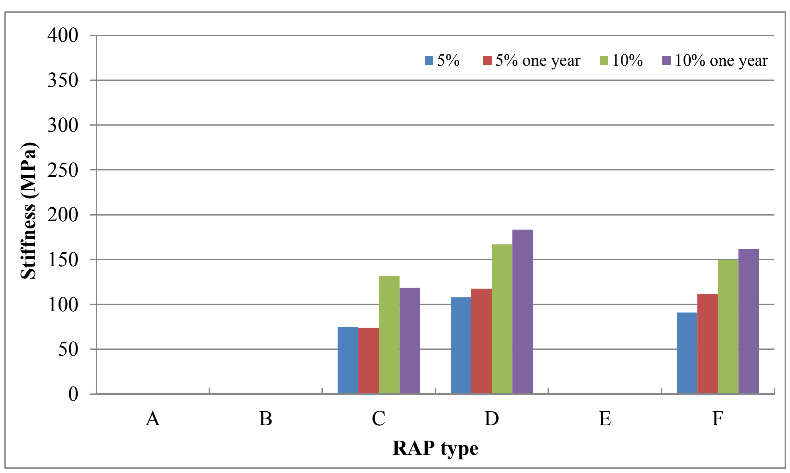
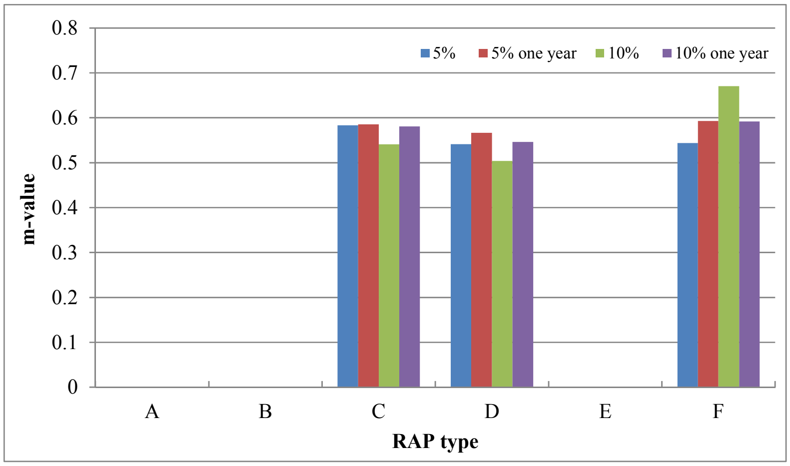
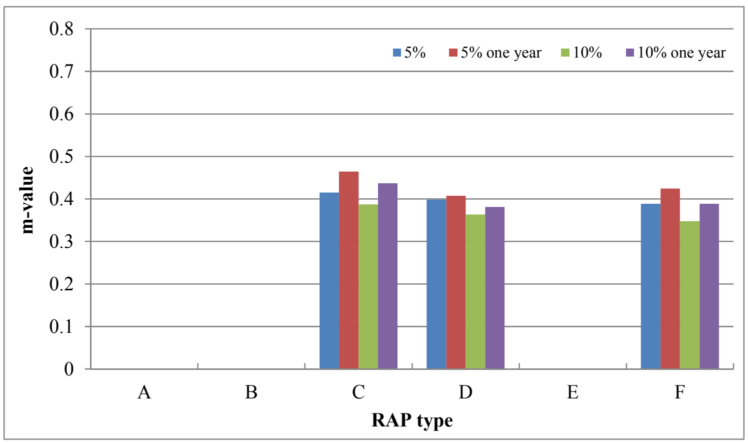


(c)

Figure 19-61: Stiffness comparisons of burned RAP sources A-F modified with RTFO binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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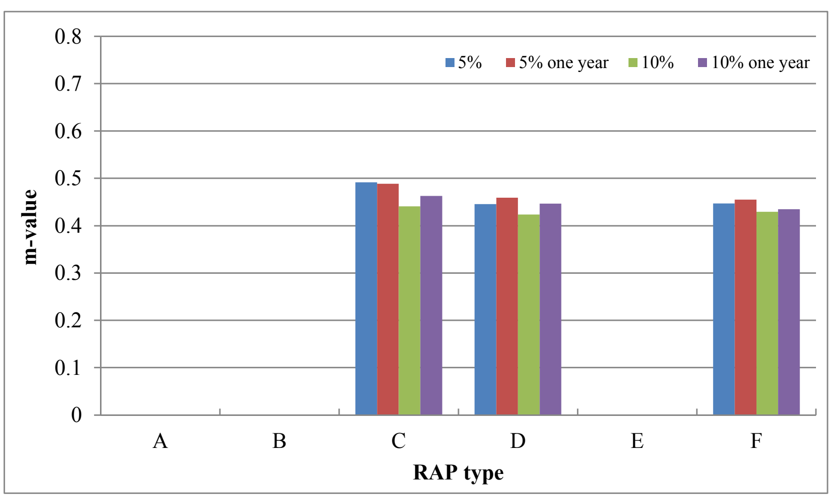
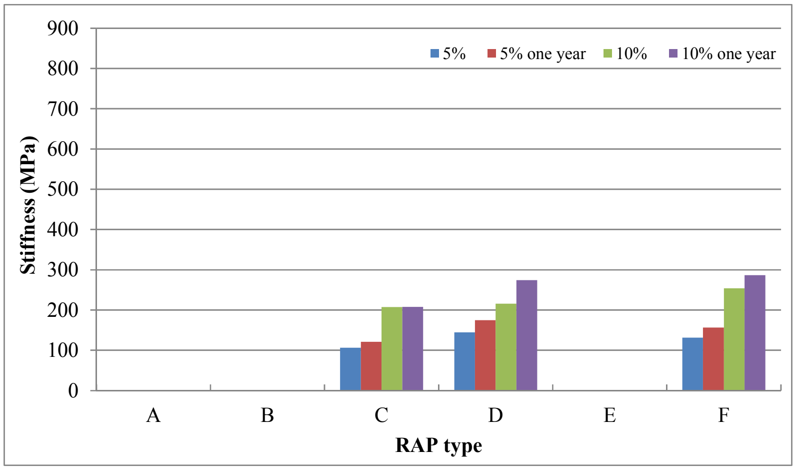


(c)

Figure 19-62: m-value comparisons of burned RAP sources A-F modified with RTFO binders at -6°C before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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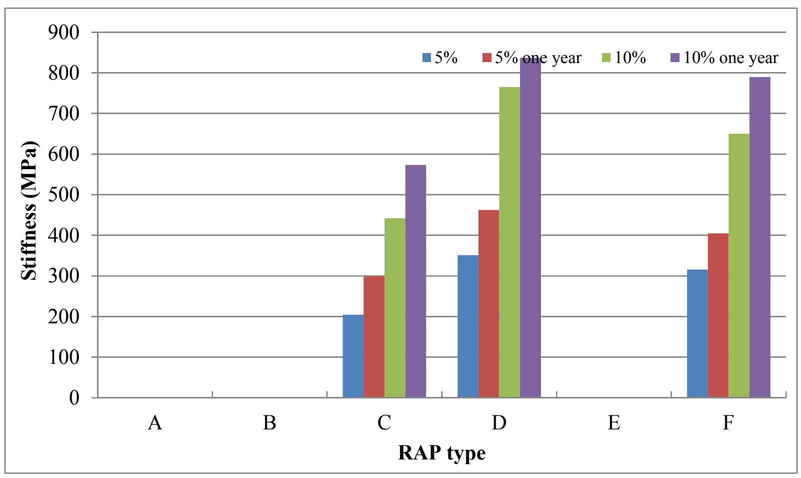

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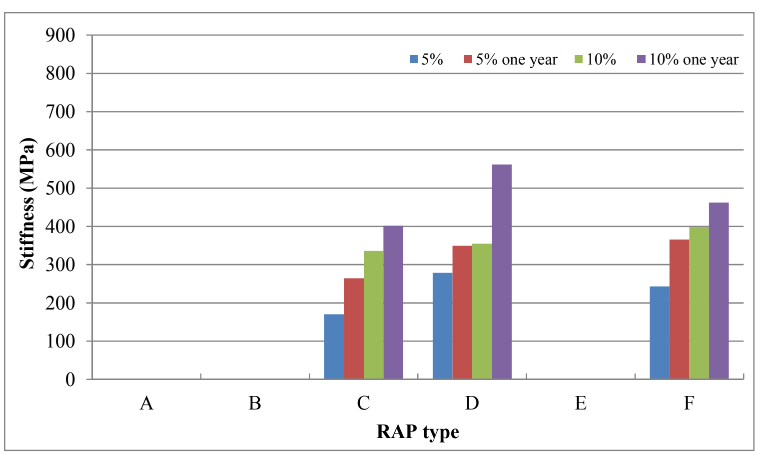
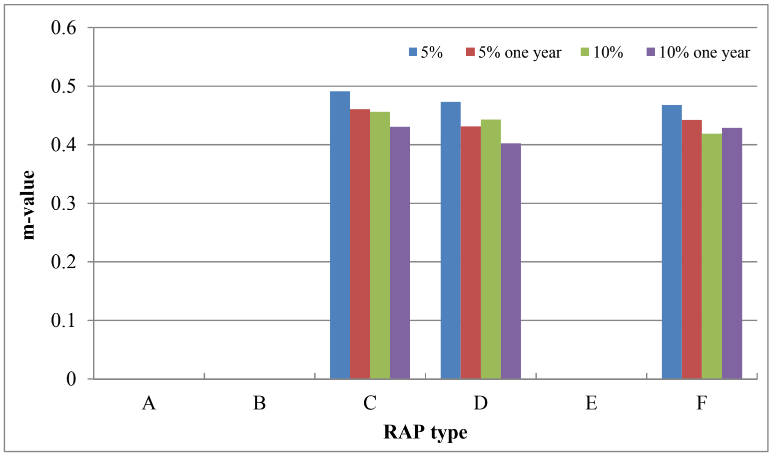
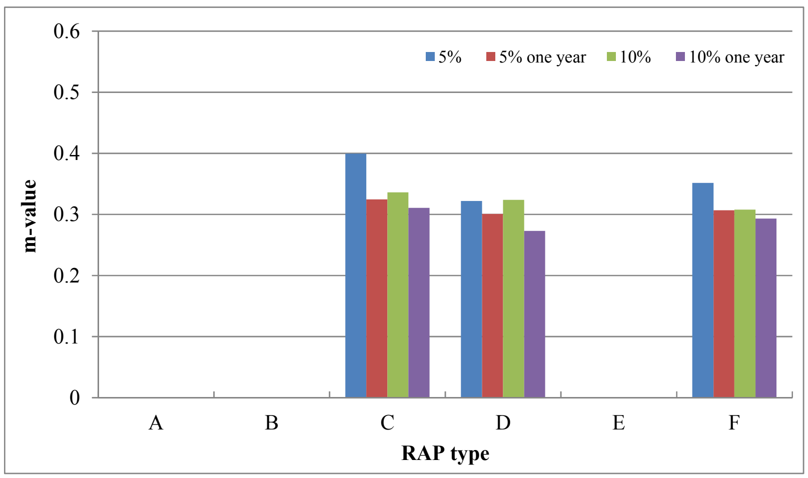


(c)

Figure 19-63: Stiffness comparisons of burned RAP sources A-F modified with RTFO binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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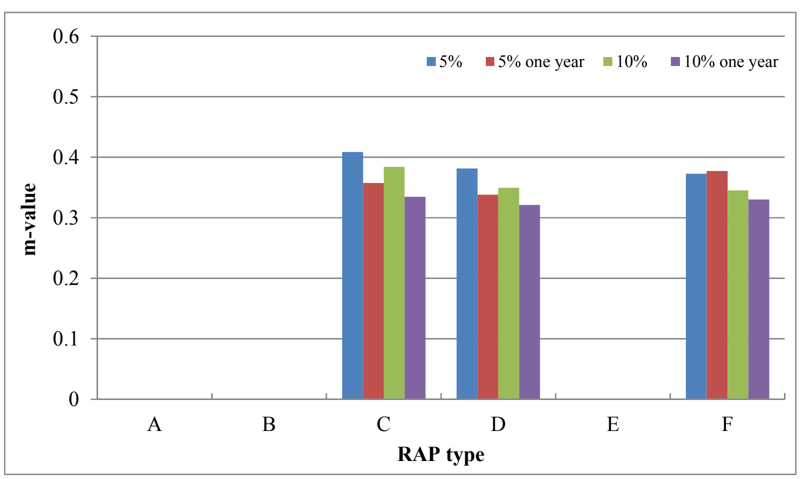
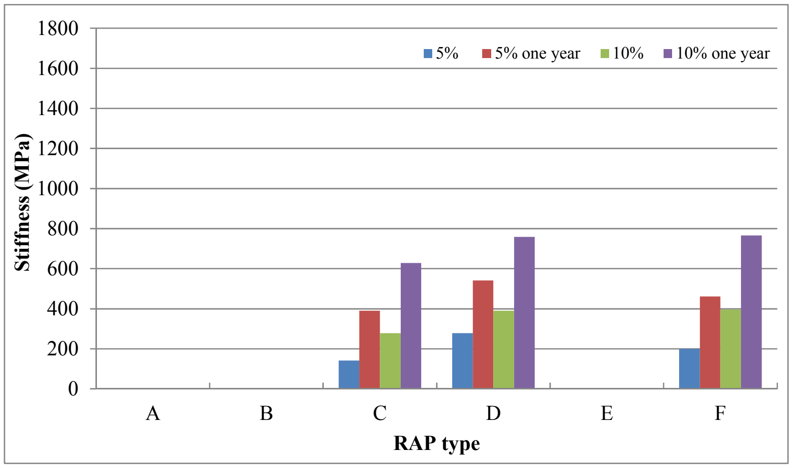
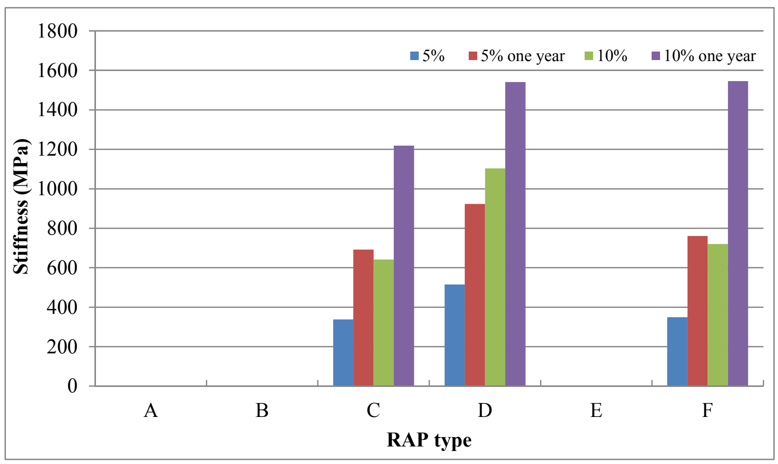


(c)

Figure 19-64: m-value comparisons of burned RAP sources A-F modified with RTFO binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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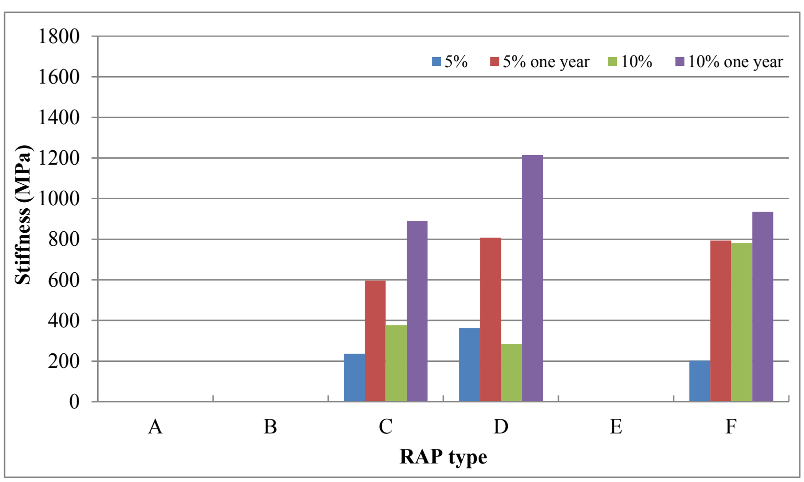
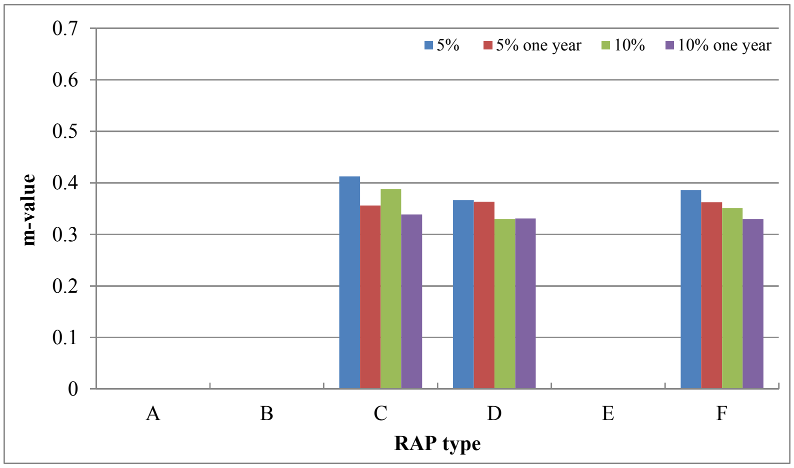
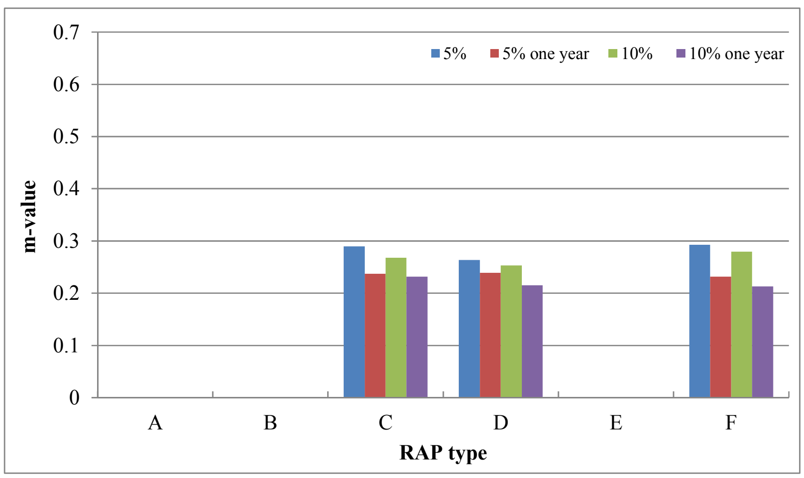


(c)

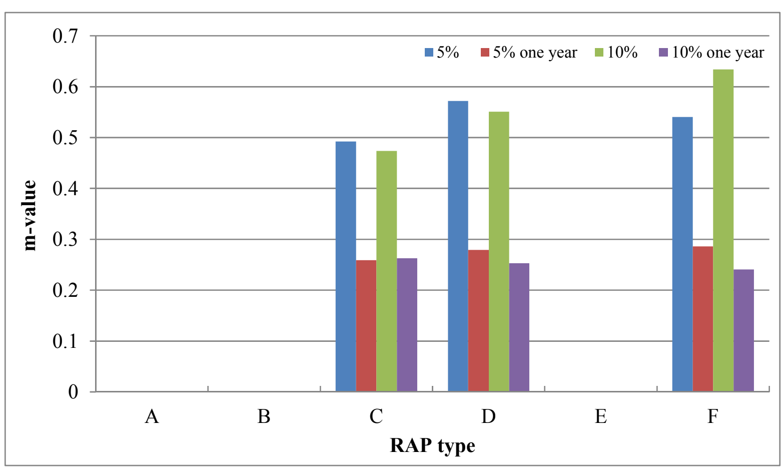
Figure 19-65: Stiffness comparisons of burned RAP sources A-F modified with RTFO binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)

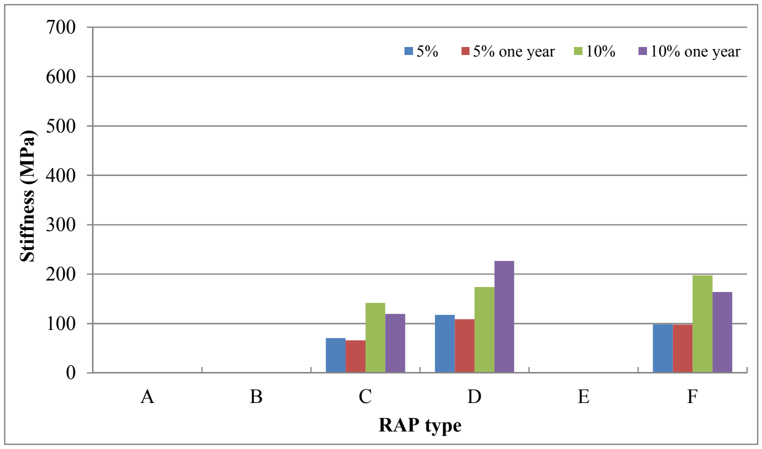


(b)



(c)

Figure 19-66: m-value comparisons of burned RAP sources A-F modified with RTFO binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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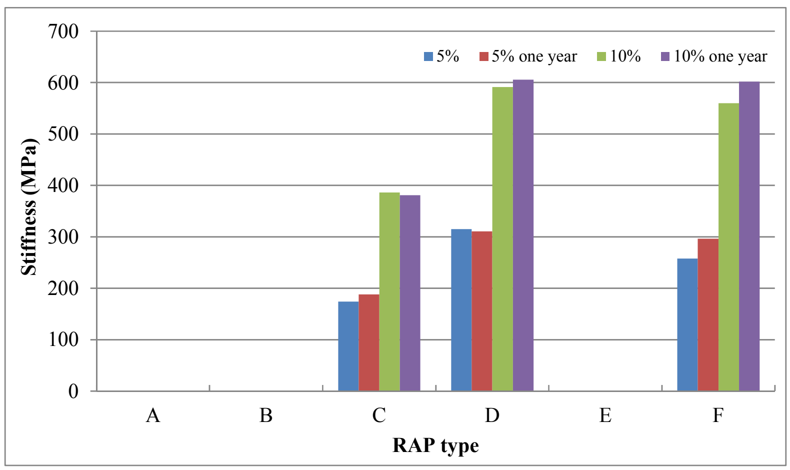

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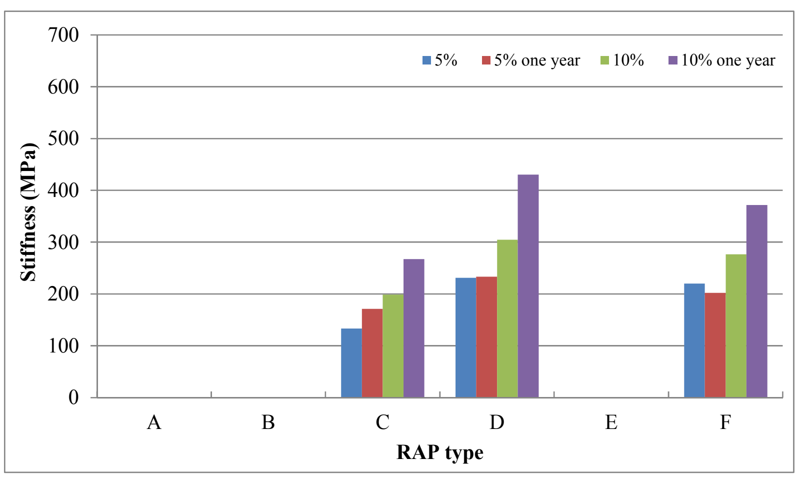
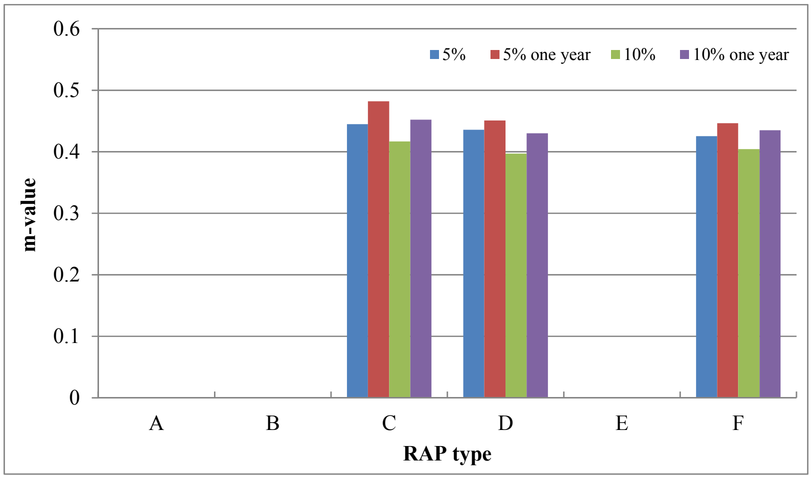
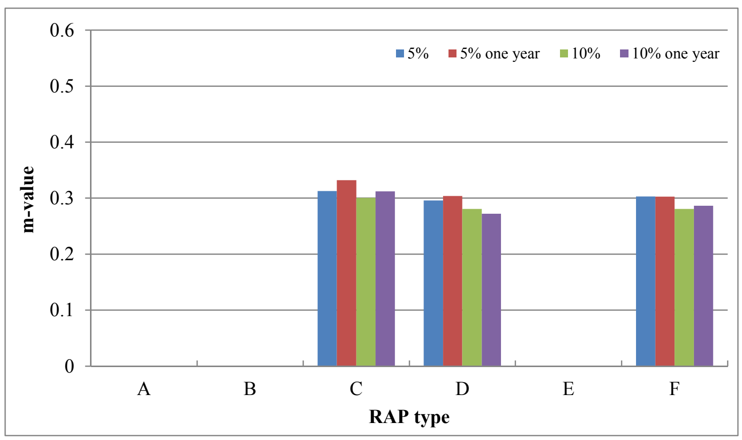


(c)

Figure 19-67: Stiffness comparisons of burned RAP sources A-F modified with PAV binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



(a)



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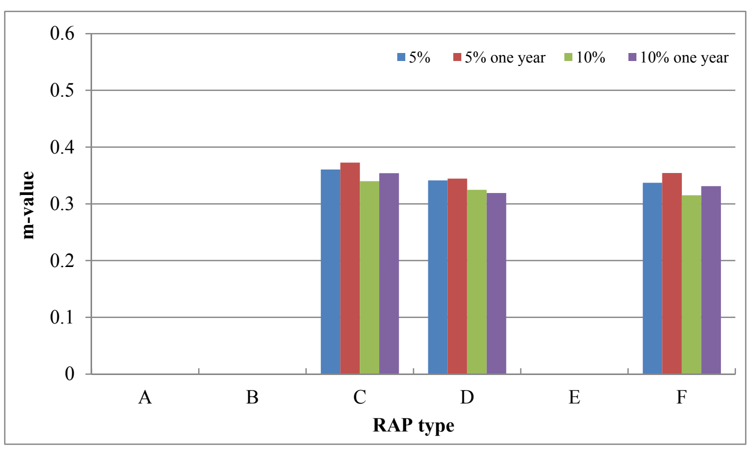
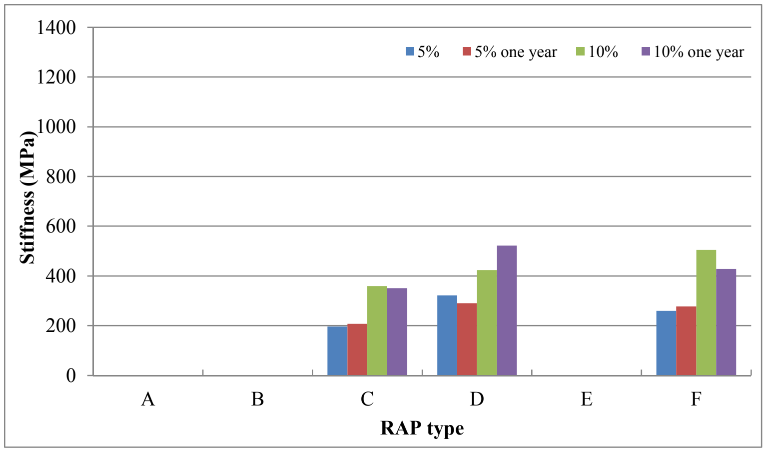


(c)

Figure 19-68: m-value comparisons of burned RAP sources A-F modified with PAV binders at -6ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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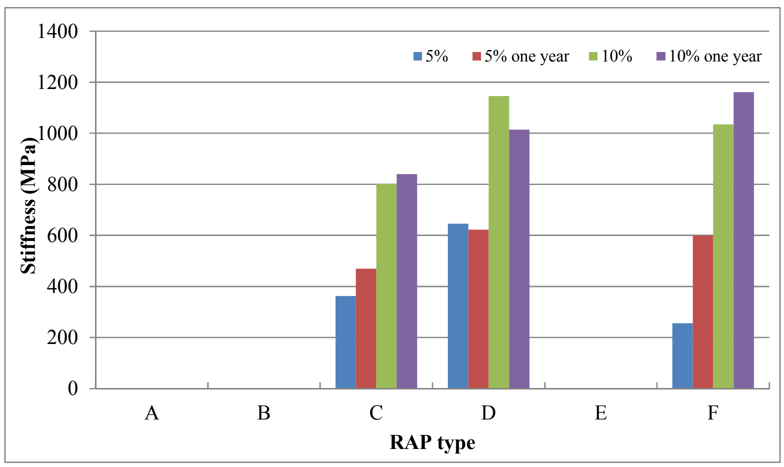

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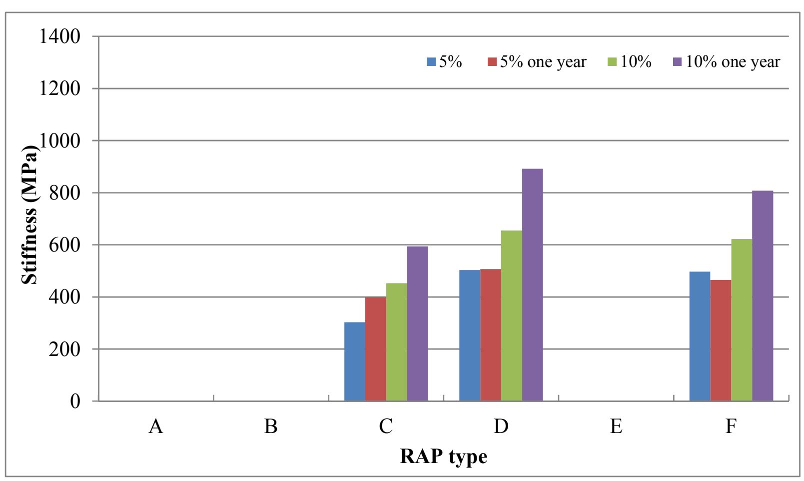
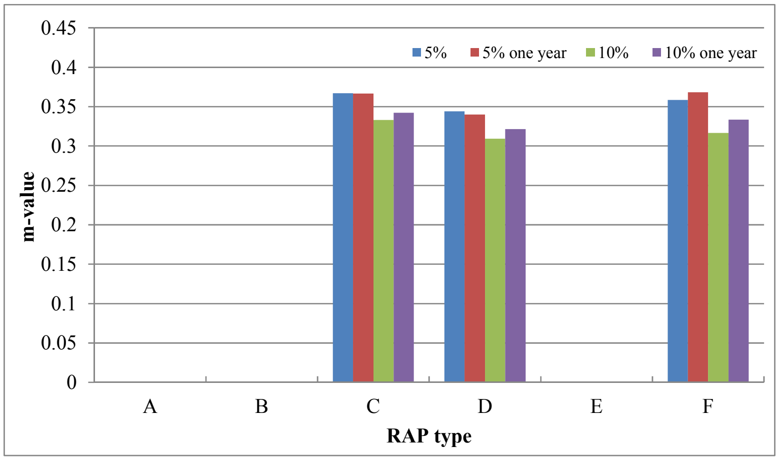


(c)

Figure 19-69: Stiffness comparisons of burned RAP sources A-F modified with PAV binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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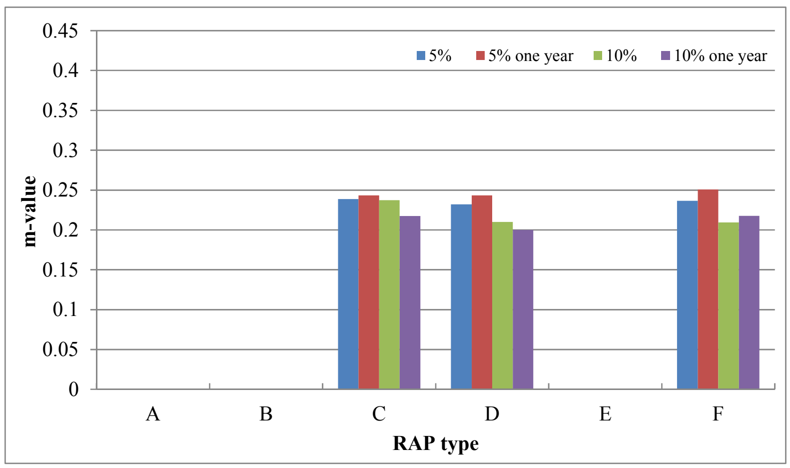

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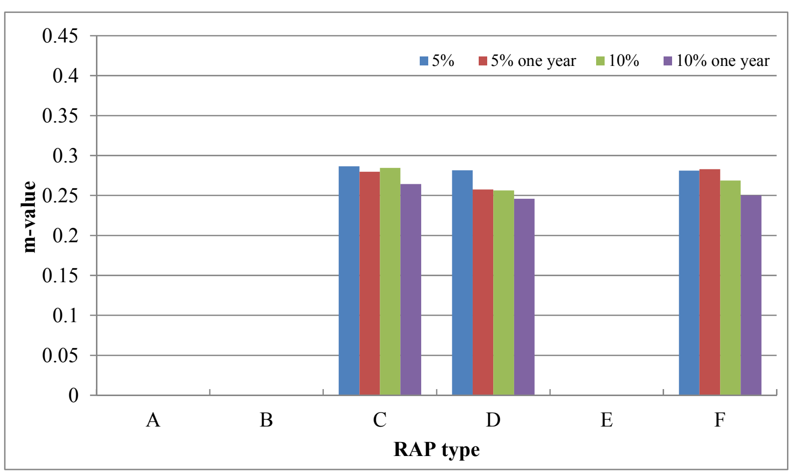
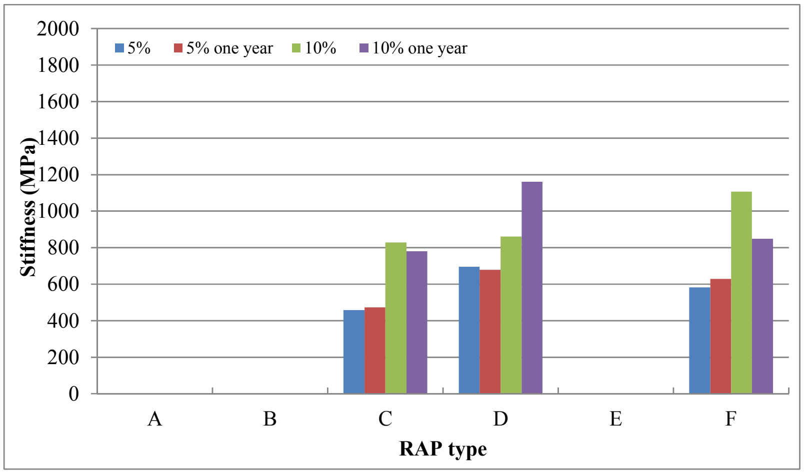


(c)

Figure 19-70: m-value comparisons of burned RAP sources A-F modified with PAV binders at -12ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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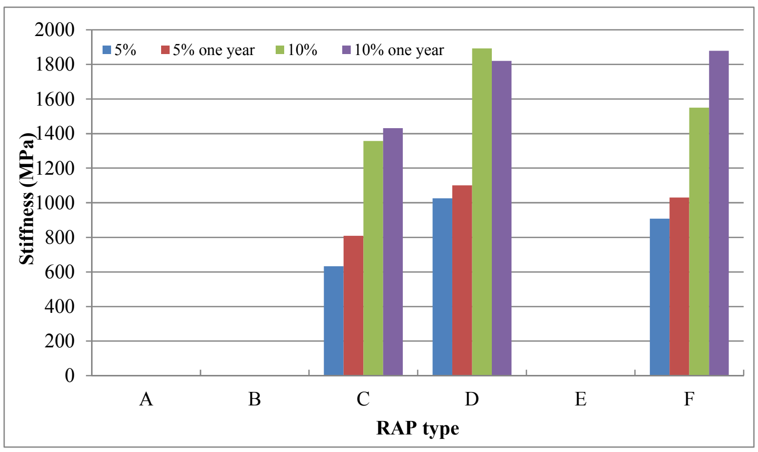

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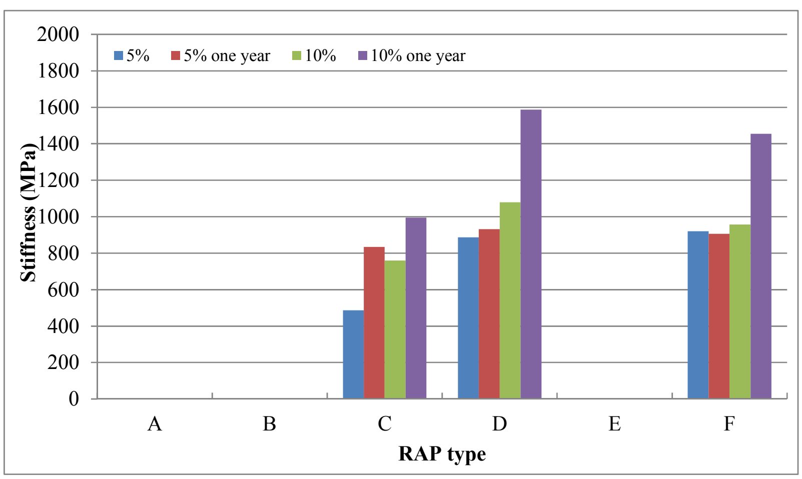
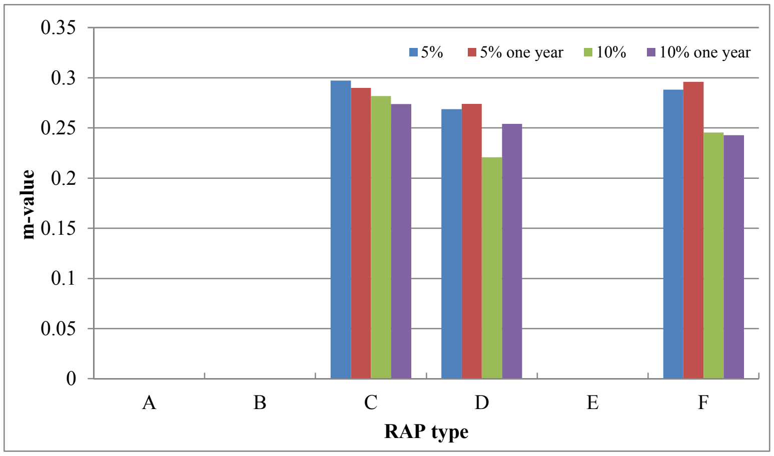


(c)

Figure 19-71: Stiffness comparisons of burned RAP sources A-F modified with PAV binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22



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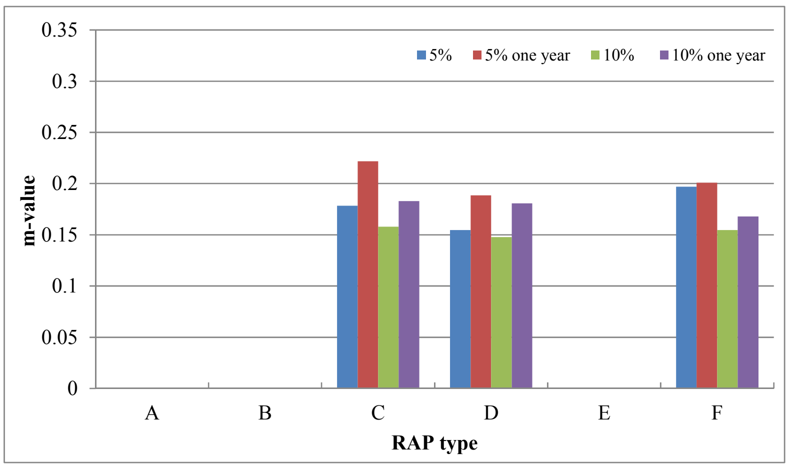

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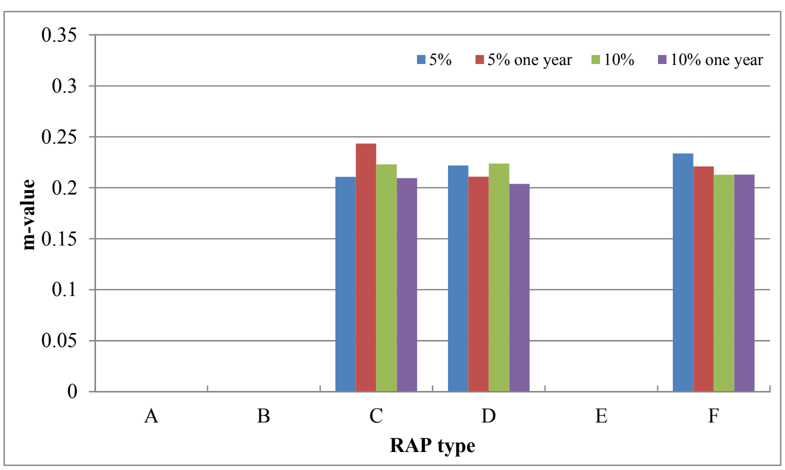

(c)

Figure 19-72: m-value comparisons of burned RAP sources A-F modified with PAV binders at -18ºC before and after one year, (a) PG 58-28, (b) PG 64-22, (c) PG 76-22

20 References: Cited or Reviewed

1. Adamson, R. M., Dempsey, J. P., and Mulmule, S. V., “Fracture Analysis of Semicircular and Semicircular-bend Geometries,” Int. J. Fract., Vol. 77, No. 3, 1996, pp. 213–222.

2. Al-Qadi, I. L., A. Loulizi, S. Aref, J.-F. Masson, and K. M. McGhee. Modification of Bending Beam Rheometer Specimen for Low- Temperature Evaluation of Bituminous Crack Sealants. Journal of the Transportation Research Board, No. 1938, 2005, pp. 97–106.

3. Asi. I. M., Wahhab, H. I. A. A. Dubabi, I. A. and Ali, M. F. (1997), “Performance modeling of Arabian asphalt using HP-GPC,” Journal of Materials Engineering and Performance, Vol. 6(4).

4. ARA, Inc. NCHRP Final Report 1-37A: Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. TRB, National Research Council, Washington, D.C., 2004.

5. ASTM E399-90, Standard Test Method for Plane–Strain Fracture Toughness of Metallic Materials. Annual Book of ASTM Standards, Vol.03.01, ASTM International, 2002, pp. 443–473.

6. Attia M. and Abdelrahman M., Modeling the Effect of Moisture on Resilient Modulus of Untreated Reclaimed Asphalt Pavement Transportation Research Record: Journal of the Transportation Research Board, No. 2167, 2010, pp. 30–40.

7. Ayatollahi, M. R., and Aliha, M. R. M., “On Determination of Mode II Fracture Toughness Using Semicircular Bend Specimen,” Int. J. Solids Struct., Vol. 43, No. 17, 2006, pp. 5217– 5227.

8. Basic Asphalt Recycling Manual (BARM). Asphalt Recycling and Reclaiming Association, Annapolis, Md., 2001.

9. Behnia B., Dave E. V., Ahmed S., Buttlar W. G.,and Reis H. Effects of Recycled Asphalt Pavement Amounts on Low-Temperature Cracking Performance of Asphalt Mixtures Using Acoustic Emissions, Transportation Research Record: Journal of the Transportation Research Board, No. 2208, 2011, pp. 64–71.

10. Bejarano, M. O., and J. T. Harvey. Deep In Situ Recycling of Asphalt Concrete Pavements as Granular Base—Design, Construction and Performance Evaluation Experience in California. Proc., 8th Conference on Asphalt Pavements for South Africa, Sun City, North West Province, South Africa, 2004.

11. Beyond Roads, Questions and Answers (BRQA). Asphalt Education Partnership. www.beyondroads.com/index.cfm?fuseaction□page&filename□asphalt QandA.htm. Accessed March 15, 2006.

12. Breen J., and Stephens J, The glass transition temperature and mechanical properties of asphalt, report No. JHR-67-16, 1967

13. Burr, B. L., R. R. Davison, H. B. Jemison, C. J. Glover, and J. A. Bullin. Asphalt Hardening in Extraction Solvents. In Transportation Research Record 1323, TRB, National Research Council, Washington, D.C., 1991. pp. 70–76.

14. Carey, D. E., and M. R. Paul. Evaluation of Asphalt Cement Extraction and Recovery Methods. FHWA, U.S. Department of Transportation, 1982.

15. Chong, K. P., and Kuruppu, M. D., "New Specimen for Fracture Toughness Determination for Rock and Other Materials," Int. J. Fract., Vol. 26, 1984, pp. R59–R62.

16. Cipione, C. A., R. R. Davison, B. L. Burr, C. J. Glover, and J. A. Bullin. Evaluation of Solvents for Extraction of Residual Asphalt from Aggregates. In Transportation Research Record 1323, TRB, National Research Council, Washington, D.C., 1991, pp. 47–52.

17. Daniel, J. S., and A. Lachance. Mechanistic and Volumetric Properties of Asphalt Mixtures with Recycled Asphalt Pavement. In Transportation Research Record: Journal of the Transportation Research Board, No. 1929, 2005, pp. 28–36.

18. Daniel J. S., Pochily J. L., and 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, Transportation Research Record: Journal of the Transportation Research Board, No. 2180, 2010, pp. 19–29.

19. Full Depth Reclamation (FDR). Asphalt Recycling and Reclaiming Association, Annapolis, Md. http://www.arra.org/full_depth_reclamation.html. Accessed Nov. 15, 2006.

20. Hofman, R., S. M. Oosterbaan, J. G. Erkens, and J. van der Kooij. Semi- Circular Bending Test to Assess the Resistance Against Crack Growth. 6th RILEM Symposium on Performance Testing and Evaluation of Bituminous Materials, Zurich, Switzerland, 2003, pp. 257–263.

21. Hong F., Chen D., and 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 Transportation Research Record: Journal of the Transportation Research Board, No. 2180, 2010, pp. 58–66.

22. Huang, B., Shu, X., and Zuo, G., "Laboratory Evaluation of Semicircular Bending Tensile Strength Test for Hot-Mix Asphalt Mixtures," TRB 2005 Annual Meeting CD-ROM, Paper No. 05-0130.

23. Huang, Y. H. Pavement Analysis and Design. Prentice Hall, Englewood Cliffs, N.J., 1993.

24. Jennings, P. W. (1980), "High Pressure liquid chromatography as a method of measuring asphalt composition," Report No. FHWA-MT-7930, Dept. of Chemistry, Montana St. Univ., Bozeman, Mt.

25. Jeon E., Steven B., and Harvey J. T., Comprehensive Laboratory Testing and Performance Evaluation of Recycled Pulverized Hot-Mix Asphalt Material

Transportation Research Record: Journal of the Transportation Research Board, No. 2104, 2009, pp. 42–52

26. Kandhal, P. S., S. S. Rao., D. E. Watson, and B. Yound. Performance of Recycled Hot Mix Asphalt Mixtures. Research Report 95-1, National Center for Asphalt Technology, Auburn, Ala., 1995.

27. Kandhal, P. S., and K. Y. Foo. Designing Recycled Hot Mix Asphalt Mixtures Using Superpave Technology. Report 96-5. National Center for Asphalt Technology, Auburn, Ala., 1997.

28. Kearney, E. J., and J. E. Huffman. Full-Depth Reclamation Process. In Transportation Research Record: Journal of the Transportation Research Board, No. 1684, TRB, National Research Council, Washington, D.C., 1999, pp. 203–209.

29. Kim, K. W., Burati, J. L. and Amirkhanian, S. N. (1993), “Relation of HP-GPC profile with mechanical properties of AC mixtures,” Journal of Materials in Civil Engineering, ASCE, Vol. 5(4), pp. 447-459.

30. Kim, K. W., Burati, J. L. and J. S. Park. (1995), “Methodology for defining LMS portion in asphalt chromatogram,” Journal of Materials in Civil Engineering, ASCE, Vol. 7(1), pp. 31-40.

31. Kim, K. W., Doh, Y. S. and Amirkhanian, S. N. (2004), “Effect of polymers on aging of asphalt binder,” Journal of Korean Society of Pavement Engineers, Vol. 6(2).

32. Kondrath, E. S. Reclaimed Asphalt Pavement in Hot Mix Asphalt. New Jersey DOT Bureau of Research. Quarterly Progress Report. Trenton, N.J., Jan. 1–March 31, 2009.

33. Lathe, G.H.; Ruthven, C.R.J. The Separation of Substance and Estimation of their Relative Molecular Sizes by the use of Columns of Starch in Water. Biochem J. 1956, 62, 665–674.

34. Moore, J.C. Gel permeation chromatography. I. A new method for molecular weight distribution of high polymers. J. Polym. Sci., 1964, 2, 835-843

35. Lim, I. L., Johnston, I. W., Choi, S. K., and Boland, J. N., “Fracture Testing of a Soft Rock with Semicircular Specimens Under Three-point Bending, Part 2—Mixed-mode,” Int. J. Rock Mech. Min. Sci., Vol. 31, No. 3, 1994, pp. 199–212.

36. Li, X., T. R. Clyne, and M. O. Marasteanu. Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality. Report Mn/DOT 2005- 02. Minnesota Department of Transportation, Maplewood, Minn., July 2004.

37. Li X., Marasteanu M. O., Williams R. C., and Clyne T. R., Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures, Transportation Research Record: Journal of the Transportation Research Board, No. 2051, 2008, pp. 90–97.

38. Li, X., M. O. Marasteanu, and M. Turos. Study of Low Temperature Cracking in Asphalt Mixtures Using Mechanical Testing and Acoustic Emission Methods. Journal of the Association of Asphalt Paving Technologists, Vol. 76, 2007, pp. 274–294.

39. Loria L., Hajj E. Y., Sebaaly P. E., Barton M., Kass S., and Liske T., Performance Evaluation of Asphalt Mixtures with High Recycled Asphalt Pavement Content, Journal of the Transportation Research Board, No. 2208, 2011, pp. 72–81.

40. Ma T., Mahmoud E., and Bahia H.U., Estimation of Reclaimed Asphalt Pavement Binder Low-Temperature Properties Without Extraction Development of Testing Procedure Journal of the Transportation Research Board, No. 2179, 2010, pp. 58–65.

41. McDaniel, R. Performance Tests for RAP Mixtures and Update on RAP Plant Mix Study. Presented at 2008 Meeting of the FHWA Expert Task Group on RAP, Oct. 2008.

42. Mogawer W. S., Austerman A. J., Bonaquist R., and Roussel M., Performance Characteristics of Thin-Lift Overlay Mixtures High Reclaimed Asphalt Pavement Content, Recycled Asphalt Shingles, and Warm-Mix Asphalt Technology, Transportation Research Record: Journal of the Transportation Research Board, No. 2208, 2011, pp. 17–25.

43. Mogawer W. S., Austerman A. J., and Bonaquist R. "Determining the Influence of Plant Type and Production Parameters on Performance of Plant-Produced Reclaimed Asphalt Pavement Mixtures," Journal of the Transportation Research Board, No. 2268, 2012, pp. 71–81.

44. NCHRP Synthesis of Highway Practice 54: Recycling Materials for Highways. TRB, National Research Council, Washington, D.C., 1978, p. 1.

45. Peterson, R. L., H. R. Soleymani, R. M. Anderson, and R. S. McDaniel. Recovery and Testing of RAP Binders from Recycled Asphalt Pavements. Journal of the Association of Asphalt Paving Technologies, Vol. 69, 2000, p. 72.

46. Scullion, T., W. S. Guthrie, and S. D. Sebesta. Field Performance and Design Recommendations for Full Depth Recycling in Texas. Report 0-4182-1. Texas Transportation Institute, Texas A&M University System, College Station, March 2003.

47. Shah A., McDaniel R. S., Huber G. A., and Gallivan V.L. Investigation of Properties of Plant-Produced Reclaimed Asphalt Pavement Mixtures, Journal of the Transportation Research Board, No. 1998, 2007, pp. 103–111.

48. Shen J., Amirkhanian S.N. and Xiao F., "High-Pressure Gel Permeation Chromatography Characterization of Aging of Recycled Crumb-Rubber-Modified Binders Containing Rejuvenating Agents" , Journal of Transportation Research Board (TRB), Washington D.C., No. 1962, pp 21-27, 2006

49. Soleymani, H. R., H. U. Bahia, and A. T. Bergan. Time-Temperature Dependency of Blended and Rejuvenated Asphalt Binders. Journal of the Association of Asphalt Paving Technologists, Vol. 68, 1999, pp. 129–152.

50. Steven, B. D., L. Lane, and J. T. Harvey. Life Cycle Cost Analysis for Pulverized Hot-Mix Asphalt Used As an Unbound Base. Draft Technical Memorandum UCPRC-TM-2008-09. University of California Pavement Research Center, Davis, 2008.

51. Stroup-Gardiner, M., and J. W. Nelson. Use of Normal Propyl Bromide Solvents for Extraction and Recovery of Asphalts Cements. NCAT 2000-06, National Center for Asphalt Technology, Auburn, Ala., 2000.

52. Sullivan, J. Pavement Recycling Executive Summary and Report. Report FHWA-SA-95-060, FHWA, U.S. Department of Transportation, March 1996.

53. Swiertz D., Mahmoud E., and Bahia H. U., Estimating the Effect of Recycled Asphalt Pavements and Asphalt Shingles on Fresh Binder, Low-Temperature Properties Without Extraction and Recovery Transportation Research Record: Journal of the Transportation Research Board, No. 2208, 2011, pp. 48–55.

54. Tran B. T. and Hassan R. A., Performance of Hot-Mix Asphalt Containing Recycled Asphalt Pavement Transportation Research Record: Journal of the Transportation Research Board, No. 2205, 2011, pp. 121–129.

55. Tabatabaee, H. A., Velasquez, R. A., Bahia, H, Modeling Thermal Stress in Asphalt Mixtures Undergoing Glass Transition and Physical Hardening, TRB CD-ROM, 2012

56. Wagoner, M. P., W. G. Buttlar, G. H. Paulino, and P. Blankenship. Investigation of the Fracture Resistance of Hot-Mix Asphalt Concrete Using a Disk-Shaped Compact Tension Test. Journal of the Transportation Research Board, No. 1929, 2005, pp. 183–192

57. Watson D. E., Vargas-Nordcbeck A., Moore J., Jared D., and P. Wu, Evaluation of the Use of Reclaimed Asphalt Pavement in Stone Matrix Asphalt Mixtures, Transportation Research Record: Journal of the Transportation Research Board, No. 2051, 2008, pp. 64–70.

58. West R., Kvasnak A., Tran N., Powell B., and 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. Journal of the Transportation Research Board, No. 2126, 2009, pp. 100–108.

59. West, R. Top 10 Needs. Presented at the HMA Recycling Expert Task Group, Manchester, N.H., April 2009.

60. Weissman, S. L., J. Harvey, J. L. Sackman, and F. Long. Selection of Laboratory Test Specimen Dimension for Permanent Deformation of Asphalt Concrete Pavements. Journal of the Transportation Research Board, No. 1681, 1999, pp. 113–120.

61. Xiao F., Amirkhanian S.N., and Wu B., "Fatigue and Stiffness Evaluations of Reclaimed Asphalt Pavement in Hot Mix Asphalt Mixtures", Journal of Testing and Evaluation(ASTM), Vol. 39, No.1, *pp*. 50-58, 2011

62. Xiao F., Amirkhanian S. N. and Juang H.C., "Rutting Resistance of Rubberized Asphalt Concrete Pavement Containing Reclaimed Asphalt Pavement Mixtures", Journal of Materials in Civil Engineering (ASCE) Vol. 19, No.6, pp 475-483, 2007